Appendix H. Central Valley Chinook Salmon Rearing Habitat Required to Satisfy the Anadromous Fish Restoration Program Doubling Goal

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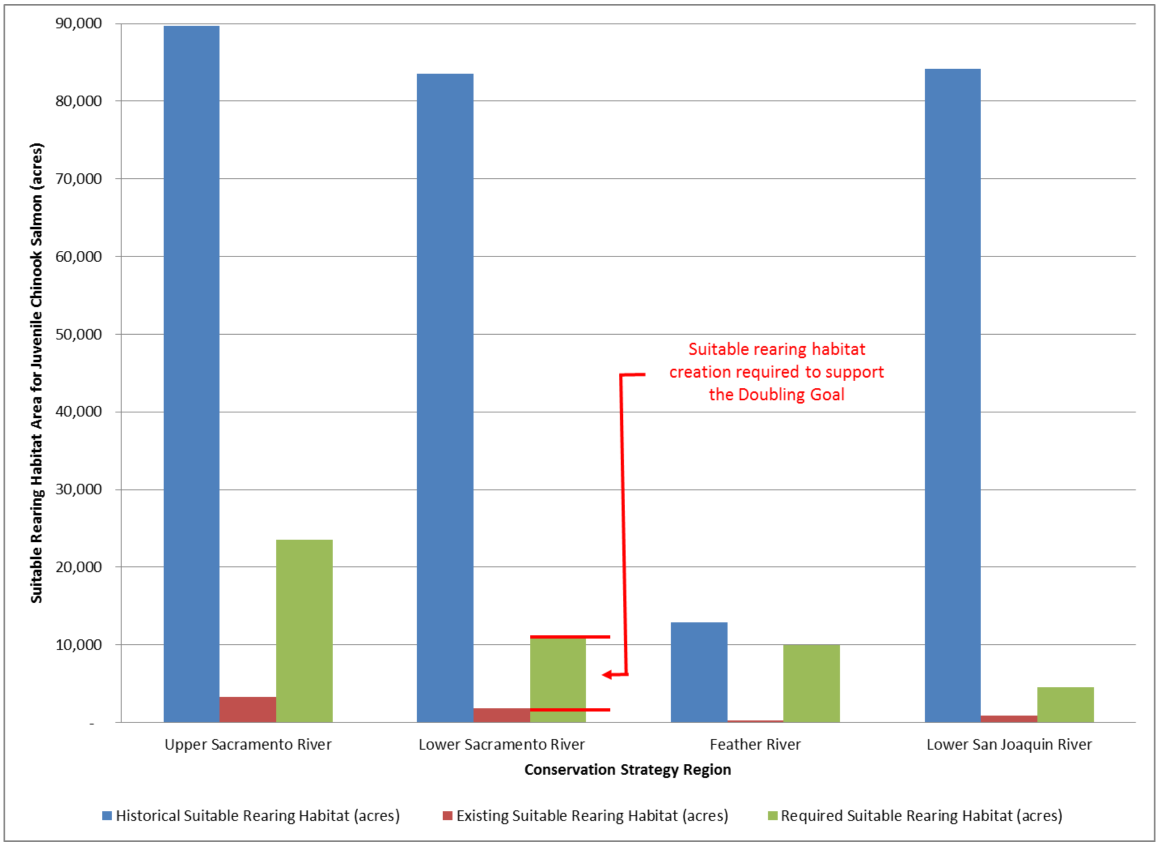
1.0 Executive Summary

NewFields and Cramer Fish Sciences, in collaboration with the California Department of Water Resources FloodSAFE Environmental Stewardship and Statewide Resources Office Conservation Strategy team, applied best available tools and data to estimate the area of suitable juvenile salmonid rearing habitat required in each of the Conservation Planning Areas (CPAs) to achieve the Anadromous Fish Restoration Program (AFRP) "doubling goal" for Chinook salmon populations. The AFRP goal was used to align the Conservation Strategy objectives with existing, long-standing efforts by partner resource management agencies. Historical and existing suitable rearing habitat area for juvenile salmonids was estimated with the Estimated Annual Habitat approach that uses measured hydrology and modeled hydraulic relationships between river flow and inundation area to calculate areas of inundation with timing, duration, and frequency suitable for juvenile California Chinook salmon rearing. The rearing habitat required to support the doubling goal populations was estimated using the Emigrating Salmonid Habitat Estimation model. The details of the approach and the full range of calculated results are presented in the following sections and appendices.

Figure 1-1 is a comparison of average estimates of historical, existing, and required suitable rearing habitat for juvenile salmonids (to achieve the AFRP doubling goal) in each CPA. "Historical Rearing Habitat" is the area of physically suitable habitat historically (i.e., before construction of Central Valley dams and levees) inundated with timing, duration, and frequency suitable for juvenile Chinook salmon rearing. "Existing Rearing Habitat" is the area of physically suitable habitat currently inundated (i.e. after construction of Central Valley dams and levees) with timing, duration, and frequency suitable for juvenile Chinook salmon rearing. "Required Rearing Habitat" is the area of suitable habitat needed to support the AFRP doubling goal for Chinook salmon in the Central Valley. The area of suitable rearing habitat creation that would support the doubling goal is the difference between Required Rearing Habitat and Existing Rearing Habitat. Historical Rearing Habitat provides an unimpaired frame of reference for each CPA. It is important to note that creating sufficient suitable rearing habitat to bridge the gap between Required Rearing Habitat and Existing Rearing Habitat calculated for each CPA is not necessarily the charge of the Central Valley Flood Protection Plan. However, the Conservation Strategy will be able to use the information from this analysis as a measure to evaluate incremental progress toward satisfying suitable rearing habitat required to support the doubling goal in each CPA.



Note: Historical and existing values assume average suitability of the total area inundated by flows with timing, duration, and frequency suitable for juvenile California Chinook salmon rearing. Required values assume migration, growth, and survival rates averaged for early and late migration strategy juvenile salmonid life histories.

Figure 1-1. Summary of *Average* Historical, Existing, and Required Suitable Rearing Habitat Area to Support the AFRP Doubling Goal in Each of the CPAs

2.0 Introduction and Purpose

To restore degraded river corridors and develop large-scale, sustainable watershed strategies, it is essential for managers to consider the habitat requirements of keystone (focal) species and reestablish the amount and range of habitat features under which such species prosper. An important component of a habitat restoration plan is development of an evaluation strategy to assess the effectiveness of restoration efforts and improve future programs. To maximize the benefits of restoration activities and to increase the likelihood of success and cost-effectiveness of restoration programs, decisions about locations and amounts of habitat to be restored should be guided by quantitative measures of preferred habitat features for focal species; this also applies to the maintenance of appropriate habitat for long-term sustainability of vital populations of focal species.

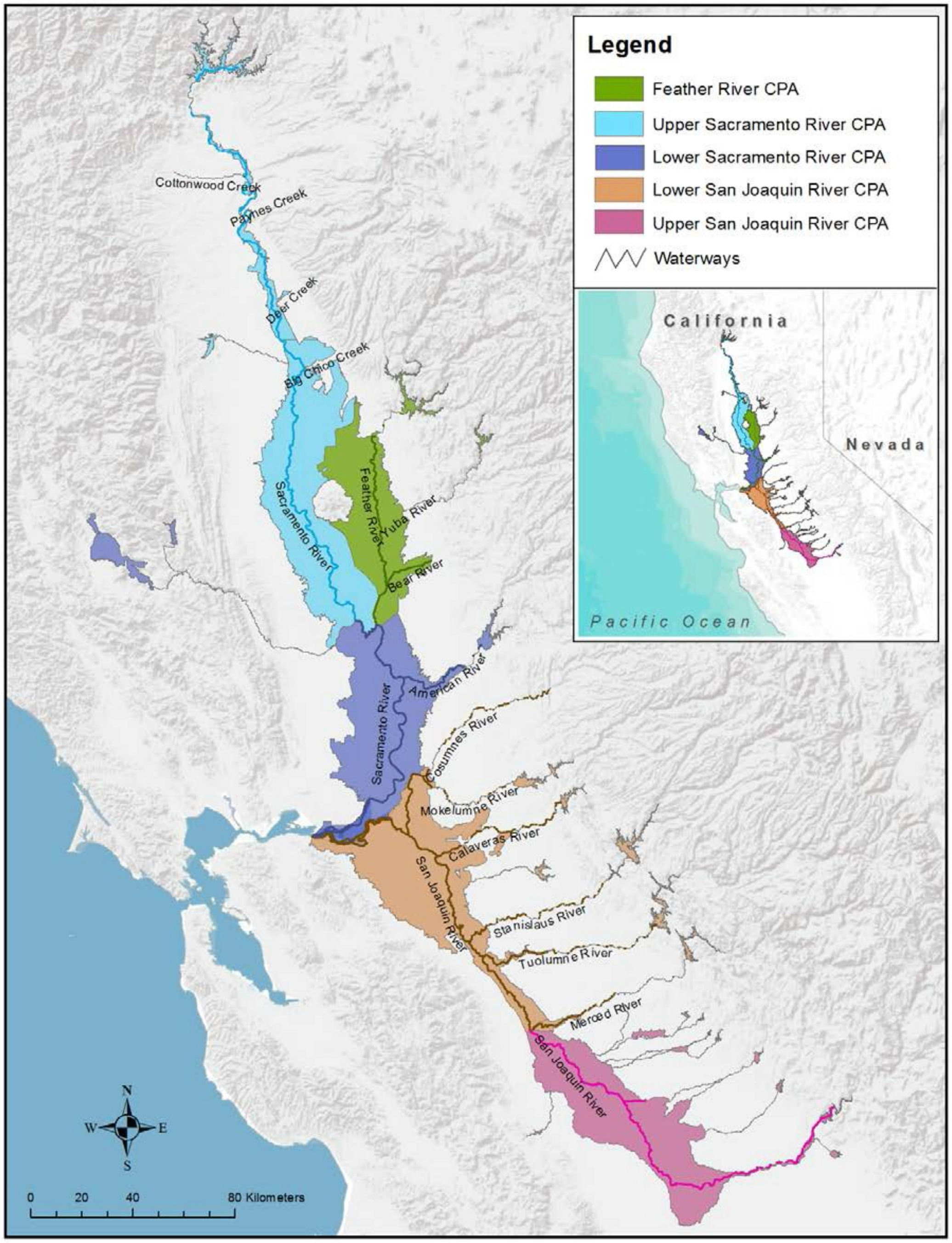
The purpose of this analysis is to refine previously developed suitable rearing habitat objectives for the Conservation Strategy of the Central Valley Flood Protection Plan (CVFPP). The juvenile rearing habitat needs of Central Valley (CV) Chinook salmon[1], an iconic species with significant ecological, social, and financial implications for the State of California, are the focus of this effort. The results of this investigation provide initial targeted area estimates for creation of suitable rearing habitat for juvenile salmonids in each Conservation Planning Area (CPA) (Figure 2-1), and a means of prioritizing creation of rearing habitat within and across CPAs. The best available tools and supporting data were used to estimate suitable rearing habitat required in the Central Valley CPAs to support the doubling goal[2], existing suitable rearing habitat within the highly modified CPA environment, and historical suitable rearing habitat likely present in Central Valley CPAs prior to dam operation, levee construction, and large scale development.

Existing and historical suitable rearing habitat was estimated using the Estimated Annual Habitat (EAH) approach (Matella and Jagt 2013) that uses measured hydrology and modeled hydraulic relationships between flow and inundation area to calculate areas of inundation with timing, duration, and frequency to support juvenile Chinook salmon. Suitable rearing habitat required to satisfy the doubling goal was calculated using the Emigrating Salmonid Habitat Estimation (ESHE) model, which considers territory size required for emigrating juvenile salmonids, using empirically derived migration rates, growth rates, and survival rates. In implementing these two approaches, consistent assumptions were adopted about the duration, timing, and frequency of flows and the physical suitability of inundated areas required to provide suitable rearing habitat for juvenile salmonids.

[1] "CV Chinook salmon" includes the following Evolutionarily Significant Units: CV fall- and late fall–run Chinook salmon, Sacramento River winter-run Chinook salmon, and CV spring-run Chinook salmon.

[2] Section 3406(b)(1) of the CVPIA (enacted in 1992), states that the AFRP is to "develop within three years of enactment and implement a program which makes all reasonable efforts to ensure that, by the year 2002, natural production of anadromous fish in Central Valley rivers and streams will be sustainable, on a long-term basis, at levels not less than twice the average levels attained during the period of 1967–1991…"

In the future, creation of new suitable rearing habitat will be evaluated and designed using the approach described here and accounted for by comparing each new increment of suitable rearing habitat to the suitable rearing habitat required to support the doubling goal. It is important to note that creation of the required suitable rearing habitat calculated for each CPA is not necessarily the charge of the CVFPP. However, the Conservation Strategy will be able to use the information from this analysis as a measure to evaluate incremental progress toward achieving suitable rearing habitat required in each CPA to satisfy the doubling goal. Not only do seasonal floodplains provide critical habitat that is essential for the growth and development of juvenile salmonids, but annual inundation of floodplains is the principal force determining productivity and biotic interactions in river-floodplain systems (Junk et al. 1989; Sommer et al. 2001). Therefore, for natural production of CV Chinook salmon to approach long-term, sustainable abundance levels (the objective of the doubling goal) , the Sacramento–San Joaquin River system must support sufficient floodplain habitat critical to fish production.



Note: This analysis considered the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs. This analysis did not include the Upper San Joaquin River CPA because a previous study was completed as part of the San Joaquin River Restoration Program (SJRRP) to recommend the minimum area of suitable rearing habitat for juvenile salmonids required to meet fall- and spring-run Chinook salmon targets for the Upper San Joaquin River CPA (SJRRP 2012).

Figure 2-1. Map of Conservation Planning Areas

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3.0 Historical Suitable Rearing Habitat for Juvenile Salmonids

3.1 General Approach

Historical suitable rearing habitat area for juvenile salmonids was estimated using a combination of historical habitat suitability mapping, historical hydrology data and analysis, historical hydraulic analysis, and spatial modeling in a Geographic Information System (GIS). The following analysis steps detail the general approach implemented to estimate the historical suitable rearing habitat in each CPA:

1) Subreaches of the mainstem Sacramento River, San Joaquin River, Feather River, and all tributaries with AFRP doubling goals were delineated based on a review of relevant historical hydrology data from U.S. Geological Survey (USGS), California Data Exchange Center (CDEC) and other gages (Table 3-1) to create subreaches within which hydrologic conditions were generally similar (Figure 3-1).

Table 3-1. Summary Information for Streamflow Gages Used in the Analysis of Historical Suitable Rearing Habitat for Juvenile Salmonids

CPA	Sub-CPA River Reach	Gage Name	Gage ID	Evaluation Period	Criteria Flow (cfs)*
Upper Sacramento	Paynes to Deer	Bend Bridge Near Red Bluff - Sacramento River	11377100	1891 to 1948	20,731
Upper Sacramento	Colusa to Verona	Wilkins Slough - Sacramento River	11390500	1938 to 1948	17,882
Feather	Thermalito to Yuba	Gridley - Feather River	GRL	1964 to 1968	14,700
Feather	Yuba to Bear	Gridley - Feather River	N/A	1964 to 1968	14,700
Feather	Bear River	Bear River near Wheatland	11424000	1928 to 1964	1,167
Feather	Bear to Sutter	Gridley and Bear River combined	N/A	1964 to 1968	15,408
Lower Sacramento	Verona to American	Verona - Sacramento River	11425500	1929 to 1967	41,878
Lower Sacramento	American River	American River at Fair Oaks	11446500	1904 to 1955	9,370
Lower San Joaquin	Merced River	Stevinson - Merced River	11272500	1940 to 1966	1,022
Lower San Joaquin	Merced to Tuolumne	Newman - San Joaquin River	11274000	1912 to 1941	5,127
Lower San Joaquin	Tuolumne River	Modesto - Tuolumne River	11290000	1895 to 1969	2,237
Lower San Joaquin	Stanislaus River	Ripon - Stanislaus River	11303000	1940 to 1977	2,257
Lower San Joaquin	Stanislaus to Stockton	Vernalis - San Joaquin River	11303500	1923 to 1941	8,808

*Criteria: Timing = December 1 to May 31; Duration = 14 days continuous; Frequency = 50% (once every two years)

2) Historical streamflow data from the gages used in #1 above were queried for pre-dam hydrology data (Table 3-1) determined by identifying the date of completion of the nearest controlling dam in each subreach and selecting streamflow data for the period before completion of that dam.

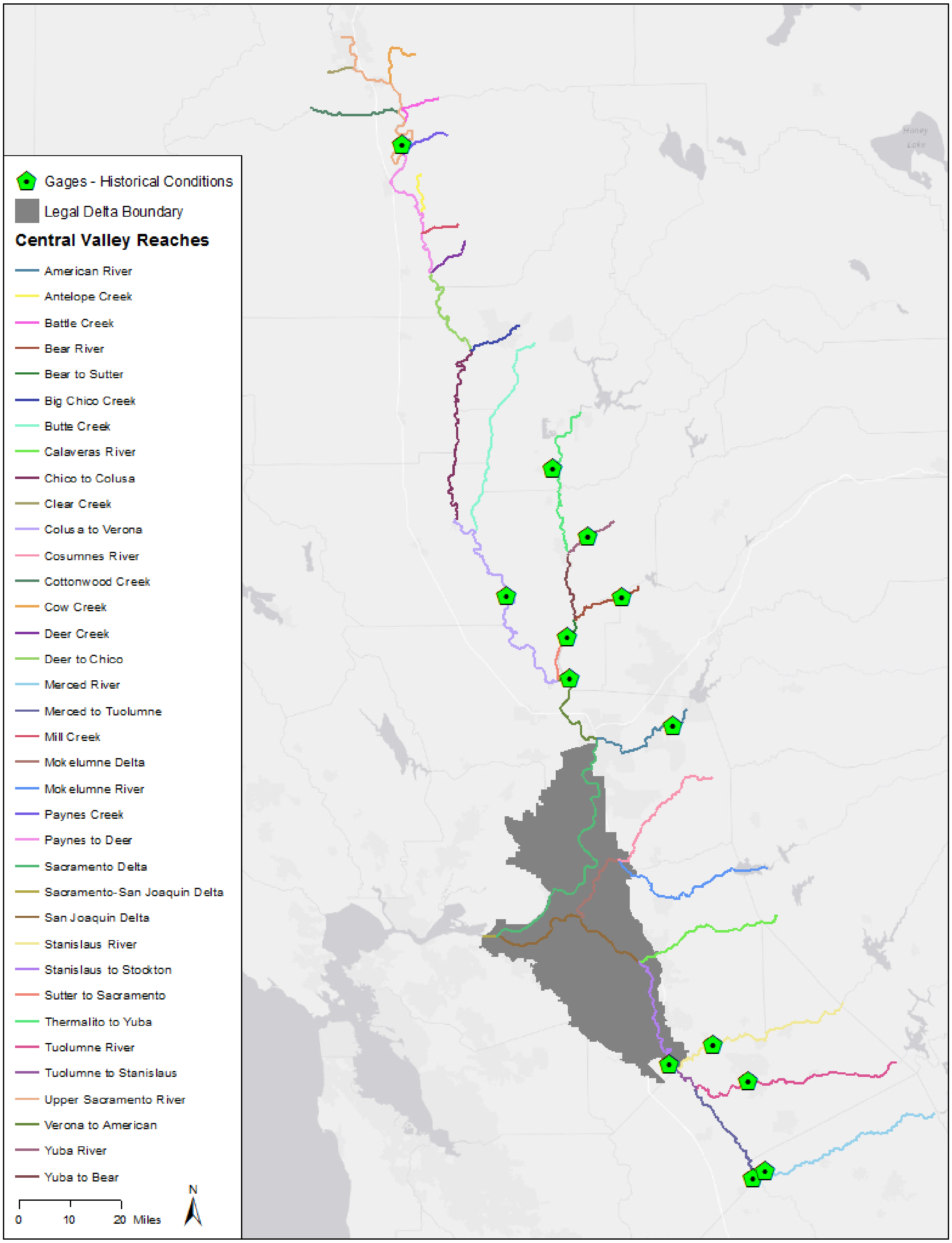


Figure 3-1. Location of Streamflow Gages Used in the Analysis of Historical Suitable Rearing Habitat for Juvenile Salmonids

3) Using the EAH approach[3] (Matella and Jagt 2013), maximum flows satisfying the following criteria were calculated for each subreach:

   - Timing: December 1– May 31
   - Duration: 14 days
   - Frequency: Once every 2 years (50 percent)

   These criteria were drawn from literature on California Central Valley salmonids and ensure that suitable rearing habitat used in this analysis would at a minimum benefit each generation of fish (assuming average adult salmon spawning age of 3 years as reported by Moyle 2002) and achieve primary production, zooplankton and invertebrate colonization, and juvenile salmonid growth needs for successful rearing (Merz and Chan 2005; Jeffres et al. 2008; Grosholz and Gallo 2006).

