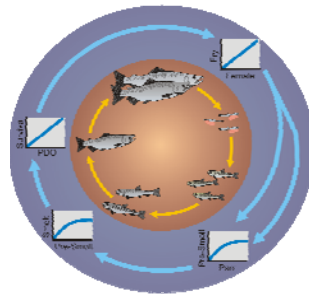


North-of-Delta-Offstream-Storage (NODOS) Sacramento River Winter Run Chinook IOS Model

Draft Model Description and Documentation



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Interactive Object-oriented Simulation (IOS) Winter Run Chinook Life Cycle Model

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Table of Contents

1.0	Introduction	3
2.0	Model Structure	4
2.1	Lifestage Functional Relationships and Parameters	4
	2.1.1 Adult Salmon Spawning	4
	2.1.2 Eggs and Alevins	7
	2.1.3 Juvenile Rearing and Migration	11
	2.1.4 Delta	18
	2.1.5 Ocean Adults	21
2.2	Spatial Specificity	22
	2.2.1 Reach Subsystems	23
	2.2.2 Delta Subsystem	24
	2.2.3 Ocean Subsystem	24
2.3	Temporal Properties	24
3.0	References	24



1.0 Introduction

This winter-run Chinook life-cycle model has been developed to help understand population effects of water project operations and alternative fishery management strategies. The California Department of Water Resources contracted with Cramer Fish Sciences to develop life cycle models in order to evaluate potential effects and design alternatives for the North-of-Delta-Offstream-Storage project. This task required integration of complex environmental conditions (e.g. river discharge, temperature, habitat quality at a reach scale) and fish behavior (e.g. emigration timing, habitat selection). Life-cycle modeling was chosen to provide a quantitative framework that can accumulate effects of flow, temperature, diversions and habitat conditions on multiple life-stages of Chinook salmon occurring at a variety of times and locations within the Sacramento River system. By tracking the abundance and survival of Chinook salmon through successive life-stages, life-cycle modeling makes it possible to “roll up” effects at specific times and places to examine their cumulative effect at the population level.

The winter-run Chinook salmon life cycle model is not entirely new. The winter-run Project Work Team reviewed the winter-run IMF (integrated modeling framework) in 2003 and our full report of response to comments is posted on the project website (<http://www.fishsciences.net/projects>). Enhancements to that model have continued since that time, and most recently a manuscript describing the model has been submitted to the Transactions of the American Fisheries Society.

User friendliness and transparency were extremely high priorities for this modeling effort. In order to empower resource managers to accurately evaluate management alternatives, we have intentionally resisted using compiled programming languages that make it difficult for users to look inside or modify a model, and instead we have recommended the use of Excel spreadsheets. However, we have recently transitioned to powerful, specialized modeling software called GoldSim (www.goldsim.com). Our new fish modeling platform (created in GoldSim) is called IOS (Interactive Object-oriented Salmonid Simulation). We specifically chose the GoldSim software platform to advance our salmon life-cycle models because it provides full transparency of equations and calculation steps, ease of use, and intuitive model design. Any parameter or outcome of interest can be plotted or displayed for the user. The model can easily be queried to display population attributes of interest at any life stage, time step, or stream reach that the user desires. In addition, spreadsheets or database files can be dynamically linked to allow data import or export of model output.

With IOS, the model is depicted graphically in a nested hierarchy (Figure 1) which allows the user to view or describe the model at any level, and then to drill down or expand back up to the desired next level of detail. For example, the top level hierarchy can start with a geographic overview, then stream reaches, and within those reaches are nested in successive order: reach, life stage, functions within life stage, and input data for functions.

This documentation provides an overview of the winter-run Chinook salmon life-cycle model structure, a synopsis of the supporting biology used to develop this model structure. This effort is intended to evolve over time along with the growing body of best available science.

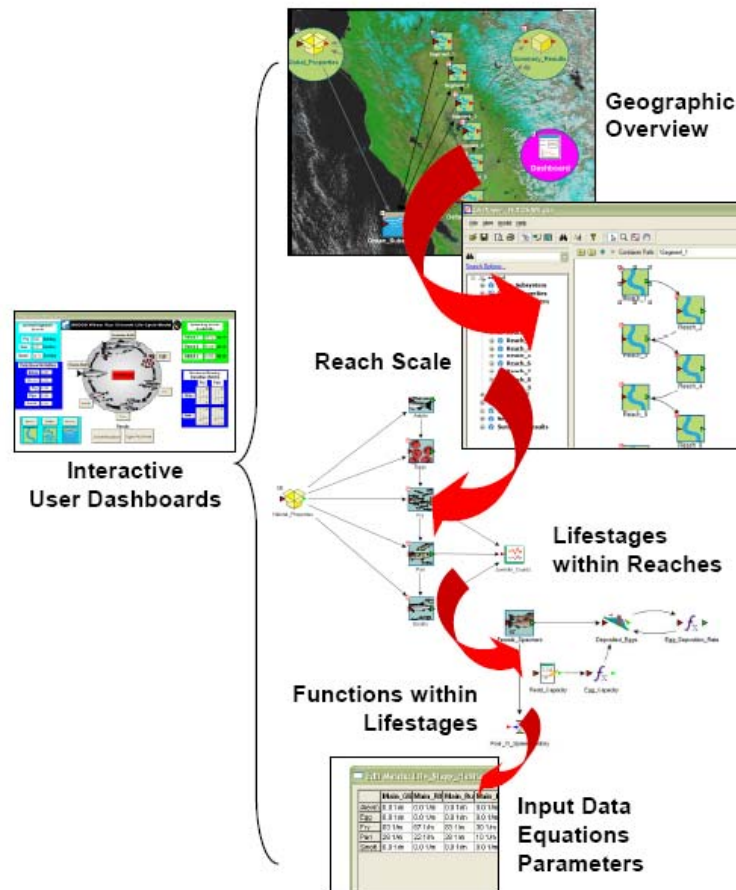


Figure 1. IOS is organized hierarchically, with intuitive, conceptual model elements near the top while functional relationships, equations and input data values revealed as the user drills into model elements and containers. Dashboards (left, center) provide a user friendly interface where model documentation, simulations settings and simulation results are readily available.

2.0 Model Structure

2.1 LIFESTAGE FUNCTIONAL RELATIONSHIPS AND PARAMETERS

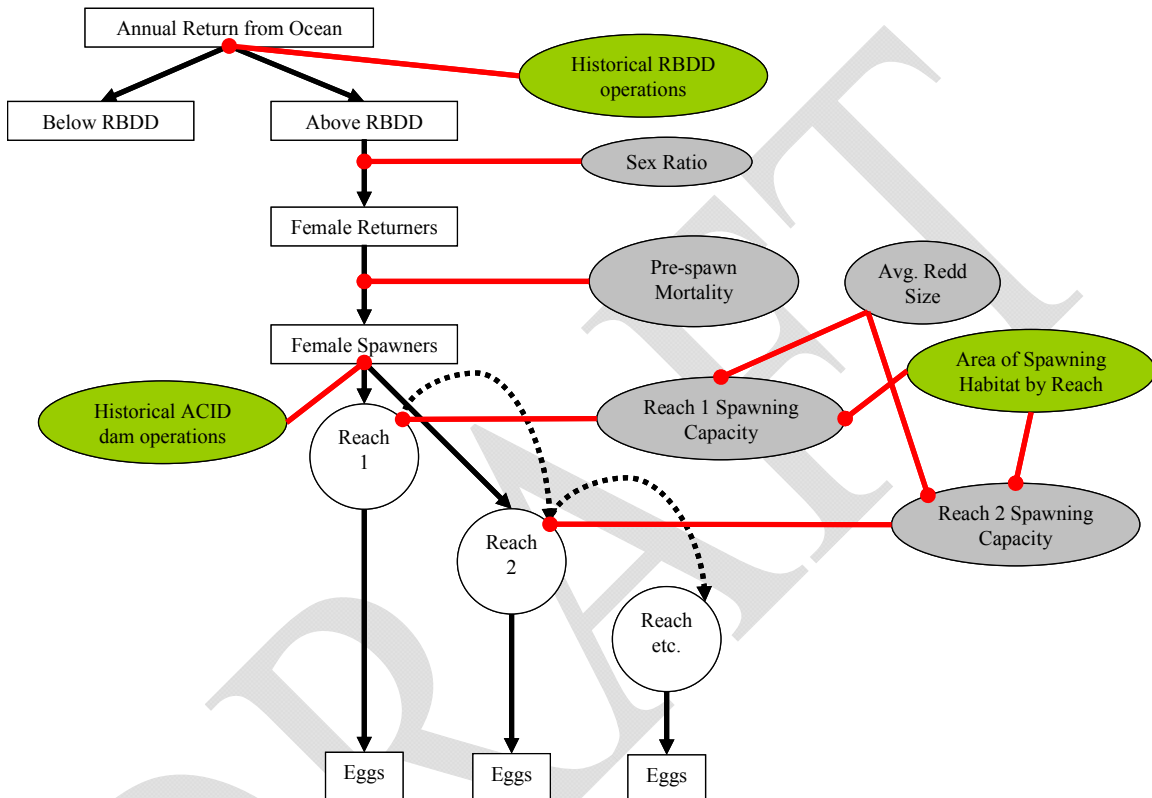
2.1.1 Adult Salmon Spawning

Spawning Distribution among Reaches

Upstream migration of adult winter-run Chinook, like that of all Pacific salmonids, is a complex process influenced by multiple environmental and physiological factors (Quinn and Myers, 2004). We modeled migration from the ocean each year by hierarchically distributing adults among river reaches for spawning. This process responds to the status of migration barriers and the location and capacity of each reach.



