In Cooperation with the Bureau of Reclamation

Evaluation of Shasta Dam Scenarios Using a Salmon Production Model

By John M. Bartholow and John Heasley

Administrative Report, August 17, 2006

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
P. Patrick Leahy, Director

U.S. Geological Survey, Reston, Virginia 2006

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Contents

Figures

Tables

Evaluation of Shasta Dam Scenarios Using a Salmon Production Model

By John M. Bartholow and John Heasley[1]

Executive Summary

We parameterized and applied a deterministic salmon production model to help evaluate streamflow and water temperatures predicted as representative of several scenarios being proposed for raising the Shasta Dam on the Sacramento River, California. The model (Salmod) predicts the degree to which river flows and temperatures may reduce freshwater production potential for the four races of Chinook salmon (*O. tshawytscha*) that inhabit the Sacramento River. Model simulations were used to evaluate the relative production associated with hydrologic and meteorologic scenarios representing 70+ years.

This model application is an outgrowth of previously described work on both the Sacramento and Klamath Rivers, though neither model has been quantitatively calibrated. Specific parameter requirements, data sources, and significant assumptions are discussed in detail. Model uncertainty has been comprehensively highlighted through a sensitivity analysis that focuses on those model parameters that were both sensitive and uncertain.

The model predicts that effects on average numeric production of the various Chinook races would be quite small (less than 2 percent) and likely difficult to measure on the river with certainty. Predicted improvements in thermally induced mortality, especially in specific low-water years, tend to be offset by more frequent and disadvantageous reductions in spawning and juvenile rearing habitat.

Specific recommendations are made regarding future modeling activities and further reducing model parameter uncertainty.

Introduction

Historical Perspective

A bit of (simplified) history is in order. It is widely believed that a major portion of salmon holding, spawning and rearing habitat in the upper Sacramento River Basin was concentrated in the tributaries upstream from what is now Shasta Lake. Large portions of these tributaries would have been cold, spring-fed systems with suitable water temperatures on almost a year-round basis. But when Shasta and Keswick Dams were constructed during the 1940s, they blocked access to suitable Chinook salmon habitat upstream from these locations,

---

[1] John Heasley is a contractor working for U.S. Geological Survey through ASRC Management Services.

concentrating spawning for the four salmon runs in the Red Bluff to Keswick portion of the Sacramento River.

On occasion, water temperatures exceed the preferred range for Chinook salmon downstream from Keswick Reservoir for a variety of interrelated reasons. Flow management can lead to seasonally low discharges, especially during drought years. Shasta Lake is large and strongly stratifies annually, and as reservoir storage declines in the fall, cold hypolimnetic waters can be exhausted, warming the discharge considerably. Warm air temperatures and the open nature of the Sacramento River in this portion of California's Central Valley contributed to rapid warming downstream of the dams when flows are low, thus squeezing the thermally tolerable habitat into a relatively short section of the river downstream from Keswick. In addition, it is believed that years with high, cold spring releases encouraged winter-run adults to spawn far downstream subjecting incubating eggs to warm water temperatures and egg loss later in the summer (U.S. Fish and Wildlife Service, 1990).

The critically dry year of 1976–77 and low-flow years of the mid-1980s were widely recognized as creating water temperatures that potentially put continued survival of the listed winter-run Chinook at jeopardy (Healey, 1977). Starting in 1987, the Bureau of Reclamation released cool water through Shasta's low-level outlet, bypassing the power-producing penstock and foregoing considerable revenue. This resulted in the evaluation, and eventual installation, of an $80+ million temperature control device (TCD) on the upstream face of Shasta Dam designed to permit normal hydropower releases. Ironically, the U.S. Fish and Wildlife Service had recommended a lower level penstock outlet prior to the construction of Shasta Dam specifically for temperature control (U.S. Fish and Wildlife Service, 1940, as cited in U.S. Fish and Wildlife Service, 1990).