4) Using the California Central Valley Floodplain Evaluation and Delineation Program (CVFED) Hydrologic Engineering Center River Analysis System (HEC-RAS) 1-D hydraulic model (Figure 3-2), water surface profiles were generated for each subreach at the flows satisfying the juvenile salmonid rearing habitat suitability criteria described in #3 above.

5) Using the water surface profiles generated in #4 above and the CVFED Light Detection and Ranging (LiDAR)-based topography, total inundated areas were calculated for each subreach assuming pre-levee topography (i.e., no levees).

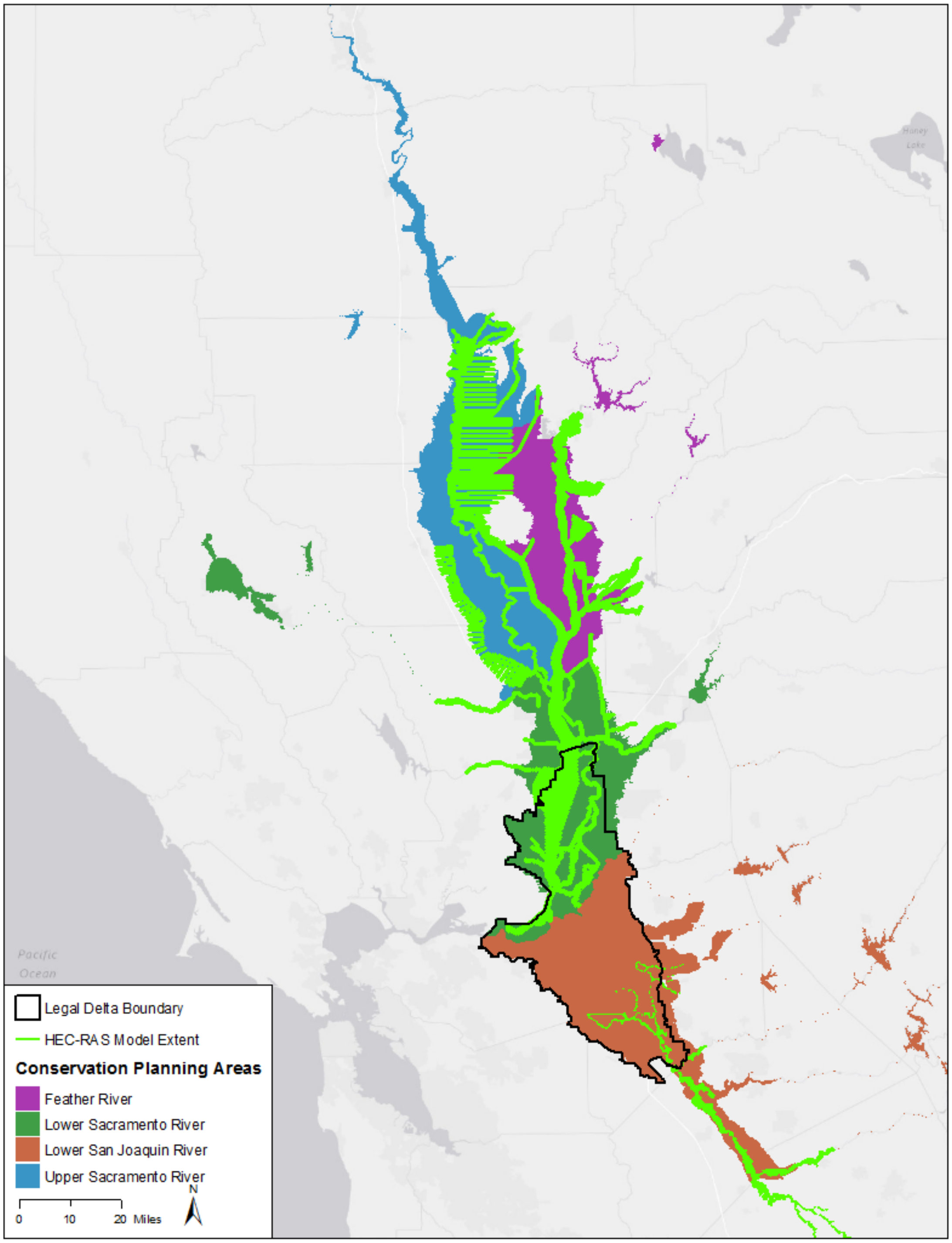
6) Inundated areas outside of the CPAs were clipped out using a GIS application and not counted in this analysis.

7) Inundated areas outside of historical channel, riparian, floodplain and wetland areas mapped in *From the Sierra to the Sea*[4] (The Bay Institute 1998) (Figure 3-3) were clipped out using a GIS application and not counted in this analysis.

8) Inundated areas inside of historical channel, riparian, floodplain and wetland areas mapped in *From the Sierra to the Sea* were all multiplied by a suitability factor for floodplain that ranged from a low value of 22 percent suitable to a high value of 27 percent suitable (San Joaquin River Restoration Program [SJRRP] 2012). This range of values is the upper quartile of the 7- to 27-percent range from SJRRP 2012 and assumes that historical floodplain suitability was more similar to the high suitability floodplain areas measured in the SJRRP 2012 study. While

[3] The EAH metric quantifies the area inundated by a flow of a given duration for all possible frequencies (i.e., zero to 100 percent). Although this is a good general metric to use in screening a wide variety of potential inundated area benefits, EAH could overestimate or underestimate the potential to increase the area inundated by flows that satisfy a specific frequency criteria. Therefore, because this analysis focuses on the 2-year recurrence interval flows for juvenile salmonid rearing, results are presented as frequency-specific areas rather than presenting the EAH metric that considers all possible frequencies.

[4] From the Sierra to the Sea was completed by The Bay Institute in 1998 and was designed to provide a coherent and defensible ecological framework and information base for restoration California's Central Valley and Bay Delta ecosystem.



Note: The upper reach of the Upper Sacramento River CPA and several Sacramento River and San Joaquin River tributaries are not covered by the CVFED HEC-RAS model.

Figure 3-2. Map of CPAs, CVFED HEC-RAS Model Extent, and Legal Delta Used in Both the Historical and Existing Suitable Rearing Habitat Calculations

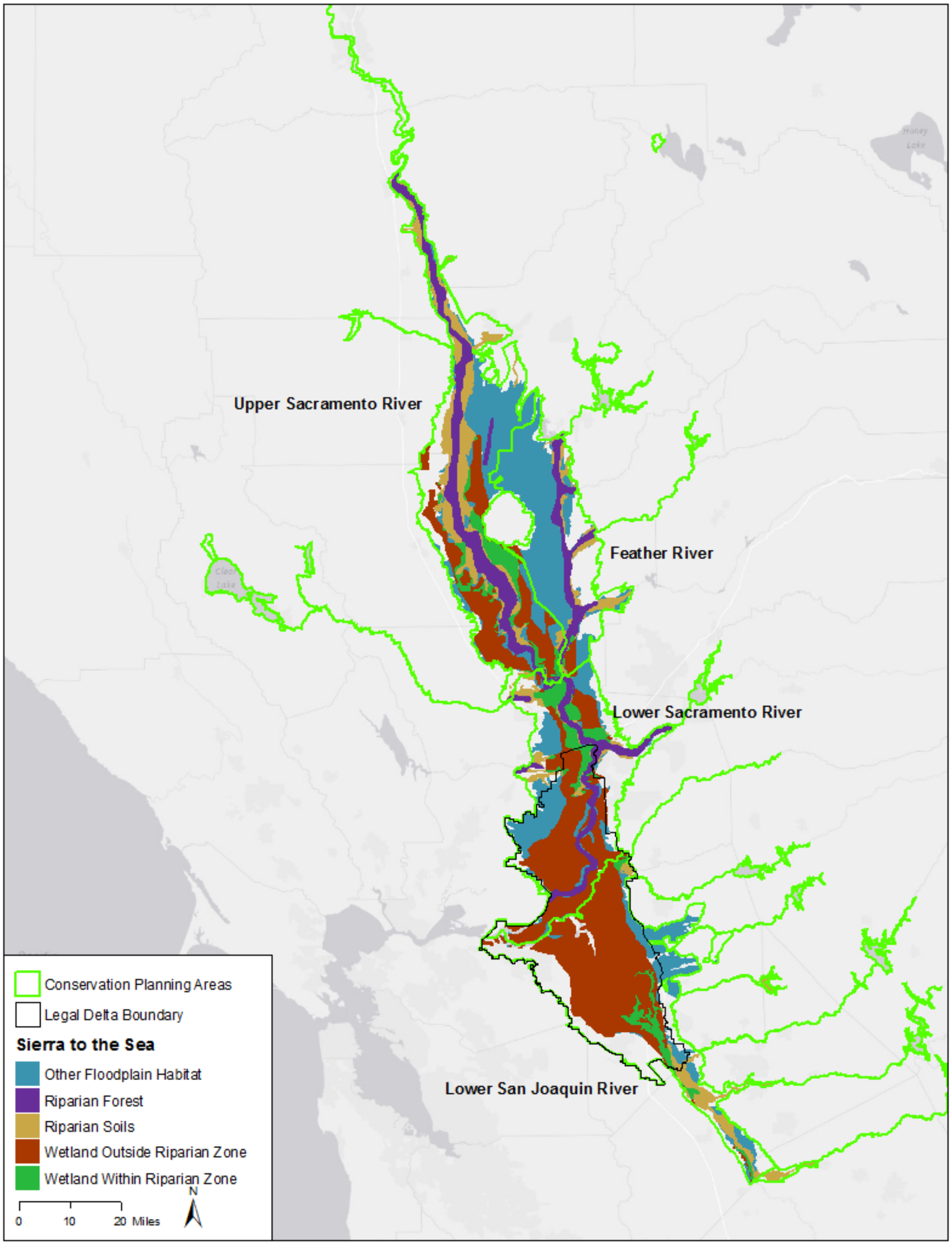


Figure 3-3. Map of CPA Boundaries, *From the Sierra to the* Sea Historical Inundated Habitat Types, and Legal Delta Boundary Used in the Historical Suitable Rearing Habitat Calculations

this likely overestimates the suitability of historical active river channel areas, the active river channel comprised only a small fraction of the total historically inundated area.

9) Suitable inundated areas were summed by subreach for each CPA and counted as historically suitable rearing habitat for juvenile salmonids.

3.2 Exceptions to General Approach

3.2.1 Delta

For the portions of the Lower Sacramento River and the Lower San Joaquin River CPAs inside the Legal Delta boundary (Figures 3-1 and 3-2), all areas mapped in *From the Sierra to the Sea* as waterways, intertidal wetland, tidal wetland, and other floodplain habitat were multiplied by the floodplain suitability factor (22–27 percent) described above, and the resulting area was counted as historically suitable rearing habitat for juvenile salmonids. While this likely overestimates the suitability of historical waterway areas in the Delta, these waterways comprised only a small fraction of the total historically inundated area in the Delta.

3.2.2 Tributaries and Mainstem Channels without HEC-RAS Model

The CVFED HEC-RAS model used in this analysis does not cover all of the main-stem river channels and tributaries included in the doubling goal regions (Figure 3-2). Therefore, in the channel areas without a HES-RAS model, an alternative method was used to estimate historical suitable rearing habitat. All of the areas mapped as historical channel, riparian, floodplain, and wetland in *From the Sierra to the Sea* were multiplied by the floodplain suitability factor (22–27 percent) described above, and the resulting area was counted as historically suitable rearing habitat for juvenile salmonids in these non-HES-RAS modeled areas. Again, while this approach likely overestimates the suitability of historical channel areas, channels were only a small fraction of the total historically inundated area.

3.3 Results

Tables 3-2 through 3-5 summarize historical suitable rearing habitat estimates for juvenile Chinook salmon by subreach in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively. Total inundated areas at flows satisfying rearing criteria were 366,300 acres, 341,000 acres, 52,400 acres, and 343,700 acres in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively. Suitable rearing habitat areas assuming low suitability of inundated areas were 80,586 acres, 75,020 acres, 11,528 acres, and 75,614 acres in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively. Suitable rearing habitat areas assuming high suitability of inundated areas were 98,901 acres, 92,070 acres, 14,148 acres, and 92,799 acres in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively.

Table 3-2. Summary of Historical Conditions Suitable Rearing Habitat in the Upper Sacramento River CPA

Upper Sacramento River CPA		Suitable Inundated Area	
Reach Description	**Total Inundated Area (acres)**	**Assuming Low Suitability (22% Factor Applied)**	**Assuming High Suitability (27% Factor Applied)**
Upper Sacramento River	72,600	15,972	19,602
Sacramento River - Chico to Colusa	155,500	34,210	41,985
Sacramento River - Colusa to Verona	130,000	28,600	35,100
Feather River - Sutter to Sacramento	8,200	1,804	2,214
TOTAL	**366,300**	**80,586**	**98,901**

Table 3-3. Summary of Historical Conditions Suitable Rearing Habitat in the Lower Sacramento River CPA

Lower Sacramento River CPA		Suitable Inundated Area	
Reach Description	**Total Inundated Area (acres)**	**Assuming Low Suitability (22% Factor Applied)**	**Assuming High Suitability (27% Factor Applied)**
Sacramento River - Verona to American	64,300	14,146	17,361
American River	8,400	1,848	2,268
Delta	268,300	59,026	72,441
TOTAL	**341,000**	**75,020**	**92,070**

Table 3-4. Summary of Historical Conditions Suitable Rearing Habitat in the Feather River CPA

Feather River CPA		**Suitable Inundated Area**	
Reach Description	**Total Inundated Area (acres)**	**Assuming Low Suitability (22% Factor Applied)**	**Assuming High Suitability (27% Factor Applied)**
Feather River - Thermalito to Yuba River	12,300	2,706	3,321
Yuba River	400	88	108
Feather River - Yuba River to Bear River	11,900	2,618	3,213
Bear River	16,300	3,586	4,401
Feather River - Bear River to Sutter Bypass	11,500	2,530	3,105
TOTAL	**52,400**	**11,528**	**14,148**

The total and suitable inundated areas presented above depend on several assumptions that should be considered when interpreting these results. First, that the timing, duration, and frequency criteria applied to flows are representative of juvenile salmonid rearing requirements, and second, that the suitability factors applied are consistent with juvenile salmonid rearing habitat use. The sensitivity of the results presented here to the first assumption is relatively low, as historical inundation fills most of the area in each CPA. The sensitivity of the analysis to suitability factors is captured in the range of results presented for low to high suitability assumptions. Another important assumption is that the pre-dam hydrology used in this analysis accurately represents historical variability of flows. Since pre-dam hydrology records are quite limited, it is likely that this approach underestimates historical flows that would have satisfied rearing criteria.

Perhaps the most significant assumption, however, is that the use of recent topography (without levees) accurately represents the historical land surface. It is likely that the historical land surface was significantly more varied in elevation, which could have significantly changed (both increased and decreased, depending on location) the suitable rearing habitat values calculated in this analysis. Taken together, these assumptions and limitations have likely resulted in an underestimate of historically suitable rearing habitat for juvenile Chinook salmon.

Table 3-5. Summary of Historical Conditions Suitable Rearing Habitat in the Lower San Joaquin River CPA

Lower San Joaquin River CPA		**Suitable Inundated Area**	
Reach Description	**Total Inundated Area (acres)**	**Assuming Low Suitability (22% Factor Applied)**	**Assuming High Suitability (27% Factor Applied)**
Merced River	400	88	108
San Joaquin River - Merced to Tuolumne	2,400	528	648
Tuolumne River	600	132	162
San Joaquin River - Tuolumne to Stanislaus	1,000	220	270
Stanislaus River	100	22	27
Delta	339,200	74,624	91,584
TOTAL	**343,700**	**75,614**	**92,799**

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4.0 Existing Suitable Rearing Habitat for Juvenile Salmonids

4.1 General Approach

The general approach used to estimate existing suitable rearing habitat was very similar to the approach used to estimate historical suitable rearing habitat, except that post-dam hydrology and post-levee topography were used in the hydrologic and hydraulic evaluations, and existing condition suitability factors (described below) were applied to total inundated areas. In addition, Sierra to the Sea mapping was not used on the existing suitable rearing habitat calculations. The following steps detail the approach implemented to estimate existing suitable rearing habitat in each of the CPAs:

1) Subreaches of the mainstem Sacramento River, San Joaquin River, Feather River, and all tributaries with AFRP doubling goals were delineated based on a review of all relevant existing hydrology data from U.S. Geological Survey (USGS), California Data Exchange Center (CDEC) and other gages (Table 4-1) to create subreaches within which hydrologic conditions were generally similar (Figure 4-1).

