Attachment 5.D.2, SALMOD Model

5.D.2 SALMOD Model

5.D.2.1 Introduction

This technical memorandum outlines the key features and capabilities of the SALMOD software. In addition, this memo describes the application of the SALMOD model to simulate Sacramento River Chinook salmon populations. This memo implicitly assumes some understanding about the Sacramento River and fisheries, in general.

5.D.2.2 SALMOD Software

SALMOD simulates the dynamics of freshwater salmonid populations, both anadromous and resident. The conceptual model was developed using fish experts concerned with Trinity River Chinook restoration in workshop settings (Williamson et al. 1993), building on the foundation laid by similar models. SALMOD is a component of the Instream Flow Incremental Methodology, or IFIM. The model's premise is that egg and fish mortality are directly related to spatially and temporally variable microhabitat and macrohabitat limitations, which themselves are related to the timing and amount of streamflow and other meteorological variables. Habitat quality and capacity are characterized by the hydraulic and thermal properties of individual mesohabitats, which are used as spatial "computation units" in the model. The model tracks a population of spatially distinct cohorts that originate as eggs and grow from one life stage to another as a function of local water temperature. SALMOD has been constructed, in part, as a way to integrate habitat limitations to a population through time and space, both microhabitat and macrohabitat. However, SALMOD does not consider elements that may be important in some situations, specifically water quality other than temperature (e.g., heavy metals, low dissolved oxygen).

5.D.2.3 Model Structure

SALMOD is described in detail in Bartholow et al. (1993). This section outlines the model structure. It summarizes the spatial, temporal, and biological resolution and the biological- and physical-state variables simulated in SALMOD.

SALMOD simulates population dynamics for salmonids in freshwater and does not include population dynamics for ocean habitat. SALMOD is a spatially explicit model (Dunning et al. 1995) in which habitat quality and carrying capacity are characterized by the hydraulic and thermal properties of individual mesohabitats, which serve as spatial computational units in the model. The study area is divided into individual mesohabitat types (e.g., pools, riffles, or runs) categorized primarily by channel structure and hydraulic geometry but modified by the distribution of features such as fish cover. Thus, habitat quality in all computational units of a given mesohabitat type changes similarly in response to streamflow variation.

SALMOD is organized around events occurring during a biological year beginning with spawning and typically concluding with fish that are physiologically "ready" (e.g., pre-smolts) swimming downstream toward the ocean. It operates on a weekly timestep for 1 or more biological years. Input variables (e.g., streamflow, water temperature, number, and distribution of adult spawners) are represented by their weekly average values.

SALMOD tracks a population of spatially distinct cohorts that originate as eggs and grow from one life stage to another as a function of local water temperature. The biological characteristics of fish within a cohort are the same. Fish cohorts are tracked by life stage and size class within the spatial computational units. Streamflow and habitat type determine available habitat area for a particular life stage for each timestep and computational unit. Habitat area (quantified as weighted usable area or WUA) is computed from flow versus microhabitat area functions developed empirically or by using PHABSIM (Milhous et al. 1989) or similar physical habitat models. Habitat capacity for each life stage is a fixed maximum number of fish (or biomass) per unit of habitat area available estimated from literature or empirical data. Thus, the maximum number of individuals that can reside in each computational unit is calculated for each timestep based on streamflow, habitat type, and available microhabitat. Fish in excess of the habitat's capacity must seek habitat elsewhere. Fish outside the model domain (from stocking, hatchery production, or tributaries) may be added to the modeled stream at any point in their life cycle.

Biological-state variables describe the characteristics of each cohort within each computational unit by defining the number of eggs or fish, mean weight of fish, mean length of fish, percent egg development (deposition to emergence), number of redds comprising an egg cohort, number of in vivo eggs per ripe spawning female, life stage of cohort, and class within the life stage.

Physical-state variables include streamflow, water temperature, and habitat type. Flow and water temperature are given by multiple data sets for distinct spatial reaches at weekly intervals.

5.D.2.3.1 Key Processes

SALMOD represents the population dynamics during the freshwater life stages of an anadromous fish species that returns to the stream as an adult to spawn. Model processes include spawning (egg deposition), egg and alevin development and growth, mortality, and movement (due to habitat limitation, freshets, and seasonal stimuli). Pre-smolts do not graduate to the smolt stage within the model. Instead, they exit the study area and the population is reinitialized with survey estimates of spawning adults each biological year. Changes in model-state variables are a function of several processes, the order of which is user-defined. Each process is applied to each cohort within all computational units for a single timestep. A brief description of how these processes are modeled in SALMOD is given below.

5.D.2.3.1.1 Spawning

The number of eggs deposited is determined in the model by the following factors: number of female spawners, number of eggs per female spawner, spawning habitat capacity, distribution of spawners through time and space, and water temperature. SALMOD allocates adult spawners to designated segments of the river at the beginning of each simulation year. SALMOD requires the specification of the number of adults spawning in each section of river, the proportion of female spawners to non-spawners, and their weights to "seed" the model. Spawn timing in SALMOD is set to occur regularly within a certain time window. Input to the model includes the proportion of adults ready to spawn each week of the designated period. Spawning is not specifically a function of streamflow or habitat availability, although it does depend on water temperature being within a certain range. The specified proportions will hold unless other factors preclude spawning, such as temperatures being too high, or not enough spawning habitat even with superimposition (creation of new redds on existing redds). When temperatures are too high, the spawners wait until temperatures are favorable for spawning, and when spawning habitat is unavailable, the adults shed their eggs and die.

5.D.2.3.1.2 Fecundity

Fecundity is a simple relationship for the number of eggs per gram of spawning female weight. This relationship is supplied as an input in SALMOD.

5.D.2.3.1.3 Redd Area and Superimposition

SALMOD calculates the amount of spawning habitat required each week for the number of female spawners ready to spawn given the value supplied for the area of an average redd's egg pocket. The model also calculates the probability of redd superimposition for previously constructed and undefended redds (McNeil 1967) by knowing the area occupied by existing redds. SALMOD simulates superimposition using three distinct probability algorithms. The model does not allow superimposition of redds created within the same weekly timestep; in effect, this means that redds are defended for 1 week.

5.D.2.3.1.4 Egg Development and Juvenile Growth

Growth rate of individuals in cohort is a user-specified function of local water temperature. For egg cohorts, development rate is a temperature-dependent additive increment until emergence. For nonegg cohorts, growth rate is a temperature-dependent value that varies with fish size.

5.D.2.3.1.5 Egg Development Rate

After deposition, eggs incubate and hatch in approximately 6 to 12 weeks depending on local river temperatures. Alevins remain in the gravel for an additional period, living off the still-attached yolk sac and emerge when accumulated development is 100%. An egg cohort that reaches 100% development is assumed to emerge during a single timestep and is assigned immediately to the fry stage with a user-specified mean weight and length.

5.D.2.3.1.6 Juvenile Growth Rates

In SALMOD, growth rate is solely a function of mean weekly water temperature and is based on a relationship between percent growth per day and temperature. SALMOD allows growth only for juveniles not forced to move with an assumption that energy is preferentially expended by movers searching for new territory and is not available for growth. In contrast, SALMOD allows growth during volitional seasonal downstream movement. Fish growth is computed from changes in weight. Length is estimated from an empirical weight to length relationship. However, if fish lose weight, their length remains the same and fish must regain lost weight before there is growth in length. The non-egg cohorts graduate to a new stage or size class when their mean length reaches the upper limit specified for their current size class.

5.D.2.3.1.7 Mortality

SALMOD accounts for mortality caused by both continuously acting and discrete causes. Continuously acting causes include base mortality, temperature-related mortality, and population density-related mortality (movement due to habitat constraints). Discrete causes include mortality due to redd superimposition and movement caused by sudden increase in streamflow (freshet). Mortality rates are user-defined and may be included or excluded for any life stage.

5.D.2.3.1.7.1 Base Mortality

Base or background mortality rates cover all causes of death not otherwise modeled by SALMOD. For example, “normal” or “background level” predation, disease, mortality due to chronically low dissolved oxygen egg survival and unscreened diversions are included in this category. The user specifies the weekly fractional mortality rates for the fish in various life stages.