If the Red Bluff Diversion Dam (RBDD; rkm 391) is closed, 60% of the escapement is distributed above the RBDD and 40% is distributed below. RBDD passage was informed by radio-tagging studies conducted by Hallock et al. (1982) and Vogel et al. (1988) that found that the RBDD blocked 43-44% of winter-run Chinook that approached the dam when closed. If the RBDD is open, 100% of the escapement is distributed into upstream reaches.



Adult Salmon Migration and Spawning Conceptual Diagram

Similarly, adults enter the uppermost reach (Reach 1) when the Anderson-Cottonwood Irrigation District (ACID) dam is open but only Reach 2 when it is closed. ACID dam is considered open for years 2001 and onward when state-of-the-art fish passage facilities were installed to allow easy passage of adult salmon (CDFG, 2002). Before 2001, a fish ladder was located on the north abutment of ACID dam but was very ineffective because the ladder was too narrow and its flow too low (60 cfs) to fully attract and pass upstream migrating fish (NMFS, 1997). Historical aerial counts of winter-run Chinook redds conducted by CDFG show very sporadic spawning occurring above ACID dam before 2001, with only 2.4% of the spawner distribution occurring above ACID on average. Therefore, in our model spawners do not spawn above ACID dam prior to 2001.

Following this effect of migration barriers, the number of returning adults is reduced to females only using a sex ratio constant (see below) and reduced by a pre-spawn mortality constant (see below). This number of female spawners is allocated into the uppermost



available reach. Each reach has a spawning capacity (see below) and all female spawners in excess of this capacity are 'spilled' into the next reach downstream. This process thus distributes the entire quantity of female spawners amongst the reaches in a hierarchical fashion.

Adult Sex Ratio

Following Cramer et al.(2007b), 65% of returning adults each year are assumed to be females. Snider et al. (2002) found that the percentage of females among carcasses examined during spawner surveys from 1996-2001 ranged from 72% to 90% and average 83%. However, Cramer et al. (2007b) believed that carcass surveys are usually biased high in favor of females because females remain near the redd.

Pre-spawn mortality

Pre-spawn mortality is set at 5% each year. This value reflects the finding that 95% was the lowest percentage of fully-spawned female carcasses found on carcass surveys above the RBDD for winter-run Chinook during 1996-2002 (Snider *et al.*, 2002).

Spawning Capacity

Spawning capacity is determined using the assumption that each female spawner produces one redd. The maximum number of female spawners in a reach is calculated as the quotient of the average redd size and the area of spawning habitat in the reach. We used an average redd size of 4.5 m² following that used in the Sacramento River SALMOD model (Bartholow and Heasley, 2006). This redd size was recommended to the SALMOD builders by Mark Gard of the U.S. Fish and Wildlife Service in Sacramento, CA. The area of available spawning habitat in each reach was extracted from Figure 3-2 in the State of the System Report (Stillwater_Sciences, 2006). The data in that report were collected by digital analysis of Appendix A in the Upper Sacramento River Spawning Gravel Study (CDWR, 1980).

Fecundity

The number of female spawners in each reach is multiplied by fecundity (avg. # of eggs/female) to produce the number of eggs deposited in each reach. We used a fecundity of 3353 based on the average fecundity of winter-run Chinook females spawned at the Coleman National Fish Hatchery during 1956-1982 (Hallock and Fisher, 1985).

Egg Deposition Timing

Winter-run chinook spawn from mid-April to mid-August (Vogel and Marine, 1991). To model this timing we used an egg deposition rate that is determined by a calendar-based, approximately-normal distribution of spawning that starts April 15 and ends August 15. To create an approximately normal distribution of spawning that starts April 15 and ends August 15, we calculated a Cumulative Normal Distribution where $x = \text{Day of Year}$, Mean = 165,

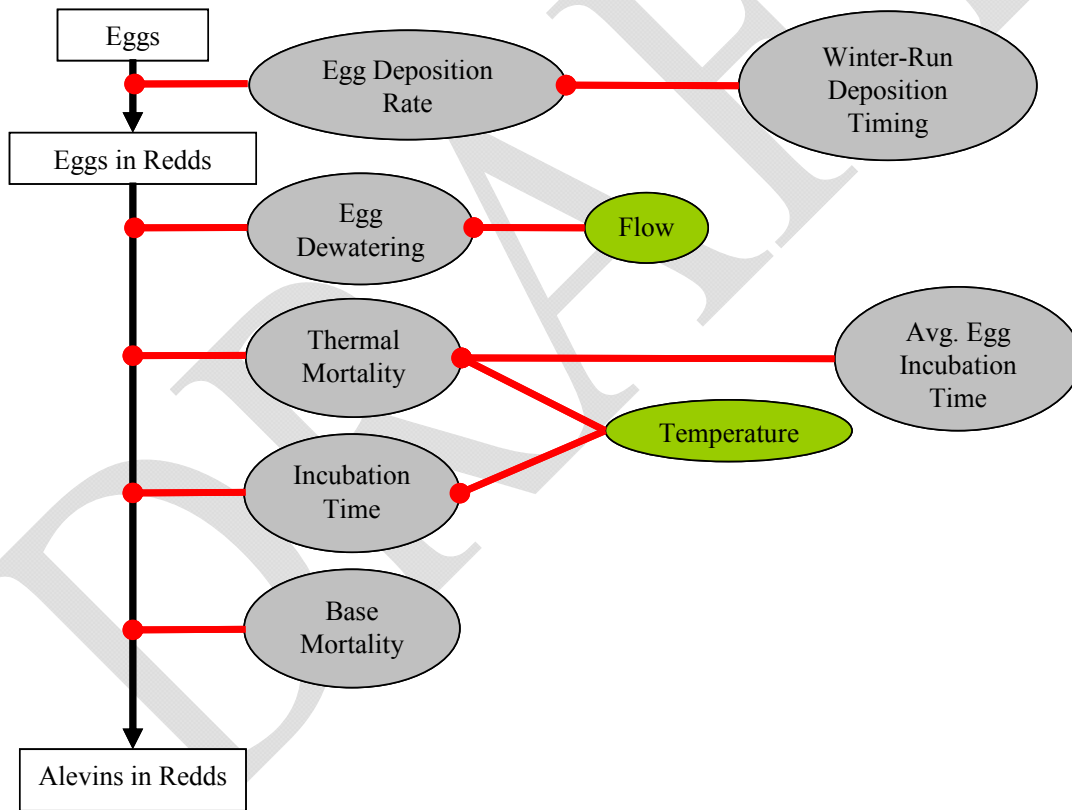


and Standard Deviation = 25. The daily spawning rate values were scaled by 1/8 and the distribution was truncated at April 15 and August 15 to maintain the correct time range for spawning.

2.1.2 Eggs and Alevins

Redd Dewatering

Redd dewatering was modeled as a function of the relationship between river flow during spawning and the lowest river flow during incubation: the greater the drop in flow after spawning, the greater the proportion of redds that are dewatered (USFWS, 2006). We make the assumption that the proportion of redds dewatered is equivalent to the proportion of eggs killed by dewatering. Thus we do not keep track of individual redds, rather we keep track of the total number of incubating eggs.