2) Existing conditions streamflow data from the gages used in #1 above were queried for post-dam hydrology data (Table 4-1) determined by identifying the date of completion of the controlling dam in each subreach and selecting streamflow data for the period after completion. This analysis assumes that recent post-dam hydrology is representative of existing and near-term future hydrology, perhaps with the exception of basins where dams are undergoing Federal Energy Regulatory Commission relicensing and the outcomes for instream flow agreements are uncertain. While future hydrology will likely change, most significantly as climate change effects become more pronounced, this analysis has not yet considered alternative future hydrology.

3) Using the EAH approach, maximum flows in each subreach satisfying the following criteria (same as for historical suitable rearing habitat) were calculated:

    - Timing: December 1– May 31
    - Duration: 14 days
    - Frequency: Once every 2 years (50 percent)

4) Using the CVFED HEC-RAS 1-D hydraulic model (Figure 3-2), water surface profiles were generated for each subreach at the flows satisfying the juvenile salmonid rearing habitat suitability criteria in #3 above.

Table 4-1. Summary Information for Streamflow Gages Used in the Analysis of Existing Suitable Rearing Habitat for Juvenile Salmonids

CPA	Sub-CPA River Reach	Gage Name	Gage ID	Evaluation Period	Criteria Flow (cfs)*
Upper Sacramento	Paynes to Deer	Bend Bridge Near Red Bluff - Sacramento River	11377100	1950 to 2013	20,963
Upper Sacramento	Deer Creek to Chico	Hamilton City - Sacramento River	HMC	1991 to 2013	22,482
Upper Sacramento	Big Chico Creek	Big Chico Creek near Chico	BIC	1997 to 2013	336
Upper Sacramento	Chico to Colusa	Ord Ferry - Sacramento River	ORD	1993 to 2013	24,194
Upper Sacramento	Colusa to Verona	Colusa - Sacramento River	11389500	1950 to 2013	23,741
Upper Sacramento	Colusa to Verona	Wilkins Slough - Sacramento River	11390500	1950 to 2013	20,730
Feather	Thermalito to Yuba	Gridley - Feather River	GRL	1969 to 2013	6,983
Feather	Yuba River	Marysville - Yuba River	MRY	1997 to 2013	3,181
Feather	Yuba to Bear	Gridley - Feather River	GRL	1969 to 2013	6,983
Feather	Bear River	Bear River near Wheatland	11424000	1966 to 2013	927
Feather	Bear to Sutter	Gridley and Bear River combined	N/A	1969 to 2013	7,686
Lower Sacramento	Verona to American	Verona - Sacramento River	11425500	1969 to 2013	39,019
Lower Sacramento	American River	American River at Fair Oaks	11446500	1957 to 2013	5,570
Lower Sacramento	Sacramento Delta	Freeport - Sacramento River	11447650	1950 to 2013	47,643
Lower Sacramento	Sacramento Delta	Delta Cross Channel - Sacramento River	11447890	1992 to 2013	23,393
Lower Sacramento	Sacramento Delta	Georgiana Slough - Sacramento River	11447905	1993 to 2013	10,662
Lower Sacramento	Yolo Bypass	Yolo Bypass near Woodland	11453000	1969 to 2013	5,010
Lower Sacramento	Sacramento Delta	Rio Vista - Sacramento River	11455420	1995 to 2013	49,213
Lower San Joaquin	Merced River	Merced Falls - Merced River	MMH	1998 to 2013	1,925
Lower San Joaquin	Merced River	Stevinson - Merced River	11272500	1968 to 2013	876
Lower San Joaquin	Merced to Tuolumne	Newman - San Joaquin River	11274000	1943 to 2013	2,214
Lower San Joaquin	Merced to Tuolumne	Crow's Landing - San Joaquin River	11274550	1995 to 2013	2,360
Lower San Joaquin	Merced to Tuolumne	Patterson - San Joaquin River	SJP	1999 to 2013	1,540
Lower San Joaquin	Tuolumne River	Modesto - Tuolumne River	11290000	1972 to 2013	1,674
Lower San Joaquin	Tuolumne to Stanislaus	Patterson and Modesto combined	N/A	1999 to 2013	2,685
Lower San Joaquin	Stanislaus River	Ripon - Stanislaus River	11303000	1980 to 2013	1,658
Lower San Joaquin	Stanislaus to Stockton	Vernalis - San Joaquin River	11303500	1943 to 2013	6,449
*Criteria: Timing = December 1 to May 31; Duration = 14 days continuous; Frequency = 50% (once every two years)					

Note: Sub-CPA river reaches use hydrology data from the accompanying streamflow gage.

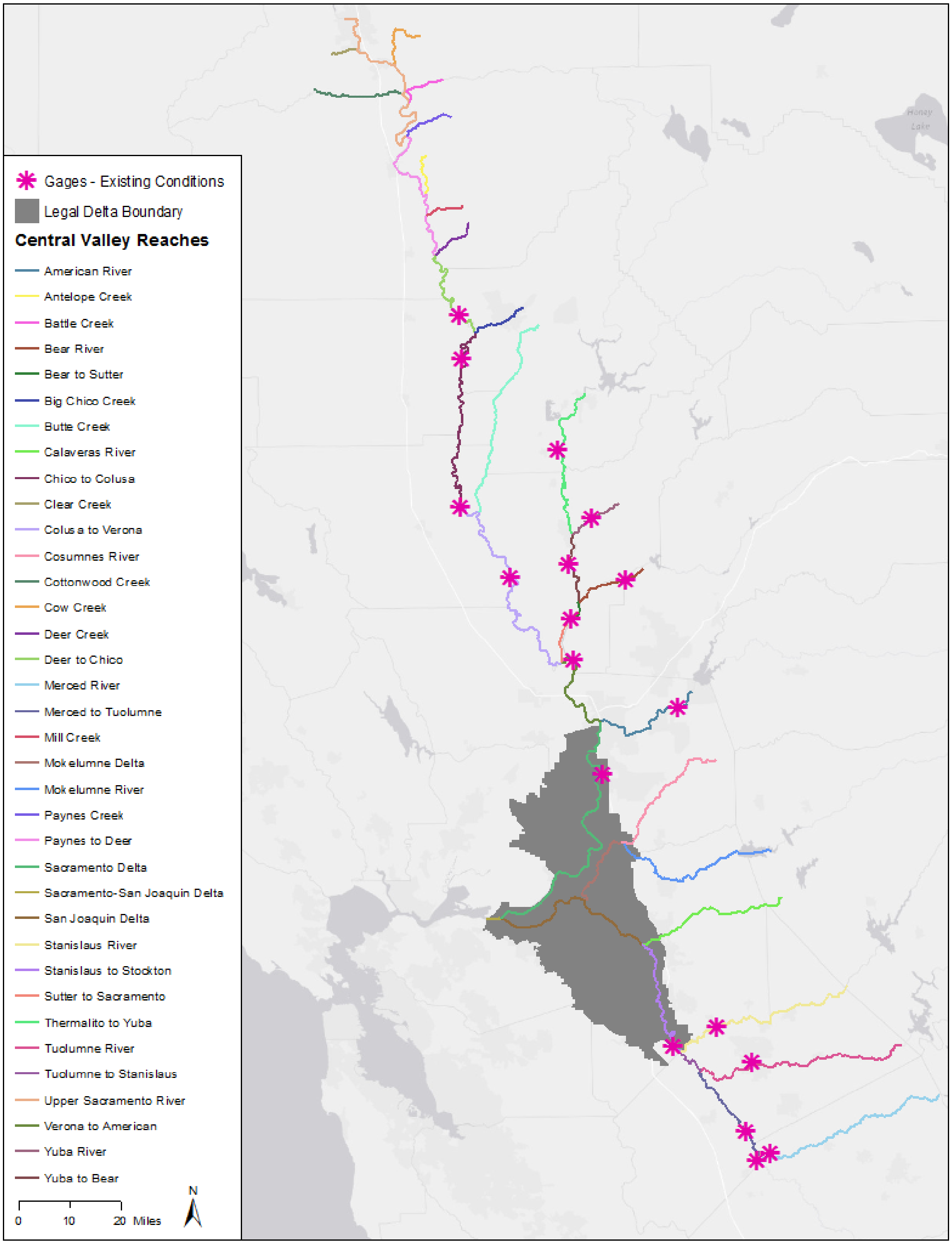

Figure 4-1. Location of Streamflow Gages Used in the Analysis of Existing Suitable Rearing Habitat for Juvenile Salmonids

5) Using the water surface profiles generated in #4 above and the CVFED LiDAR-based topography, total inundated areas (primarily between existing levees) were calculated for each subreach.

6) Inundated areas outside of the CPAs were clipped out using a GIS application and not counted in this analysis.

7) Inundated areas were assigned to channel, floodplain, and tributary[5] categories based on Central Valley riparian vegetation and land use mapping (Geographical Information Center 2011).

8) The suitability factor for the channel category (Table 4-2) in each CPA was determined by calculating the percentage of channel area with depth less than 4 feet (Aceituno 1993; Aceituno and Rutherfurd 1990) at the flow satisfying the criteria in #3 above for representative reaches throughout the Central Valley. This resulted in an average suitability of 0.9 percent across all CPAs. This relatively low value reflects the condition that existing mainstem rivers in the Central Valley typically have only a narrow margin area with suitable rearing habitat conditions for juvenile Chinook salmon.

Table 4-2. Inundated Area Suitability Factors for Existing Conditions Analysis

CPA	Channel Suitability Factor (%)[1]	Floodplain Suitability Factor (%)[2]		Tributary Suitability Factor (%)[3]	
		Low	High	Low	High
Upper Sacramento River	0.9	7	27	2.5	5.2
Lower Sacramento River	0.9	7	27	4.4	8.8
Feather River	0.9	7	27	0.5	1.7
Lower San Joaquin River	0.9	7	27	4.7	7.5

[1] Average channel area less than 4 feet deep at the flow satisfying rearing criteria in representative reaches throughout all CPAs.

[2] Full range from SJRRP 2012.

[3] Upper Sacramento from this study Section 4.3.2 #4; Lower Sacramento from Beakes et al. 2012; Feather from USFWS 2010; Lower San Joaquin from Cramer Fish Sciences 2013.

9) The suitability factor for the floodplain category (Table 4-2) was determined from a detailed study of the depth, velocity, and cover conditions for a range of existing floodplain types along the San Joaquin River (SJRRP 2012) and ranged from 7 to 27 percent.

[5] Approach for tributaries described in Section 4.2.2.

10) Total inundated area in each category was multiplied by the suitability factor for the appropriate category and resulting suitable rearing habitat areas were summed by subreach for each CPA and counted as existing suitable rearing habitat for juvenile salmonids.

4.2 Exceptions to General Approach

4.2.1 Delta

Because the existing tidal Delta has very different habitat types than the historical Delta and existing channel and floodplain areas in the Central Valley, the following approach was used to calculate existing suitable rearing habitat in the Delta portions of the Lower Sacramento River and Lower San Joaquin River CPAs:

1) The Legal Delta boundary (Figures 3-1 and 3-2) was used to delineate areas considered in this category.

2) USGS bathymetry data (Foxgrover et al. 2003) was used to determine depths in all inundated areas of the Delta (primarily leveed channels).

3) Inundated areas with depths less than 4 feet were considered potentially suitable for juvenile Chinook salmon rearing (Aceituno 1993; Aceituno and Rutherfurd 1990).

4) Inundated areas with suitable depths adjacent to land areas with natural cover types including wetland, riparian, floodplain vegetation, and other relatively natural cover types (Geographic Information Center 2011) were counted as existing suitable habitat for rearing juvenile salmonids.

5) Inundated areas with suitable depths adjacent to land areas with urban, agriculture, and other highly impacted cover types were not counted as existing suitable habitat for rearing juvenile salmonids.

4.2.2 Tributaries and Mainstem Channels without HEC-RAS Model

For the portion of the Upper Sacramento River CPA and tributaries to the mainstem rivers in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs without a CVFED HEC-RAS model (Figure 3-2), the following approach was used to calculate existing suitable rearing habitat:

1) Total inundated area was estimated as the area within mapped active channel areas (Geographic Information Center 2011). This assumes that higher river corridor gradient conditions exist in tributaries, and that existing suitable habitat for rearing juvenile salmonids occurs primarily in the active channel and near-channel riparian portions of these areas.

2) Total inundated area on the Upper Sacramento mainstem was apportioned to channel and floodplain categories based on the average proportion of floodplain and channel habitat in modeled reaches of the Upper Sacramento River CPA.

3) Channel and floodplain suitability on the Upper Sacramento River mainstem were determined as 0.9 percent and 7–27 percent, respectively, using the approach described in #8 and #9 in Section 4.2, above.

4) Tributary suitability in the Upper Sacramento River CPA was determined by calculating the percentage of channel area with depth less than 4 feet (Aceituno 1993; Aceituno and Rutherfurd 1990) using measured stages in tributaries at flows satisfying rearing criteria and ranged from 2.5 to 5.2 percent (Table 4-2).

5) Tributary suitability in the Lower Sacramento River CPA was determined as the range in percent of Weighted Usable Area (WUA) that was considered suitable for juvenile Chinook salmon across a range of instream flow values in the American River, a tributary of the Sacramento River (Beakes et al. 2012). Tributary suitability ranged from 4.4 to 8.8 percent (Table 4-2) in this CPA.

6) Tributary suitability in the Feather River CPA was determined as the range in percent of WUA that was considered suitable for juvenile Chinook salmon across a range of instream flow values in the Yuba River, a tributary of the Feather River (U.S. Fish and Wildlife Service [USFWS] 2010). Tributary suitability ranged from 0.5 to 1.7 percent (Table 4-2) in this CPA.

7) Tributary suitability in the Lower San Joaquin River CPA was determined as the percent of wetted channel habitat that was considered suitable for fry and juvenile salmonids in the Stanislaus River, a tributary of the San Joaquin River (Cramer Fish Sciences 2013). Tributary suitability ranged from 4.7 to 7.5 percent (Table 4-2) in this CPA.

8) Total inundated areas were multiplied by the appropriate suitability factor and the resulting areas added to the existing suitable habitat for rearing juvenile salmonids in each CPA.

4.3 Results

Tables 4-3 through 4-6 summarize existing suitable rearing habitat estimates for juvenile salmonids by subreach in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively. Total inundated areas at flows satisfying rearing criteria were 27,800 acres, 12,300 acres, 3,700 acres, and 7,900 acres in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively. Suitable rearing habitat areas assuming low suitability of inundated areas were 1,399 acres, 767 acres, 107 acres, and 419 acres in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively. Suitable rearing habitat areas assuming high suitability of inundated areas were 5,169 acres, 2,862 acres, 352 acres, and 1,404 acres in the Upper Sacramento River, Lower Sacramento River, Feather River, and Lower San Joaquin River CPAs, respectively.

Table 4-3. Summary of Existing Conditions Suitable Rearing Habitat in the Upper Sacramento River CPA

Upper Sacramento River CPA		Inundated Area Category								Total Suitable Rearing Habitat Area (acres)	
		Channel		Floodplain			Tributary				
Reach Description	Total Inundated Area (acres)	Total Inundated Channel Area (acres)	Suitable Inundated Channel Area (acres)	Total Inundated Floodplain Area (acres)	Suitable Inundated Floodplain Area (acres) @ Low (7%) Suitability	Suitable Inundated Floodplain Area (acres) @ High (27%) Suitability	Total Inundated Tributary Area (acres)	Suitable Inundated Tributary Area (acres) @ Low (2.5%) Suitability	Suitable Inundated Tributary Area (acres) @ High (5.2%) Suitability	Assuming Low Suitability	Assuming High Suitability
Upper Sacramento River	2,600	1,500	13	1,100	77	297				90	310
Sacramento River - Paynes Creek to Deer Creek	2,100	1,200	10	900	63	243				73	253
Sacramento River - Deer Creek to Chico Creek	1,400	800	7	600	42	162				49	169
Mill Creek							10	0	1	0	1
Deer Creek							30	1	2	1	2
Sacramento River - Chico Creek to Colusa	4,400	2,700	23	1,700	119	459				142	482
Sacramento River - Colusa to Verona	3,800	2,100	18	1,700	119	459				137	477
Butte Creek	300						300	8	16	8	16
Sutter Bypass	12,800			12,800	896	3,456				896	3,456
Feather River - Sutter to Sacramento	400	400	3	-	-	-				3	3
TOTAL	**27,800**	**8,700**	**75**	**18,800**	**1,316**	**5,076**	**340**	**9**	**18**	**1,399**	**5,169**

Table 4-4. Summary of Existing Conditions Suitable Rearing Habitat in the Lower Sacramento River CPA

Lower Sacramento River CPA		Inundated Area Category								Total Suitable Rearing Habitat Area (acres)	
		Channel		Floodplain			Tributary				
Reach Description	Total Inundated Area (acres)	Total Inundated Channel Area (acres)	Suitable Inundated Channel Area (acres)	Total Inundated Floodplain Area (acres)	Suitable Inundated Floodplain Area (acres) @ Low (7%) Suitability	Suitable Inundated Floodplain Area (acres) @ High (27%) Suitability	Total Inundated Tributary Area (acres)	Suitable Inundated Tributary Area (acres) @ Low (4.4%) Suitability	Suitable Inundated Tributary Area (acres) @ High (8.8%) Suitability	Assuming Low Suitability	Assuming High Suitability
Sacramento River - Verona to American	1,400	1,200	10	200	14	54				24	64
American River	800						800	35	70	35	70
Delta	2,000			2,000	140	540				140	540
Yolo Bypass	8,100			8,100	567	2,187				567	2,187
TOTAL	**12,300**	**1,200**	**10**	**10,300**	**721**	**2,781**	**800**	**35**	**70**	**767**	**2,862**

Table 4-5. Summary of Existing Conditions Suitable Rearing Habitat in the Feather River CPA

Feather River CPA		Inundated Area Category								Total Suitable Rearing Habitat Area (acres)	
		Channel		Floodplain			Tributary				
Reach Description	Total Inundated Area (acres)	Total Inundated Channel Area (acres)	Suitable Inundated Channel Area (acres)	Total Inundated Floodplain Area (acres)	Suitable Inundated Floodplain Area (acres) @ Low (7%) Suitability	Suitable Inundated Floodplain Area (acres) @ High (27%) Suitability	Total Inundated Tributary Area (acres)	Suitable Inundated Tributary Area (acres) @ Low (0.5%) Suitability	Suitable Inundated Tributary Area (acres) @ High (1.7%) Suitability	Assuming Low Suitability	Assuming High Suitability
Feather River - Thermalito to Yuba River	2,200	1,100	9	1,100	77	297				86	306
Yuba River	100						100	0.5	2	1	2
Feather River - Yuba River to Bear River	1,000	900	8	100	7	27				15	35
Feather River - Bear River to Sutter Bypass	400	400	3	20	1	5				5	9
TOTAL	**3,700**	**2,400**	**21**	**1,220**	**85**	**329**	**100**	**1**	**2**	**107**	**352**

Table 4-6. Summary of Existing Conditions Suitable Rearing Habitat in the Lower San Joaquin River CPA

Reach Description	Total Inundated Area (acres)	Total Inundated Channel Area (acres)	Suitable Inundated Channel Area (acres)	Total Inundated Floodplain Area (acres)	Suitable Inundated Floodplain Area (acres) @ Low (7%) Suitability	Suitable Inundated Floodplain Area (acres) @ High (27%) Suitability	Total Inundated Tributary Area (acres)	Suitable Inundated Tributary Area (acres) @ Low (4.7%) Suitability	Suitable Inundated Tributary Area (acres) @ High (7.5%) Suitability	Assuming Low Suitability	Assuming High Suitability
Merced River	500						500	24	38	24	38
San Joaquin River - Merced to Tuolumne	1,100	700	6	400	28	108				34	114
Tuolumne River	600						600	28	45	28	45
San Joaquin River - Tuolumne to Stanislaus	900	300	3	600	42	162				45	165
Stanislaus River	500						500	24	38	24	38
San Joaquin River - Stanislaus to Stockton	800	700	6	200	14	54				20	60
Delta	3,500			3,500	245	945				245	945
TOTAL	**7,900**	**1,700**	**15**	**4,700**	**329**	**1,269**	**1,600**	**75**	**120**	**419**	**1,404**

The total and suitable inundated areas presented above depend on two key assumptions that should be considered when interpreting these results. First, that the timing, duration, and frequency criteria applied to flows are representative of juvenile salmonid rearing requirements, and second, that the suitability factors applied are consistent with juvenile salmonid rearing habitat use. The sensitivity of the results presented here to the first assumption is relatively low, as existing inundation is more strongly controlled by levees than by the flow level. The sensitivity of the analysis to suitability factors is captured in the range of results presented for low to high suitability assumptions. A third assumption—that the CVFED HEC-RAS model accurately models hydraulics for the range of flows evaluated here—could also limit the accuracy of the results. This model was developed for extreme flood flows and therefore may overestimate water surface elevations for the relatively low flows considered in this analysis. There are also several important assumptions and limitations related to the treatment of the bypasses, which are described below.