5.D.2.3.1.7.2 Thermal Mortality

Water temperature is considered a direct source of mortality independent of food supply, predation, and other causes of mortality. Thermal effects on salmon include: (1) physiological changes, including direct or indirect mortality, growth rate, embryonic development, and susceptibility to parasites and disease; (2) behavioral changes, including seeking special habitats such as thermal refugia, altering feeding activity, shifting spatial distributions, and altering species interaction; (3) changes to periodicity, including duration of incubation, onset of spawning, onset of migration, and gonad maturation; and (4) interaction with other water quality constituents, including dissolved oxygen. These thermal effects are not explicitly modeled in SALMOD, but implied in the weekly fractional mortality rates as a function of temperature.

Thermal mortality values for SALMOD reflect 7-day exposure-related effects of water temperature. Acute mortality is generally defined as mortality resulting from exposure of up to 96 hours. However, SALMOD’s 7-day (168-hour) timestep encompasses both acute and longer-term (chronic) mortality. SALMOD uses mean weekly water temperatures instead of maximum daily temperatures because chronic, sub-lethal temperatures are often more significant than acute lethal temperatures, with the effects being both cumulative and positively correlated with the duration and severity of exposure (Ligon et al. 1999). Sub-lethal effects are also associated with sub-optimal growth rates, reduced swimming performance and associated predation, increased disease risk, and impaired smoltification (USEPA 2003; Marine and Cech 2004).

SALMOD computes thermal mortality for each life stage: egg and alevin, fry, juvenile, and adult. There is also a special in vivo category for eggs inside female spawners. Literature suggests that exposure of eggs to high temperatures in vivo may not directly kill the eggs, but rather result in unviable fry that have high mortality. SALMOD, however, calculates in vivo mortality as if it occurred pre-spawn. Note that in vivo egg mortality is calculated independently of other adult mortality. Also, note that when an adult female dies, her eggs also die. Similar to base mortality, the user specifies the weekly fractional mortality rates for the fish in various life stages.

5.D.2.3.1.7.3 Seasonal Movement and Associated Mortality

SALMOD moves juveniles that have reached a specified life stage or size class a specified distance downstream through a specified period. The assumption is that these fish are physiologically ready and that some combination of external timing cues (e.g., water temperature, streamflow) triggers the downstream volitional movement of (pre)smolts (McDonald 1960; Bjornn 1971). SALMOD requires user-specified values for proportion moved, distance moved, and associated mortality rate. Note that SALMOD does not adjust movement distance based on the river's streamflow, although this effect has been documented for the Columbia and Snake Rivers (Berggren and Filardo 1993). This is an area of potential improvement in the model, although reasonable estimates of travel time are needed relative to streamflow for the juvenile life stages. Movement rates found by Berggren and Filardo (1993) are not applicable because in that study, movement rates were computed for fish moving through impoundments.

5.D.2.3.1.7.4 Movement due to Habitat Constraints and Associated Mortality

In SALMOD, movement resulting from habitat limitations occurs when the biomass exceeds the available habitat capacity. Partial or entire cohorts are moved sequentially from one computational unit to another. Within a life stage, cohorts are moved starting with the smaller size classes. Cohorts that have recently moved tend to move again when faced with habitat constraints (Bartholow et al. 1993). Mortality related to habitat movement depends on life stage, size class, and the cumulative distance moved. This mortality is not a weekly rate; instead, a rate is applied for each movement step. For the n^{th} movement step, the cumulative distance moved is used to compute the mortality rate.

5.D.2.3.1.7.5 Freshet Movement and Associated Mortality

Freshets, sudden increases in streamflow, have been associated with displacement of fry in some rivers (Godin 1981; Irvine 1986; Saltveit et al. 1995). It is not clear whether such displacement is due to volitional movement, is involuntary, or is a combination of the two. Nor is it clear whether the stimulus is streamflow, turbidity, temperature, or some combination. Note that a water temperature "signal" may not occur in regulated rivers immediately downstream from sizable impoundments. SALMOD has three options for defining a freshet: (1) when the current timestep flow is greater than or equal to twice the previous timestep flow *or* is greater than or equal to twice the average of the three previous timestep flows; (2) when the current timestep flow is greater than or equal to twice the previous timestep flow *and* is greater than or equal to twice the average of the three previous timestep flows; (3) user specified in the *Flow.Dat* input file. SALMOD can displace juvenile life stages according to user-specified parameters governing the proportion of fish moved per weekly period, the distance they are displaced downstream and associated mortality.

5.D.2.3.1.7.6 Mortality Associated with Redd Superimposition

Redd superimposition destroys redds wholly or partially and causes direct egg mortality. Redds are only superimposed if the entire spawning habitat in the computational unit has been used and the number of redds superimposed is the number of redds created by the current cohort in excess of the available redd space. The reduction in the number of previously constructed redds and accompanying egg mortality from superimposition is computed by assuming that all redds are equally likely to be destroyed. Therefore, losses to previous cohorts occur in proportion to their redd abundance.

Egg and alevin mortality due to reductions in redd numbers occurs if incubation habitat declines from what was available at the time of spawning. If flows decrease over time, previously constructed redds may be dewatered, and if flows increase, previously constructed redds may be scoured out. Spawning and incubation habitat are directly related to one another, as functions of flow, and a reduction in spawning habitat will correspond to a reduction in incubation habitat, causing mortality. Note that because flow changes may shift the physical location of suitable spawning areas, SALMOD may incorrectly estimate superimposition mortality depending on the model chosen and the temporal pattern of habitat fluctuations.

5.D.2.4 Documentation

Extensive literature is available documenting the SALMOD model and its applications, including project reports, journal publications, and other environmental documentation. This section summarizes a few key publications. The documents and reports are separated into three categories as described below.

5.D.2.4.1 SALMOD General Development and Use

Williamson et al. (1993), Bartholow et al. (1993), and Bartholow et al. (2001) describe the objectives and concepts behind SALMOD development, the key processes that SALMOD can simulate, the computational engine, and usage of the model.

5.D.2.4.2 SALMOD General Applications

Bartholow et al. (1993) and Bartholow (1996) describes the application of SALMOD to simulate Chinook salmon population in the Trinity River. Most of the initial development of SALMOD occurred during this application. Further, most of the mortality and growth rates developed in the Trinity River application were carried forward and refined for other Chinook salmon applications. Bartholow and Henriksen (2006) describe the application of SALMOD to model the Klamath River Chinook salmon population.

5.D.2.4.3 SALMOD Sacramento River Specific Applications

Kent (1999) developed the first application of SALMOD for fall-run Chinook salmon in the upper Sacramento River from Keswick Dam to Battle Creek. Bartholow (2003 and 2005) further refined this application and extended the application to late-fall-, winter-, and spring-run Chinook. Another Sacramento River application as part of the Shasta Lake Water Resources Investigation Plan Formulation Report (USBR 2006) extended the downstream boundary from Battle Creek to the inundation pool of the Red Bluff Diversion Dam. The model developed for SLWRI PFR was applied in the assessment of the North-of-Delta Offstream Storage Plan Formulation Report alternatives.

5.D.2.4.4 Rationale for Approach in the Context of Management Objectives

SALMOD can improve the understanding of the linkage between habitat dynamics and smolt growth, movement, and survival. It can quantify the impacts of flow and temperature regimes of alternatives on annual production potential. SALMOD can illustrate the differences among water year types. SALMOD can identify the optimal conditions in terms of habitat, flow, and temperature for attaining maximum growth and production. However, sufficient care should be taken while assessing alternatives that include processes not explicitly modeled in SALMOD or that need changes to the assumed parameters and data. Alternatives that include reduced diversions or improvements to rearing habitats are a few examples.

Metrics such as annual production potential, annual mortality, and length and weight of the smolts help address management-oriented questions. The production numbers obtained from SALMOD are best used as an index in comparing to a specified baseline condition rather than absolute values.

5.D.2.4.5 Reliability and Acceptability of Approach

As described in the previous sections, SALMOD has been applied to several river systems. It was applied to the Sacramento River in three efforts. The data and parameters for the Sacramento River were well refined in these applications. SALMOD model and its applications are published in many peer-reviewed journals. However, no formal peer-review process was undertaken at the time of this documentation effort.

