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JULY 2014

LIFE CYCLE MODELING FRAMEWORK FOR SACRAMENTO RIVER WINTER-RUN CHINOOK SALMON

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U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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U.S. DEPARTMENT OF COMMERCE
Penny S. Pritzker, Secretary of Commerce
National Oceanic and Atmospheric Administration
Dr. Kathryn D. Sullivan, Acting Administrator
National Marine Fisheries Service
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Abstract
In this document, we describe a strategy for quantitatively evaluating how Federal Central Valley Project (CVP) and California State Water Project (SWP) management actions affect Central Valley Chinook salmon populations. Examples of management actions include changes in water project operations, addition or removal of barriers, and a variety of habitat restoration initiatives. The analytical framework consists of linking and applying hydrological, hydraulic, water quality, and salmon population models.

The hydrological model CALSIM II describes how water resource management determines instream flows. The hydraulic models HEC-RAS and DSM2 translate these flows into depths and velocities that partly determine the capacity of riverine and estuarine habitats. Various water quality models for temperature, salinity, and potentially other parameters also determine the quantity and quality of freshwater and estuarine habitats. Finally, a stage-structured population dynamics model (also known as a life cycle model) links the habitat information to density-dependent stage transitions (describing movement, survival, and reproduction) that drive the dynamics of salmon populations.

We are developing the life cycle model in phases with the initial version focusing on winter-run Chinook. Survival in the delta will be modeled primarily relying on empirical relationships between the environment (flows, exports, and temperature) and survival of juvenile salmon. In subsequent work, salmon survival through the delta will be modeled by tracking the predicted movements of individual salmon based on DSM2's Particle Tracking Model (PTM). We will also add a hatchery component, evaluate additional winter-run management scenarios, and expand the model to evaluate spring-run and fall-run Chinook under various management scenarios.

I. Introduction

California depends on state and federal water projects that provide large scale flood control, water storage, and water transport. The Central Valley water project facilities (including reservoirs, engineered channels, flood bypasses, pumps, and canals) and their operations have radically altered the river systems upon which Chinook salmon and other anadromous fishes depend. Balancing competing desires for fisheries, flood control, water supply and other ecosystem goods and services is a durable natural resource management challenge. The ongoing efforts to develop and approve new water project operating plans and the Bay Delta Conservation Plan (BDCP) require the National Marine Fisheries Service (NMFS) to evaluate how complex and interacting management actions affect salmon populations. This document describes a salmon population dynamics model and supporting hydrological, hydraulic, and water quality models that together form a framework for analyzing the effects of complex water management, habitat restoration, and climate change scenarios on salmon populations. The models are developed for the Central Valley but could be modified for use with other salmon species and in other rivers.

II. Structure of the Analytical Framework

Overview

Our general approach is to link existing physical models to a stage-structured life cycle model through stage-transition parameters that are a function of the environment (as described by the physical models). In this section, we briefly describe the life cycle model and the supporting physical models.

Life Cycle Model

Typically, stage-structured salmon life cycle models define stages (or states) by development, e.g., egg, juvenile, adult. Transition among states reflects the possibly density-dependent processes of survival, maturation and reproduction. In the model described here, we consider both developmental stage and geographic location to define the state (e.g., fry in the mainstem river, fry in a large floodplain). Transitions among states then reflect not only survival and reproduction but also movement among habitat areas.

State transitions can be flexibly described by an extension of the Beverton-Holt stock-recruitment relationship that allows (but does not require) individuals exceeding the capacity of a habitat to move downstream, rather than die in that habitat (Greene and Beechie 2004). The three parameters describing state transitions (survival, capacity, and movement rate) are viewed as potential functions of environmental conditions, such as flow, water temperature, and the amount of suitable habitat (e.g., depth and velocities within the tolerance of the life stage in question).

Because growth prospects differ among habitats, alterations to habitats may not only change the survival of a certain developmental stage of salmon, but also patterns of rearing, migration, and size at ocean entry (i.e., life history diversity). Because size at and time of ocean entry can be important determinants of survival, effects on patterns of life history expression may have important consequences at the population level. Our model can capture such effects.

There is an important trade-off between realism and tractability when deciding how finely to divide the stages in a stage-structured model. Each stage transition requires one or more parameters, and as the dimensionality and resolution of stage variables increases, the model complexity and data requirement increase geometrically. The model needs to be complex enough to address the questions motivating its development, but no more. It is also a good strategy to start simple and add complexity only as necessary. In this work, we begin with developmental stages of eggs, fry, smolts, ocean sub-adults, and mature adults, and geographic states of the mainstem river, floodplain, delta, bays, and ocean (Figure 1).

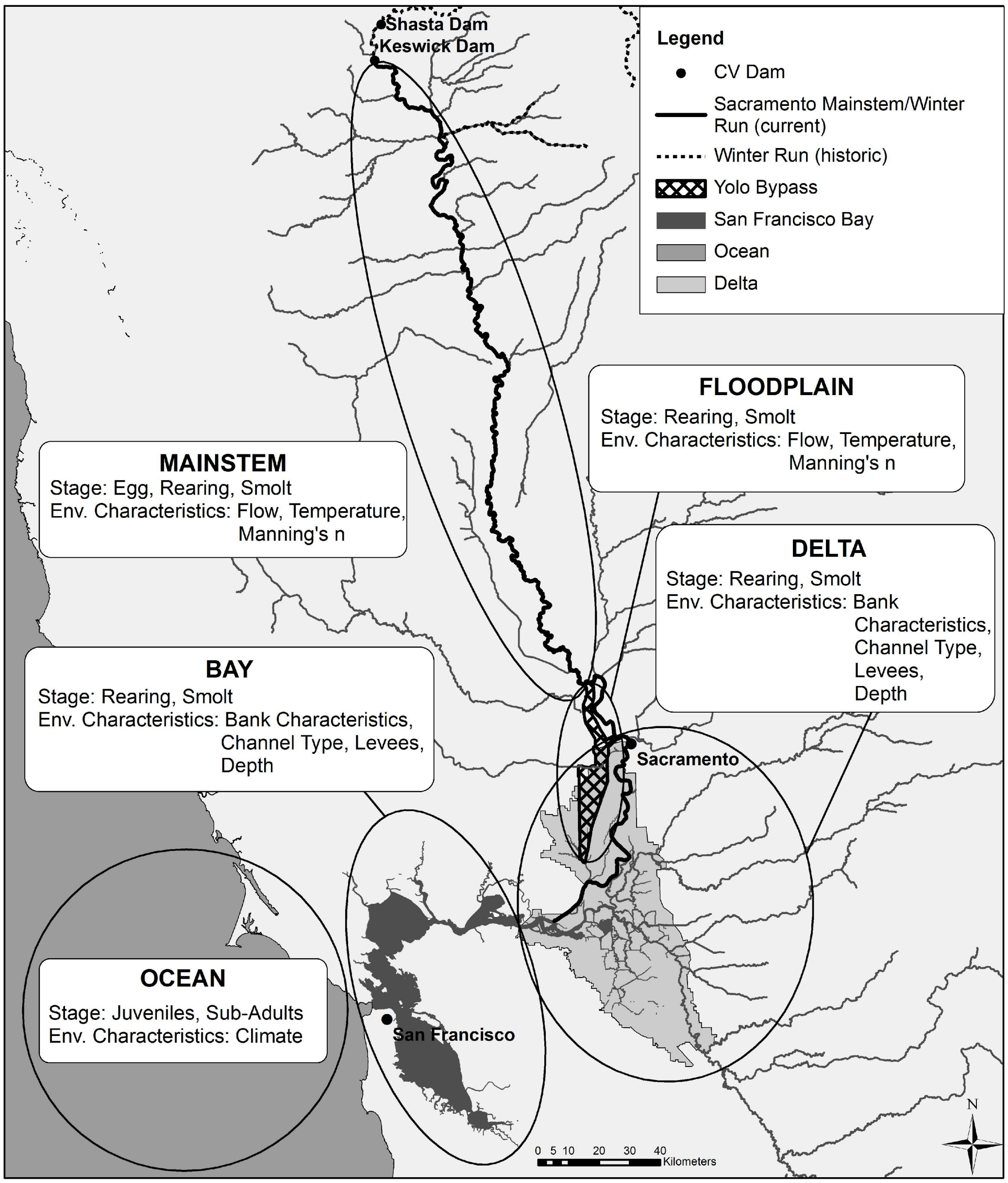

Figure 1. Geographic distribution of Chinook life stages and examples of environmental characteristics that influence survival.