Egg Incubation Conceptual Diagram

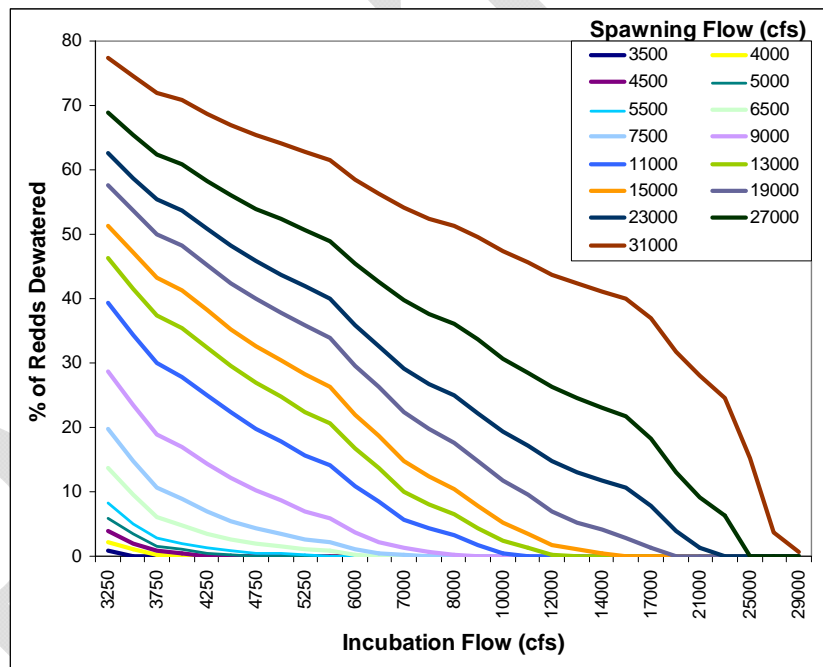
The dewatering relationship we used comes directly from a USFWS report on the Sacramento River (USFWS, 2006). USFWS (2006) used a 2-dimensional hydraulic and habitat model (RIVER2D) to simulate the percent of redds dewatered across 8 winter-run Chinook spawning areas on the Sacramento River (Keswick Dam to Battle Creek). The



results of these simulations as detailed in the table “Percentage of Winter-run Chinook Salmon Redds Dewatered - ACID Dam Boards Out” on pages 63-64 of USFWS (2006). This table reports the percent of winter-run Chinook redds dewatered as a function of the difference between spawning flow and incubation flow. See Figure 2-1.

In our model, spawning flow is the flow on the day in which eggs were deposited. The lowest incubation flow is the smallest flow during the 105 days following egg deposition. We chose 105 days as the average duration of total incubation (egg + alevin incubation) by running the IOS model under hindcast conditions over the years 1968-2001 and extracting the average egg and alevin incubation time for each year. Average egg incubation time was 59 days, and the average alevin incubation time was 46 days, for a total of 105 days of incubation.

Figure 2-1. Percent of winter-run Chinook redds dewatered as a function of the difference between spawning flow and incubation flow.



Incubation Time

Egg and alevin incubation time is modeled as a time delay whose duration is determined by the temperature on the day of egg deposition or hatching, respectively. The relationship between temperature and incubation time is determined by the following power function (Beacham and Murray, 1990, model 5 with parameter estimates from Table A.2 therein):

$$\log_e D = \log_e a + b \log_e (T - c) + d \log_e S$$

where:

D = hatching or emergence time after fertilization

T = Temperature (°C)

S = timing of spawning (Day of Year when spawning begins)

$\log_e a$ = 7.726 (hatching), 10.319 (emergence)

b = -1.320 (hatching), -1.994 (emergence)

c = -2.252 (hatching), -7.195 (emergence)



$d = -0.078$ (hatching), -0.003 (emergence)

We model the time period from fertilization to hatch (eggs) and the time from hatch to emergence (alevins) separately. Thus, for a given temperature the egg incubation time is D_{hatching} and the alevin incubation time is $D_{\text{emergence}} - D_{\text{hatching}}$. These Temperature-Incubation Time relationships are shown in Figure 2-2.

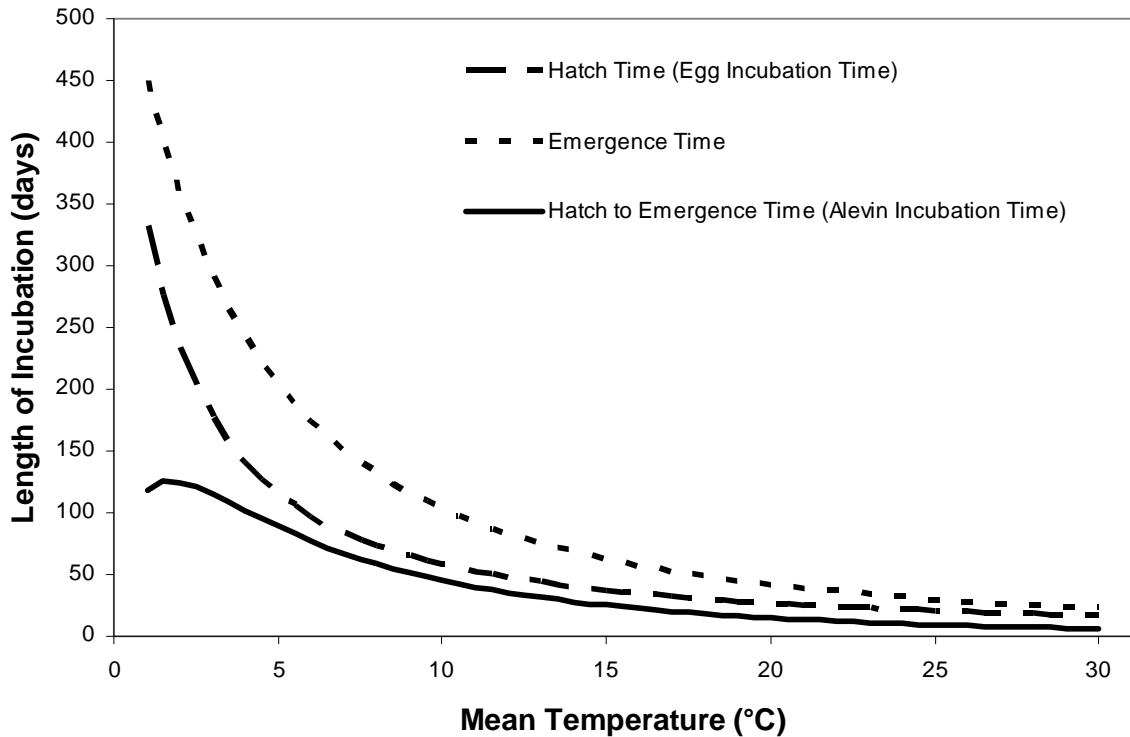


Figure 2-2. Relationship between temperature and incubation time for eggs and alevins. Alevin incubation time is the difference between Hatch Time and Emergence Time.

Base Mortality and Thermal Mortality

Base mortality for eggs and alevins represents incubation mortality due to unknown or indirect causes and was set at 0.014 % per day. This value was reached by running historic simulations of the model and changing base mortality values until an average annual egg-fry survival rate of approximately 30% was attained. Egg to fry survival has been observed to be approximately 30% in the Sacramento River (Martin *et al.*, 2001).

Thermal mortality for eggs and alevins was modeled as a function of temperature using experimental data from Richardson and Harrison (1990). Richardson and Harrison’s (1990) mortality rates were reported for variable time periods thus these data were converted to daily rates using the following formula (Bartholow and Heasley, 2006):

$$M_1 = 1 - (1 - M_n)^{1/n}$$



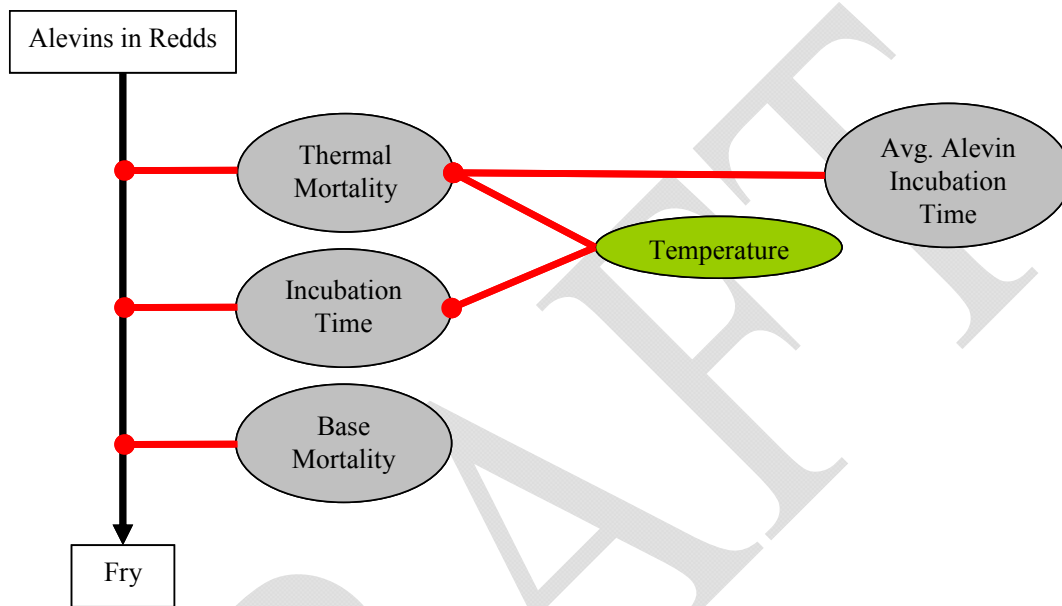
where:

M_1 = daily mortality rate (%/day)

n = the reference period (number of days)

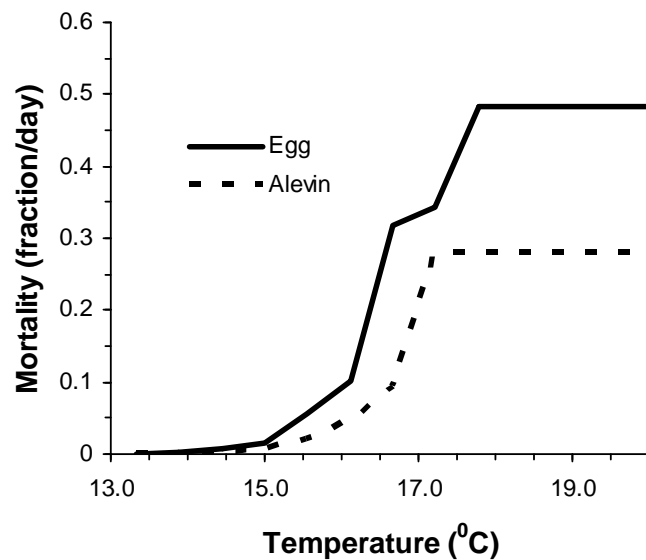
M_n = the mortality rate

A plot of the thermal mortality curves for eggs and alevins are shown in Figure 3.



Alevin Development Conceptual Diagram

Figure 3. Daily thermal mortality for incubating eggs and alevins.





Daily base and thermal mortalities are combined and applied after the incubation time delay as the integral of total daily mortality over the incubation period using the following formula:

$$\text{Mortality during incubation} = e^{-Mn}$$

where:

e = Euler's number (2.718 . . .)

M = integral of daily mortality (base & thermal) over time n

n = average incubation time (59 days for eggs, 46 days for alevins)

The use of 59 days for eggs and 46 days for alevins represents their respective proportions of the average total incubation time (105 days; see Redd Dewatering, above).

2.1.3 Juvenile Rearing and Migration

Fry/Parr Growth and Maturation

Specific daily growth rates (% of weight/day) for fry and parr are a function of temperature (Shelbourn *et al.*, 1973). The temperature-growth rate curve for fry was adapted from experimental growth data on juvenile Chinook salmon adjusted for a 60% ration (60% of maximum daily intake; Brett *et al.*, 1982). 60% ration approximates natural feeding levels for Chinook salmon (Brett *et al.*, 1982). The temperature-growth rate curve for parr was created by scaling down the fry curve (Figure 4). This was accomplished using a scaling equation created to reproduce the difference between fry and parr temperature-growth rate curves in Sockeye salmon (Shelbourn *et al.*, 1973).

We used the three different weight ranges of fish that were used to estimate juvenile growth by Shelbourn et al. (1973) to delineate the weight ranges for each juvenile Chinook lifestage (slightly adjusted to avoid overlap of weights). Table 1 displays the minimum and maximum weights used for defining the size range for each Juvenile Chinook lifestage.

Figure 4. Temperature-growth rate curves for Chinook fry and parr.

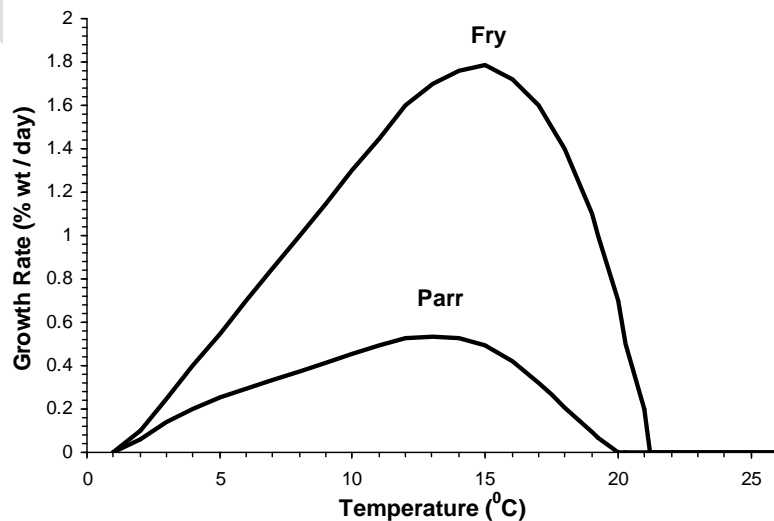




Table 1. Minimum and maximum weights and corresponding length conversions used to define the size range for each juvenile Chinook lifestage .

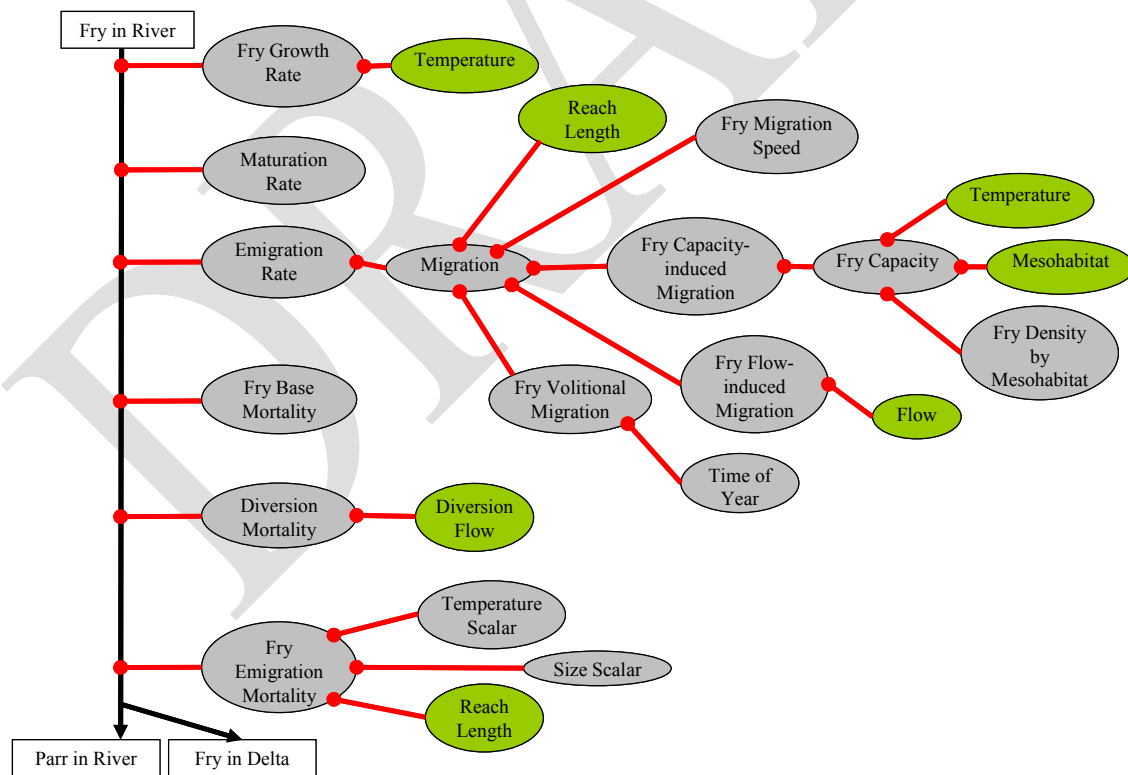
	LifeStage Size Cut-offs					
	Fry		Parr		Smolt	
	Min	Max	Min	Max	Min	Max
Weight (g)	0.5	1.9	1.9	5.2	5.2	30.1
Length (mm)	40	58	58	78	78	128

Fish weight was converted to length by using a weight-length relationship developed by Petrusso and Hayes (2001) for Chinook salmon in the Sacramento River, California:

$$\text{Weight} = .001348 * \text{Length}^3 * 3.4852$$

where Weight is in mg and Length is in mm

The resulting three length ranges correspond well with the length cut-offs for each life stage (except the maximum length for smolts) used in the Sacramento River SALMOD model (Bartholow and Heasley, 2006).