Models like SALMOD are attaining confirmation in scientific literature. For example, Capra et al. (1995) demonstrated that spawning habitat availability reductions over continuous 20-day periods correlate well with production of age 0+ trout. Building on Capra’s work, Sabaton et al. (1997) and Gouraud et al. (2001) have further explored the field of limiting factors, both microhabitat and macrohabitat, by using population models similar to SALMOD, with promising results.

5.D.2.4.6 Quality Assurance and Data Quality Assessment

At present, this information is unavailable.

5.D.2.4.7 Corroboration

At present, this information is unavailable.

5.D.2.4.8 Assumptions/Limitations

Assumptions and limitations of SALMOD include the following:

1. The habitat quantification as a function of streamflow is reasonably accurate.

2. The habitat quantification as a function of streamflow is static. That is, none of the flow options considered result in changes to the channel geometry or substrate composition (gravel quantity or quality) that may actually occur as a result of reservoir flood releases or minimum flows.

3. The juvenile rearing criteria are identical between pre- and immature smolts, an assumption supported by Hoffman and Deibel (1984), though they did note some differences.

4. SALMOD may be inappropriate in situations where the number of spawners is small. SALMOD relies on treating many rate values (e.g., base mortality) as average values. When the number of fish in each cohort is small (fewer than 500), random events (attributable to either environmental stochasticity or individual fish variability) not captured by the model can play a larger role in survival than what SALMOD "expects."

5.D.2.4.9 Planned Future Development

There are no planned future development activities for SALMOD at the time of this documentation effort, according to the developers of the model.

5.D.2.5 Application

5.D.2.5.1 System Boundaries (Spatial, Temporal and Biological Domain)

5.D.2.5.1.1 Study Area

The study area for this Sacramento River application covers an 85-kilometer (km) (53-mile) stretch of the Sacramento River from Keswick Dam to just upstream from the Red Bluff Diversion Dam (RBDD) at latitude of approximately 40.5°N (Figure 5.D.2-1). Keswick Dam forms the current upstream boundary of anadromous migration in the Sacramento River, and the RBDD marks the current downstream limit of habitat that has been consistently classified by mesohabitat type and evaluated using PHABSIM or a similar tool. The study area terminates at this point because the RBDD gates alter the inundation pool's hydraulics; thus, the pool has not been modeled for habitat value.

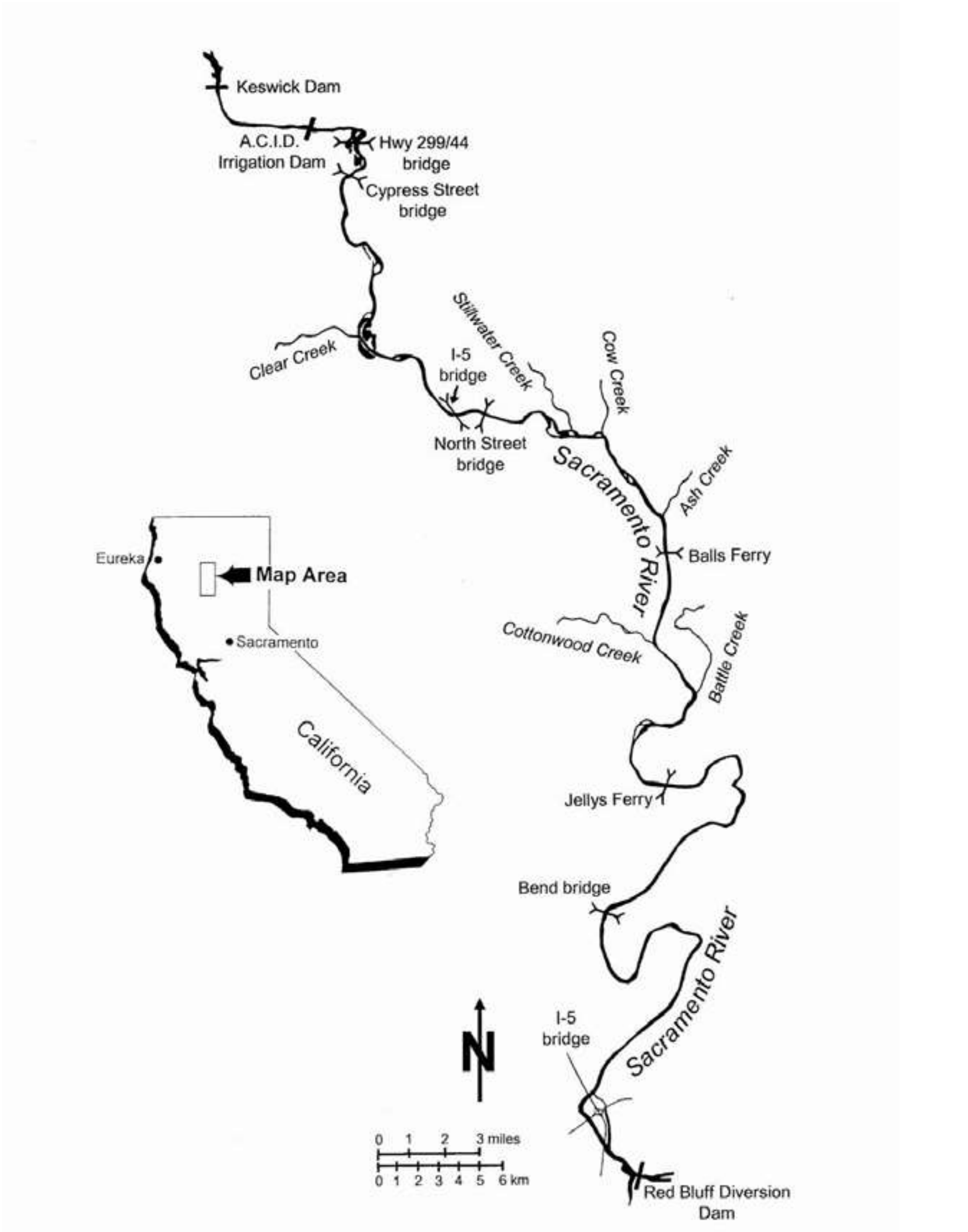


Figure 5.D.2-1. Study Area

5.D.2.5.2 Modeled Salmon Species

For the Sacramento River, the following four runs of Chinook salmon are of concern, each with different life-history timing: fall, late-fall, spring, and winter. In assessing the impacts of alternative flows and water temperatures to the four runs of salmon, it is assumed that they do not use, or compete for, the same microhabitat at the same time. Therefore, four SALMOD data sets were constructed, each with different simulation timing and each uniquely named.

5.D.2.5.3 Biological Year Timing

Sacramento River Chinook salmon life-history timing is illustrated in Figure 5.D.2-2 (Vogel and Marine 1991). The data from Figure 5.D.2-2 become the fixed timing template for SALMOD's treatment of each run's biological year. It is also assumed that most of the juveniles of each run will emigrate as ocean-type Chinook salmon (migrate to the ocean during their first year) if they are physiologically ready.