Linking Management Actions to the Salmon Response

Central Valley water management goals and constraints determine the project operations (Figure 2). For example, a management goal might be to increase the water flow in a certain portion of the river to provide conditions suitable for the listed salmonids present. This goal would in turn determine a specific project operation or suite of project operations, such as releasing water from a reservoir.

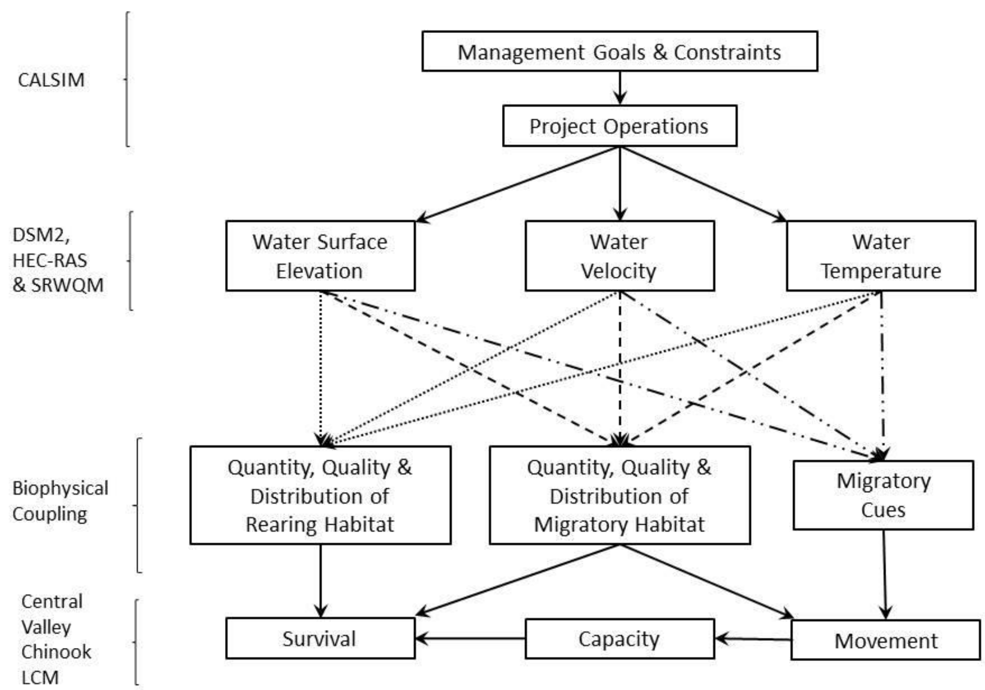

Figure 2. Conceptual model of how water project management goals and constraints influence the movement and survival of salmon through effects on hydrology, hydraulics, and water quality. The labeling along the left side of the diagram identifies corresponding model components.

The quantity and quality of rearing and migratory habitat are viewed as key drivers of reproduction, survival, and migration of freshwater life stages. Various life stages have velocity, depth, and temperature preferences and tolerances, and these factors are influenced by water project operations and climate.

Hydrology (the amount and timing of flows) will be modeled with the California Simulation Model II (CALSIM II). Hydraulics (depth and velocity) and water quality will be modeled with the Delta Simulation Model II (DSM2) and its water quality sub-model QUAL, the Hydrologic Engineering Center's River Analysis System (HEC-RAS), the U.S. Bureau of Reclamation's (USBR) Sacramento River Water Quality Model (SRWQM), and other temperature models. Many of the stage transition equations describing the salmon life cycle (detailed in Section III) are directly or indirectly functions of water quality, depth, or velocity, thereby linking management actions to the salmon life cycle. The combination of models and the linkages among them form a framework for analyzing alternative management scenarios (Figure 3). In the following section, we briefly review the physical models before describing the life cycle model in detail.

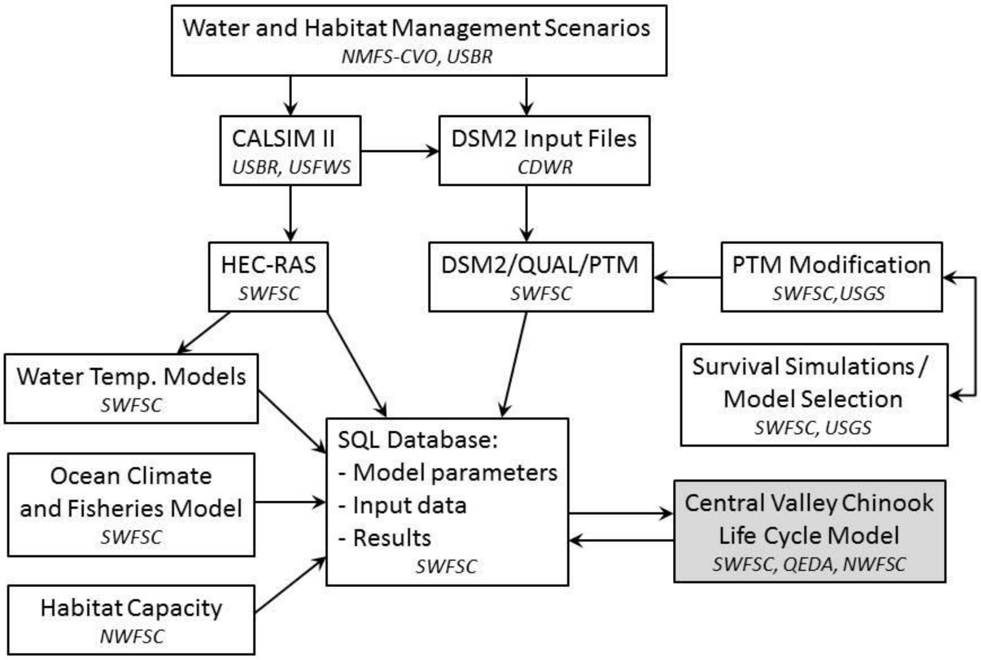

Figure 3. Schematic of the computation framework.

Submodels Used in the Life Cycle Model

CALSIM II

CALSIM II is a quantitative hydrologic planning model developed by the California Department of Water Resources (CDWR) and the USBR. It simulates the SWP and the CVP operations and flows in tributaries to the Sacramento-San Joaquin Delta. CALSIM II uses optimization techniques to route water through a CVP-SWP systems network representation. The model operates on a monthly time-step covering water years 1922 to 2003. Using historical rainfall and runoff data, the model simulates the operation of the current water resources infrastructure in the Sacramento and San Joaquin river basins on a month-to-month basis during this 82-year period. The model can also forecast future scenarios in which operational rules, climate, land use, infrastructure, and water demands are changed.

HEC-RAS

HEC-RAS is a model developed by the U.S. Army Corps of Engineers (USACE) to simulate one-dimensional hydrodynamics for riverine systems. HEC-RAS can calculate water stages, flows, and velocities for both steady and unsteady flow conditions. Inputs to the model consist of a series of river cross-sections (i.e., a bathymetric template) upon which the flow-routing and shallow water equations are solved. HEC-RAS is a widely-used, well-documented, and proven hydrodynamic model. CDWR conducted a comprehensive cross-section survey, which yielded a fully-calibrated HEC-RAS setup for the Sacramento River and major tributaries and canals for the fluvial portion of the system. We intend to downscale or disaggregate the monthly flows into a finer timescale to capture submonthly flow effects, which are not apparent in monthly means. This is important for determining the degree of inundation of the Yolo Bypass.