Fry Conceptual Diagram



The rate at which juveniles transition from one lifestage to the next (maturation rate) is dependent on the mean size of the lifestage population in each reach. For example, the maturation rate from fry to parr is zero percent per day until the mean size of fry reaches the midpoint between the minimum and maximum sizes for fry. Once the mean size reaches this midpoint the maturation rate increases exponentially to a maximum of 100% per day (see Figure 5). This functionality assumes that juvenile growth is exponential and that there is a constant influx of new members to a life stage at the minimum size.

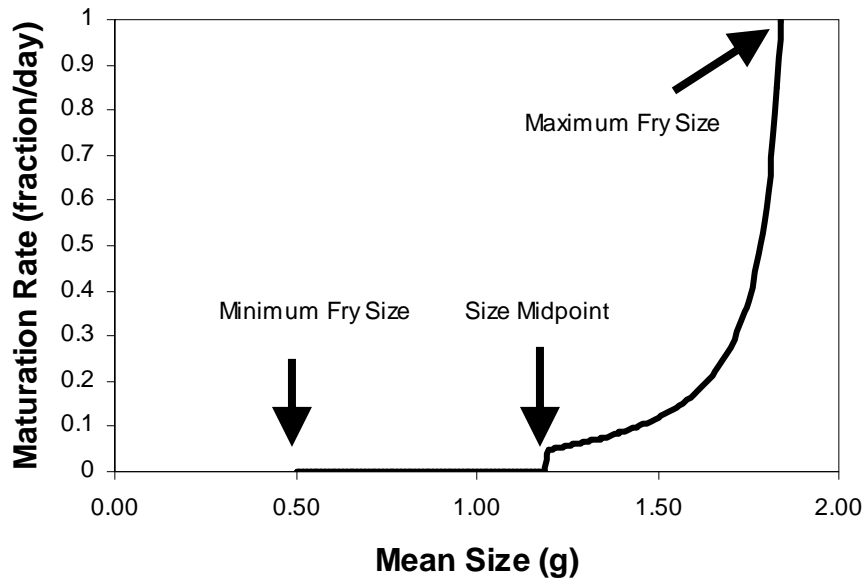


Figure 5. Plot of daily maturation rate for fry.

Downstream Migration

Downstream migration functions by calculating the percentage of juveniles in a reach that are migrating each day. This calculation is performed independently for each juvenile lifestage. The daily proportion of migrating fish in each lifestage is used to calculate the number of fry, parr, and smolts that actually emigrate from (leave) a reach on a given day. In order to account for transit time through a reach, the number of daily migrants is divided by the amount of time required to traverse the reach. This amount of time is the quotient of the reach length and the lifestage-specific migration speed.

For fry and parr, the percent migrating every day derives from three sources: capacity-induced, flow-induced, and volitional. These three percentages are combined sequentially to produce the total percent migrating in a reach on a given day. For smolts, the fraction migrating each day is fixed at 100% because we assumed smolts were always migrating downstream rather than rearing. Migration speeds for each lifestage were estimated using the relationship between juvenile Chinook migration speed and fish length reported by Giorgi et al. (1997) in the Columbia River. Fry (40-58mm) migrate at 1.84 km/day, parr (58-78mm) at 4.75 km/day, and smolts (78-150mm) at 19.71 km/day.



Capacity-Induced Migration

All fry and parr that exceed reach capacity on a given day are added to the number of fish migrating. Reach capacity is determined by three factors: the linear quantity of 9 mesohabitat types, the maximum linear density of fry and parr in each of these mesohabitats, and a temperature scalar that reduces capacity at high temperatures.

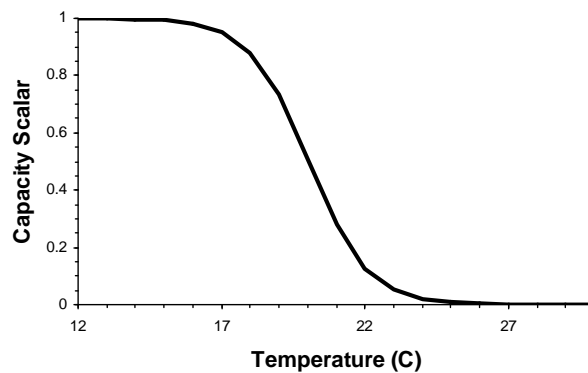
Reach specific mesohabitat types were quantified based upon habitat mapping conducted for instream flow incremental modeling by USFWS (Mark Gard, U.S. Fish and Wildlife Service, unpublished data). The maximum linear density of fry and parr in each mesohabitat type was estimated based upon studies conducted on salmon abundance and mesohabitat use on the Feather River (Table 5).

Table 5. Maximum linear densities of fry and parr in each of the 9 mesohabitat types.

	Main River Channel Mesohabitat					Side Channel Mesohabitat			
	Glide	Riffle	Run	Pool	Boulder Run	Glide	Riffle	Run	Pool
Maximum Fry Density	83/m	67/m	83/m	30/m	83/m	83/m	67/m	83/m	30/m
Maximum Parr Density	28/m	22/m	28/m	10/m	28/m	28/m	22/m	28/m	10/m

The temperature-dependent scalar of reach capacity was developed by Ackerman et al. (2007; p. 59) for the Cramer Fish Sciences Population Life-Cycle Model for Lower Clackamas River Salmonids. In IOS it is used to scale down both fry and parr capacities when water temperature exceeds approximately 16 °C (Figure 4).

Figure 4. Temperature-dependent scalar of capacity developed by Ackerman et al. (2007; p. 59) for the Cramer Fish Sciences Population Life-Cycle Model for Lower Clackamas River Salmonids.



Flow-Induced Migration

We assumed that fry and parr are swept downstream during very high flows (flows high enough to scour redds; Williams, 2006). Hatton and Clark (1942) reported catching sac fry in 1940, a few days after the daily average discharge on the American River reached approximately 56,000 cfs. In the Sacramento River, Bigelow (1996) first observed gravel displacement at 50,000 cfs, and observed significant bed-changing events at 60,000 cfs. Therefore, we set flow-induced migration of fry and parr to begin at 50,000 cfs, and linearly increase to 100% migrating each day at 60,000 cfs (Figure 5).

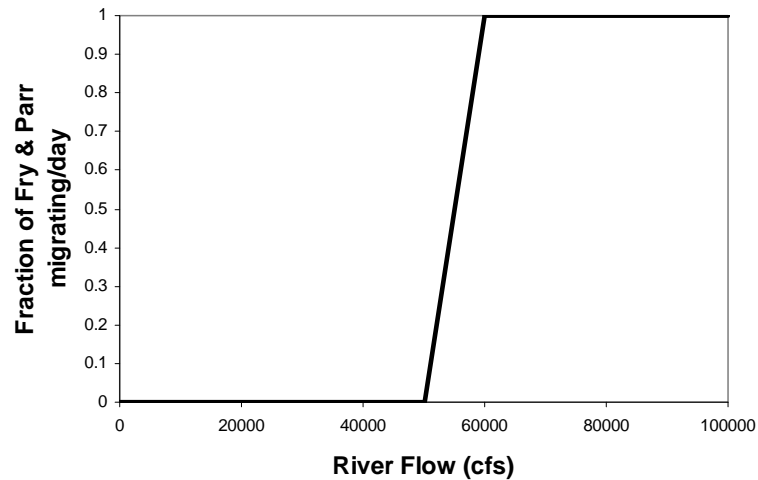


Figure 5. Flow-induced migration for fry and parr.

Volitional Migration

Data from screw trap monitoring below the RBDD indicate that the majority of juvenile Winter Run Chinook that migrate past RBDD are fry ($\leq 55\text{mm}$; Martin *et al.*, 2001; Poytress, 2007). Monthly RBDD passage estimates for brood years 1995-1999 show an average fry proportion of 75% per brood year (Martin *et al.*, 2001). In order to accurately model this migration behavior we added volitional migration functionality to the IOS model. Volitional migration sets the proportion of daily migrants for fry and parr based on calendar time. The calendar-based volitional migration patterns for fry and parr are shown in Figure 6. We created these patterns with the intention of producing 75% fry passage at the RBDD each year and mimicking the timing of juvenile passage seen in RBDD screw trap data. After initial implementation in the IOS model, the preliminary volitional migration patterns were modified using trial-and-error modeling runs under historical conditions of river flow and temperature (hindcast).

Juvenile Mortality

Migration Mortality

Fish that emigrate from a reach are subjected to migration mortality. Migration mortality varies according to distance migrated (reach length), temperature, and size (juvenile lifestage). The product of distance-dependent survival and temperature and size scalars determines the daily proportion of emigrating fry, parr, and smolts that die while emigrating to the adjacent downstream reach.