4.3.1 Yolo Bypass

The Yolo Bypass was included in the calculation of existing suitable rearing habitat in the Lower Sacramento CPA based on Sommer et al.'s (2001) finding that the Sacramento River was connected to the bypass for an average of 23 days in 58 percent of years between 1956 and 1998 and the finding in this study that flows in the bypass at and downstream of significant West Side tributaries, including Cache Creek, satisfied timing, duration, and frequency criteria. While the hydraulic modeling used in this analysis may not capture Yolo Bypass inundation dynamics perfectly, it appears to be consistent with ongoing analyses being conducted to satisfy the National Marine Fisheries Service (NMFS) Biological Opinion (BO) (NMFS 2009) requirements. More detailed analysis should be considered because the Yolo Bypass has been shown to provide valuable rearing habitat for juvenile salmonids (Sommer et al. 2001).

4.3.2 Sutter Bypass

Nearly the entire area of the Sutter Bypass was included in this analysis because it is inundated at flows satisfying criteria. However, this bypass comprises a large proportion of the existing suitable rearing habitat for the Upper Sacramento CPA, and because suitability of Sutter Bypass is not well understood, future efforts should refine this understanding to improve the estimate of existing suitable rearing habitat provided by the bypass.

4.3.3 Butte Basin

The inundated area in the Butte Basin was not included in the calculation of existing floodplain rearing habitat for the Upper Sacramento River CPA because it is not directly connected to the main Sacramento River channel at flows satisfying criteria. Therefore, although it is recognized that floodplain rearing habitat is likely available to juvenile salmonids produced in the Butte Creek watershed, it is not expected that this rearing habitat would be accessible to juvenile salmonids produced upstream or downstream of Butte Creek in the Upper Sacramento River CPA. And because our resolution for calculating available and required suitable habitat is at the CPA-level, we decided to exclude inundated area in Butte Basin because only fish originating in Butte Creek would be exposed to this habitat. Butte Creek origin fish only make up 2 percent of spring-run and less than 1 percent of fall-run Chinook salmon entering the Upper Sacramento River CPA.

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5.0 Calculating Suitable Juvenile Salmonid Rearing Habitat Required to Support the AFRP Doubling Goal

5.1 Background

This section describes the calculation of the floodplain rearing habitat needed to support the AFRP doubling goals. The Central Valley ESHE model was built to estimate the amount of usable habitat, including valuable floodplain rearing habitat, needed in selected portions of the CPAs (Figure 5-1), with AFRP adult doubling goals. In the results section of this document, the habitat need was combined with the existing and historical habitat described in the previous section to quantify the current need for additional floodplain rearing habitat in the CPAs.

5.2 Chinook Salmon Life History

The Sacramento–San Joaquin River system supports four races of Chinook salmon: the fall, late fall, winter, and spring runs. These races and the large runs they once supported (at least 1–2 million adults annually) (Yoshiyama et al. 1998, 2000) reflect the diverse and productive habitats that historically existed within the region. The four CV Chinook salmon races (runs) are named for the season when the majority of the adult spawning run enters freshwater; the timing of runs varies from stream to stream. The majority of young salmon of these races migrate to the ocean during the first few months following emergence, although some may remain in freshwater and migrate as yearlings.

Newly emerged young are often found in shallow, slow-moving water and transition to deeper, faster water as they increase in size (see Cramer and Ackerman 2009). Habitat complexity (e.g., woody debris, overhanging vegetation, and seasonally inundated areas) provides juveniles with hiding, resting, and feeding habitat, increasing their ability to grow, develop, and survive emigration. Juvenile diets often vary by habitat type, but terrestrial and aquatic invertebrates and larval fish and eggs are important prey for juvenile salmon upstream of the Delta (Merz and Vanicek 1996; Sommer et al. 2001). Prey size and ingestion rates are affected by juvenile size and water temperature (Merz 2002). At times, floodplains provide better juvenile rearing opportunities because they often create optimum temperatures, offer habitats rich in prey items and away from salmon predators, and provide refuge from high flows (Sommer et al. 2001; Jeffres et al. 2008). Habitat availability, water quality, and predation are examples of environmental factors that can affect successful rearing (Lindley and Mohr 2003).

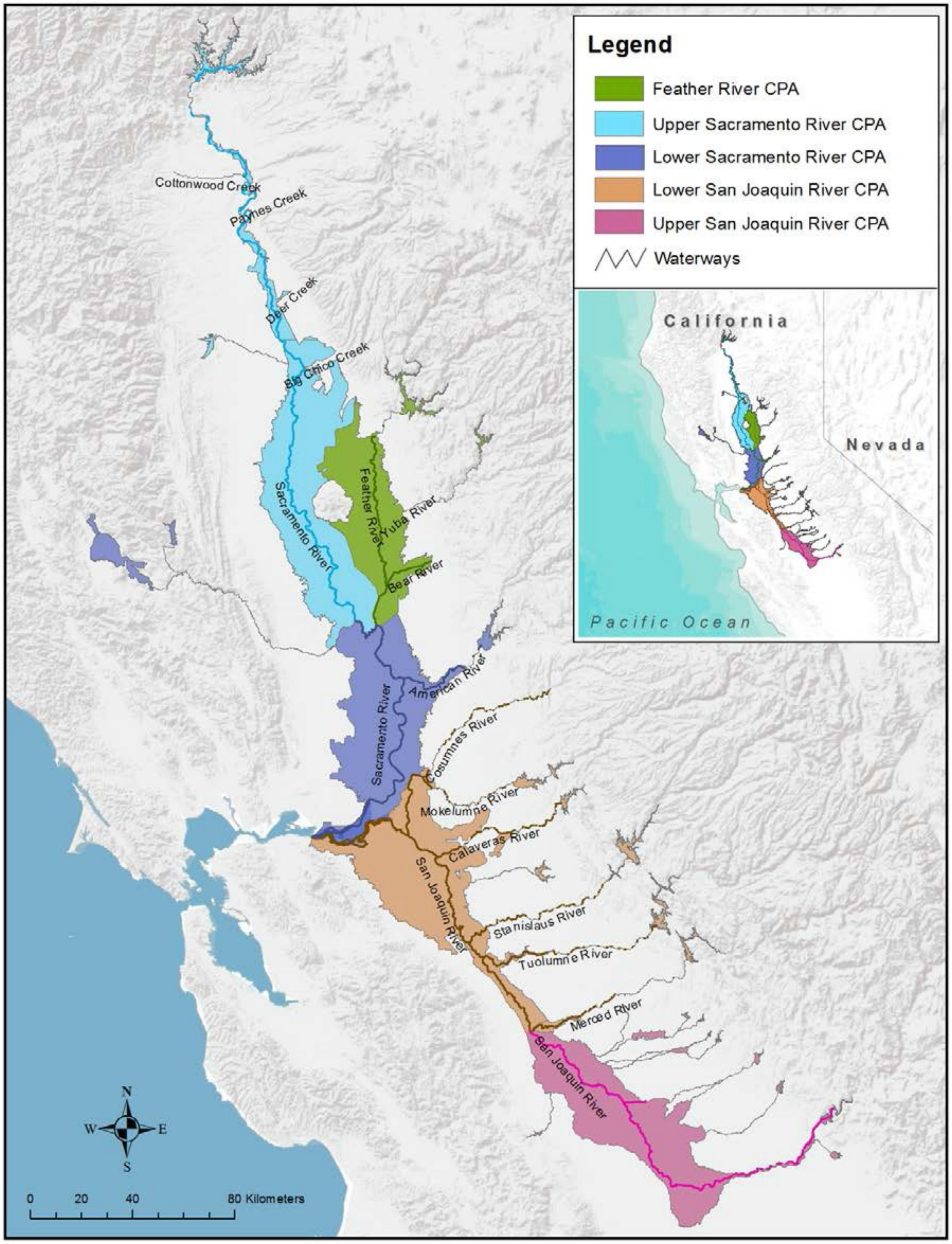


Figure 5-1. Watersheds and CPAs Where Central Valley Chinook Salmon Juvenile Emigrants Are Modeled by the Central Valley ESHE Model

For some juvenile Chinook salmon, leaving the tributary stream (emigration) takes place relatively quickly (i.e., over a few days or weeks). For other members of the same population, emigration is drawn out, with individuals presumably stopping and establishing territories along the way (i.e., over months). Regardless of life-history strategy, territories such as holding, resting, and feeding areas are likely the most useful predictors of the space required by an individual member of the salmon family (salmonid) and are therefore the most useful way to determine required habitat during emigration (Grant et al. 1998; Keeley 2000).

Observations of the combination of salmonid feeding and territorial behavior have been of interest to fisheries biologists for some time, because territory size is thought to limit the density and production of stream-dwelling salmonids (Chapman 1966; Allen 1969; Grant and Kramer 1990). Territory size requirements of individual fish of a given size are generally constant regardless of the local numbers of fish (abundance) (Grant and Kramer 1990; Cramer and Ackerman 2009). In open (i.e., natural) systems, territory requirements result in competition for space and displacement of smaller and weaker individuals (Titus 1990; Keeley 2003; Cramer and Ackerman 2009). Smaller and weaker individuals in turn occupy suboptimal territories (see Titus 1990) and are likely to experience increased stress, which reduces growth and fitness, causing increased mortality. Therefore, providing an adequate quantity and quality of rearing territory during emigration can reduce the negative effects associated with competition for space on a population level.

5.3 Modeling Approach

The approach used was to build the Central Valley ESHE model, a deterministic simulation model that tracks the rearing and emigration of individual daily groups (cohorts) of juvenile CV Chinook salmon from spawning grounds to San Francisco Bay entry (at Chipps Island). The model tracks their abundance and size and the amount of suitable rearing and emigration habitat required to sustain the number of juvenile salmon present within a region. The model runs through a 1-year period, from 1 October through 31 September of the following year. Model outputs provide daily estimates of the number of juvenile spring-run, fall-run, late fall–run and winter-run Chinook salmon present in each region and the required area of suitable habitat (ASH) needed to support them throughout the rearing and emigration period. ASH is the typical term used to report output from the ESHE model; however, in this report ASH is also referred to as “total habitat need.”

The simulation model approach has been successfully applied to evaluate the effects of other restoration actions on CV Chinook salmon populations; some examples are as follows:

- The San Joaquin River ESHE model was used to quantify the rearing and emigration habitat needs of future restored populations of fall-run and spring-run Chinook salmon in the San Joaquin River as part of the San Joaquin River Restoration Program (2012).
- The Interactive Object-Oriented Simulation (IOS) life cycle model (Zeug et al. 2012) was used to evaluate the effects of the National Marine Fisheries Service’s alternative scenarios

for Central Valley water operations on the life cycle and abundance trends of winter-run Chinook salmon.

- The Delta Passage Model (DPM) was used to evaluate the effects of Bay Delta Conservation Plan water scenarios on the Delta emigration survival of all Central Valley runs of Chinook salmon.

5.3.1 Territory Concept

Drawing from experimental salmonid studies (see Grant and Kramer 1990 and Grant et al. 1998), the Central Valley ESHE model relies on the finding that the maximum number of individuals a habitat area can support is limited by territory size. Therefore, the juvenile salmon carrying capacity, or the abundance of fish that can be supported in a given area (capacity), is a function of the available ASH and average fish territory size:

capacity = ASH / territory size (Equation 1)

Salmon require specific habitat conditions for rearing, including suitable water depths, velocities (Raleigh et al. 1986; Keeley and Slaney 1996), and temperatures (Marine and Cech 2004).

Therefore, juvenile salmon will generally only rear (and set up territories) in habitat that meets their preferred range of habitat conditions. This defines the ASH as the total area of habitat meeting rearing requirements. In most natural systems, ASH is only a small fraction of total inundated area. Therefore, ASH can also be defined as the proportion of total inundated area that has suitable components, such as depths and velocities. Within ASH, habitat complexity (e.g., woody debris) and food abundance influence habitat quality, which in turn increases or decreases fish territory size.

In order for the Central Valley EHSE model to enumerate the amount of suitable rearing and emigration habitat required to support future population abundance goals, Equation 1 was reorganized to calculate ASH as a function of fish abundance and territory size:

ASH = abundance • territory size (Equation 2)

When applied in the Central Valley ESHE model, Equation 2 estimates the date-specific and CPA-specific ASH required to support the cumulative territory size requirements of the total number (abundance) of juvenile salmon present in the CPAs throughout the juvenile rearing and emigration period.

5.3.2 Modeling Platform

The Central Valley ESHE model was built in NetLogo, a multiagent programmable modeling environment. NetLogo is readily accessible because it is free, open source, and cross-platform. The highly readable syntax of the programming language, thorough documentation, and widgets for graphical-user-interface elements allow for rapid prototyping of new models in NetLogo.

These elements allow users to explore the effects of changing parameters on model behavior without any programming experience. NetLogo is also a powerful tool for scientific modeling (Lytinen and Railsback 2012) with a built-in parameter-sweeping feature and parallel processing.

5.3.3 Model Components

The Central Valley ESHE model is made up of several components that are supported by functions and parameter values taken from appropriate literature and regional studies (Table 5-1). These components are (1) initial abundance—the abundance of juvenile salmon entering the model; (2) entry location—the entry of juveniles into the model in each watershed at the downstream end of observed spawning grounds; (3) initial timing and size—the timing and average size of juvenile salmon entering the model in each watershed; (4) growth—the daily growth and resulting size of juvenile salmon in each region; (5) migration rate—the daily downstream movement of juvenile salmon in each region; (6) survival—the daily survival and abundance of juvenile salmon in each region; and (7) territory size—the territory size requirements of juvenile salmon in each region.

Table 5-1. Central Valley ESHE Model Components Applied as Fish Enter the Model and as Fish Emigrate through Model Reaches, Data Sources, and the Spatial Level at Which Each Component Is Applied in the Model

	Component	Data Source	Spatial Level
Model entry	Initial abundance	AFRP escapement targets	Watershed
	Entry location	Various State and federal agency reports	Watershed
	Initial timing and size	Rotary screw traps	Watershed
Emigration	Growth	Laboratory studies	Global
	Migration rate	Tagging studies	Regional
	Survival	Estimated by matrix model	Global
	Territory size	Field and lab studies	Global

Where possible, model components were developed using watershed-specific data or literature sources (e.g., initial abundance, entry location). However, owing to time constraints and data limitations, most model components were informed with fish sampling data from a few, relevant surrogate watersheds (e.g., initial timing and size), or regional (e.g., migration rate) or global (e.g., growth, survival, territory size) scales. The model components are described in detail in Section 5.3.5, “Model Entry,” and Section 5.3.6, “Emigration,” below.

5.3.4 Modeled Scenario

The Central Valley ESHE model was used to estimate the total amount of suitable rearing habitat needed to support sustainable CV Chinook salmon populations that annually meet the AFRP adult doubling goals. Therefore, the AFRP adult doubling goals were used to inform initial spawner abundances in the model (see “Initial Abundance,” below, for details), and in-river survival rates were set at values that would ultimately sustain the population at AFRP adult doubling goal levels (see “Survival” section, below).

To incorporate uncertainty in model outputs and provide a range of estimates of required suitable habitat, a range of observed CV Chinook salmon emigration strategies was modeled. The model was run under the range of emigration behaviors of Chinook salmon, observed at Central Valley rotary screw traps (RSTs), with both early and late emigration strategies, with the early migrants beginning their migration earlier in the season at a smaller size, and late emigrants beginning their migration later in the season at a larger size (see “Initial Timing and Size” section, below).

Because the CVFPP may call for construction of setback levees and the creation of additional floodplain habitat, and because increasing CV Chinook salmon abundance to AFRP doubling goal levels will likely require floodplain habitat restoration, juveniles in the Central Valley ESHE model exhibited growth and migration rates observed in Central Valley floodplain habitats. More specifically, juveniles in the model were set to grow faster and emigrate slower than the majority of present-day CV Chinook salmon juveniles that emigrate in mainstem habitats.

5.3.5 Model Entry

Initial Abundance

AFRP adult doubling goals were converted to juvenile emigrants to determine the initial abundances of juveniles from each race of Chinook salmon entering the model in each watershed (Table 5-2). The AFRP, as defined in Section 3406(b)(1) of the Central Valley Project Improvement Act, is to ensure that “natural production of anadromous fish in Central Valley rivers and streams will be sustainable, on a long-term basis, at levels not less than twice the average levels attained during the period of 1967–1991.” “Natural production” is defined as “the number of fish recruited to adulthood in a given year, including newly recruited fish that are harvested.” Therefore, for each watershed, the offspring of these AFRP natural production targets and their required suitable habitat during emigration were modeled.