DSM2

DSM2 is a one-dimensional mathematical model used for the simulation of hydrodynamics, water quality and particle tracking in a network of riverine or estuarine channels. It is based on the same physical principles as HEC-RAS, but unlike HEC-RAS, it is preconfigured to model the tidally-driven circulation of the Delta. DSM2 can calculate water stages, flows, velocities, and mass transport processes for conservative and non-conservative constituents (e.g., salts, water temperature, dissolved oxygen, etc.). DSM2 can also simulate the transport of neutrally buoyant individual particles. We are modifying the particle tracking portion of the model to incorporate salmon swimming behaviors so that we can model fish movement and survival within the Delta.

Water Temperature Models

SRWQM was developed to simulate mean daily reservoir and river temperatures at Shasta, Trinity, Lewiston, Whiskeytown, Keswick, and Black Butte reservoirs and the Trinity River, Clear Creek, the upper Sacramento River from Shasta Dam to Knights Landing, and Stony Creek (USBR 2008). SRWQM uses long-term operational scenarios (using CALSIM II results) and predicts mean monthly and mean daily downstream water temperatures based on CVP-SWP operations. The model employs a heat-budget approach by calculating rates of heat transfer at both the air-water interface and sediment-water interface from meteorological data.

We will use the temperature data from SRWQM in the initial version of the model. In subsequent versions, we will also model temperatures in the delta using statistical relationships between daily water temperatures and atmospheric conditions (Wagner et al. 2011). We are also compiling additional information on temperatures in the bay that we will use in future versions. Neither the bay nor delta temperatures are influenced by water operations; however, these data may be important when we evaluate climate change scenarios.

Ocean Climate and Fisheries Models

The life cycle model (LCM) uses estimates of ocean productivity to determine the survival rate of smolts transitioning from freshwater to the marine environment. These ocean productivity indicators are based on models that integrate the physical and nutrient dynamics in the coastal shelf to determine how these dynamics affect zooplankton, which are the forage food for outmigrating Chinook smolts. Ocean productivity can have important consequences for survival of Chinook smolts, driving large fluctuations in abundance. Poor ocean conditions are disproportionately bad for smaller smotls (Woodson et al. 2013).

After their first summer in the ocean, Chinook salmon from the Sacramento and San Joaquin rivers are vulnerable to the ocean commercial and recreational fisheries. Estimates of impact rates on vulnerable age classes of Chinook salmon are computed as part of the Pacific Fisheries Management Council (PFMC) annual forecast of harvest rates and review of previous years' observed catch rates. For runs that are not actively targeted, such as winter-run and spring-run Chinook, analyses of coded wire tag (CWT) groups are used to infer impact rates for these races (e.g., O'Farrell et al. 2012).

Habitat Capacity

Juvenile salmonids rear in the mainstem, delta, floodplain, and bay habitats (Figure 1). The model incorporates the dynamics of rearing by using density-dependent movement out of habitats as each habitat approaches maximum capacity for juvenile Chinook. The capacities of each of the habitats are calculated in each month using a series of habitat-specific models that relate habitat quality to a spatial capacity estimate for rearing juvenile Chinook salmon. Habitat quality is defined uniquely for each habitat type (mainstem, delta, etc.) to reflect the different habitat attributes in that specific habitat type. For example, the mainstem habitat quality is a function of velocity, depth, and bed roughness. Higher quality habitats are capable of supporting higher densities of rearing Chinook salmon, with the range of densities being determined from studies in the Central Valley and in river systems in the Pacific Northwest, where appropriate.

Defining habitat capacity. For each habitat type (mainstem, delta, and bay), capacity was calculated each month as:

$$K_i = \sum_{j=1}^{n} A_j d_j$$

where K_i is the capacity for a given habitat type i, n is the total number of categories describing habitat variation, A_j is the total habitat area for a particular category, and d_j is the maximum density attributable to a habitat of a specific category. Three variables were determined for each habitat, the ranges of each were divided into high and low quality, and all combinations were examined, resulting in a total of eight categories (2 x 2 x 2) of habitat quality for each habitat type (Table 1). Ranges of high and low habitat quality were based on published studies of habitat use by Chinook salmon fry across their range and examination of data collected by USFWS within the Sacramento-San Joaquin Delta and San Francisco Bay.

Table 1. Habitat variables influencing capacity for each habitat type.

Habitat type	Variable	Habitat quality	Variable range
Mainstem	Velocity	High	<= 0.15 m/s
		Low	> 0.15 m/s
	Depth	High	> 0.2 m, <= 1 m
		Low	<= 0.2 m, > 1 m
	Roughness	High	> 0.04
		Low	<= 0.04
Delta	Channel type	High	Blind channels
		Low	Mainstem, distributaries, open water
	Depth	High	> 0.2 m, <= 1.5 m
		Low	<= 0.2 m, > 1.5 m
	Cover	High	Vegetated
		Low	Not vegetated
Bay	Shoreline type	High	Beaches, marshes, vegetated banks, tidal flats
		Low	Riprap, structures, rocky shores, exposed habitats
	Depth	High	> 0.2 m, <= 1.5 m
		Low	<= 0.2 m, > 1.5 m
	Salinity	High	<= 10 ppt
		Low	> 10 ppt

Defining maximum densities. Determining maximum densities for each combination of habitat variables is complicated by the fact that most river systems in the Central Valley are now hatchery-dominated with fish primed for outmigration. In addition, the Central Valley river system is at historically low natural abundance levels compared to expected or potential density levels. Because of this deficiency in the Central Valley system, we used salmon fry density data from the Skagit River system, which in contrast has very low hatchery inputs, has been monitored in mainstem, delta, and bay habitats, and exhibits evidence of reaching maximum density in years of high abundance (Greene et al. 2005; Beamer et al. 2005). These data from the Skagit River were compared with Central Valley density estimates calculated by USFWS. For each of these data sets, we used the upper 90 to 95 percentile levels of density to define the maximum density levels, and assumed the highest five percentile density levels were sampling outliers.

Determining habitat areas. Two approaches were used to map the spatial extents of different combinations of habitat variables. In the mainstem and floodplain, the HEC-RAS model divides the river into units based on multiple cross-sections defining depth ranges. Each unit defined by the cross-sections has velocity and roughness parameters associated with it. Different levels of flow in a given month or year change the distribution of velocity and depth. Total habitat area in each of the eight classes is calculated by integrating over the river channels modeled by HEC-RAS.

For the delta and bay, channel type, depth, cover, salinity, and shoreline type were mapped from existing delta and bay Geographic Information Systems (GIS) products. Delta and bay polygons[1] were classified into high quality habitat types (blind tidal channels) and low quality habitat types (mainstem, distributaries, large water bodies, and bay). For the channel typing, we used several datasets as base layers, including National Wetlands Inventory (NWI) wetland polygons, San Francisco Estuary Institute's Bay Area Aquatic Resource Inventory (BAARI) stream lines and polygons, Hydro24ca channel polygons (USBR, Mid-Pacific Region GIS Service Center), aerial photos, and Google Earth. Most channel types could be mapped using these datasets except for the blind tidal channels. Instead of directly mapping blind tidal channels, we estimated these areas using allometric relationships between wetland areas and blind tidal channel areas. We tested allometric equations developed in the Skagit River by Beamer et al. (2005) and Hood (2007) to determine which equations were best suited to apply to the Central Valley and chose an allometric equation that returned conservative estimation results:

$$\text{BTC (ha)} = 0.0024 * \text{Wetland(ha)}^{1.56}$$

where BTC is the area of blind tidal channels. We also applied the minimum area requirement (0.94 ha) to define blind tidal channels in a wetland from Hood (2007).