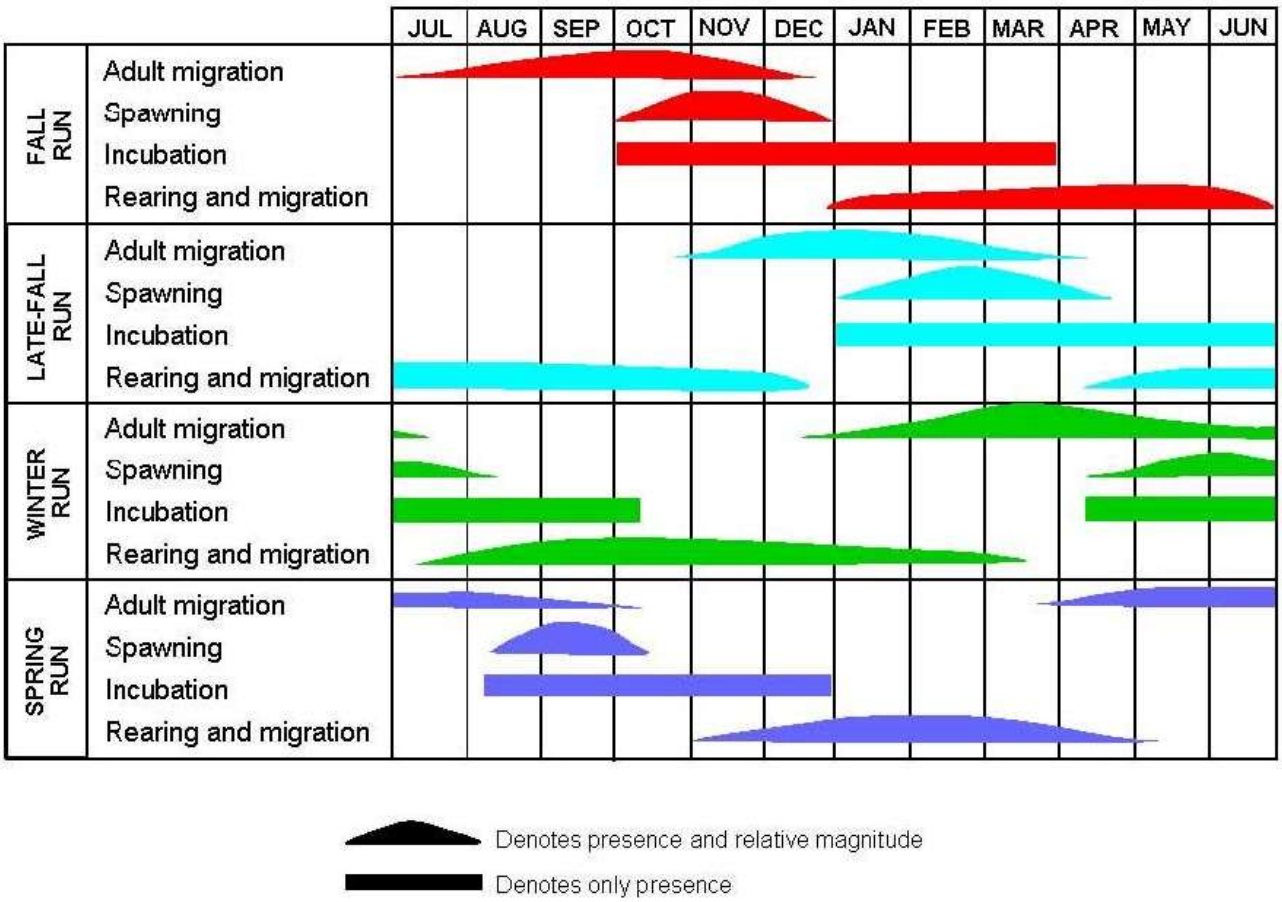


Figure 5.D.2-2. Approximate Timing of Various Runs of Chinook Salmon

5.D.2.5.4 Important Length, Time, and Biological Scales

5.D.2.5.4.1 Computational Units

Microhabitat refers to the collection of physical characteristics (depth, velocity, substrate, cover) that determine suitability of a given river's "space" for fish of a given life stage (e.g., adults, juveniles), essentially on a square meter or finer scale.

By contrast, mesohabitat refers to larger channel forms such as riffles, pools, or runs that respond similarly to changes in flow. One of SALMOD's inputs is a description of mesohabitats for the study area. This list is arranged from upstream to downstream and tabulates the sequence of mesohabitat types and their length. Each habitat in the list becomes a computational unit for the SALMOD model. The list ends with a table giving the longitudinal boundaries of where flows and water temperatures change in the model, referred to as segments. Although the flows and temperatures are supplied as separate input files, the list at the end of the habitat sequence denotes which computational units belong to which flow and temperature segments.

The habitat description developed by Kent (1999) extended from Keswick Dam to Battle Creek. Subsequently, the U.S. Geological Survey (USGS) contracted with the U.S. Fish and Wildlife Service (USFWS) Sacramento office to extend the mesohabitat description from Battle Creek to the inundation pool of created by the RBDD. The inundated habitat within the inundation pool has not been satisfactorily measured hydraulically, and the flashboards are in place only intermittently. Thus, the study area terminated at the downstream end of the free-flowing river.

A given river reach may have been typed in such a manner that a given habitat type only covered one-half of the river's width, while the other one-half was another habitat type. Areas around islands were often mapped as complex habitat mosaics. For those segments containing habitat mosaics, a multistep process was used to divide the reach into sequential computational units. The total area for the reach was computed as the sum of the habitat areas for all constituent polygons. The length of each computational unit was computed as the ratio of the habitat polygon's area to the reach area times the total reach length. Computational units were ordered according to the upstream to downstream position of their respective habitat polygons. Side channels were treated as if they were internal to the river reach and added as sequential computational units. In total, 61 computational units were created from the original 56 habitat polygons, covering 22.27 miles of the river. This process preserves each unique habitat type and reflects the diversity of habitats available and their approximate length. However, it does not reflect the true complexity around islands and may not reflect the exact sequence of habitat types encountered by a migrating salmonid. For example, if a juvenile took a right-channel path around an island, the habitat types encountered would be different from those experienced by a juvenile taking the other channel.

Flow and temperature segments were developed from Reclamation's HEC-5Q model application and reflect approximate locations where tributaries are accounted for or other "compliance" points. Within each segment, flows and temperatures are assumed homogeneous. The Anderson-Cottonwood Irrigation District (A.C.I.D.) diversion is a major diversion within the study area. Balls Ferry, Jellys Ferry, and Bend Bridge are temperature compliance points on the Sacramento River. Table 5.D.2-1 was used to develop estimates of river kilometers to assign the flow and water-temperature segment boundaries. These distances were compared with delineated computational unit boundaries. Some of the computational units were split in two so that the flow and temperature segment boundaries approximately coincided with computational unit boundaries.

Finally, all computational units greater than 500 meters long were split so that the maximum length of any computational unit was 500 meters. In total, the stream habitat description resulted in 279 computational units from Keswick Dam to the Red Bluff inundation pool (approximately 85 km [53 miles] in length) where the stream description was truncated.

Table 5.D.2-1. Flow and Water Temperature Segmentation for this Study Area

Segment Number	Length (miles)	Flow and Temperature Segments
1	3.5	Keswick Dam to A.C.I.D. Diversion Dam
2	2	A.C.I.D. Diversion Dam to Hwy 299/44 Bridge
3	7.5	Hwy 299/44 Bridge to Clear Creek
4	4.5	Clear Creek to Churn Creek
5	4.4	Churn Creek to Cow Creek
6	2.8	Cow Creek to Bear and Ash Creeks
7	1.1	Bear and Ash Creeks to Balls Ferry Bridge
8	2.7	Balls Ferry Bridge to Anderson Creek
9	0.5	Anderson Creek to Cottonwood Creek
10	1.7	Cottonwood Creek to Battle Creek
11	4.8	Battle Creek to Jellys Ferry Bridge
12	5.8	Jellys Ferry Bridge to Bend Bridge Gage
13	7.4	Bend Bridge Gage to Paynes Creek
14	10.3	Paynes Creek to Red Bluff Diversion Dam

5.D.2.5.5 Assigning Habitat Descriptions to Computational Units

In SALMOD, each mesohabitat must have a corresponding estimate of the amount of weighted usable area, or WUA, an index to suitable microhabitat, available throughout a range of flows for each life stage. Kent (1999) had compiled estimates of WUA for fall-run Chinook salmon for each mesohabitat type from hydraulic data collected in a 1990s study by the California Department of Water Resources (DWR), but updated them to include new habitat suitability criteria from USFWS. Bartholow (2003) expanded Kent's analysis to include the other three runs. The scheme that Kent developed was slightly modified by Bartholow (2003). New information regarding which computational units did or did not appear to support spawning and a limited amount of run-specific spawning WUA estimates were included, both with the assistance of Mark Gard (USFWS, Sacramento). The result was a tri-part naming scheme for each computational unit that includes habitat type and subtype and an indicator of spawning or no spawning. Inspection of USFWS (2005a and b) reveals that there is not likely to be much difference in at least the qualitative shape of the WUA relative to streamflow curves for other life stages. However, this approach may not have captured the correct amount of habitat available in this segment. It was assumed that all computational units with spawning habitat were spawnable.