To convert adult abundance to juveniles, AFRP adult abundances were converted to female spawners by assuming a sex ratio of 0.5. Next, female spawners were converted to deposited eggs by multiplying by 5,423, the average observed fecundity of fall-run Chinook salmon on the Mokelumne River (Kaufman et al. 2009). Finally, eggs were converted to juveniles by multiplying by 0.25, the approximate average egg-fry survival rate estimated in the upper Sacramento River (Martin et al. 2001). The resulting number of juveniles entering the model in each watershed for each race is presented in Table 5-2.

Entry Location

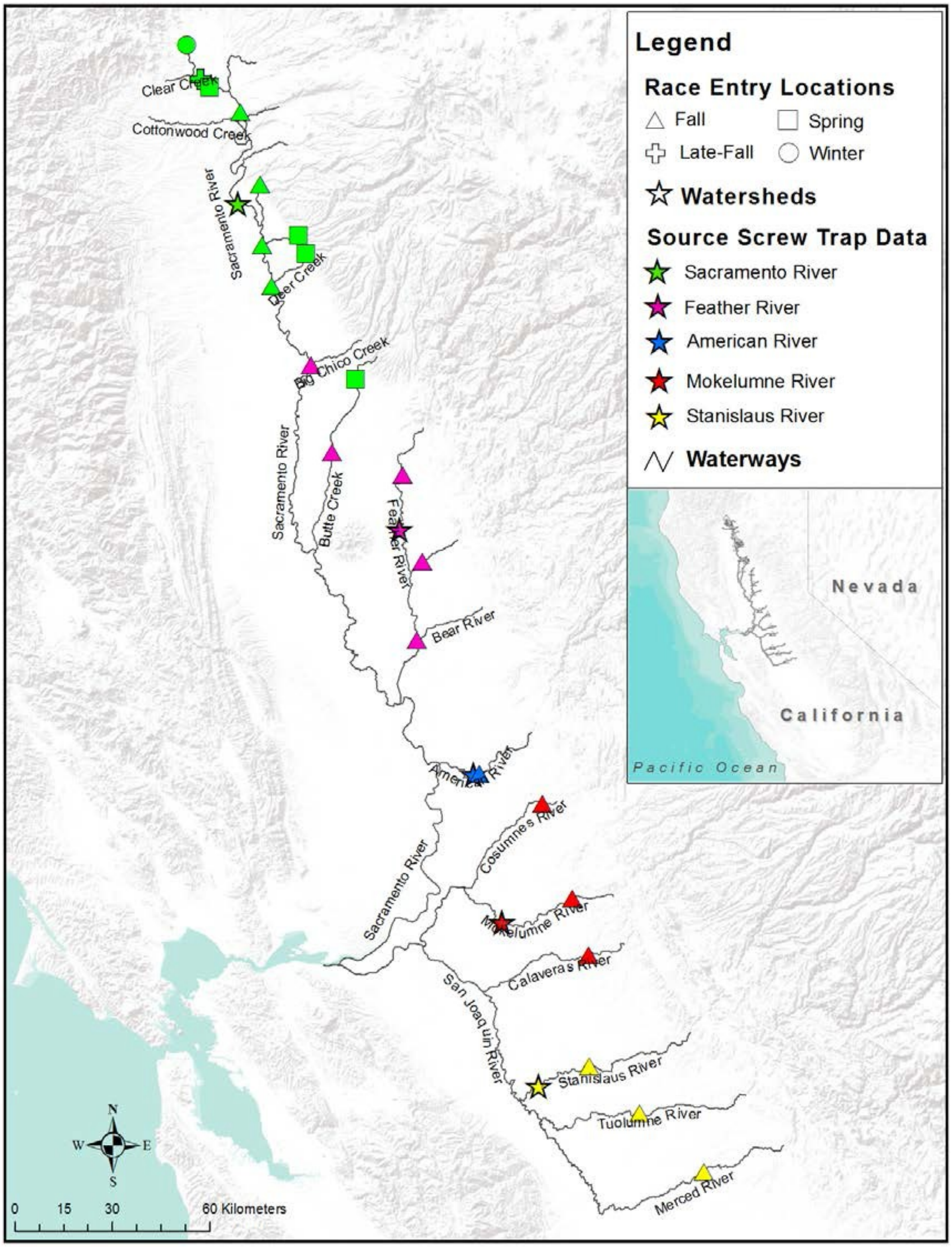
The entry location was set for each Chinook salmon race in each watershed at the end of the spawning grounds, under the assumption that juveniles would begin their emigration downstream of the habitat where they first emerged from the gravel (Figure 5-2, Table 5-3). State and federal agency reports were used as sources to define the approximate locations of the ends of the

Table 5-2. AFRP Adult Doubling Goal Values and Resulting Number of Juveniles Entering the Model in Each Watershed for Each Race

Region	River	Run	AFRP Doubling Goal	Juveniles Entering The Model
Lower San Joaquin	Cosumnes River	Fall	3,300	2,236,988
	Mokelumne River	Fall	9,300	6,304,238
	Calaveras River	Fall	2,200	1,491,325
	Tuolumne River	Fall	38,000	25,759,250
	Stanislaus River	Fall	22,000	14,913,250
	Merced River	Fall	18,000	12,201,750
Feather River	Feather River	Fall	170,000	115,238,750
	Yuba River	Fall	66,000	44,739,750
	Bear River	Fall	450	305,044
Lower Sacramento	American River	Fall	160,000	108,460,000
Upper Sacramento	Sacramento River and Tributaries above RBDD	Fall	258,700	175,366,263
		Late-fall	44,550	30,199,331
		Winter	110,000	74,566,250
		Spring	59,000	39,994,625
	Antelope Creek	Fall	720	488,070
	Mill Creek	Fall	4,200	2,847,075
		Spring	4,400	2,982,650
	Deer Creek	Fall	1,500	1,016,813
		Spring	6,500	4,406,188
	Butte Creek	Fall	1,500	1,016,813
		Spring	2,000	1,355,750
	Big Chico Creek	Fall	800	542,300

spawning grounds (Table 5-3). The ends of the spawning grounds in the ESHE model coincided with the beginnings of potential rearing habitat evaluated using the EAH-based approach described above.

For all mainstem Sacramento River and Sacramento tributary populations above the Red Bluff Diversion Dam (RBDD), a single model entry location was calculated for each race, weighted by spawner abundance (Table 5-3). Race-specific spawner distribution data in the mainstem Sacramento River was applied using the 3 most recent years (2007–2009) of aerial redd surveys conducted by USFWS. Reach-specific spawner proportions were then multiplied by the AFRP doubling goal estimates for each race to estimate the number of mainstem spawners of each race entering at each river kilometer (RKM). Next, for tributary populations entering above RBDD (Paynes Creek, Battle Creek, Cottonwood Creek, Cow Creek, Clear Creek, and other



Note: Colors for each entry location match the RST data applied for that particular race and watershed.

Figure 5-2. The Model Entry Locations (Ends of Spawning Grounds) for Each Chinook Salmon Race in Each Watershed and RST Locations Used to Define Entry Timing and Size for Juvenile Emigrants in the Model

Table 5-3. Model Entry Locations for Each Chinook Salmon Race in Each Watershed, References Used to Inform the Approximate Locations of the Ends of the Spawning Grounds, and RST Data Applied to Each Population to Inform Initial Timing and Size of Juvenile Emigrants

Watershed	Run	Model Entry (RKM)	Reference	RST Used
Cosumnes River	Fall	42	Snider and Reavis 2000	Mokelumne
Mokelumne River	Fall	90	Bilski and Rible 2010	Mokelumne
Calaveras River	Fall	39	Marsh 2006	Mokelumne
Tuolumne River	Fall	42	California Department of Fish and Game 2002	Stanislaus
Stanislaus River	Fall	34	Pyper et al. 2006	Stanislaus
Merced River	Fall	44	Johnson 2002	Stanislaus
Feather River	Fall	85	Hartwigsen et al. 2002	Feather
Yuba River	Fall	5	Campos and Massa 2012	Feather
Bear River	Fall	0	Jones & Stokes 2005	Feather
American River	Fall	16	Healey 2005	American
Sacramento River and tributaries above RBDD	Fall	441	Killam 2012	RBDD
	Late fall	460	Killam 2012	RBDD
	Winter	476	Killam 2012	RBDD
	Spring	455	Killam 2012	RBDD
Antelope Creek	Fall	56	Arrison 2008	RBDD
Mill Creek	Fall	0	Arrison 2008	RBDD
	Spring	25	Arrison 2008	RBDD
Deer Creek	Fall	0	Arrison 2008	RBDD
	Spring	29	Arrison 2008	RBDD
Butte Creek	Fall	32	McReynolds et al. 2006	Feather
	Spring	58	McReynolds et al. 2006	RBDD
Big Chico Creek	Fall	21	McReynolds et al. 2006	Feather

miscellaneous creeks) the respective AFRP doubling goal estimates were applied to their Sacramento River entry location (RKM). Finally, the overall model entry location (RKM) for each race in the upper Sacramento River mainstem was determined by calculating the average location of the spawning grounds weighted by spawner abundance.

Initial Timing and Size

The available RST data from Central Valley watersheds were used to inform initial timing and size of juveniles entering the model. RST data were applied from five different focal watersheds across the Central Valley (Table 5-3). Because variation in daily catch rates of RSTs can be highly influenced by variability in capture efficiency, RST data were used only if catch was corrected for trap efficiency, thereby reducing bias in estimates of emigration timing. In watersheds where no RST existed or catch data were not corrected for trap efficiency, data from the closest RST that captured the race of interest were used. The daily proportion of the annual abundance of juvenile emigrants of each race captured at each RST was estimated to inform entry timing, and the average daily fork length of emigrating juveniles of each race was applied to inform initial size (see individual RST data below).

Because juvenile emigration was defined as beginning at the ends of the spawning grounds, and all the RSTs from the five focal watersheds were located downstream of the spawning grounds, a back-calculation algorithm was developed to estimate the initial entry timing and initial sizes of juveniles that were captured in the RSTs. To do this, the average migration rates of coded-wire tagged (CWT) juvenile Chinook salmon observed in Central Valley watersheds was applied to the distance between the RST location and the bottom of the spawning grounds.

The back-calculation algorithm started by applying a growth curve developed for juvenile Sacramento River fall-run Chinook salmon by Fisher (1992) to estimate the age of the fish captured at the RST based on the measured fork length (FL) (Figure 5-3):

$$FL = \exp(3.516 + 0.007 * age) \quad \text{(Equation 3)}$$

Then, each fish was classified as presmolt (<70 millimeters [mm]) or smolt (≥70 mm) based on fork length, a common length cutoff used for the transition to smolts in the Central Valley (Brandes and McLain 2001). CWT mark-recapture data from Butte Creek (Hill and Webber 1999; Ward and McReynolds 2004; Ward et al. 2004a, 2004b, 2004c; McReynolds et al. 2005, 2006, 2007) was used to estimate the median migration rate of presmolts (13 kilometers [km]/day) and smolts (34 km/day) for the focal watersheds in the Sacramento River Valley (i.e., American River, Feather River, Sacramento River). A combination of CWT, acoustic tag, and mark-recapture data from the Stanislaus River (Demko et al. 1999; Demko and Cramer 2000; Watry et al. 2007, 2008, 2009) was used to estimate the median migration rate of presmolts (5 km/day) and smolts (10 km/day) for the focal watersheds in the San Joaquin River Valley (i.e., Mokelumne River and Stanislaus River).

The algorithm then iterated through the process of moving fish upstream at the average migration rate on a daily basis (and updating age and size) until they had either reached the bottom of the spawning grounds or had an estimated age of zero. The age was then used along with the Fisher (1992) growth curve to determine the fork length of that fish at the bottom of the spawning grounds.

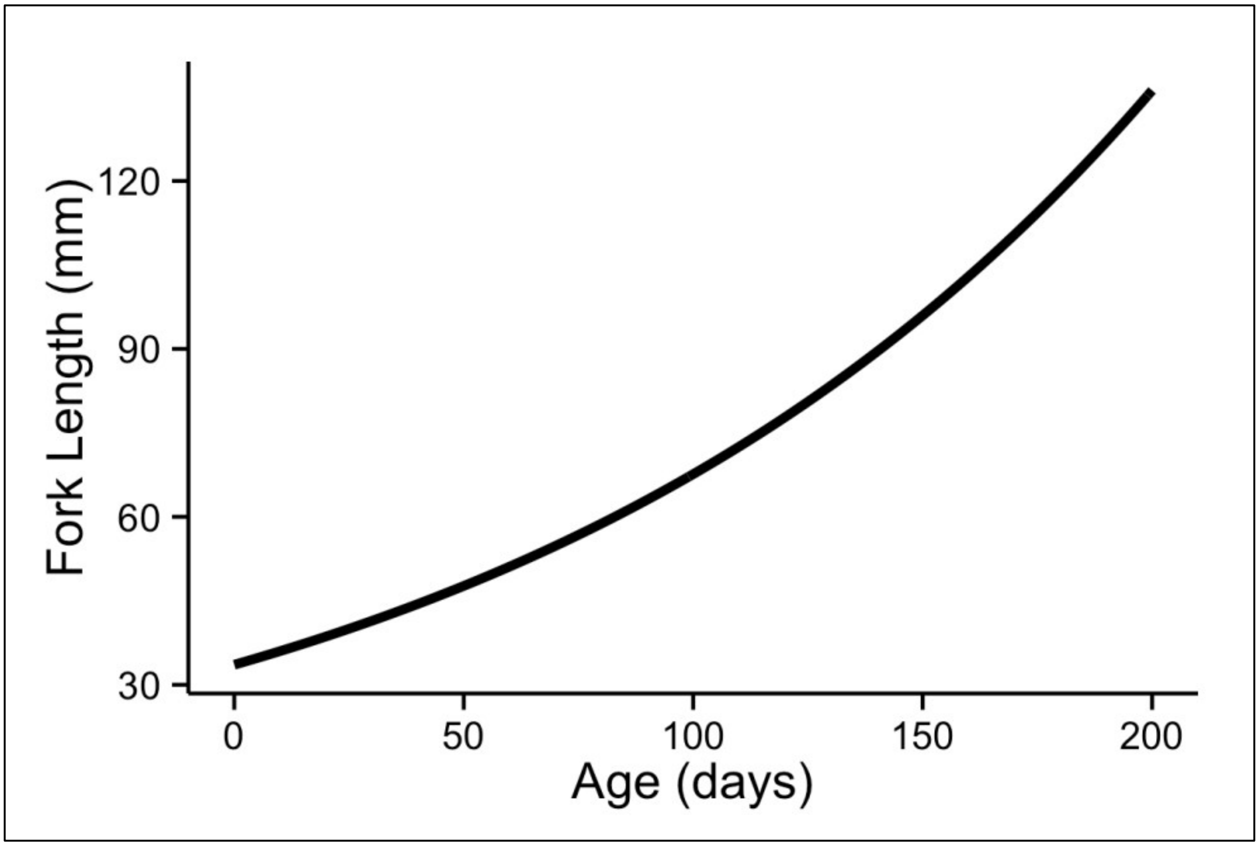


Figure 5-3. Age-Length Curve Developed for Juvenile Sacramento River Fall-Run Chinook Salmon by Fisher (1992), Used in the Model to Back-Calculate Fish Size from the RST Location to the Ends of the Spawning Grounds

To model a range in entry timing and size distributions, RST data were used from 2 example water years that captured the most extreme differences in emigration strategies. For each RST, a water year was selected when juveniles exhibited a characteristic “early” emigration strategy, with emigrants beginning their migration earlier in the season, and a second water year was selected when juveniles exhibited a characteristic “late” emigration strategy, with emigrants beginning their migration later in the season. For the American River, initial timing and size curves were applied for only a single water year (1999) because all water years examined (1994–1999) appeared to exhibit an “early” emigration strategy.

Mokelumne River Rotary Screw Trap

Chinook salmon daily abundance and average fork length data from the Mokelumne River RST, located at Woodbridge Dam (63 RKM), were used from years 2002 (late emigration strategy) and 2006 (early migration strategy) (Figures 5-4 and 5-5). RST data were collected by the East Bay Municipal Utility District.

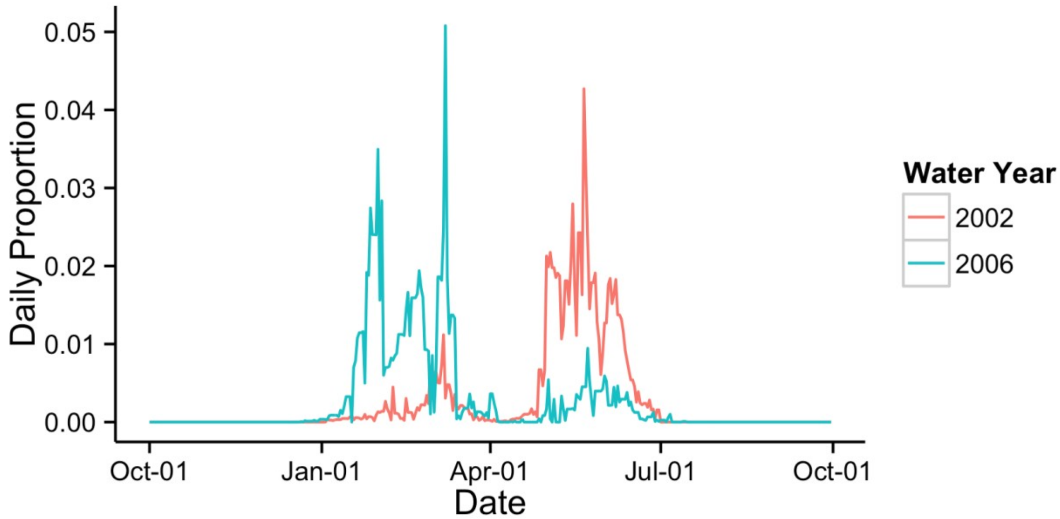


Figure 5-4. The Daily Proportion of the Annual Abundance of Juvenile Chinook Salmon Captured in the Mokelumne River RST in Years 2002 and 2006

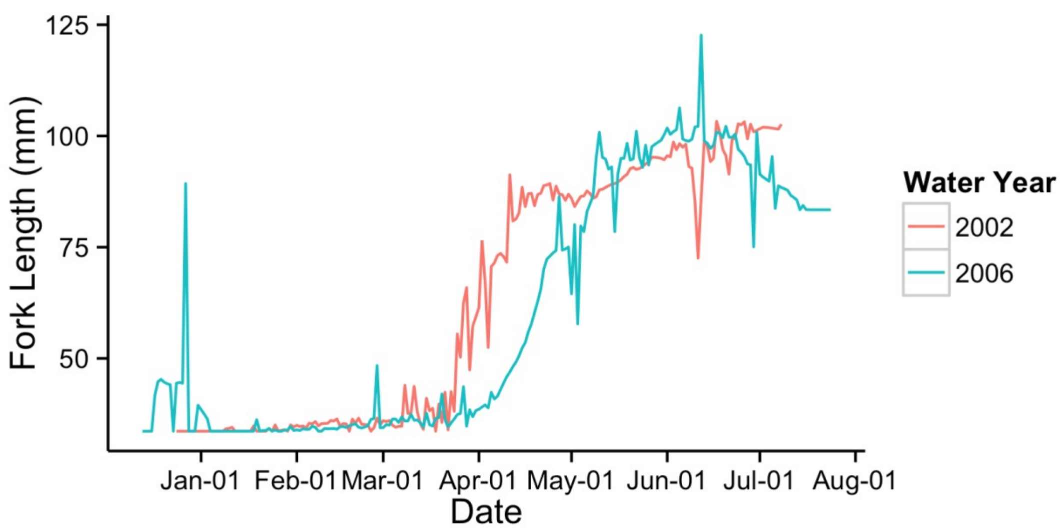


Figure 5-5. Average Daily Fork Lengths of Juvenile Chinook Salmon Captured in the Mokelumne River RST in Years 2002 and 2006

Stanislaus River Rotary Screw Trap

Chinook salmon daily abundance and average fork length data from the Stanislaus River RST, located at Caswell Memorial State Park (10 RKM), were used from years 2012 (late emigration strategy) and 1998 (early migration strategy) (Figures 5-6 and 5-7).