Salinity is another factor influencing habitat availability for juvenile Chinook salmon that can vary with water flow. The X2 position describes the distance from the Golden Gate Bridge to the 2 ppt isohaline position near the Sacramento Delta (Jassby et al. 1995). This distance predicts the amount of suitable habitat for various fish and other organisms. Based on observations of high likelihood of

[1] A closed shape used in GIS mapping that is defined by a connected sequence of x, y coordinate pairs, where the first and last coordinate pairs are the same and all other pairs are unique.

fry presence in water with salinity of up to 10 ppt in both Skagit River and San Francisco Bay fish monitoring data, we defined the low-salinity zone for Chinook as salinity < 10 ppt (i.e., habitats upstream of X10). We calculated X10 values as 75 percent of X2 values (Jassby et al. 1995), and mapped these across San Francisco Bay.

Another axis used to evaluate habitat is vegetated cover along river banks. Areas associated with vegetated cover were assumed to provide protection from predators (Semmens 2008). Such habitats in other systems are preferred by Chinook salmon (Beamer et al. 2005; Semmens 2008). The extent of these areas was estimated using Coastal Change Analysis Program (C-CAP) Land Use/Land Cover (LULC) layers. We defined sheltered habitat as forested or shrub covered areas and assumed that other areas, such as urban and bare land, did not provide sheltered habitat.

Restricting habitat areas based on connectivity. Our first analysis of habitat areas assumed all regions of the delta were equally accessible to Chinook salmon fry. This assumption may be incorrect, however, because fish monitoring has shown that fry do not inhabit certain areas in the delta. Therefore, a spatial connectivity mask, or exclusion zone, was developed to exclude certain areas from the habitat mapping. This exclusion zone was produced using month- and year-specific fish monitoring data. Poisson regression models were used to predict fish counts based on the relationships between fish counts in beach seine datasets and several covariates including river system (Sacramento or San Joaquin), distance of sampling site to its mainstem (m), physical channel depth (m), physical channel width (m), and DSM2 water stage (m). We selected these parameters based on Akaike's Information Criterion (AIC) analysis of the Poisson regression models with various combinations of the parameters. The resulting Poisson model equation was used to produce a presence-absence map for the entire delta. Restricted capacity estimates were generated by summing habitat areas with predicted fry presence.

The Chinook Salmon Life Cycle Model

The life cycle model is a stage-structured, stochastic life cycle model. Stages are defined by development and geography (Figure 1), and each stage transition is assigned a unique number (Figure 4).

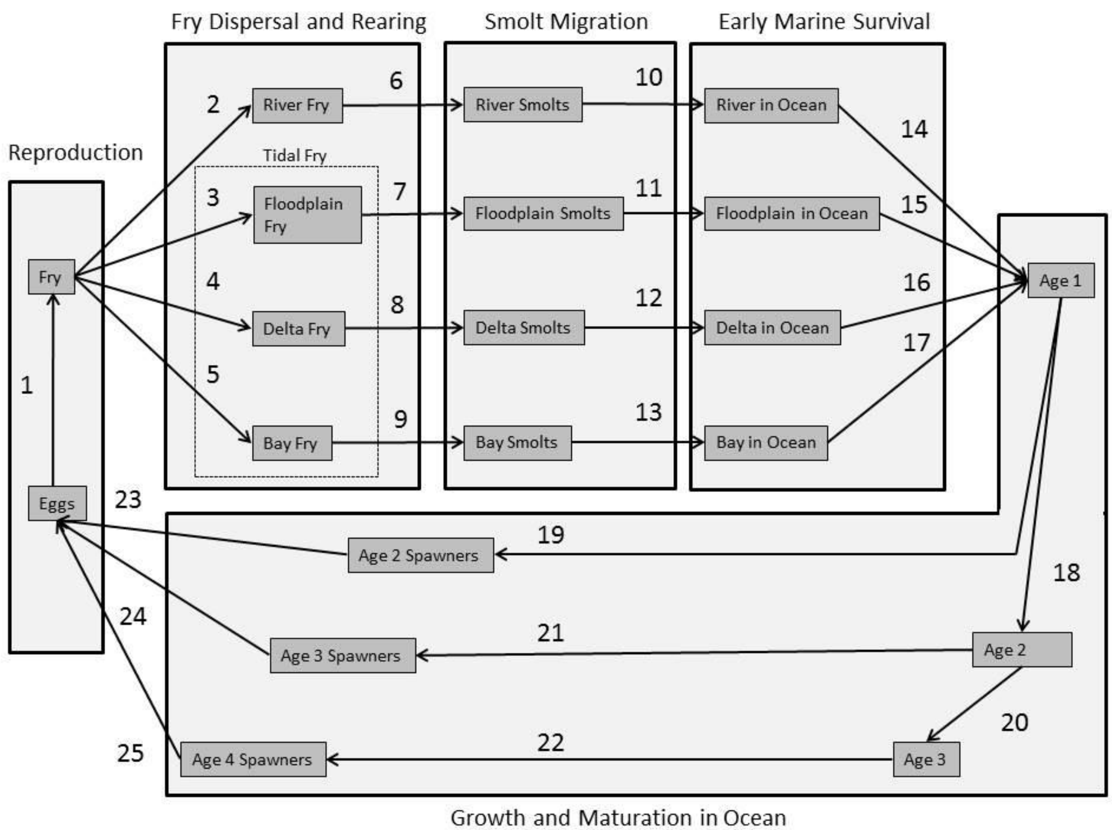

Figure 4. Central Valley Chinook transition stages. Each number represents a transition equation through which we can compute the survival probability of Chinook salmon moving from one life stage in a particular geographic area to another life stage in another geographic area. Transition equation 1 represents the survival probability for the Reproductive phase. Transition equations 2-9 represent the Fry Dispersal and Rearing phase, with transition equations 3-5 representing the Tidal Fry phase. Transition equations 10-13 represent the Smolt Migration phase. Transition equations 14-17 represent the Early Marine Survival phase. Transition equations 18-22 represent the Growth and Maturation in the Ocean phase. Transition equations 23-25 represent the survival probabilities for returning adults.

III. Transition Equations

Transition 1

Definition: Survival to Fry stage from Egg stage

Discussion: The abundance of fry is a function of the abundance of eggs and the survival rate from eggs to fry. The survival rate varies among years depending on the environmental conditions (e.g., temperature and flow) during egg incubation and fry emergence.

Equation:

$$Fry = Eggs * S_{eggs}$$

$$\text{logit}(S_{eggs}) = \mathbf{X_1}' \boldsymbol{B_{Eggs}}$$

where S_{eggs} is the survival rate of fry as a function of the coefficients, $\mathbf{X_1}$ = vector or matrix of covariate values (e.g., temperature in the natal reaches), $\boldsymbol{B_{Eggs}}$ is the vector of coefficients relating covariate effects $\mathbf{X_1}$ to survival of eggs during incubation and survival to Fry stage, and logit(x) = log(x/[1-x]) is a function that ensures that the survival rate is within the interval [0,1].

Transitions 2 - 5

Definition: Survival and dispersal from fry in the natal reaches to rearing fry in the river, floodplain, delta, and bay.

Discussion: Juvenile Chinook salmon in the Central Valley may disperse from their natal reaches shortly after emerging as fry (i.e., less than 1 month) to inhabit habitats downstream (Williams 2006). This outmigration strategy has also been observed in Chinook populations in other systems, such as the Skagit River, Washington (Greene et al. 2005). We use the term Tidal Fry (TF) to represent this life history strategy, which is consistent with Greene et al. (2005). Those fry not leaving as Tidal Fry remain in the river habitat upstream of the City of Sacramento where they stay to rear (i.e., River Fry).

Tidal Fry

To represent the Tidal Fry process in winter-run Chinook, the model can distribute Tidal Fry among habitats during the months of July to December. The majority are distributed August to November with the largest pulse in September, which is when most fry sized winter-run pass Red Bluff Diversion Dam (RBDD) (Poytress and Carillo 2012).