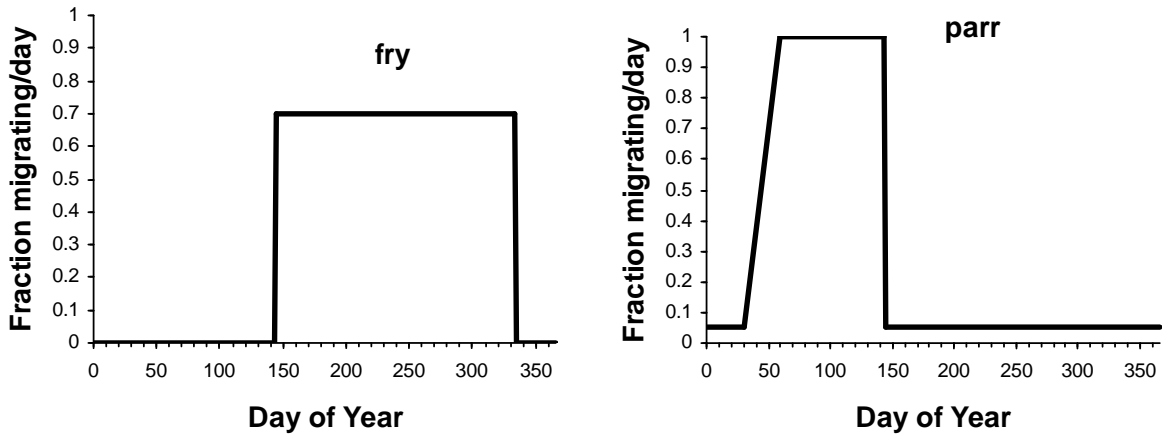
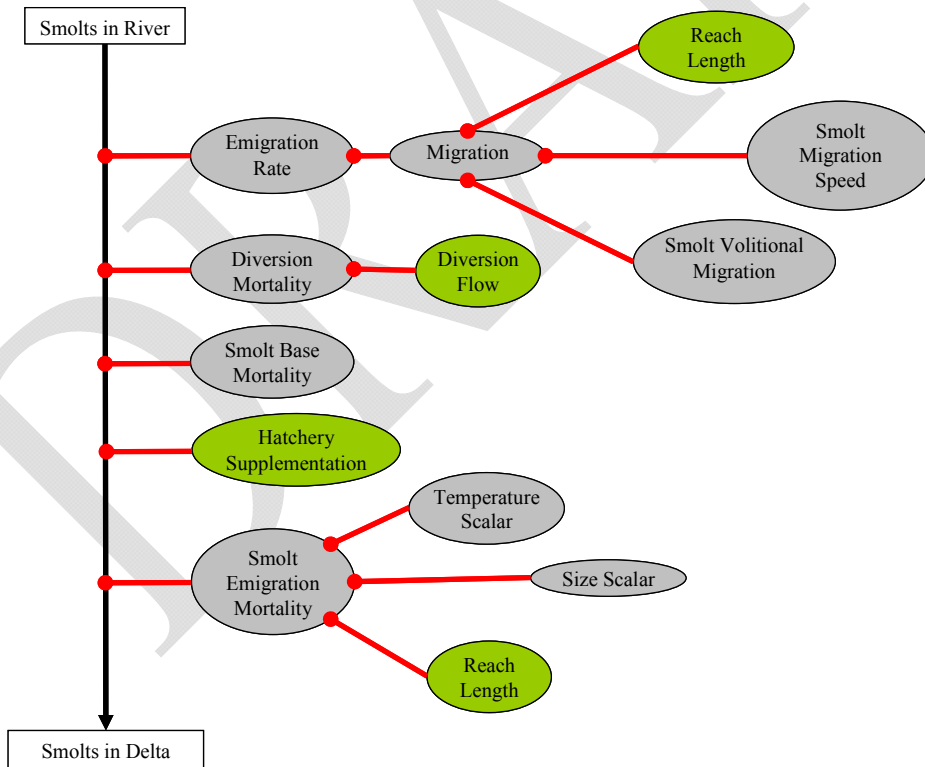


Figure 6. A. Fraction of fry migrating versus day of the year. B. Fraction of Parr migrating versus day of the year.



Smolt Conceptual Diagram



Migration survival was estimated as a linear function of migration distance (reach length) as used by Cramer Fish Sciences (CFS) for the Klamath River Life-Cycle Model (Cramer *et al.*, 2007a). Cramer *et al.* (2007a) first estimated the baseline (i.e. maximum) survival rate per 100 km under optimal temperature and flow conditions (S_{Base}) by finding the highest survival estimate per 100 km from several studies that examined juvenile Chinook migration survival. The relative effect of migration distance on survival was described by:

$$\text{Migration Survival} = (S_{Base})^{d_i/100};$$

where $S_{Base} = 0.95$, and $d_i =$ length of each reach i . The reach length that a daily cohort of juveniles was emigrating from was used to calculate daily migration survival to the adjacent downstream reach (Figure 7).

Migration survival decreases with increasing temperature through use of a water temperature scalar (Figure 8). The water temperature scalar is estimated from experiments conducted by Baker *et al.* (1995) that estimated the influence of water temperature on the survival of Chinook salmon smolts migrating through the California Delta. The logistic relationship between smolt survival and water temperature estimated by Baker *et al.* (1995) was used in IOS as a scalar on migration survival:

$$S_i = \frac{1}{1 + e^{-a-bT_i}};$$

where $S_i =$ migration survival scalar in reach i , $a = 15.56$, $b = -0.6765$, and $T =$ mean daily water temperature in reach i .

A size-dependent scalar on migration survival was created to impose a greater risk of migration mortality for smaller individuals (fry and parr) compared to smolts. The parr survival scalar is .985, while the fry survival scalar is .975. The values for the size-dependent scalars were set using a trial-and-error process during model hindcasting in order to attain historically accurate size proportions of juveniles at RBDD.

Finally, distance-dependent survival is multiplied by the temperature and size scalars to calculate a daily migration mortality for fry, parr, and smolts in each reach.

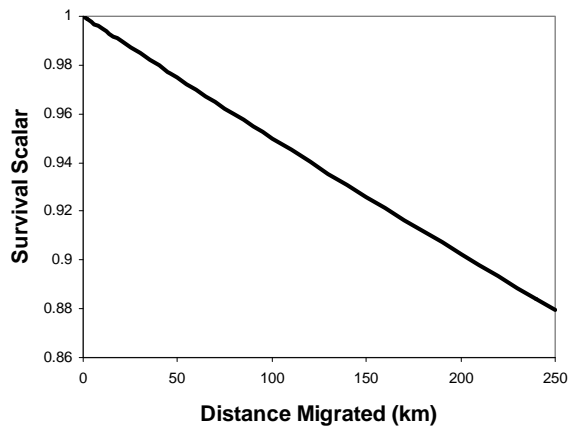


Figure 7. Migration survival as a function of distance migrated (reach length).

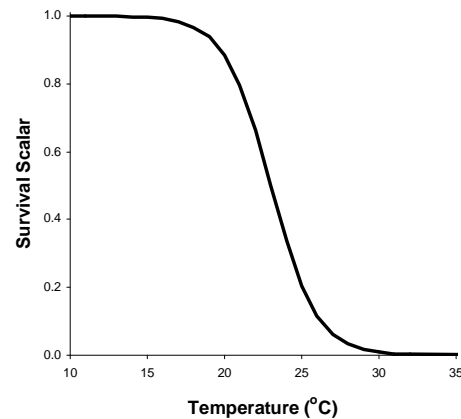


Figure 8. Water temperature scalar on migration survival.

Diversion Mortality

In reaches where flow is diverted from the Sacramento River, the proportion of juveniles (all lifestages) that encounter diversion screens is assumed to be proportional to the flow diverted. Following a NOAA Fisheries statement on experimental fish guidance devices (NOAA, 1994) we set the screen encounter mortality at 2%.

Background Mortality

Background mortality represents all sources of mortality not accounted for by migration mortality and diversion mortality. We established daily background mortality rates for fry, parr, and smolts using trial-and-error modeling runs under historical conditions of river flow and temperature (hindcast). Background mortalities for fry = 0.001/day, parr = 0.0008/day, and smolts 0.0006/day.

2.1.4 Delta

Fry, parr and smolts that emigrate from reach 22 enter the Delta, where a daily mortality is applied based on the empirical model of Newman and Rice (Newman and Rice, 2002; Newman, 2003). Subsequently, a lifestage specific Delta travel delay is applied to survivors to represent the amount of time required for juveniles to traverse the Delta.