5.D.2.5.6 Microhabitat (WUA) Estimates for SALMOD

Weighted usable area for spawning in the Sacramento River peaks at relatively low flows (~2,000 to 5,000 cubic feet per second [cfs]). If flows exceed this range and WUA decreases, SALMOD predicts bed scour. However, true bed scour is unlikely until high flows are encountered. Some redd dune movement may occur and entomb egg pockets even with flows up to 5,000 cfs by moving surface materials over the tops of redds, affecting their hydraulic conditions and potential survival. Unlike previous applications of SALMOD, where the egg incubation habitat was assumed identical to spawning habitat, egg incubation WUA was derived directly from the estimated spawning WUA by retaining the rising limb of the spawning curve with increasing streamflow, but then holding the maximum WUA value constant with increasing flow. This is equivalent to keeping the eggs wet regardless of depth. Because the Sacramento River channel is generally large, bed scour is assumed to be above 50,000 cfs given gravel displacement and the significant bed-changing events above 60,000 cfs. The maximum WUA value was truncated when flows exceed 50,000 cfs, linearly reducing the habitat value to zero at 60,000 cfs because of increasing probability of redd-destroying bed scour or entombment. Zero habitat above 60,000 cfs assumes that redd scour or entombment causes 100% egg mortality. Note that SALMOD's weekly timestep may underestimate the frequency of scour from daily peak flow events, especially if those flows were derived from the CalSim II monthly flow model using a daily disaggregation process.

5.D.2.5.7 Simulation Period and Computational Timestep

The simulation period for this application was 80 biological years (1923 to 2002). Each biological year is independent and is initialized with same number of fish at the beginning of every year. As noted previously, SALMOD is a weekly timestep model. SALMOD has a fixed timing template for the model's treatment of each run's biological year. Based on Figure 5.D.2-2, the weekly timestep was identified corresponding to the start of the biological year for each of the four runs of Chinook salmon (Table 5.D.2-2). Simulation timesteps referenced in SALMOD's input files are simply by chronological week number. Note that simulation processes are initiated on the first day of the week, but simulation results are tabulated on the last day.

Table 5.D.2-2. Correspondence between SALMOD Weekly Timestep and start of the Biological Year for each of the Four Runs of Chinook Salmon

Simulation week	Fall Run	Late-Fall Run	Winter Run	Spring Run
1	2-Sep	3-Dec	4-Feb	6-May

5.D.2.5.8 Life Stage Categorization

The naming of life stages and size classes is flexible in SALMOD and generally reflects the nomenclature used by the local biologists. The egg class covers both eggs and in-gravel alevins (larvae or pre-emergent fry) with a developmental index roughly dividing the two equally in time. Smolts are referred to as immature solely because these fish may be of a size indicative of a smolt but are not yet tolerant of saltwater, and they are still many kilometers from the ocean. Table 5.D.2-3 lists the class attributes chosen for the Sacramento River and is a modification of the categorization used on the Trinity and Klamath Rivers.

Table 5.D.2-3. Life Stage and Size Class Naming and Break Points

SALMOD Life Stage	Other Names for Life Stage	Development Index (0 to 1.0) for Eggs, Length Class (mm) for Juveniles		
			Min	Max
	Eggs		0.0	0.6
	Alevins		0.6	1.0
Fry	Yolk-sac fry	F1 =	30	40
	Fry	F2 =	40	60
Pre-smolts	Parr	P1 =	60	70
	Silvery parr	P2 =	70	80
		P3 =	80	100
Immature smolts	Smolts	S1 =	100	150
		S2 =	150	200
		S3 =	200	269

5.D.2.6 System Characteristics

5.D.2.6.1 Spawning

5.D.2.6.1.1 Spawner Characteristics

SALMOD requires the specification of the number of fish and attributes of adults such as weight for male and female fish and sex ratio to “seed” the model. A sex ratio of 48% spawning females to all other returning adults or grilse is assumed.

5.D.2.6.2 Fecundity

SALMOD uses a simple relationship for the number of eggs per gram of spawning female weight. Kent (1999) used the ratio from the records of the Coleman National Fish Hatchery Lot History Reports from the hatchery’s annual reports for fiscal years 1970 to 1997. This value is currently scaled to 5,000 eggs for a 12-kg fish. It is assumed Kent was referring to fall-run Chinook salmon. The National Marine Fisheries Service (NMFS) (no date) has noted that winter-run Chinook salmon have a lower fecundity (average of 3,353 eggs per female) than most other Chinook salmon populations, including Central Valley fall-run Chinook salmon (average of 5,498 eggs per female). Because of this potentially lowered reproductive potential, winter-run fecundity was reduced to 60% of that of the other runs.

5.D.2.6.3 Redd Area and Superimposition

A female spawner typically excavates multiple egg pockets by repeatedly digging in an upstream direction and depositing newly swept material on top of downstream egg pockets; the total area of disturbance may be more than 10 square meters (m^2) (Neilson and Banford 1983). However, input values to SALMOD specify the approximate area of only the egg pockets for its calculation of superimposition mortality. The egg pocket refers to that area where deep streambed disturbance is at a maximum, indicative of essentially complete destruction of previously deposited eggs. The egg pocket area is typically much smaller than the total area of disturbance.

Bartholow (2003) chose a value of 4.5 m^2. SALMOD can simulate superimposition by using three distinct probability algorithms. For this application, the "avoidance" option was selected to reduce the assumed redd egg pocket area to 2 m^2 in deference to California Department of Fish and Wildlife's (CDFW's) concerns. These changes, in effect, allow more spawners to use the same amount of spawning habitat with less superimposition.

5.D.2.6.4 Spatial and Temporal Distribution of Spawners

SALMOD allocates adult spawners to designated segments of the river at the beginning of each simulation year; these segments may be defined differently from the flow and temperature division points described previously. The values in Table 5.D.2-4 were used to seed the study area for each simulation year, distinguishing the effects of flow and water temperature, as opposed to escapement, in estimating salmon production. Note that the spatial distribution of spawners is assumed essentially the same with higher spawner numbers as it has been in the recent past with lower returns. Assumptions of the spawning distributions were based on average 2003–2014 redd survey data, provided by David Swank at NMFS in April 2015.

Table 5.D.2-4. Assumed Distribution of Spawners in Eight Spawning Segments of the Study Area

Spawning Segment Number	Description	Cumulative Distance from Keswick (meters)	Spawning Distribution (%)			
			Fall	Late-Fall	Winter	Spring
1	Keswick to A.C.I.D.	5,791	19.50%	71.30%	45.10%	12.83%
2	A.C.I.D to Highway 44 Bridge	9,025	6.60%	5.20%	42.10%	33.97%
3	Highway 44 Br. to Airport Road Bridge	28,810	14.70%	3.90%	12.20%	29.76%
4	Airport Road Br. to Balls Ferry Bridge	41,411	19.40%	8.90%	0.30%	11.12%
5	Balls Ferry Bridge to Battle Creek.	49,207	12.50%	5.90%	0.10%	7.41%
6	Battle Creek to Jellys Ferry Bridge	56,538	15.20%	3.10%	0.10%	1.50%
7	Jellys Ferry Bridge to Bend Bridge	71,413	8.00%	1.20%	0.10%	2.61%
8	Bend Bridge to Red Bluff inundation zone	84,828	4.20%	0.60%	0.00%	0.80%
	Totals		**100.0%**	**100.0%**	**100.0%**	**100.0%**

Note:
It was assumed that there were no redds in the Red Bluff inundation zone

The model is provided with the proportion of adults ready to spawn each week of the designated period (Figure 5.D.2-3). These proportions will hold unless other factors preclude spawning, such as temperatures being too high (they wait) or not enough spawning habitat even with superimposition (the adults shed their eggs and die). Updated assumptions of the temporal distribution of winter-run spawners based on average 2003–2014 redd survey data, provided by David Swank at NMFS in July 2015.