All habitats are not equally accessible from all other habitats. For example, we assume that the Yolo bypass or floodplain habitat is not accessible from the delta habitat (Figure 5). Furthermore, not all habitats can be accessed in all months. The entrance to the floodplain habitat is dependent upon flows that are high enough to overtop the Fremont Weir and allow access to the Yolo Bypass. Currently, flooding into the Yolo Bypass begins when Sacramento River flow exceeds 1586 m^3s^{-1} (56,000 cfs) at Verona. Entrance to the floodplain habitat is therefore dependent upon overtopping of the Fremont Weir during the month of dispersal. The model uses monthly time steps, and the monthly average flow does not adequately reflect the proportion of time in which flow overtops the Freemont Weir. Instead, the average monthly flow of 991 m^3s^{-1} (35,000 cfs) provided a better indicator of the flow into the Yolo bypass. If the Yolo bypass is accessible during the month, then a proportion of Tidal Fry can enter during that month, otherwise Tidal Fry move to the delta and bay habitats to rear in that month.

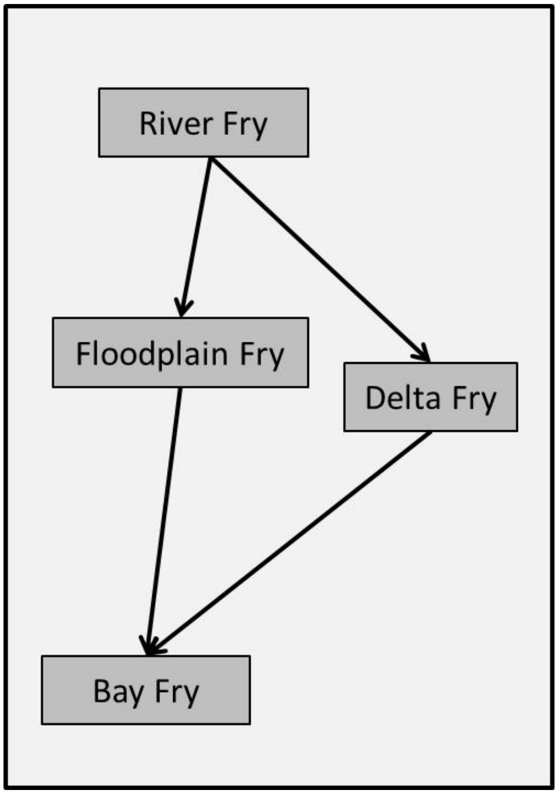

Figure 5. Connectivity among habitats for winter-run Chinook fry.

Equations:
The Tidal Fry are a function of the proportion of Tidal Fry (P_{TF}) and the total number of fry.

$\text{TidalFry} = P_{TF}{*}\text{Fry}$

The portion of fry that emigrate as Tidal Fry, P_{TF}, may vary among years as a function of flow. This process has been hypothesized to describe patterns of fry moving downstream in larger proportions in wet years versus dry years and thus captured at Chipps Island trawls and bay oriented beach seine stations (Pat Brandes, USFWS, Personal Communication, 2013).

Two possible approaches to modeling access to the floodplain habitat were developed: the first approach assumes an indicator relationship, such that whenever there are flows into the Yolo bypass, a proportion of the Tidal Fry move into the floodplain habitat; whereas, the second approach uses the proportion of flow in the Yolo bypass relative to flow in the Sacramento River with a parameter that allows the proportion of fish to be greater or less than the proportion of flow.

Alternative 1:
$\text{TidalFry}_{\text{FP}} = S_{TF,FP} * \text{TidalFry} * P_{FP} * \text{I}(Q_{\text{Verona}} > 991.1\ m^3 s^{-1})$

where Q_{Verona} is the Sacramento River flow at Verona, I( ) is an indicator function that equates to 1 when the condition in the parenthesis is met, P_{FP} is a parameter describing the proportion of Tidal Fry that enter the floodplain habitat, and $S_{TF,FP}$ is the survival rate of Tidal Fry from the natal reach to the floodplain habitat.

Alternative 2:
$\text{TidalFry}_{\text{FP}} = S_{TF,FP} * \text{TidalFry} * B_{FP} * Q_{\text{Yolo}}/(Q_{\text{Verona}} + Q_{\text{Yolo}})$

where Q_{Yolo} is the flow into the Yolo bypass, Q_{Verona} is the flow at Verona on the Sacramento River, and B_{FP} is a parameter that describes the degree to which fish move with flow, $0 \leq B_{FP} * Q_{\text{Yolo}}/(Q_{\text{Verona}} + Q_{\text{Yolo}}) \leq 1$. Note that $B_{FP}=1$ indicates that fish move in the same proportion with flow, whereas $B_{FP} > 1$ would reflect more fish than flow.

Those Tidal Fry that do not enter the floodplain habitat move downstream to the delta and bay habitats to rear. For those Tidal Fry that do not enter the floodplain habitat, the positioning of the Delta Cross Channel (DCC) gate affects the values of S_{TF} to the delta and bay habitats (i.e., $S_{TF,Delta}$ and $S_{TF,Bay}$).

Those fry that do not migrate out as Tidal Fry remain in the river habitat as River Fry and are the initial abundances in the rearing portion of the life cycle.

River Fry = $S_{F,R}$*(1 - P_{TF})*Fry

where $S_{F,R}$ is the survival rate of fry remaining in the river habitat.

Rearing

Definition: Fry rear among river, floodplain, delta, and bay habitats according to density dependent movement functions.

Discussion: This transition moves juvenile salmonids among the river, floodplain, delta, and bay habitats as a function of the area-specific fry survival rates, area-specific fry capacities, and migration rate in the absence of density dependence. The transitions among habitats can be described by a schematic (Figure 6).

Winter-run sized fish pass Knights Landing in most years between November and January. The timing of passage appears to be variable, however, and depends upon the flows at Wilkinson Slough; when flows exceed 400 m^3s^{-1} at Wilkinson Slough, rotary screw trap catches of winter-run sized Chinook salmon increase at Knights Landing (del Rosario et al. 2013). Once this flow threshold has been exceeded, winter-run Chinook can move into habitats (with the exception of Tidal Fry, which have already dispersed). The life cycle model conditions the timing of the movement out of the river habitat and into downstream habitats by a flow trigger that can vary among years.

The schematic (Figure 6) shows the inputs to a monthly transition in the delta as an example. The abundance (N_{Delta}) in this month is a sum of the previous month's residents, migrants arriving from the upstream (river) habitat from the previous month, and Tidal Fry from the natal reach in the previous month. The Capacity of the habitat, the Survival rate within the habitat, the Migration rate in the absence of density dependence, and the previous month's resident abundance determine how many residents remain in the delta in the current month, and how many migrants will move downstream to the bay habitat in the following month.