Survival of smolts passing through the Delta into San Francisco Bay ($Surv_{Delta, yr}$) has not been directly estimated for winter Chinook salmon, but has been extensively studied for juvenile fall and late-fall Chinook salmon. We assumed the environmental mechanisms that had a strong influence on survival through the Delta for fall Chinook salmon smolts would also apply to winter Chinook salmon smolts passing through the Delta. We therefore derived survival through the Delta from CWT experiments with juvenile fall Chinook salmon analyzed by Newman and Rice (2002). Newman (2003) estimated survival of fall-run juveniles migrating through the Delta during April to June by determining the difference in



recoveries of CWTs from paired releases of 61 CWT groups. Those pairings each included a group released above the Delta in the vicinity of Rkm 50-100 paired with a group released in the estuary below the confluence of the Sacramento and San Joaquin rivers. Newman and Rice (2002) and Newman (2003) completed a variety of analyses to identify the most likely factors affecting smolt survival through the Delta, which included flow and temperature in the Sacramento River at Freeport, exports of water from the South Delta State Water Project and Central Valley Project pumping facilities, turbidity on the Sacramento River at Courtland, salinity at the confluence of the Sacramento and San Joaquin rivers (Collinsville), and whether the gates to the Delta Cross Channel (DCC) were open or closed. We used the statistically significant coefficients estimated by Newman (2003) to predict survival through the Delta as follows:

$$\text{Surv}_{\text{Delta, yr}} = 0.65 + 0.86 \cdot \log_e(\text{Flow}) - 0.81 \cdot \text{Temp} - 0.32 \cdot \text{Export} + 0.37 \cdot \text{Turb} + 0.35 \cdot \text{Sal} - 0.75 \cdot \text{Gate}$$

Where:

- Surv_{Delta} = log_e transformation [$\log_e(p/(1-p))$] of proportion (p) surviving from Courtland to Chipps Island.
- Flow = the natural logarithm of the median flow at Freeport in cfs from release date to last day of recoveries at Chipps Island
- Temp = water temperature at release site.
- Exports = median daily values (cfs) for period from release date to last day of river recovery.
- Turb = average Formazine Turbidity Unit calculated near Courtland for the period from release date to the last day of river recoveries.
- Sal = average conductivity at Collinsville, measured in micro mho/cm, for the period from two days before the first day of recovery to the last day of recoveries at Chipps Island.
- Gate = average of daily positions of the DCC gates, where each day a value of 0 or 1 signaled both gates closed or open, respectively.

Because Newman (2003) standardized all variables except the DCC position indicator, we converted environmental variables to standardized values using the following equation:

$$\text{Std. val} = (x - \mu) / \sigma$$

Where:

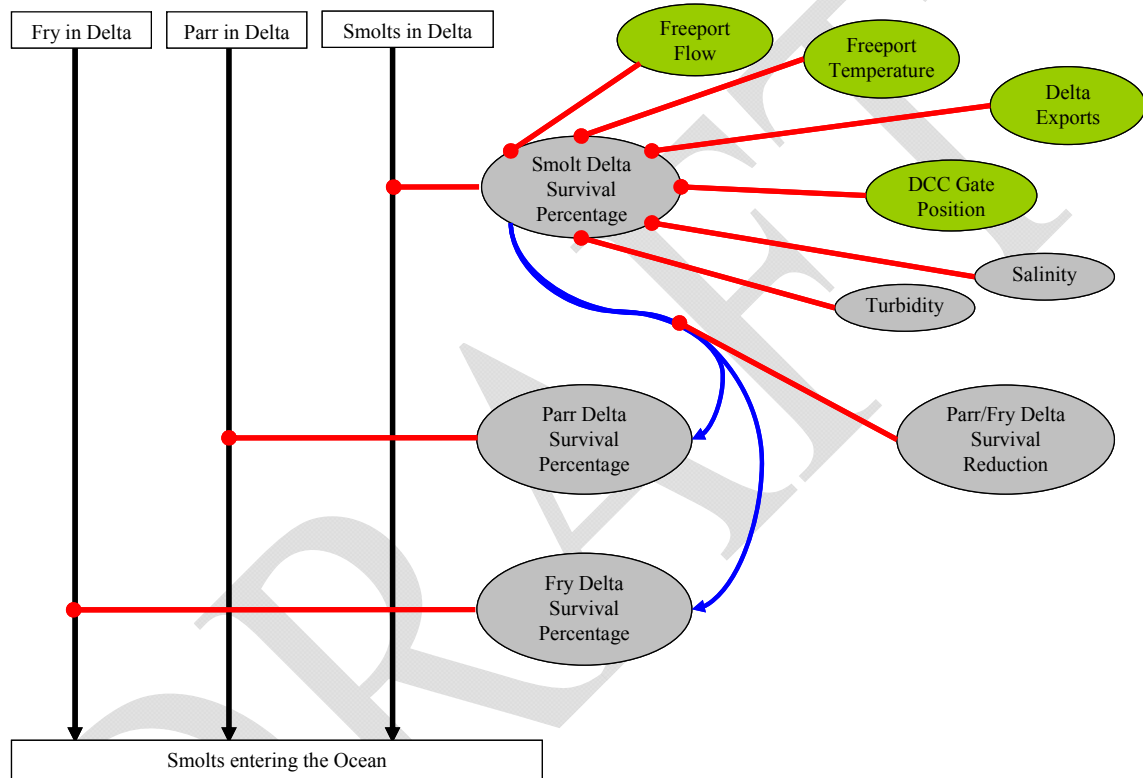
- Std. val = a standardized value
- x = input values for the environmental variables
- μ = mean value for the environmental variable
- σ = standard deviation for the environmental variable

Data on salinity are sparse, so we set salinity to be calculated as a function of flow. A regression of salinity at Collinsville (Rkm 5) on Sacramento River flow at Freeport (Rkm



75), during December to March since 2000, produced the exponential function $Sal = 102,003 \cdot e^{-0.0002 \cdot Flow}$ that accounted for 65% of variation in salinity ($P < 0.0001$).

The survival probability equation of Newman and Rice (2002; Newman, 2003) is solved in an Excel Spreadsheet (“Reaches”, tab “Delta”) and imported into GoldSim on a daily timestep. This equation uses standardized physical data (e.g., temperature) from a 15-day future average in order to represent Delta conditions during the Delta migration period for smolts on a given day.



Juvenile Salmon Delta Survival Conceptual Diagram

Because Newman’s Delta survival model calculates the survival of Chinook smolts, we could not apply Newman’s model to fry and parr without modification. However, we did not find empirical evidence to inform size-dependent Delta survival. For now, our Delta survival probabilities are reduced by a factor of 1/3 for fry and parr to represent higher Delta mortality for smaller sized fish.

A lifestage-specific Delta travel delay is applied to survivors to represent the amount of time required for juveniles to traverse the Delta. The travel delay for smolts = 15 days, parr = 60 days, and fry = 90 days. Longer travel delays for fry and parr represent slower movement

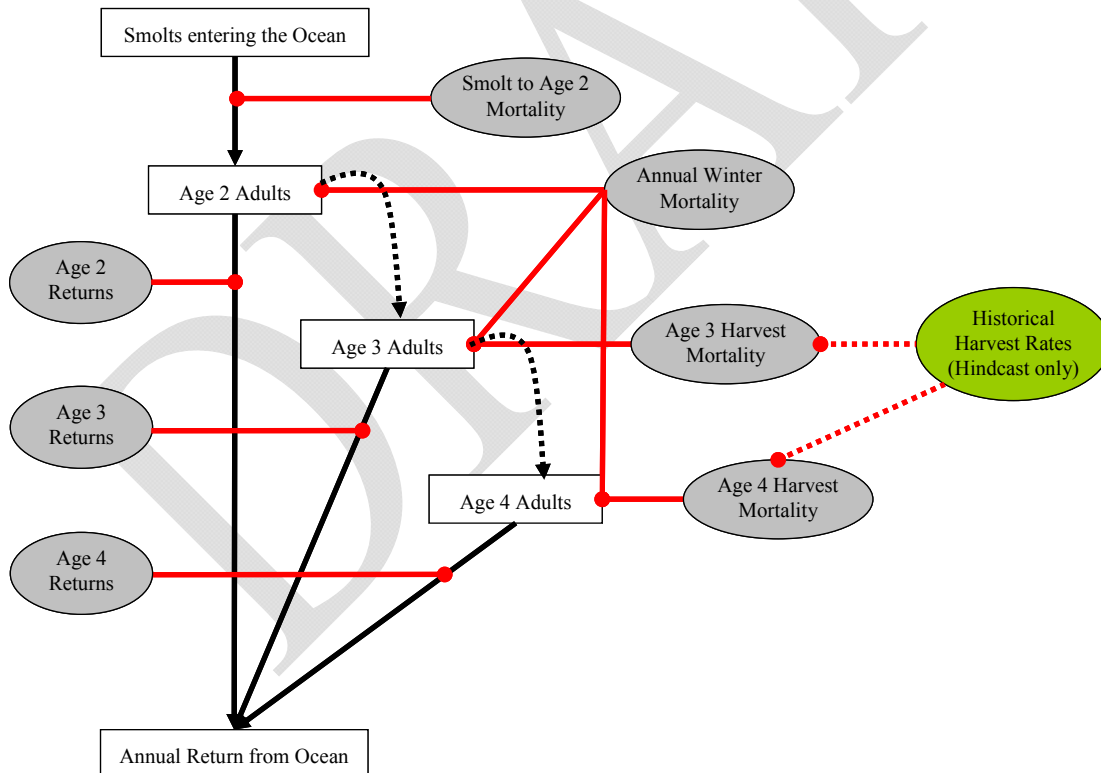


and time for maturation into smolts. Delay amounts were determined using a trial-and-error process during model hindcasting in order to attain historically accurate bay arrival timing.