Given that the updated temporal distribution of the winter-run spawners extends the spawning season for the winter-run, the durations of some of the key SALMOD processes were updated for winter-run. The processes for which the durations were modified are listed below:

- Carry: week 1 to week 29
- Spawn: week 13 to week 29
- Invivo Mortality: week 1 to week 29
- Habitat Movement for fry, presmolts and immature smolts: week 27 to week 52

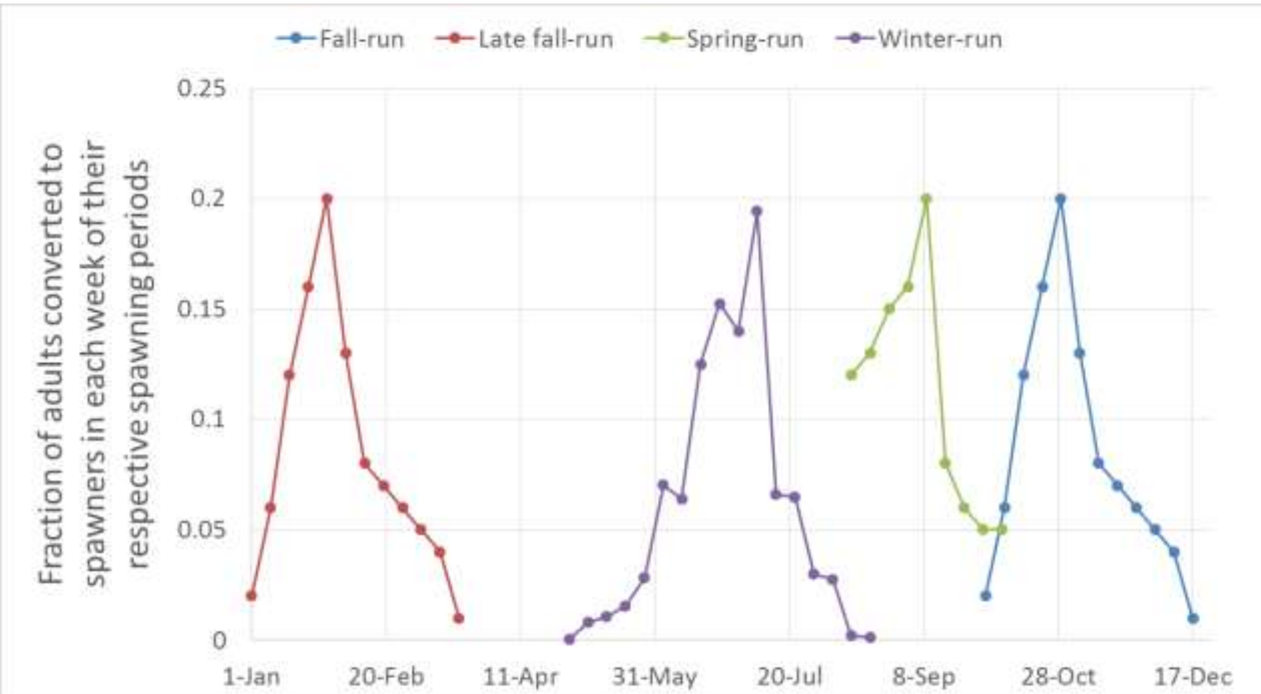


Figure 5.D.2-3. Fraction of Adults Converted to Spawners in each Week of their Respective Spawning Periods

5.D.2.6.5 Egg Development and Juvenile Growth

5.D.2.6.5.1 Egg Development Rate

A quadratic equation was used to calculate each day's thermal contribution from deposition to hatch (Crisp 1981). The resulting rate values were decreased to 60% to approximate the time from hatch to emergence (a slight modification of Crisp 1988), as used by Bartholow (2003). The resulting rate function supplied to SALMOD is shown in Figure 5.D.2-4. This function shows that eggs will mature more rapidly at 10°C (50°F) than at 2°C (35.6°F). Note that thermal accumulation begins with egg deposition and does not account for ova maturation in vivo.

5.D.2.6.6 Minimum Emergence Temperature

The minimum emergence temperature for egg-alevin was set to 6°C (42.8°F). SALMOD has no upper temperature threshold. If temperatures are too hot, fry will die.

5.D.2.6.6.1 Emergent Length

Eggs incubate after deposition and hatch after 6 to 12 weeks, depending on water temperatures. The average weight of a fry on emergence from the gravel is 0.275g, given by Kent (1999), which is equivalent to a 34-mm fish. Bartholow (2003) imposed a ± 4-mm deviation from this initial value, estimated from data shown in Vogel and Marine (1991), and this value is used for this application.

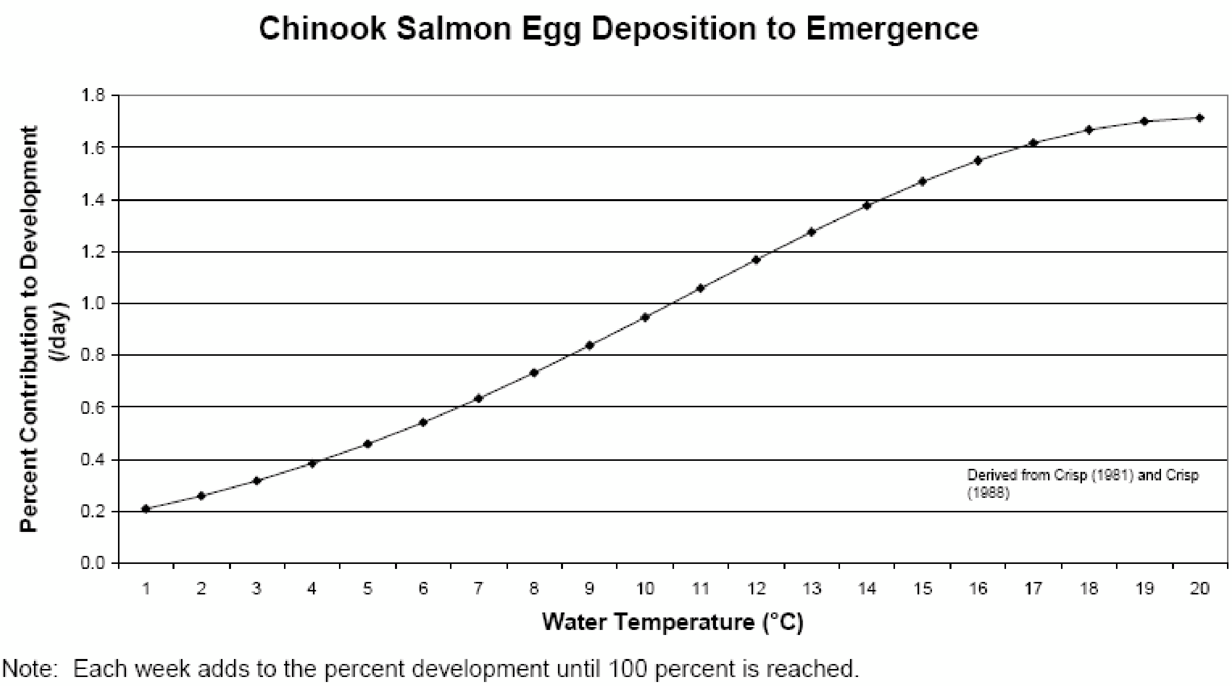
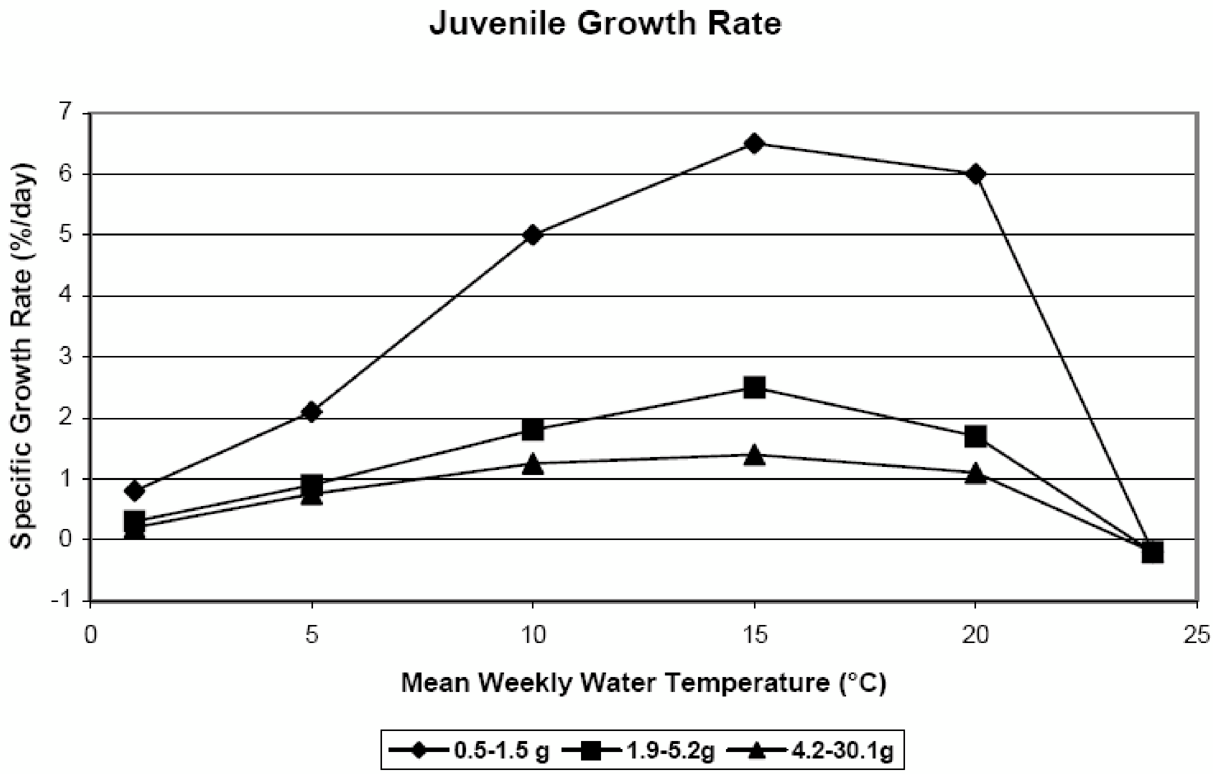