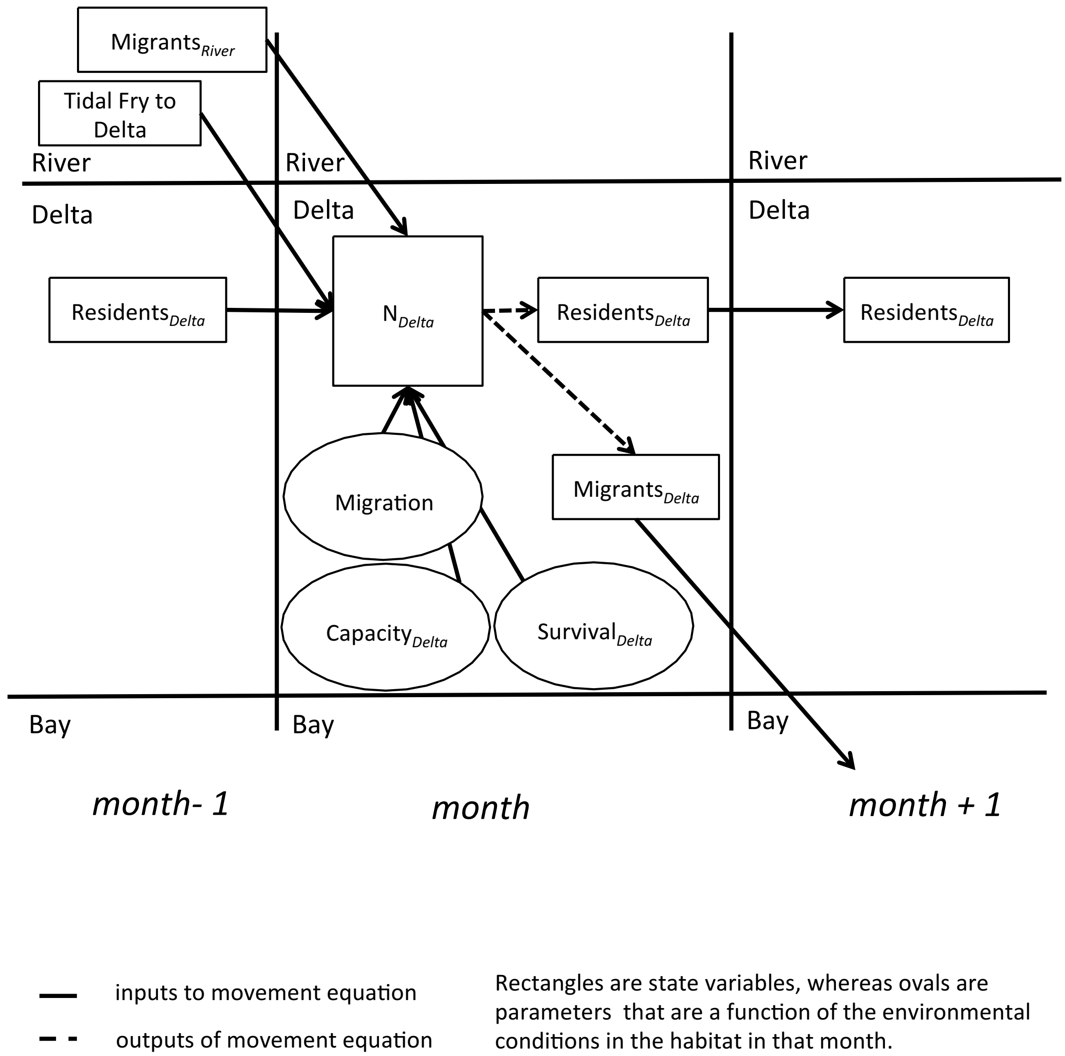

Figure 6. Schematic depicting the dynamics of Dispersers, Residents, and Migrants among habitats at the monthly time step of the model. Rectangles represent abundances of juvenile salmon, whereas ovals depict parameters of the density dependent movement function. Solid lines represent inputs to the transition function, whereas dashed lines represent outputs.

Equations:

The number of residents in the month (time subscript suppressed) is calculated from the following equation (Figure 9):

$\text{Residents}_i = S_i(1 - m)\, N_i / (1 + N_i/K_i)$,

where S_i is the survival rate, N_i is the pre-transition abundance, and K_i is the capacity for habitat type i = River, Floodplain, Delta, Bay, and m is the migration rate in the absence of density dependence.

The number of migrants in the month is calculated from the following equation (Figure 7):

$\text{Migrants}_i = S_i N_i - \text{Residents}_i$

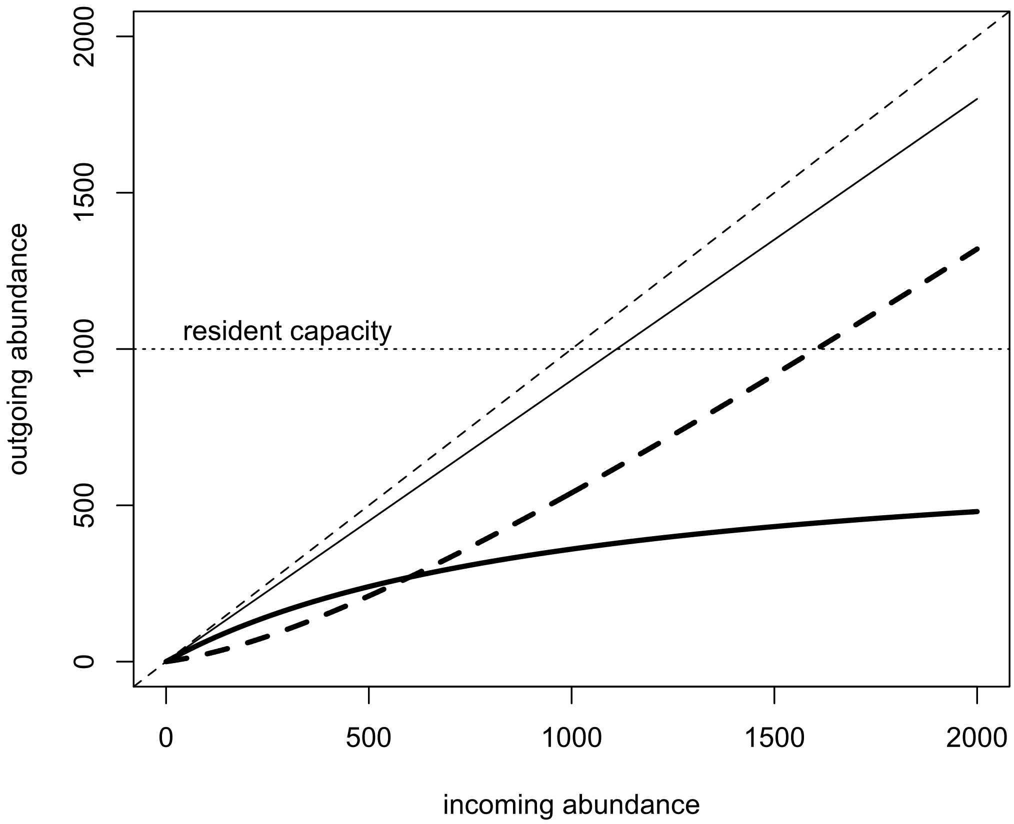

Figure 7. Example of the Beverton-Holt movement function in which the outgoing abundance (thin solid black line) is split between migrants (thick dashed line) and residents (solid dark line), that are affected by the resident capacity (thin dotted line). The 1:1 line (thin dashed line) is also plotted for reference. Parameter values used in the plotted relationship are survival, *S* = 0.90; migration, *m* = 0.2; and capacity, *K*= 1000.

The parameters of the density dependent movement function can be as simple as constant capacity, survival, and migration rate values over all months, habitats, and years. Alternatively, these parameter values can be dynamic and vary over year, month, and habitat to reflect the spatio-temporal dynamics in the availability of habitat for fry. We have chosen the latter approach here to incorporate these dynamics into the life cycle model.

Transitions 6 - 9

Definition: Smolting of residents in the river, floodplain, delta, and bay rearing habitats

Description: The smolting process is a complex endocrine and behavioral shift that may be affected by feeding opportunities as well as environmental drivers of photoperiod and temperature (McCormick et al. 2000; Myrick and Cech 2004; Björnsson et al. 2011). The bottom-oriented parr shift behaviorally from positioning into the flow to orienting with the flow to improve migration. Furthermore, fish that may have established stations and thus defended territories, now school to reduce the chance of predation. In addition there is a shift in the physiology to facilitate migration and the eventual associated shift to osmoregulate in the marine environment. These physiological and behavioral processes are preceded by changes in the endocrinology of the fish that are receptive to environmental cues (Björnsson et al. 2011).

The life cycle model does not track size explicitly, so relationships between feeding and smolting may be implicitly applied via differential habitat-based smolting rates that are related to habitat quality and expected food availability. The timing of smoltification in the life cycle model is an explicit function of temperature and photoperiod, however. It is important to note that Transitions 6 – 9 are between Residents and Smolts (as opposed to Migrants and Smolts); therefore, these are not individuals that were shifted out of the habitat because of capacity limitation, but rather individuals that initiated downstream migration having reared in the habitat until they were prepared to leave.