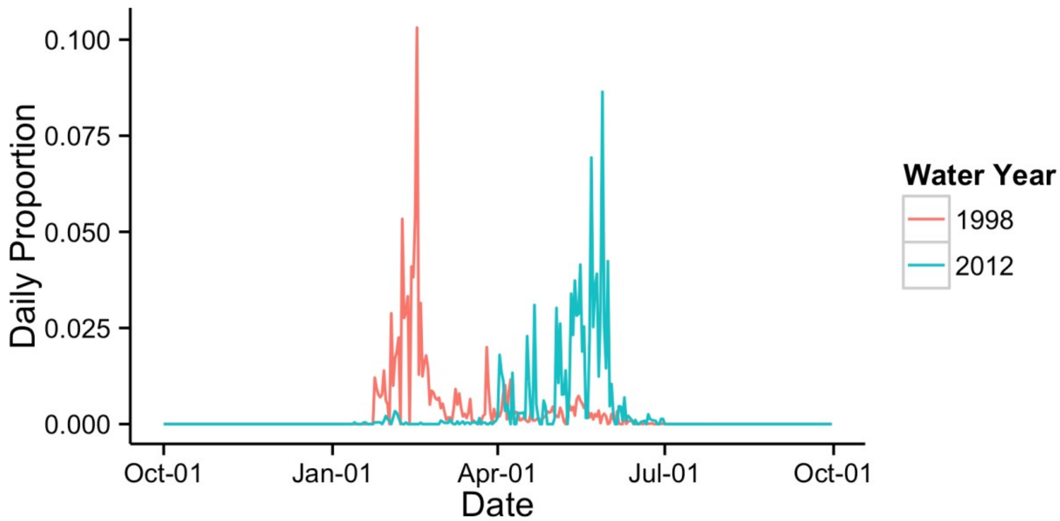


Figure 5-6. Daily Proportion of the Annual Abundance of Juvenile Chinook Salmon Captured in the Stanislaus River RST in Years 1998 and 2012

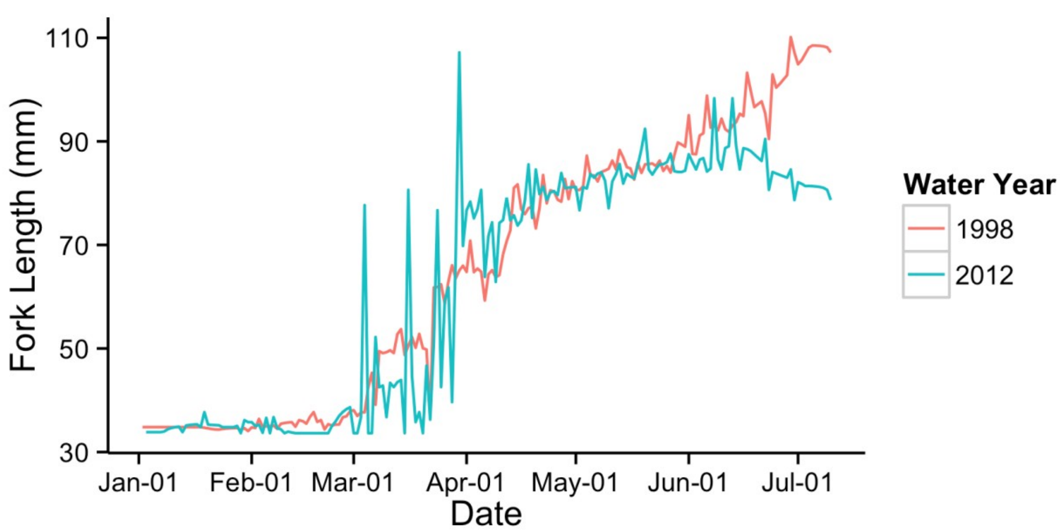


Figure 5-7. Average Daily Fork Lengths of Juvenile Chinook Salmon Captured in the Stanislaus River RST in Years 1998 and 2012

Feather River Rotary Screw Trap

Chinook salmon daily abundance and average fork length data from the Feather River RST, located in the high-flow channel (64 RKM), were used from years 2002 (late emigration strategy) and 2011 (early migration strategy) (Figures 5-8 and 5-9). RST data were collected by the California Department of Water Resources.

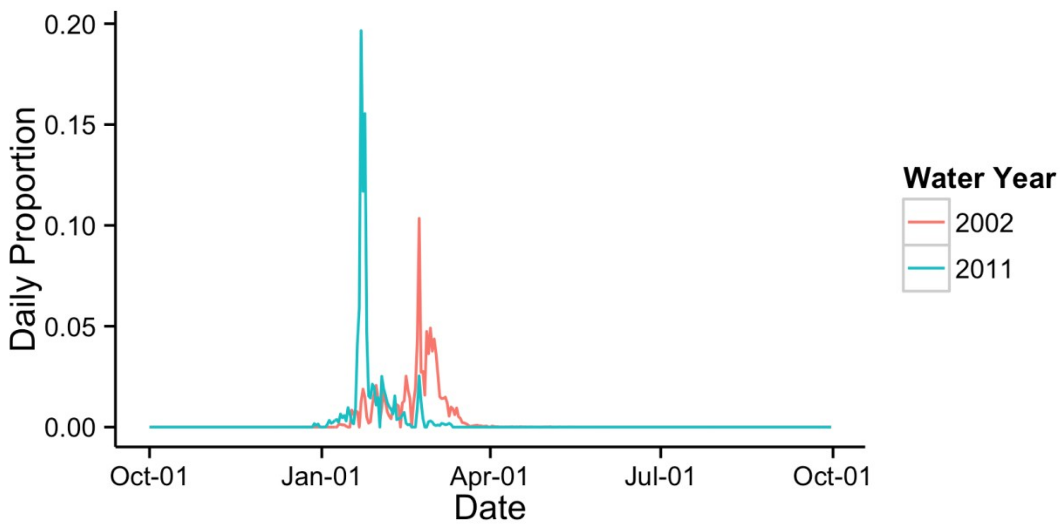


Figure 5-8. Daily Proportion of the Annual Abundance of Juvenile Chinook Salmon Captured in the Feather River RST in Years 2002 and 2011

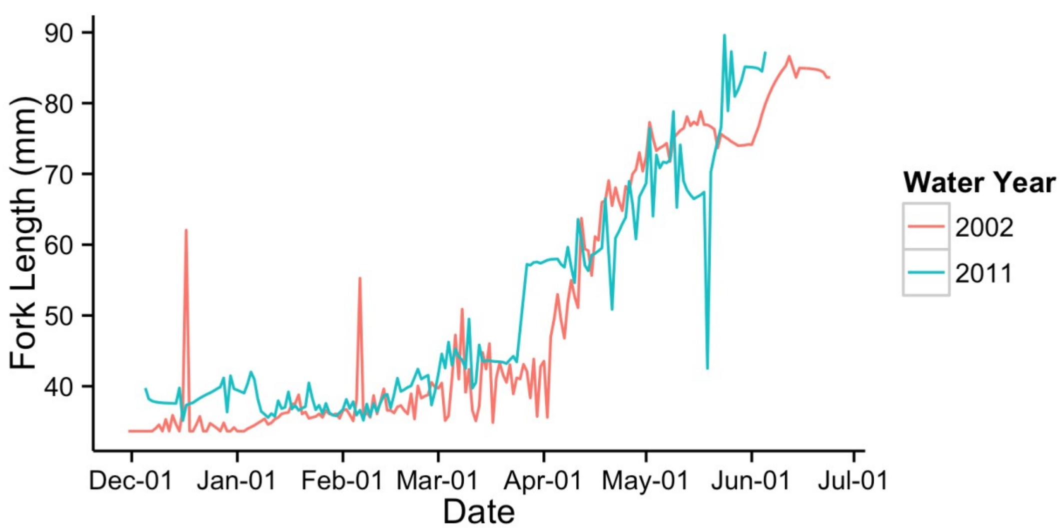


Figure 5-9. Average Daily Fork Lengths of Juvenile Chinook Salmon Captured in the Feather River RST in Years 2002 and 2011

American River Rotary Screw Trap

Chinook salmon weekly abundance and average fork length data from the American River RST, located at RKM 14, were used from 1999 (Figures 5-10 and 5-11). RST data were collected by the California Department of Fish and Wildlife.

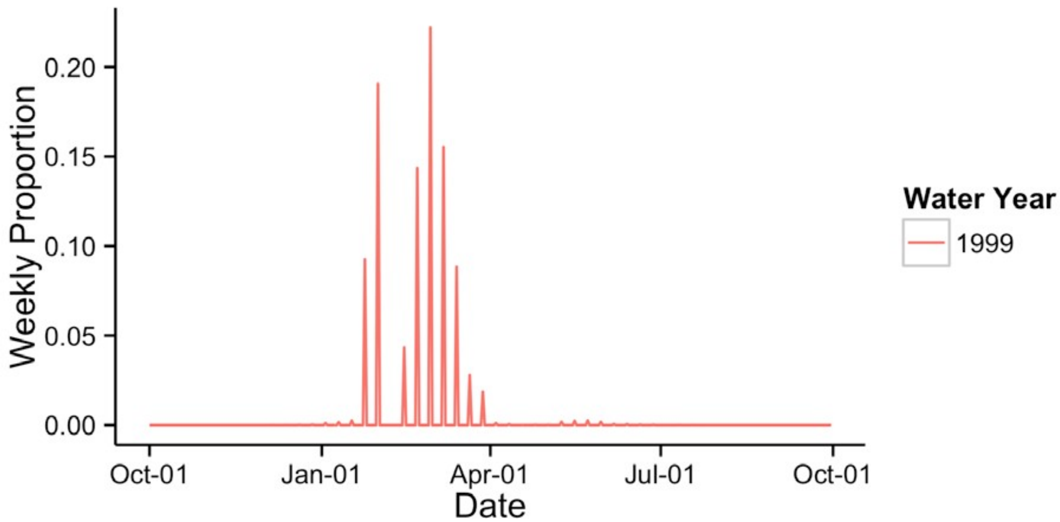


Figure 5-10. Weekly Proportion of the Annual Abundance of Juvenile Chinook Salmon Captured in the American River RST in 1999

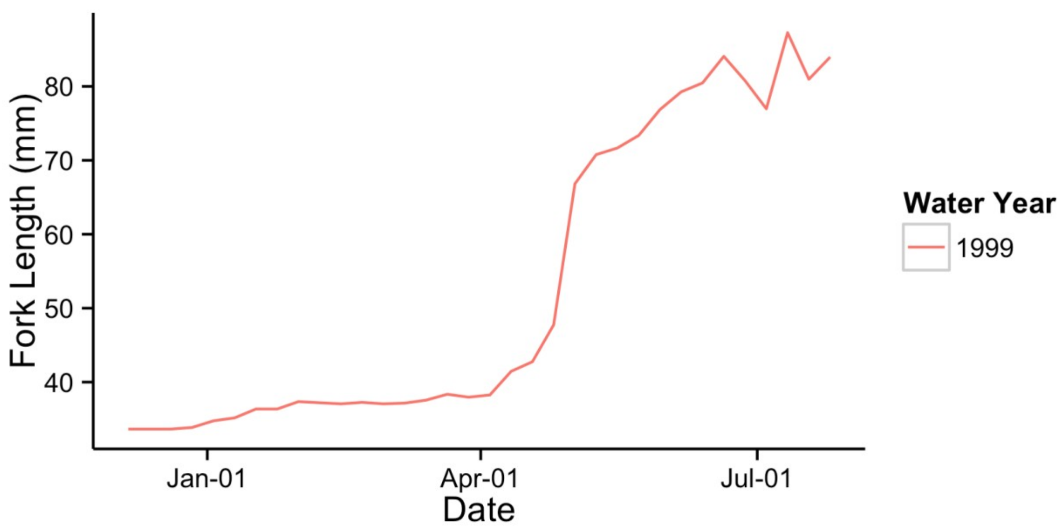


Figure 5-11. Average Weekly Fork Lengths of Juvenile Chinook Salmon Captured in the American River RST in 1999

Sacramento River Rotary Screw Trap at Red Bluff Diversion Dam

Chinook salmon daily abundance and average fork length data from the Sacramento River RST, located at the RBDD (391 RKM), were used from years 2009 (late emigration strategy) and 2006 (early migration strategy) (Figures 5-12 and 5-13). RST data were collected by USFWS.

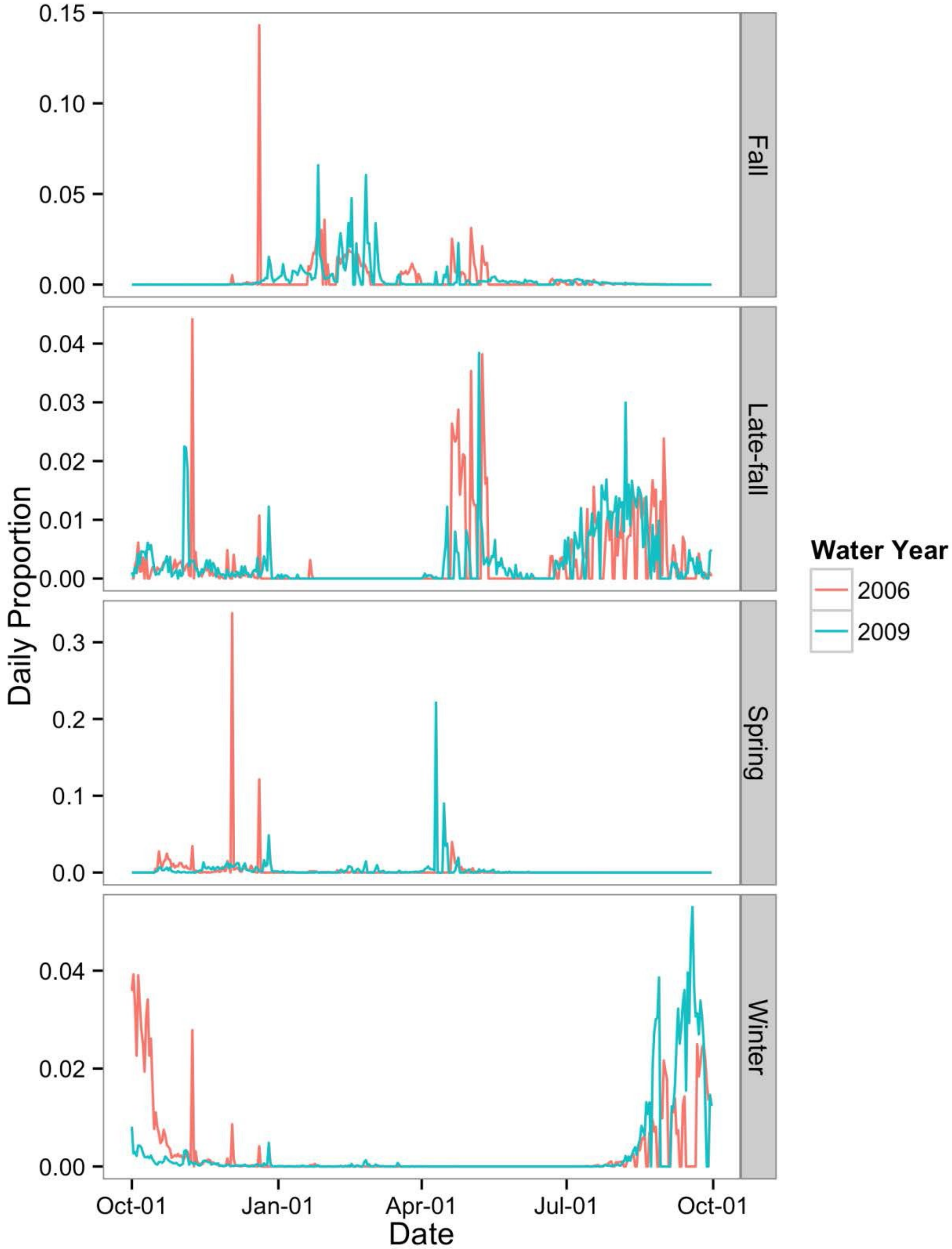


Figure 5-12. Daily Proportion of the Annual Abundance of Juvenile Chinook Salmon Captured in the Sacramento River RST at RBDD in Years 2006 and 2009