Figure 5.D.2-4. Egg and Alevin Development Rate as a Function of Mean Weekly Water Temperature

5.D.2.6.7 Juvenile Growth Rates

Growth as a function of water temperature for juvenile life stages was obtained from Shelbourne et al. (1973). Note that this function (Figure 5.D.2-5) assumes a constant food supply with juveniles fed to excess. The weight-to-length relationship is used in SALMOD to convert from one metric to the other. Fish grow in body mass (weight) and are then assigned the appropriate length. The weight:length relationship supplied to SALMOD for the Sacramento River is detailed in Table 5.D.2-5.



Note: Values are from Shelborne et al. (1973).

Figure 5.D.2-5. Juvenile Growth Rate for Different Weight Fish (grams) as a Function of Mean Weekly Temperature

Table 5.D.2-5. Weight-to-Length Relationship for Sacramento River Fall-Run Chinook Salmon

Weight (g)	Fork Length (mm)	Weight (g)	Fork Length (mm)	Weight (g)	Fork Length (mm)
1.112	48	5.663	80	40.1	150
1.275	50	6.839	85	92	200
1.742	55	8.17	90	310.5	300
2.3	60	9.667	95	1,437.5	500
2.961	65	11.34	100	3,944.5	700
3.734	70	15.258	110	5,888	800
4.632	75	20.008	120	12,000	900

5.D.2.7 Mortality

5.D.2.7.1 Base Mortality Rates

The weekly base mortality rates used in this application were eggs, 0.035; fry, 0.025; pre-smolts, 0.025; immature smolts, 0.025; and adults, 0.002. The fractional rates used came from the calibrated Trinity River model and are identical to those used previously on the Sacramento River (Bartholow 2003).

5.D.2.7.2 Thermal Mortality Rates

5.D.2.7.2.1 Egg-Alevin Thermal Mortality Rates

Reclamation (USBR 1991) evaluated the effectiveness of adding temperature control to Shasta Dam on the Sacramento River by developing a salmon mortality model parameterized with values supplied by USFWS. These mortality values provided the basis for egg and embryo (including in vivo egg) mortality rates used in SALMOD. Instantaneous weekly in-gravel egg mortality rates for SALMOD were computed based on the average daily mortality rates reported by Richardson and Harrison (1990). The mortality rates used for eggs and sac fry (embryos) by Richardson and Harrison (1990) were averaged to be consistent with the combined life history simulated in SALMOD for the Sacramento River.

5.D.2.7.2.2 In Vivo Egg Mortality Rates

In previous model applications, SALMOD was parameterized using an in vivo mortality rate as a function of water temperature identical to the rate used for in-gravel eggs. In this application, it is assumed that the in-gravel egg thermal mortality rates still apply for in vivo eggs; however, the adults are behaviorally capable of buffering themselves (and their eggs) from the warmest in-river temperatures. The study by Berman and Quinn (1991) demonstrated that adult spring-run Chinook salmon could maintain an average internal body temperature 2.5°C (4.5°F) below ambient river temperatures through a combination of specific cool-water habitat selection and behavioral timing. For lack of any other value, the 2.5°C (4.5°F) difference found by Berman and Quinn (1991) for the Yakima River in Washington was used to correct the specified in-gravel temperatures. In other words, the model treats an ambient water temperature of 17.5°C (63.5°F) as if it were only 15°C (59°F) for in vivo eggs in calculating thermal mortality.

5.D.2.7.2.3 Juvenile and Adult Thermal Mortality Rates

Thermal mortality rates for juvenile and adult life stages were derived from Baker et al. (1995) who used coded-wire tag data to conclude that hatchery-raised fall-run Chinook salmon migrating through the Sacramento-San Joaquin Delta had an upper incipient lethal temperature (LT50) of 23.01±1.08°C (73.4±1.9°F). However, as has been discussed for in vivo eggs, adults may also be buffered from ambient thermal mortality. To be consistent with the in vivo mortality compromise, adults are buffered using the same 2.5°C (4.5°F) value. The mortality curves used in this application are shown in Figure 5.D.2-6. Note that mortality values for in vivo eggs and adults shown in Figure 5.D.2-6 have been shifted to the right by 2.5°C.

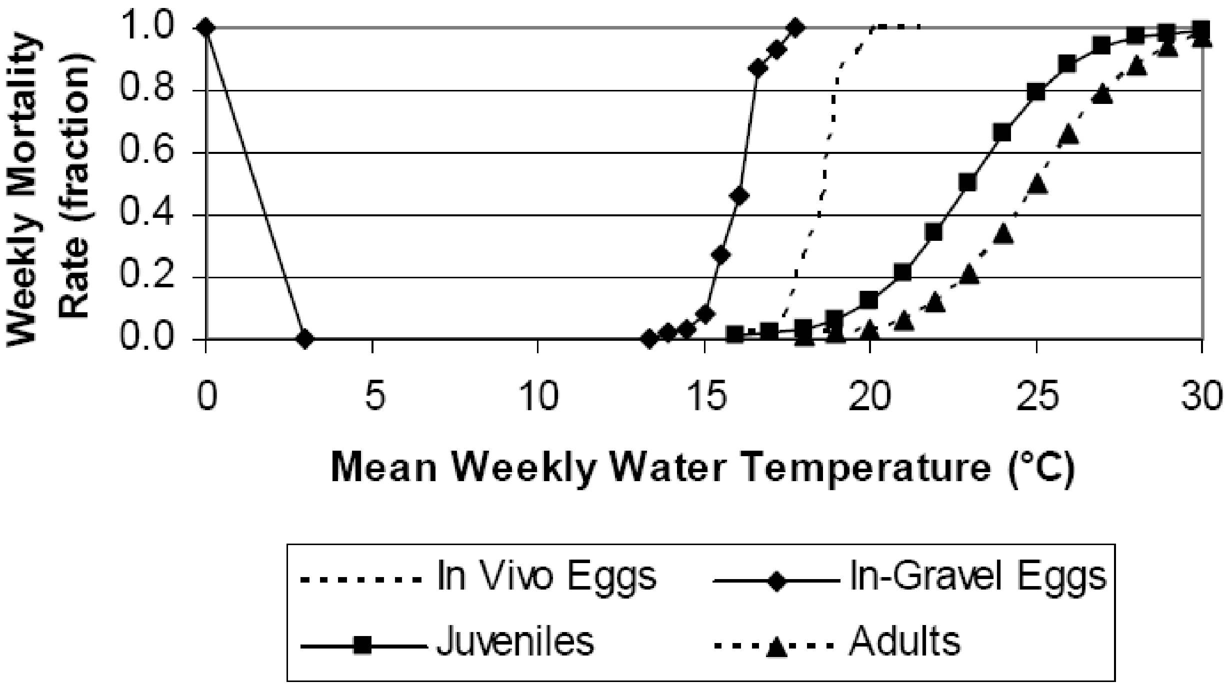


Figure 5.D.2-6. Fall-Run Chinook Thermal Mortality as a Function of Mean Weekly Water Temperature used in SALMOD Simulations

5.D.2.7.3 Movement and Associated Mortality

5.D.2.7.3.1 Freshet Movement

Due to the lack of direct evidence for movement induced by freshets in the Sacramento River, freshet movement is not simulated.