The proportion of juveniles smolting in a given month is a function of the temperature in that month and the photoperiod. The photoperiod acts as a timer to ensure that juveniles smolt to appropriately time the downstream portion of their migration. As successive months progress, the likelihood of fish remaining in a particular habitat decreases. For example, the majority of winter-run migrate out of the habitats by May, coinciding with the peak flux of winter-run sized fish at Chipps Island (del Rosario et al. 2013).

Equations:

$Smolts_{i,k} = P_{SM,i,k} * Residents_{i,k}$

Where $P_{SM,i,k}$ is the probability of smolting in month *k* in habitat *i* (*i* = River, Floodplain, Delta or Bay) by the Residents from the previous month (*k*-1) in that habitat.

Suppressing the subscript for habitat, the probability of smolting is modeled as a proportion ordered logistic regression model (Agresti 2002) of the form:

$logit(P_{SM,k}) = Z_k + B_{smolt}*(T_k - T_k')$

where $-\infty < Z_1 < Z_2 \ldots < Z_k < \infty$ are the monthly rates of smoltification based on photoperiod and their ordering ensures that the probability increases over months, B_{smolt} is the effect of temperature anomalies on the photoperiod-based rate and $(T_k - T')$ is the temperature anomaly in month k over the baseline temperature T_k'.

Transition 10

Definition: Smolts that reared in the river migrate to the ocean

Discussion: Outmigrating smolts will transit the system with the goal of migrating out of the river and through the delta and bay as quickly as possible.

For winter-run Chinook, juveniles ranging in size from 100mm to 120mm pass RBDD beginning in mid-January (Poytress and Carrillo 2008; Poytress and Carrillo 2012). Because these sizes coincide with the median sizes of winter-run passing Chipps Island in March leaving the system (del Rosario et al. 2013), we assume that these are outmigrating smolts that have reared in the river and are beginning their migration to the ocean. As a result, acoustic tagged late-fall run smolts may provide useful estimates of outmigration survival (e.g., Perry et al. 2010).

Equations:

The numbers of smolts that arrive at the ocean after rearing in the river are a function of the survival rate due to migrating from the river habitat to the ocean.

River in Ocean = $S_{10}\text{Smolts}_{\text{River}}$

where River in Ocean are the smolts that migrated to the ocean from the river habitat with survival rate S_{10}.

Transition 11

Definition: Smolts that reared in the floodplain migrate to the ocean

Discussion: Outmigration of winter-run sized juveniles from the Yolo Bypass appears to occur between late February and mid-March among years when the Yolo bypass flooded (2003, 2004, and 2006) (del Rosario et al. 2013). In those years, winter-run were able to access the floodplain habitat due to the timing of flow thresholds for movement of winter-run at Wilkinson Slough and the timing of downstream access to Yolo Bypass due to overtopping of the Freemont Weir.

Equations:

The numbers of smolts that arrive at the ocean after rearing in the floodplain are a function of the survival rate due to migrating from the floodplain habitat to the ocean.

Floodplain in Ocean = $S_{11}\text{Smolts}_{\text{Floodplain}}$

where Floodplain in Ocean are the smolts that migrated to the ocean from the floodplain habitat with survival rate $S_{11.}$

Transition 12

Definition: Smolts that reared in the delta migrate to the ocean

Discussion: We assume that the winter-run that have reared in the delta are located in the interior portion of the delta habitat. Winter-run sized Chinook salmon depart the delta in March and April as indicated by the median catch rates of winter-run sized fish in the Chipps Island trawls (del Rosario et al. 2013). Sizes of winter-run during those months can vary from 100 to 140mm with median fork lengths of approximately 110mm. The survival rates from acoustic tagged late-fall run smolts may provide useful estimates of winter-run in this transition (e.g., Perry et al. 2010) in addition to the suite of covariates identified by Newman (2003) for relating survival of outmigrating smolts to environmental conditions in the delta.

Equation:

The numbers of smolts that arrive at the ocean after rearing in the delta are a function of the survival rate due to migrating from the delta habitat to the ocean.

Delta in Ocean = $S_{12}\text{Smolts}_{\text{Delta}}$

where Delta in Ocean are the smolts that migrated to the ocean from the delta habitat with survival rate S_{12}.

Transition 13

Definition: Smolts that reared in the bay migrate to the ocean

Discussion: The bay habitat represents a transition to the marine environment and it appears that migrating juvenile Chinook salmon transit the bay relatively quickly (MacFarlane and Norton 2002); yet, the survival rates of acoustically tagged late-fall Chinook may be low throughout this reach during outmigration (Sean Hayes, NMFS, personal communication, September 25, 2013).

Equation:

The numbers of smolts that arrive at the ocean after rearing in the bay are a function of the survival rate due to migrating from the bay habitat to the ocean.

$\text{Bay in Ocean} = S_{13}\text{Smolts}_{\text{Bay}}$

where Bay in Ocean are the smolts that migrated to the ocean from the bay habitat with survival rate S_{13}.

Transitions 14 - 17

Definition: Survival of smolts that reared in different habitats in the Gulf of Farallones region.

Discussion: Survival during the early ocean phase can have important effects on the overall cohort strength of the population, particularly when the nearshore ocean fails to provide a productive environment for juvenile Chinook. In the San Francisco estuary, outmigrating Chinook salmon do not use the bay habitat for feeding and arrive in the Gulf of the Farallones with relatively low lipid content (McFarlane and Norton 2002). In years where there are delays in the spring transition or upwelling has been shifted off the coast, fall-run Chinook salmon in particular, may be strongly affected by these environmental conditions (Lindley et al. 2009; Wells et al. 2007). In addition, the effects of nearshore productivity appear to be influenced by the size of the outmigrating smolts; in years of low ocean productivity the smaller sized fish appear to have substantially lower survival rates than larger sized fish, whereas in high productivity years all sizes appear to benefit equally (Woodson et al. 2013).

In the Sacramento-San Joaquin River system, several studies have found evidence for increased growth rates in juvenile Chinook rearing in favorable habitats (e.g., Kjelson et al. 1982; Sommer et al. 2001; Limm and Marchetti 2009) with favorable habitats typically defined as off-channel rearing areas. In other systems, such patterns are prevalent as well. For example in the Fraser River, British Columbia, higher growth rates were observed in off-channel marshes relative to river habitat (Levy and Northcote 1982) and in the Skagit River, Washington juvenile Chinook rearing in the estuary were larger than juvenile Chinook rearing in the river (Congleton et al. 1981). Once fish have undergone smoltification, it appears that they are unlikely to use the San Francisco Bay estuary in its current condition for compensatory growth prior to outmigration into the ocean (Kjelson et al. 1982; MacFarlane and Norton 2002). Furthermore, otolith work by Miller et al. (2010) indicated that in a sample of 100 returning Chinook adults, most fish did not spend time rearing in the bay once reaching the smolt stage.

Because the life cycle model does not track size explicitly, the influence of size is incorporated implicitly via differential survival rates to Age 1. The survival rate from each rearing habitat to Age 1 has a different sensitivity to ocean productivity: bay and delta habitats have the greatest sensitivity, whereas floodplain and river habitats are less sensitive.

Equations:

Age 1_{River} = S_{14}River in Ocean

Age $1_{Floodplain}$ = S_{15}Floodplain in Ocean

Age 1_{Delta} = S_{16}Delta in Ocean

Age 1_{Bay} = S_{17}Bay in Ocean

where the abundances in the Age 1 stage are a function of the number of smolts arriving in the ocean and the habitat-specific survival rate. The habitat-specific survival rate reflects the potential for individuals to rear to a larger size (e.g., floodplain rearing) relative to other habitats such as the delta or bay (Sommer et al. 2001).

The total number of Age 1 winter-run in the Gulf of the Farallones is obtained by summing over the different rearing habitats.