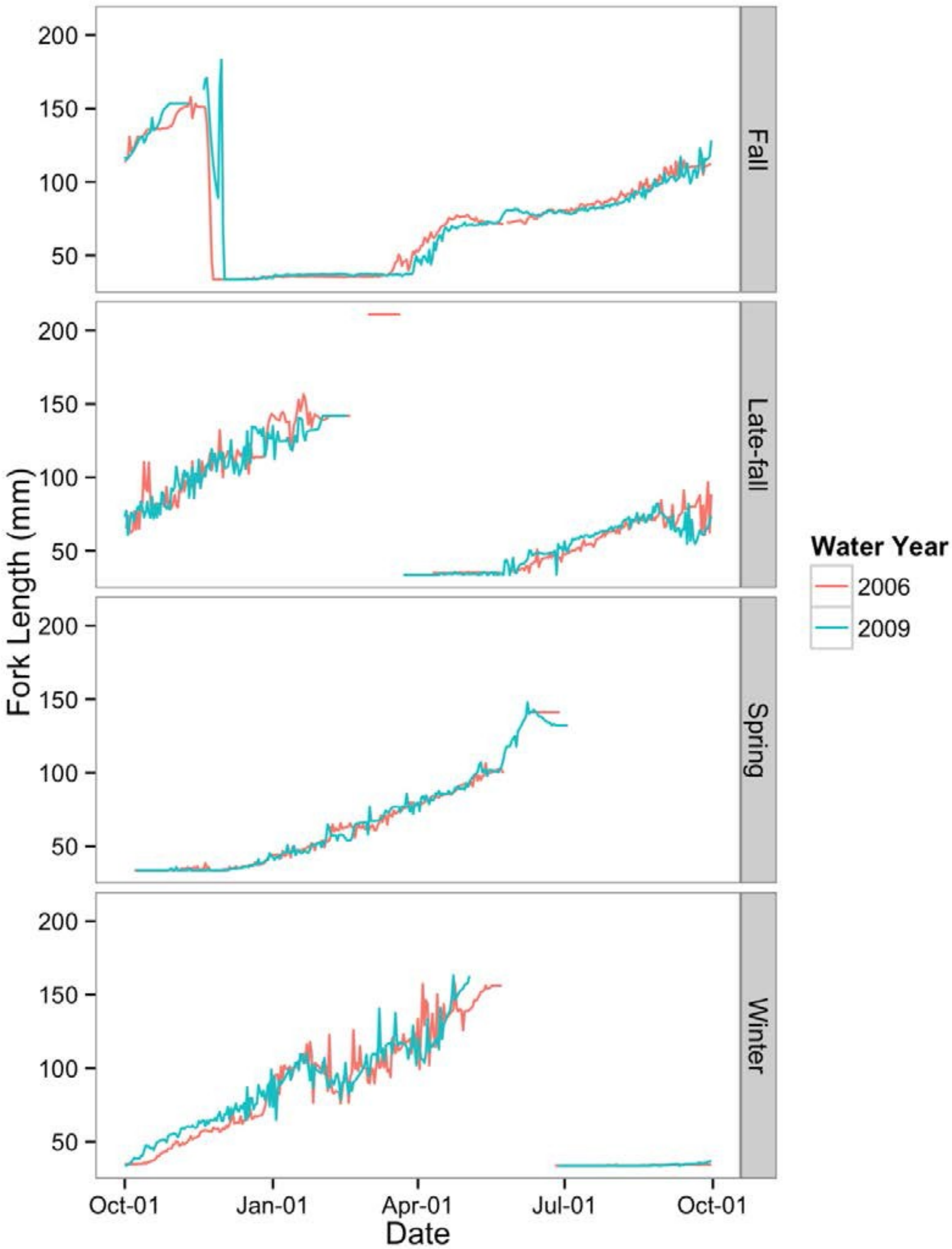


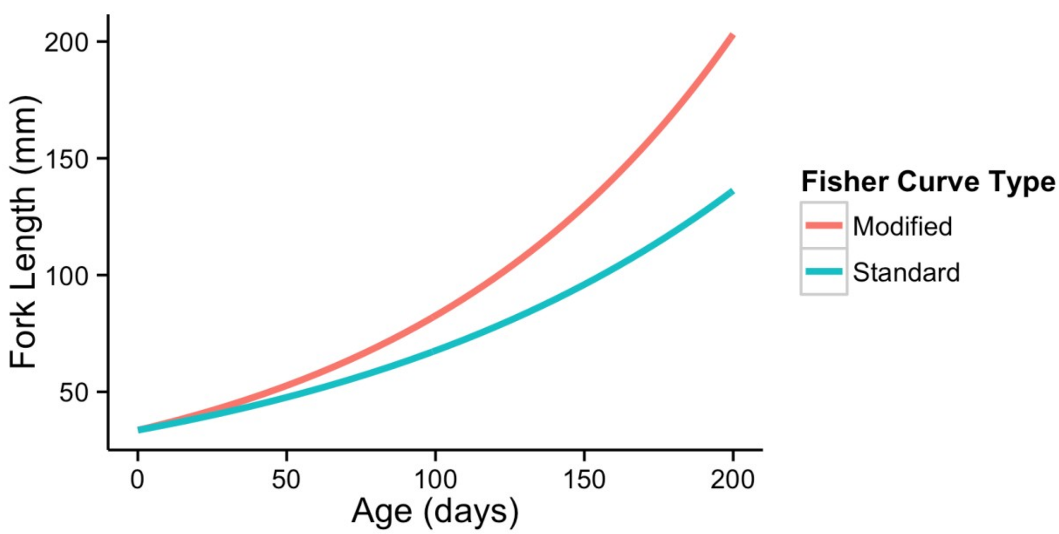
Figure 5-13. Average Daily Fork Lengths of Juvenile Chinook Salmon Captured in the Sacramento RST at the RBDD in Years 2006 and 2009

5.3.6 Emigration

Growth and Migration Rate

Because it was assumed that CVFPP actions could result in the creation of additional floodplain habitat, and because increasing CV Chinook salmon abundance to AFRP doubling goal levels will likely require floodplain habitat restoration, juveniles in the Central Valley ESHE model exhibited growth and migration rates observed in Central Valley floodplain habitats. It assumed that juveniles that rear on a floodplain will greatly increase their migration rates once they meet a threshold size and begin directed seaward migration. The Yolo Bypass was used as a representative example of floodplain rearing habitat and growth and migration rates observed during experimental studies in the Yolo Bypass (Sommer et al. 2001) were applied to all fish in the model. Residence time and initial and final size of fish released in the Yolo Bypass were used to estimate migration rates and modify the Fisher (1992) age-length curve, by fitting it to observed juvenile Chinook salmon growth and migration rates in the Yolo Bypass (Figure 5-14; Attachment H1). The resulting modified growth curve is based on a higher proportionate growth rate than was the original Fisher (1992) curve:

$$\text{Fork Length (FL)} = \exp(3.516 + 0.009 * \text{age}) \quad \text{(Equation 4)}$$



Note: The blue line is the age-length curve developed for juvenile Sacramento River fall-run Chinook salmon by Fisher (1992), used in the model to back-calculate fish size from the RST location to the ends of the spawning grounds. The red line is the modified curve fitted to growth rates of juvenile Chinook salmon in the Yolo Bypass, used in the model to predict daily sizes of juveniles during emigration (see Attachment H1).

Figure 5-14. Comparison of Age-Length Curves

The resulting size threshold for increased migration rate was 88 mm, with migration rates of 1 km/day and 21.3 km/day for fish <88 mm and fish ≥ 88 mm, respectively.

Survival

Even though AFRP adult doubling goals were used to inform initial spawner abundances in the model (see "Initial Abundance" for details), the goal was to estimate the total amount of suitable rearing habitat needed to support sustainable CV Chinook salmon populations that annually meet the AFRP adult goals. Therefore, in-river survival rates had to be set at values that would ultimately sustain the population at AFRP adult doubling goal levels. A matrix model created for Chinook salmon in the Columbia River Basin (Kareiva et al. 2000) was modified to estimate the in-river (spawning grounds to Chipps Island) survival value for emigrating juveniles. We modified the parameter values applied by Kareiva et al. (2000) to better reflect Chinook salmon life history in the Central Valley, California (Table 5-4).

Table 5-4. Modified Parameter Values and Supporting References of a Matrix Model from Kareiva et al. (2000) Used to Estimate In-river (Spawning Grounds to Chipps Island) Survival Value for Emigrating Juveniles

Category	Parameter	Kareiva et al. 2000	This Study	
			Proportion	Reference
Survival	Survival from egg to yearling	0.022	0.001	
	egg survival	N/A	0.25	Martin et al. 2001
	outmigration	N/A	0.05	*solved for
	estuary	N/A	0.05	*solved for
	yearling to age 2	0.729	0.8	
	age 2 to age 3	0.8	0.8	
	age 3 to age 4	0.8	0.8	
	age 4 to age 5	0.8	N/A	
	upstream migration	0.7	0.95	PFMC 2011
Return Rate	age 2	N/A	0.08	Grover et al. 2004
	age 3	0.013	0.96	Grover et al. 2004
	age 4	0.159	1	Grover et al. 2004
	age 5	1	N/A	
Fecundity	age 2	N/A	4185	Kaufman et al. 2009
	age 3	3257	5838	Kaufman et al. 2009
	age 4	4095	5994	Kaufman et al. 2009
	age 5	5149	N/A	

* = these parameter values were solved for using the matrix model

Many model parameters from Kareiva et al. (2000) were modified to reflect the life history of CV Chinook salmon. Egg survival was set at 0.25, the approximate average egg-fry survival rate estimated in the upper Sacramento River (Martin et al. 2001). Unlike Kareiva et al. (2000), we assumed that all fish emigrate during their first year of life and therefore included outmigration survival and estuary survival in our calculation of survival from egg to yearling. We set yearling to age 2 survival at 0.8 because we assumed that Central Valley yearlings to 2-yr-olds reside in the ocean, and therefore set survival at the same annual survival rate Kareiva et al. (2000) used for all ocean dwelling age classes. We set upstream migration survival of adults to 0.95 because

5 percent is the approximate average annual in-river harvest rate of fall-run Chinook salmon (Pacific Fishery Management Council 2011). We set age-specific return rates from the ocean at values observed for Central Valley spring-run Chinook salmon (Grover et al. 2004). Lastly, we set age-specific fecundities at values observed for fall-run Chinook salmon in Mokelumne River, California (Kaufman et al. 2009).

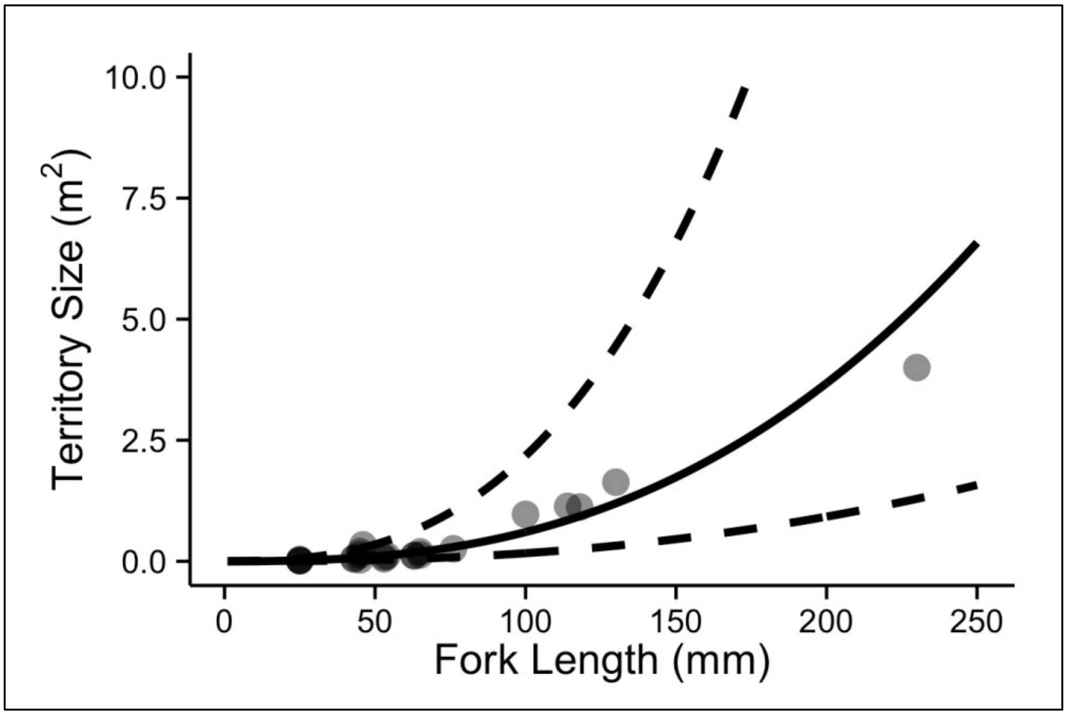
We solved for survival of juvenile Chinook salmon in the estuary and during in-river outmigration under the assumption that survival from ocean entry to age 3 typically ranges from 2 to 4 percent on average (Satterthwaite et al. 2014). The matrix model resulted in estimates of estuary and in-river survival of 5 percent. The outmigration survival rate was applied on a per-kilometer basis in the model for each Central Valley population.

Territory Size

Territory size of juveniles was modeled as a function of fork length based on a territory-size versus fork-length relationship estimated for salmonids from Grant and Kramer (1990) (Figure 5-15). The territory-size fork-length curve may vary depending on food availability, intruder pressure, water depth, and current velocity (Grant and Kramer 1990). When habitat quality is high, juvenile salmonids require less space (smaller territory size) to avoid predation and meet energetic demands through feeding. Conversely, when habitat quality is poor, juvenile salmonids require more space (larger territory size) to avoid predation and meet energetic demands. Because the quality of habitat available in the CPAs is unknown, a conservative (i.e., to limit underestimation of habitat needs) approach was applied when estimating fish territory size, using the upper 95-percent prediction interval curve from the Grant and Kramer (1990) relationship when calculating territory size from fork length (Figure 5-15):

territory size = 10^(-5.44 + 2.61*log10(fork length) + 0.54 * sqrt(1.04 + ((log10(fork length) - 1.76)^2)/1.36)) (Equation 5)

The model calculated the amount of suitable habitat area required (required ASH) to sustain the number of juvenile salmon present within a CPA on a given day. The daily required ASH in each CPA was calculated by multiplying the predicted territory size by the abundance of each cohort present in a given CPA, and summing across all cohorts. The total required ASH for all Central Valley populations combined in each CPA was estimated as the maximum of the summed daily required ASH values for each population.



Note: Circles are fish observations, the solid line is mean relationship, and dashed lines are upper and lower 95-percent prediction interval limits. The upper 95-percent prediction interval curve was applied in the model to estimate fish territory size.

Figure 5-15. Territory Size versus Fork Length Relationship for Salmonids from Grant and Kramer (1990)

5.4 Results: Total Juvenile Salmonid Rearing Habitat Needed

Table 5-5 summarizes the total juvenile salmonid rearing habitat needed in each CPA (reported as ASH) for both the late and early emigration strategy model runs.

Table 5-5. Overall Required ASH for All Central Valley Populations Combined for Each Emigration Strategy and CPA

Emigration Strategy	CPA	Required ASH (acres)
Late	Upper Sacramento River	23,000
	Lower Sacramento River	10,000
	Feather River	10,000
	Lower San Joaquin River	5,000
Early	Upper Sacramento River	24,000
	Lower Sacramento River	12,000
	Feather River	10,000
	Lower San Joaquin River	4,000

5.5 Assumptions and Limitations

Several assumptions were required to achieve model outcomes under a constrained timeline and limited resources, including lack of watershed-specific data. The following assumptions and limitations were included:

- Juveniles of different races and from different regions do not differ in growth rate, migration rate, survival rate, or territory size needs.
- The Yolo Bypass is representative of rearing habitat that might occur throughout the Central Valley.
- Survival is not size-specific.
- Survival depends on travel distance but not on travel time.
- Migration rate, growth rate, and survival rate do not depend on flow conditions.
- Overall survival is the same for each population throughout the Central Valley.
- Two years of initial timing and size data are representative of the range of emigration strategies present for that watershed.
- Timing and size distributions from RSTs are representative of juveniles emerging from the gravel (once they are backed up to the ends of spawning grounds).
- Juveniles likely switch from rearing to migrating many times throughout their emigration (or even during a single day), resulting in variation in territory needs, growth rates, migration rates, and survival rates. However, data on such fine-scale movement and rearing behavior is unavailable to inform more realistic, subdaily, fish emigration behavior modeling. Therefore, modeling was limited to a representation of the average daily movement and behavior of emigrating juveniles.
- RST data from five focal watersheds where high-quality data are available is representative of other nearby watersheds where high-quality RST data are lacking.

Despite these limitations this model provides an instructive broad scale view of rearing habitat requirements for juvenile Chinook salmon and is a step forward in developing a baseline understanding of habitat needs of CV Chinook salmon for the purpose of refining previously developed floodplain habitat objectives for the Conservation Strategy of the CVFPP. The constraint of limited pre-regulation, natural salmon behavior requires the reconciliation of numerous parameter estimates. Furthermore, this initial emigration and rearing modeling process highlights data gaps and provides direction for future research.

6.0 Results: Historical, Existing, and Required Suitable Habitat for Rearing Juvenile Salmonids

Table 6-1 summarizes the historical, existing, and total required suitable rearing habitat for juvenile salmonids in each CPA. Historical and existing values are presented for the low and high suitability factors described in Sections 3.0 and 4.0, and for an average of the low and high suitability values. Total required rearing habitat is presented for both the late and early emigration strategies, and for an average between these two migration strategies. The additional habitat needed to provide the required suitable rearing habitat is the difference between required and existing habitat acreages in Table 6-1. The corresponding area of inundated floodplain required to provide this additional suitable rearing habitat will depend on the suitability of the restored habitat (e.g., if a restored floodplain area is 20-percent suitable, the total inundated floodplain area required would be five times greater than the required suitable rearing habitat area). Regional objectives for suitable juvenile salmonid rearing habitat, and the design details of projects developed to provide this habitat should be refined on a site-specific basis in consultation with salmon ecology, hydrology, and hydraulic experts for the area of interest.

Table 6-1. Summary of Historical, Existing, and Required Suitable Rearing Habitat for Juvenile Chinook Salmon to Achieve the AFRP Doubling Goal in Each of the Analyzed CPAs

CPA Region	Historical Suitable Rearing Habitat (acres)			Existing Suitable Rearing Habitat (acres)			Required Suitable Rearing Habitat (acres)		
	Assuming Low Suitability	Assuming Average Suitability	Assuming High Suitability	Assuming Low Suitability	Assuming Average Suitability	Assuming High Suitability	Assuming Late Migration Strategy	Assuming Average of Late and Early Migration Strategies	Assuming Early Migration Strategy
Upper Sacramento River	80,586	89,744	98,901	1,399	3,284	5,169	23,000	23,500	24,000
Lower Sacramento River	75,020	83,545	92,070	767	1,814	2,862	10,000	11,000	12,000
Feather River	11,528	12,838	14,148	107	229	352	10,000	10,000	10,000
Lower San Joaquin River	75,614	84,207	92,799	419	911	1,404	5,000	4,500	4,000

This analysis does not include values for the Upper San Joaquin River CPA because a study was previously completed as part of the SJRRP to recommend a minimum area of suitable juvenile rearing habitat required to meet fall- and spring-run Chinook salmon targets for the Upper San Joaquin River CPA (SJRRP 2012). The existing area of suitable rearing habitat for juvenile Chinook salmon in the Upper San Joaquin River was estimated to be 931 acres, and the total area of suitable rearing habitat across all Restoration Program reaches ranged up to a maximum of 1,327 acres.