5.D.2.7.3.2 Seasonal Movement Timing and Attributes

Bartholow (2003) used Vogel and Marine's (1991) timing chart to estimate times for the bulk of outmigration for pre-smolts and immature smolts (not fry) of each run. However, it was found that under many circumstances, with the large number of adult spawners and generally cool water temperatures, too many fry (less than 60 mm) could remain in the study area even after 52 weeks of the biological year. For this reason, in the current application, the outmigration period was extended throughout the biological year, as shown in Table 5.D.2-6. Through the outmigration period, the proportion of each life stage actively moving is assumed to increase through time from 30 to 95%, while the corresponding mortality rate associated with this movement is assumed to decrease through time from 1.5 to 1%, as shown in Figure 5.D.2-7. The maximum distance moved by pre- and immature smolts in different size classes is listed in Table 5.D.2-7.

Table 5.D.2-6. Timing of Outmigration for Pre-Smolts and Immature Smolts

Run	Time period
Fall	27-May to 26-August
Late-fall	26-August to 26-November
Winter	29-October to 28-January
Spring	28-January to 29-April

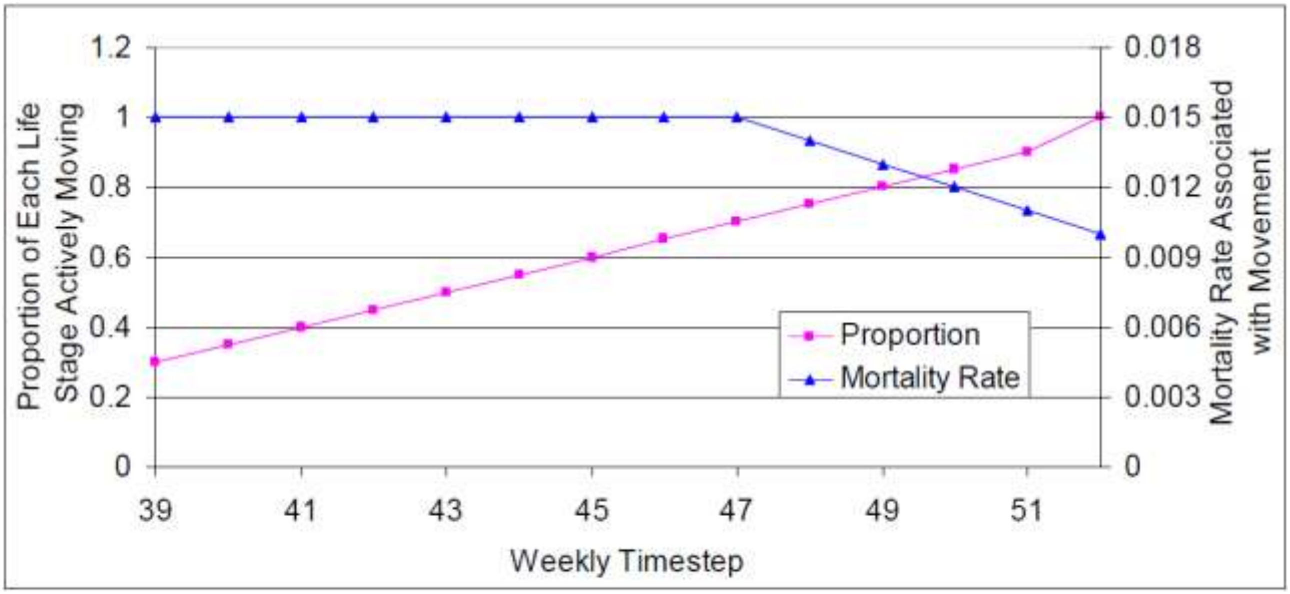


Figure 5.D.2-7. Proportion of each Life Stage Actively Moving and Corresponding Mortality Rates Assumed for Smolts

Table 5.D.2-7. Maximum Seasonal Movement Distance for Smolts

Life Stage	Size Class	Distance (m)
Pre-Smolt	P60_70	7,000
	P70_80	14,000
	P80_100	21,000
Immature Smolt	I100_150	28,000
	I150_200	32,000
	I200_269	40,000

SALMOD assumes a relatively fixed “capacity” per unit of available physical habitat for adult and juvenile fish (Chapman 1962, 1966; Mesick 1988; Beechie et al. 1994; Burns 1971). Capacity is computed by translating the flow in each computational unit into square meters of available habitat for each life stage and knowing the maximum biomass or number of individuals for that life stage that can occupy a square meter of optimum habitat. The model moves juvenile and adult fish that exceed capacity to a downstream computational unit. Table 5.D.2-8reflects the maximum biomass for each life stage used in this Sacramento River application.

Table 5.D.2-8. Maximum Biomass per Unit WUA for Each Life Stage used in Sacramento River Application

Life Stage	Maximum Grams/Square Meter of WUA
Fry	250.00
Pre-smolts	1,162.00
Immature smolts	1,162.00
Adults	52.58.00

5.D.2.7.4 Habitat-Induced Movement and Mortality Rate

There is a mortality rate associated with habitat-constrained movement, i.e. the farther fish must travel to encounter unoccupied habitat, the greater their mortality. In SALMOD, this is specified by the maximum distance that can be moved in one timestep (1 week) before 100% mortality, linearly interpolating back to zero mortality at zero distance.

Kent (1999) and Bartholow (2003) used 3 km as the maximum distance regardless of life stage/size class on the Sacramento River, relying on an estimate from Bill Snider (CDFW). Juveniles that must move more than 3 km in a week due to lack of suitable rearing habitat will die. For this application, the maximum distance was doubled, because of CDFW’s concerns that the model, as previously constructed, was likely underestimating production (Bartholow 2003).

5.D.2.8 Available Data Sources (Quality and Quantity)

There are three primary sources for initial parameter values for Chinook salmon modeling on the Sacramento River.

The first is from the Trinity River flow evaluation (USFWS and Hoopa Valley Tribe 1999), which in turn was an outgrowth of the work done by Williamson et al. (1993) and Bartholow et al. (1993). Kent (1999) and Bartholow (2003) who applied SALMOD for Chinook salmon on the Sacramento River downstream from Shasta Dam reinforced these values. Both of these applications added credence to parameter values, strengthened confidence in the model's predictive utility, and supplemented the analysis toolbox.

Second, because there is never a full complement of values available for any site-specific model application, literature values developed for other rivers or related species are used. By necessity, data were obtained from unpublished material when this was the best source to represent the life history of Chinook salmon in the Sacramento River. Where relevant, significant assumptions are included when data are borrowed from other species, locales, or runs.

Third, a great deal of biological information is available on the Sacramento River. Much of this information is in unpublished reports and databases, but has been used extensively in developing parameters for this modeling effort.

5.D.2.9 Reporting Metrics

Annual production potential or the number of outmigrants, annual mortality, length, and weight of the smolts are some of the reporting metrics available from SALMOD. The production numbers obtained from SALMOD are best used as an index in comparing to a specified baseline condition rather than absolute values.

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