2.1.5 Ocean Adults

The total number of surviving smolts arriving from the Delta (each brood year) is subjected to ocean mortalities applied as annual discrete events that modify an entire ocean cohort at once. Each year a fixed proportion of that year's survivors move into freshwater to spawn. The remainder stay in the Ocean until the next Ocean Year. This life stage component does not occur on a daily time step.

Once in the ocean, winter-run Chinook incur annual age-specific harvest mortalities. Because age 2 winter-Chinook are too small to be harvested, age 2 ocean harvest mortality is set at 0% (Grover *et al.*, 2004). Age-3 and age-4 winter-run Chinook incur harvest mortalities estimated from recoveries of marked salmon for years where marking data is available, and from CVI (Central Valley Index) estimates in all other years.



Ocean Mortality, Harvest and Maturity Conceptual Diagram



Recoveries of marked winter Chinook salmon have only been sufficient to estimate harvest rates from the 1969 to 1971 broods (Barroco and Boydston, 1989) and from the 1998 to 2000 broods (Grover *et al.*, 2004). In all other years, we derived a probable history of ocean harvest rates on winter Chinook salmon by comparison to the CVI (Central Valley Index) used by harvest managers to monitor ocean harvest rate. Age 3 harvest rates on winter Chinook salmon for the 1969 and 1970 broods (Barroco and Boydston, 1989) was 50% of the CVI. In recent years, harvest regulations have been specifically designed with time, area and size restrictions to reduce harvest of winter Chinook salmon while allowing retention of fall Chinook salmon. The winter Chinook salmon harvest rate at age 3 was 39% of the CVI during 2000. When using the model to simulate historic conditions (hindcasting), we assumed harvest rates at age 3 to be 50% of the CVI up to 2000 (1997 brood), and were 39% of the CVI thereafter unless direct estimates for winter Chinook salmon were available. We assumed that age 4 harvest rates in years not directly estimated were equal to 1.54 times the age 3 rates, as estimated by Barroco and Boydston (1989) with data from the 1969 and 1970 broods.

After harvest rates are applied, winter-run Chinook salmon are assumed to incur 20% mortality each winter (Grover *et al.*, 2004), then a fixed portion of the number remaining alive at each age (i.e., 2 to 4) mature and return to freshwater. We applied the approximate median maturity rates (8% at age 2, 96% at age 3, and 100% at age 4) as estimated by Grover *et al.* (2004) for the 1998-2000 broods with cohort analysis of CWT recoveries.

Following Cramer *et al.* (2007b) we utilize the following values for ocean mortality and sexual maturation:

- Winter Mortality for all age groups is 20% (Grover *et al.*, 2004)
- Smolt to Age 2 Mortality is 96%.
- Age 2 Ocean Harvest Mortality is 0% (Grover *et al.*, 2004).
- The proportion of Age 2 Returning Spawners (precocious) is 8% (Grover *et al.*, 2004).
- Age 3 Ocean Harvest Mortality is 21% (Grover *et al.*, 2004).
- The proportion of Age 3 Returning Spawners is 96% (Grover *et al.*, 2004).
- Age 4 Ocean Harvest Mortality is 66% (Grover *et al.*, 2004).
- The proportion of Age 4 Returning Spawners is 100% (Grover *et al.*, 2004)

2.2 SPATIAL SPECIFICITY

Sacramento River water temperatures, discharge, and diversions vary considerably by location. In order to capture and quantify NODOS alternative affects the model will include 22 discrete river reaches (grouped as five segments), the Sacramento-San Joaquin Delta, and the Ocean. Reach delineations are based upon previous fish modeling efforts (SALMOD; reaches 1 through 15) and on expected NODOS specific effects. For example, Segment 3 (reaches 16 through 19) captures three significant tributaries, the GCID diversion, and an area that may benefit substantially from improved cold water pool management.



Table 5. Description of reach delineations

Reach Number and Description	RM Start	RM End	Reach Length (mi)	Reach Length (km)
1. Keswick Dam to ACID Diversion Dam	302.0	298.4	3.6	5.8
2. ACID Diversion Dam to Hwy299/44 Bridge	298.4	296.4	2.0	3.2
3. Hwy 299/44 Bridge to Clear Creek	296.4	289.4	7.0	11.3
4. Clear Creek to Churn Creek	289.4	284.7	4.7	7.6
5. Churn Creek to Cow Creek	284.7	280.3	4.4	7.1
6. Cow Creek to Ash Creek	280.3	277.4	2.9	4.7
7. Ash Creek to Balls Ferry Bridge	277.4	276.2	1.2	1.9
8. Balls Ferry Bridge to Anderson Creek	276.2	273.9	2.3	3.8
9. Anderson Creek to Cottonwood Creek	273.9	273.6	0.3	0.5
10. Cottonwood Creek to Battle Creek	273.6	271.3	2.2	3.6
11. Battle Creek to Jellys Ferry Bridge	271.3	266.8	4.6	7.3
12. Jelly Ferry Bridge to Bend Bridge Gage	266.8	257.5	9.3	15.0
13. Bend Bridge Gage to Paynes Creek	257.5	252.8	4.7	7.5
14. Paynes Creek to Reeds and Red Bank Creeks	252.8	244.8	8.0	12.8
15. Reeds and Red Bank Creeks to RBDD	244.8	243.0	1.9	3.0
16. RBDD to Antelope Creek	243.0	234.8	8.1	13.1
17. Antelope Creek to Mill Creek	234.8	230.5	4.3	6.9
18. Mill Creek to Deer Creek	230.5	220.4	10.1	16.3
19. Deer Creek to GCID	220.4	205.0	15.4	24.8
20. GCID to Maxwell	205.0	178.0	27.0	43.5
21. Maxwell Diversion (Provident Irrigation Main Canal) to Hanson Island	178.0	171.0	7.0	11.3
22. Hanson Island to Delta	171.0	46.5	124.5	200.4

2.2.1 Reach Subsystems

Reach specific mesohabitat types were quantified based upon mapping conducted for instream flow incremental modeling studies by USFWS (Mark Gard, U.S. Fish and Wildlife Service, unpublished data).

Densities (number of fry or parr per linear meter) of juvenile Chinook salmon were developed from mesohabitat observations on the Feather River for different mesohabitat types (http://orovillereicensing.water.ca.gov/pdf_docs/04-28-04_att_10_f10_3A_steelhead_hab_use.pdf). Using the proportion of each habitat type per reach, the density of juveniles per linear meter for different mesohabitat types was applied to develop an overall density of juvenile Chinook salmon by reach.

Important life stage components and physical conditions are modeled in detail within each reach.



Adult Chinook salmon select spawning reaches as a function of the observed historical spawning distribution.

2.2.2 Delta Subsystem

Mortality through the Sacramento-San Joaquin delta is modeled as described earlier, as a function of weekly average water temperature, weekly average discharge, weekly average exports, Delta Cross Channel (DCC) position, and fish size.

2.2.3 Ocean Subsystem

Age specific harvest and maturity (i.e. return to freshwater for spawning) is modeled as described earlier, using fixed rates from previous models (winter run IMF) and empirical data (e.g. CDFG cohort analysis).

2.3 TEMPORAL PROPERTIES

The model operates on a daily time step and cycles through any number of years for which input data are available or from which randomized resampling is desired. Reach specific, daily average temperature and discharge data provide the basic model inputs. In addition, data on diversion rates at RBDD, GCID and Maxwell or other locations can be used to estimate direct and indirect entrainment losses.

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