Several refinements remain that could add to the value of this work in guiding creation of new suitable rearing habitat for juvenile salmonids. These refinements include more detailed analyses of existing channel, floodplain, and tributary suitability for inundated areas in each subreach; improved empirical data on emigrating salmon migration, growth, and survival rates; and interactions with experts in Central Valley salmon ecology, hydrology, and hydraulics, ideally in a scenario evaluation workshop setting where the methods and results of this investigation can be presented and improved iteratively with input from system experts.

7.0 References

Aceituno, M. E. 1993. The Relationship between Instream Flow and Physical Habitat Availability for Chinook Salmon in the Stanislaus River. May. U.S. Fish and Wildlife Service, Sacramento, California.

Aceituno, B., and I. D. Rutherfurd. 1990. Habitat Preference Criteria for Chinook Salmon of the Stanislaus River, California. U.S. Fish and Wildlife Service, Sacramento, California.

Allen, K. R. 1969. Limitations on Production in Salmonid Populations in Streams. Pages 3–18 in T. G. Northcote (Editor), Symposium on Salmon and Trout in Streams. University of British Columbia, Vancouver.

Arrison, C. H. 2008. Chinook Salmon Population and Physical Habitat Monitoring in Clear, Antelope, Mill and Deer Creeks for 2007. Sacramento River Salmon and Steelhead Assessment Project Sport Fish Restoration Annual Progress Report.

Beakes, M. P., J. W. Moore, N. Retford, R. Brown, J. E. Merz, and S. M. Sogard. 2012. Evaluating Statistical Approaches to Quantifying Juvenile Chinook Salmon Habitat in a Regulated California River. River Research and Applications.

Bilski, R., and E. Rible. 2010. Lower Mokelumne River Salmonid Redd Survey Report: October 2010 through March 2011. East Bay Municipal Utility District, Oakland, California.

Brandes, P. L., and J. S. McLain. 2001. Juvenile Chinook Salmon Abundance, Distribution, and Survival in the Sacramento–San Joaquin Estuary. California Department of Fish and Game Bulletin 179:39–136.

California Department of Fish and Game. 2002. Lower Tuolumne River Fall Chinook Salmon Escapement Survey 2001.

Campos, C., and D. Massa. 2012. Lower Yuba River Accord Monitoring and Evaluation Program Annual Redd Survey Report, 2010–2011. Prepared for Lower Yuba River Accord Planning Team.

Chapman, D. W. 1966. Food and Space as Regulators of Salmonid Populations. American Naturalist 100:345–357.

Cramer, S. P., and N. K. Ackerman. 2009. Linking Stream Carrying Capacity for Salmonids to Habitat Features. Pages 225–254 in E. E. Knudsen and J. H. Michael, Jr. (Editors), Pacific Salmon Environmental and Life History Models: Advancing Science for Sustainable Salmon in the Future. American Fisheries Society, Symposium 71, Bethesda, Maryland.

Cramer Fish Sciences. 2013. Lancaster Road Side Channel and Floodplain Juvenile Salmonid Habitat Restoration Project. Final Report. Prepared for U.S. Fish and Wildlife Service Anadromous Fish Restoration Program.

Demko, D. B., and S. P. Cramer. 2000. Outmigration Trapping of Juvenile Salmonids in the Lower Stanislaus River Caswell State Park Site. Prepared for U.S. Fish and Wildlife Service.

Demko, D. B., C. Gemperle, S. P. Cramer, and A. Phillips. 1999. Outmigration Trapping of Juvenile Salmonids in the Lower Stanislaus River Caswell State Park Site. Prepared for U.S. Fish and Wildlife Service.

Fisher, F. W. 1992. Chinook Salmon, *Oncorhynchus tshawytscha*, Growth and Occurrence in the Sacramento–San Joaquin River System. California Department of Fish and Game.

Foxgrover, A., R. E. Smith, and B. E. Jaffe. 2003. Suisun Bay and Delta Bathymetry. U.S. Geological Survey. Available at http://sfbay.wr.usgs.gov/sediment/delta/downloads.html. Accessed 1 December 2013.

Geographical Information Center. 2011. Medium Scale Central Valley Riparian Vegetation and Land Use with Aggregated Delta Veg, 2011 [ds724]. California State University, Chico, California. Available at ftp://ftp.dfg.ca.gov/BDB/GIS/BIOS/Public_Datasets/700_799/ds724.zip. Accessed 1May 2013.

Grant, J. W. A., and D. L. Kramer. 1990. Territory Size as a Predictor of the Upper Limit of Population Density of Juvenile Salmonids in Streams. Canadian Journal of Fisheries and Aquatic Sciences 47:1724–1737.

Grant, J. W. A., S. Ó. Steingrímsson, E. R. Keeley, and R. A. Cunjak. 1998. Implications of Territory Size for the Measurement and Prediction of Salmonid Abundance in Streams. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1):181–190.

Grosholz, E., and E. Gallo. 2006. The Influence of Flood Cycle and Fish Predation on Invertebrate Production on a Restored California Floodplain. Hydrobiologia 568(1):91–109.

Grover, A., A. Low, P. Ward, J. Smith, M. Mohr, and D. Viele. 2004. Recommendations for Developing Fishery Management Plan Conservation Objectives for Sacramento River Spring Chinook. SRWSC work group report to the Pacific Fisheries Management Council, exhibit C.7.b.

Hartwigsen, K., J. Kindopp, R. Kurth, and A. Seesholtz. 2002. Summary of 2001 Feather River Salmon Spawning Escapement Surveys. California Department of Water Resources.

Healey, M. 2005. Lower American River Chinook Salmon Escapement Survey, October 2004–January 2005. California Department of Fish and Game, Sacramento Valley–Central Sierra Region.

Hill, K. A., and J. D. Webber. 1999. Butte Creek Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Juvenile Outmigration and Life History, 1995–1998. California Department of Fish and Game.

Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral Floodplain Habitats Provide Best Growth Conditions for Juvenile Chinook Salmon in a California River. Environmental Biology of Fishes 83(4):449–458.Johnson, K. 2002. 2001 Merced River Fall Chinook Salmon Escapement Survey. October. California Department of Fish and Game.

Jones & Stokes. 2005. Assessment of Habitat Conditions for Chinook Salmon and Steelhead in Western Placer County, California. Sacramento, California. Prepared for Placer County Planning Department.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The Flood Pulse Concept in River–Floodplain Systems. Canadian Journal of Fish and Aquatic Sciences 106:110–127.

Kareiva, P., M. Marvier, and M. McLure. 2000. Recovery and Management Options for Spring/Summer Chinook Salmon in the Columbia River Basin. Science 290:977–979.

Kaufman, R. C., A. G. Houck, M. Workman, and J. J. Cech, Jr. 2009. Chinook Salmon Length/Fecundity: A Regression Model for the Mokelumne River, California. California Fish and Game 95:88–105.

Keeley, E. R. 2000. An Experimental Analysis of Territory Size in Juvenile Steelhead Trout. Animal Behaviour 59:477–490.

Keeley, E. R. 2003. An Experimental Analysis of Self-Thinning in Juvenile Steelhead Trout. Oikos 102:543–550.

Keeley, E. R., and P. A. Slaney. 1996. Quantitative Measures of Rearing and Spawning Habitat Characteristics for Stream-Dwelling Salmonids: Implications for Habitat Restoration. Watershed Restoration Project Report 2. British Columbia Ministry of Environment, Lands and Parks.

Killam, D. 2012. Chinook Salmon Populations for the Upper Sacramento River Basin in 2011. California Department of Fish and Game, Northern Region.

Lindley, S. T., and M. S. Mohr. 2003. Modeling the Effect of Striped Bass on the Population Viability of Sacramento River Winter-Run Chinook Salmon. Fishery Bulletin 101:321–331.

Lytinen, S. L., and S. F. Railsback. 2012. The Evolution of Agent-Based Simulation Platforms: A Review of NetLogo 5.0 and ReLogo. Proceedings of the Fourth International Symposium on Agent-Based Modeling and Simulation (21st European Meeting on Cybernetics and Systems Research). Vienna, Austria, April 2012.

Marine, K. R., and J. J. Cech. 2004. Effects of High Water Temperature on Growth, Smoltification, and Predator Avoidance in Juvenile Sacramento River Chinook Salmon. North American Journal of Fisheries Management 24:198–210.

Marsh, G. D. 2006. Historical Presence of Chinook Salmon and Steelhead in the Calaveras River. U.S. Fish and Wildlife Service.

Martin, C. D., P. D. Gaines, and R. R. Johnson. 2001. Estimating the Abundance of Sacramento River Juvenile Winter Chinook Salmon with Comparisons to Adult Escapement. Red Bluff Research Pumping Plant Report Series, Volume 5. U.S. Fish and Wildlife Service, Red Bluff, California.

Matella, M. M., and K. Jagt. 2013. An Integrative Method for Quantifying Floodplain Habitat. Journal of Water Resources Planning and Management. (ASCE)WR.1943-5452.0000401.

McReynolds, T. R., C. E. Garman, P. D. Ward, and S. L. Plemons. 2006. Butte and Big Chico Creeks Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Life History Investigation, 2004–2005. California Department of Fish and Game.

McReynolds, T. R., C. E. Garman, P. D. Ward, and S. L. Plemons. 2007. Butte and Big Chico Creeks Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Life History Investigation, 2005–2006. California Department of Fish and Game.

McReynolds, T. R., C. E. Garman, P. D. Ward, and M. C. Schommer. 2005. Butte and Big Chico Creeks Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Life History Investigation, 2003–2004. California Department of Fish and Game.

Merz, J. E. 2002. Seasonal Feeding Habits, Growth, and Movement of Steelhead Trout in the Lower Mokelumne River, California. California Fish and Game 88:95–111.

Merz, J. E., and L. K. O. Chan. 2005. Effects of gravel augmentation on macroinvertebrate assemblages in a regulated California river. River Research and Applications 21(1):61–74.

Merz, J. E., and C. D. Vanicek. 1996. Comparative Feeding Habits of Juvenile Chinook Salmon, Steelhead, and Sacramento Squawfish in the Lower American River. California Fish and Game 82:149–159.

Moyle, P. B. 2002. Inland fishes of California. University of California Press.

[NMFS] National Marine Fisheries Service. 2009. Biological and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project. Long Beach, California. Available at http://www.swr.noaa.gov/ocap/NMFS_Biological_and_Conference_Opinion_on_the_Long-Term_Operations_of_the_CVP_and_SWP.pdf.

Pacific Fishery Management Council. 2011. Preseason Report 1: Stock Abundance Analysis and Environmental Assessment—Part 1 for 2011 Ocean Salmon Fishery Regulations. A report of the Pacific Fishery Management Council pursuant to National Oceanic and Atmospheric Administration Award Number NA10NMF4410014.

Pyper, B., J. B. Lando, and C. Justice. 2006. Analyses of Weir Counts and Spawning Surveys of Adult Chinook Salmon in the Stanislaus River. Cramer Fish Sciences.

Raleigh, R. F., W. F. Miller, and P. C. Nelson. 1986. Habitat Suitability Index Models and Instream Flow Suitability Curves: Chinook Salmon. U.S. Fish and Wildlife Service Biological Report 82(10.122).

Satterthwaite, W. H., S. M. Carlson, S. D. Allen-Moran, S. Vincenzi, S. J. Bogard, and B. K. Wells. 2014. Match-Mismatch Dynamics and the Relationship between Ocean-Entry Timing and Relative Ocean Recoveries of Central Valley Fall Run Chinook Salmon. Marine Ecology Progress Series 511:237–248.

[SJRRP] San Joaquin River Restoration Program. 2012. Minimum Floodplain Habitat Area for Spring and Fall-Run Chinook Salmon in the SJRRP.

Snider, B., and B. Reavis. 2000. Cosumnes River Chinook Salmon Spawner Escapement, Rearing and Emigration Surveys, 1998–1999. California Department of Fish and Game Technical Report No. 00-7.

Sommer, T., M. L. Nobriga, B. Harrell, W. Batham, and W. J. Kimmerer. 2001. Floodplain Rearing of Juvenile Chinook Salmon: Evidence of Enhanced Growth and Survival. Canadian Journal of Fisheries and Aquatic Sciences 58:325–333.

The Bay Institute. 1998. From the Sierra to the Sea: The Ecological History of the San Francisco Bay-Delta Watershed. Novato, California. Available at http://www.bay.org/publications/from-the-sierra-to-the-sea-the-ecological-history-of-the-san-francisco-bay-delta-waters.

Titus, R. G. 1990. Territorial Behavior and Its Role in Population Regulation of Young Brown Trout (*Salmo trutta*): New Perspectives. Annales Zoologici Fennici 27:119–130.

[USFWS] U.S. Fish and Wildlife Service. 2010. Flow-Habitat Relationships for Juvenile Fall/Spring-Run Chinook Salmon and Steelhead/Rainbow Trout Rearing in the Yuba River. The Energy Planning and Instream Flow Branch, Sacramento, California.

Ward, P. D., and T. R. McReynolds. 2004. Butte and Big Chico Creeks Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Life History Investigation, 1998–2000. California Department of Fish and Game Report.

Ward, P. D., T. R. McReynolds, and C. E. Garman. 2004a. Butte and Big Chico Creeks Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Life History Investigation, 2000–2001. California Department of Fish and Game.

Ward, P. D., T. R. McReynolds, and C. E. Garman. 2004b. Butte and Big Chico Creeks Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Life History Investigation, 2001–2002. California Department of Fish and Game.

Ward, P. D., T. R. McReynolds, and C. E. Garman. 2004c. Butte and Big Chico Creeks Spring-Run Chinook Salmon, *Oncorhynchus tshawytscha*, Life History Investigation, 2002–2003. California Department of Fish and Game.

Watry, C. B., A. Gray, R. Cuthbert, B. Pyper, and K. Arendt. 2007. Out-Migrant Abundance Estimates and Coded Wire Tagging Pilot Study for Juvenile Chinook Salmon at Caswell Memorial State Park in the Lower Stanislaus River, California. Report prepared for U.S. Fish and Wildlife Service, Anadromous Fish Restoration Program, Grant No. 813326G008. Cramer Fish Sciences, Oakdale, California.

Watry, C. B., A. Gray, J. Montgomery, C. Justice, and J. E. Merz. 2008. Juvenile Salmonid Out-Migration Monitoring at Caswell Memorial State Park in the Lower Stanislaus River, California. Report prepared for U.S. Fish and Wildlife Service, Anadromous Fish Restoration Program, Grant No. 813326G008. Cramer Fish Sciences, Oakdale, California.

Watry, C. B., A. Gray, K. Jones, and J. E. Merz. 2009. Juvenile Salmonid Out-Migration Monitoring at Caswell Memorial State Park in the Lower Stanislaus River, California. Report prepared for U.S. Fish and Wildlife Service, Anadromous Fish Restoration Program, Grant No. 813326G008. Cramer Fish Sciences, Oakdale, California.

Yoshiyama, R. M., F. W. Fisher, and P. B. Moyle. 1998. Historical Abundance and Decline of Chinook Salmon in the Central Valley Region of California. North American Journal of Fisheries Management 18:487–521.

Yoshiyama, R. M., E. R. Gerstung, F. W. Fisher, and P. B. Moyle. 2000. Chinook Salmon in the California Central Valley: An Assessment. Fisheries Magazine 25:6–20.

Zeug, S. C., P. S. Bergman, B. J. Cavallo, and K. S. Jones. 2012. Application of a Life Cycle Simulation Model to Evaluate Impacts of Water Management and Conservation Actions on an Endangered Population of Chinook Salmon. Environmental Modeling and Assessment 17:455–467.

H1. ESHE Model Details

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Data from juvenile Chinook salmon released in the Yolo Bypass (Sommer et al. 2001) were used to estimate migration rate parameters and fit a Fisher (1992) age-length curve for fish migrating through a floodplain. The initial fork length of released fish (57 mm) and approximate migration distance (106 km) were used as input variables in a simulation of fish that successfully migrated (i.e., no mortality) through the Yolo Bypass from the release location at Fremont Weir to the recapture location at Chipps Island.

The simulation involves the same migration behavior as used in the Central Valley ESHE model. Small fish migrate at a slow rate until reaching a threshold size and switching to a faster migration rate. Growth rate is determined by fish size according to the Fisher age-length curve. In this simulation, values were systematically varied for the four relevant parameters (Table H1-1) to determine which parameter combination produced values for the final fork length and residence time that best matched the empirical values (91 mm and 52 days, respectively).

Table H1-1. Parameters That Were Varied in a Simulation to Find the Parameter Combination That Best Fit Empirical Data from Juvenile Chinook Salmon Migrating through the Yolo Bypass

Parameter	Values
Small fish migration rate (km/day)	0.5, 0.6, 0.7, …, 2.5
Large fish migration rate (km/day)	10, 11, 12, …, 40
Threshold fork length (mm)	70, 71, 72, …, 100
Proportionate growth rate[a]	0.005, 0.006, 0.007, …, 0.015

Note:
[a] Only the growth rate was varied for the Fisher age-length curve, not the intercept.

The simulation involved 221,991 parameter combinations (21 * 31 * 31 * 11). The percent error in final fork length and residence time was calculated separately and the values for the total percent error were summed. Percent error was calculated as follows:

$$\% \text{ Error} = (|\text{model obs} - \text{empirical obs}| / \text{empirical obs}) * 100$$

The results were sorted by total percent error and selected the parameter combination with the lowest total percent error to use in the Central Valley ESHE model (see Table H1-2) for the 10 best parameter combinations). The nine best parameter combinations all had the same total percent error. Thus, the parameter values were averaged across the top nine values. The most robust conclusion from this simulation is that the proportionate growth rate is 0.009. The top 2,192 ranked parameter combinations all have a proportionate growth rate of 0.009. The best migration rate for small fish was relatively slow (1.0 km/day). The best threshold fork length (88 mm) was close to the empirical target for final fork length (91 mm). Thus, the large fish migration rate (21.3 km/day) was a relatively unimportant parameter because so little of the migration distance was traveled at that rate.

Table H1-2. Top 10 Parameter Combinations in a Comparison of Simulated Floodplain Migration Behavior and Empirical Observations from the Yolo Bypass

Small Fish Migration Rate (km/day)	Large Fish Migration Rate (km/day)	Threshold Fork Length (mm)	Proportionate Growth Rate	Final Fork Length (mm)	Residence Time (days)	Total Percent Error (%)
0.8	10	85	0.009	91.02	52.00	0.02
1.0	10	86	0.009	91.02	52.00	0.02
1.0	19	88	0.009	91.02	52.00	0.02
1.6	13	89	0.009	91.02	52.00	0.02
1.4	18	89	0.009	91.02	52.00	0.02
1.2	23	89	0.009	91.02	52.00	0.02
1.0	28	89	0.009	91.02	52.00	0.02
0.8	33	89	0.009	91.02	52.00	0.02
0.6	38	89	0.009	91.02	52.00	0.02
1.3	40	90	0.009	91.01	51.99	0.03

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