Age 1 = Age 1_{River} + Age $1_{Floodplain}$ + Age 1_{Delta} + Age 1_{Bay}

The proportion of migrants that reared in each of the habitat types (i.e., Age 1_{River} /Age 1) is also an important model component as information on otolith microchemistry (e.g., Barnett-Johnson et al. 2008) and may provide estimates of the habitats used by winter-run Chinook fry.

Transition 18
Definition: Survival in the ocean from Age 1 to Age 2

Discussion: During their ocean residence, winter-run Chinook are located in the coastal waters south of Point Arena as estimated by Coded Wire Tag (CWT) recaptures in fisheries in those areas (Grover et al. 2004; O'Farrell et al. 2012).

Equation:

Age 2 = Age 1 * (1-M_2)* S_{18}

where S_{18} is the survival rate of Age 1 fish in the ocean and M_2 is the maturation rate that leads to 2 year old spawners. The fishery for Central Valley Chinook is composed of a commercial and recreational component; however, Age 1 winter-run are not contacted in the fishery (O'Farrell et al. 2012).

Transition 19
Definition: Maturation for Age 2

Discussion: A very small proportion of winter-run Chinook return as 2-year olds (O'Farrell et al. 2012; Grover et al. 2004), with the predominant year of return as Age 3. Yet, the small proportion of returning 2 and 4 year olds has a significant effect on the cohort dynamics of winter-run Chinook (Botsford and Brittnacher 1998). The fishery for Central Valley Chinook is composed of a commercial and recreational component; however, 2-year old winter-run are not contacted in the fishery (O'Farrell et al. 2012).

Equations:

Age 2 Spawners = Age 1*M_2*S_{19}

Where M_2 is the maturation rate that leads to Age 2 spawners and S_{19} is the natural survival rate of Age 1 to the spawning grounds.

Transition 20

Definition: Survival in the ocean from Age 2 to Age 3

Discussion: As in Winship et al. (In Review), we assume that the Age 3 survival rate was constant over time, and a function of the Age 3 fishery impact rate (I_3) and the natural survival rate. Furthermore, we assume that fishery impacts occurred prior to natural mortality during a given age.

Equations:

Age 3 = Age 2 *(1-M_2) * (1- I_3)*S_{20}

where S_{20} is the survival rate for Age 2 and I_3 is the impact rate for Age 3 fish.

Transition 21

Definition: Maturation for Age 3

Discussion: As in Winship et al. (In Review), we assume that the Age 3 survival rate was constant over time, and a function of the Age 3 fishery impact rate (I_3) and the natural mortality rate (NM_3). Furthermore, we assume that fishery impacts occurred prior to natural mortality during a given age.

Equations:

Age 3 Spawners = Age 2 * (1- I_3) *M_3*S_{21}

where I_3 is the Age 3 impact rate, M_3 is the Age 3 maturation rate, and S_{21} is the Age 3 survival rate to the spawning grounds.

Transition 22

Definition: Survival and maturation rate for Age 4

Discussion: All remaining winter-run return as 4-year olds, after surviving the fishery. We assumed that the instantaneous Age 4 fishery impact rate was twice the instantaneous Age 3 fishery impact rate (O'Farrell et al., 2012).

Equations:

Age 4 Spawners = Age 3 * (1- I_4) * S_{22}

where I_4 is the Age 4 impact rate and S_{22} is the survival rate from the end of Age 3 to the spawning grounds.

Transitions 23 - 25
Definition: Number of eggs produced by spawners of Ages 2 – 4

Description: Due to the potential for spatial limitations in the spawning reach at high winter-run spawner abundances, density dependence was incorporated into the production of eggs by spawners. Spawning occurs as a mixture of Age 2, 3, and 4, although the majority of winter-run Chinook return to spawn at Age 3.

Equation:

$$Eggs = \frac{\sum_{j=2}^{4} Sp_j * V_{eggs,j}}{1 + \frac{\sum_{j=2}^{4} Sp_j * V_{eggs,j}}{K_{Sp}}}$$

where Sp_j are the number of spawners of age j = 2, 3, 4, V_{Eggs} is the production of eggs per spawner in the absence of density dependence, and K_{Sp} is the capacity of eggs in the spawning grounds as a function of spawners. The production of eggs varies by age of return with larger Age 3 and 4 females producing more eggs than Age 2 (Newman and Lindley 2006). The capacity of the spawning reach is affected by the amount of gravel (TNC et al. 2008) and the location of the temperature compliance point set in the spring for spawning adult winter-run. The capacity for a given year is a function of the areal extent of the gravel upstream of the compliance point, the average redd size, and the number of eggs produced per spawner.

IV. Conclusion

This report outlines the general framework for modeling the effects of water project operations on a population of winter-run Chinook salmon, and details the equations governing the transitions among life stages and geographic areas that describe the life cycle and dynamics of the population.

Additional work is needed before the model can be applied:

1. Development of prior distributions for parameter values from the literature and available datasets.
2. Estimation of posterior distributions or plausible ranges of parameters, based on fitting the LCM to historical data.
3. Possible adjustment of the model structure if the fit to historical data is poor.
4. Development of management scenarios for analysis.

We anticipate preparing further documentation describing the methods and results of these four activities.

We also are working on modifications to the analytic framework that will support more detailed investigations of the effects of delta operations on winter-run Chinook salmon, and similar investigations of spring- and fall-run Chinook salmon. The most significant modification planned is replacing the empirical survival functions for fry and smolts in the delta with an agent-based simulation model of juvenile salmon rearing and migration, using DSM2 HYDRO, QUAL, and a modified PTM. We are adding behaviors (swimming, holding position, route choice), environmental behavioral cues (flow direction, velocity, salinity, tidal phase), and other biological processes (predation-driven mortality) to the PTM. Behavioral and predation models will be selected, and model parameters estimated, from statistical comparison of simulation results to CWT- and acoustic tag-based survival experiments. Because the resulting model has a theoretical and mechanistic basis, it will allow us to more reliably model survival under conditions outside of the range of data supporting the empirical relationships in the current model version.

It is fairly straightforward to modify the model structure for other populations of Central Valley Chinook (and for any salmon population where similar hydrologic and hydraulic models are available). We are working on a multi-population model for spring-run Chinook with a focus on summer water temperatures in adult holding areas. We are also developing a multi-population fall-run Chinook model that will include hatchery populations and interactions, and San Joaquin River as well as Sacramento River populations, allowing exploration of likely tradeoffs between such populations that will be affected by modifications to delta hydrodynamics.

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Appendix A. Acronyms

AIC	Akaike Information Criterion
BAARI	Bay Area Aquatic Resource Inventory
BDCP	Bay Delta Conservation Plan
BTC	Blind Tidal Channel
CALSIM II	California Simulation Model II
C-CAP	Coastal Change Analysis Program
CFS	Cubic Feet per Second
CVO	Central Valley Office
CVP	Central Valley Project
CDWR	California Department of Water Resources
CWT	Coded Wire Tag
DCC	Delta Cross Channel
DSM2	Delta Simulation Model II
DWR	Department of Water Resources
GIS	Geographic Information Systems
Ha	Hectare
HEC-RAS	Hydrologic Engineering Centers River Analysis System
LCM	Life Cycle Model
LULC	Land Use/Land Cover
NMFS	National Marine Fisheries Service
NMFS-CVO	National Marine Fisheries Service – Central Valley Office
NWFSC	Northwest Fisheries Science Center
NWI	National Wetlands Inventory
PFMC	Pacific Fisheries Marine Council
ppt	parts per thousand
PTM	Particle Tracking Model
QEDA	Quantitative Ecology and Decision Analysis
QUAL	Quality (module in DSM2)
RBDD	Red Bluff Diversion Dam
SQL Database	Structured Query Language
SRWQM	Sacramento River Water Quality Model
SWFSC	Southwest Fisheries Science Center
SWP	State Water Project
TF	Tidal Fry
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

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