Alternatives for the prospective TCD were evaluated by the U.S. Fish and Wildlife Service (1990). The TCD was seen as (1) reducing but not eliminating salmon mortality due to elevated temperatures, (2) slightly improving juvenile growth, (3) inducing salmon to spawn upstream from Red Bluff Diversion Dam (RBDD), and (4) providing turbidity control to improve rearing for salmon and steelhead. The U.S. Fish and Wildlife Service's quantitative analysis was conducted using model results supplied by the Bureau of Reclamation (1991) that predicted average monthly water temperatures at various locations along the Sacramento River and estimated daily salmon mortality attributable to the various alternatives. Though details about the models' operations and assumptions were not included in the 1990 analysis documents we have seen, the U.S. Fish and Wildlife Service concluded that the TCD would increase average survival of the winter, spring, and fall runs by 9.3, 11.4 and 2.5 percent, respectively. Late fall Chinook, they believed, would not likely be affected. The models also showed that the TCD would not be effective in all years: 5 of the 56-year model run would still exhibit substantial mortality. In particular, the U.S. Fish and Wildlife Service stated that if the TCD were ineffective for 3 years in a row, winter-run Chinook would likely be extirpated.

The installed TCD seems capable of fine-tuning water temperatures seasonally, reducing the frequency of exhausting cold water. However, recent limnological and modeling studies have refined estimates of Shasta's TCD daily discharge temperature capabilities, and have documented that the TCD appears incapable of meeting stringent downstream temperature needs in most (or perhaps all) years (Saito and Bartholow, 1997; Hanna and others 1999; Bartholow and others 2001; Nickel and others, 2004). Interestingly, the U.S. Fish and Wildlife Service analysis also noted that many years could still arise when winter-run spawning would be completely unsuccessful and concluded that "additional measures will eventually be required to fully protect salmon resources in the Sacramento River" (U.S. Fish and Wildlife Service, 1990).

The Present Study

Shasta Dam may be raised ostensibly to improve water supply in California. Raising the dam may affect the reservoir's ability to deliver cold water in some years, potentially improving salmon survival beyond what the existing TCD has done. An enlarged Shasta also is likely to alter the pattern of flow releases and storage patterns simply because more carryover storage options become available with a larger, manageable pool.

Raising Shasta Dam would be a major Federal action requiring an environmental impact statement (EIS). Every EIS requires the evaluation of multiple alternatives in a quest for the least environmentally damaging practicable alternative. Scenarios selected by the Bureau of Reclamation include:

- A "baseline" scenario representing existing and reasonably foreseeable future facilities, constraints, and delivery obligations portrayed against a backdrop of historical water availability and meteorology (referred to as Base for this analysis).
- "Six and one-half-foot dam raise" and accompanying enlarged Shasta reservoir (WSR1).
- "Twelve and one-half-foot dam raise" (WSR1.5).
- "Eighteen and one-half-foot dam raise" (WSR2).

In fairness, it is probably less appropriate to refer to these as alternatives because they are simply incremental gradations along a continuum rather than true water-management alternatives. For more information regarding the assembly and interpretation of these four scenarios, please refer to more extensive information supplied by the Bureau of Reclamation.

In addition, Chinook salmon stocks from the Sacramento River, especially the listed winter run, continue to be below their recovery goals (Anadromous Fish Restoration Program Core Group, 1995). For this reason, Reclamation needs to evaluate the effects of potentially raising Shasta Dam on downstream salmonid populations in the Sacramento River.

Hanna (2000) outlined the conceptual process of incorporating a salmon production model into an EIS-related assessment activity. He envisioned proposed hydrologic scenarios advancing through a chain of models. The chain would be started with a water-supply/quantity model (for example Calsim) capable of predicting monthly streamflows and overall mass balance given existing water-management constraints and obligations. The water quantity model's output would be fed into a reservoir and river water quality model (for example HEC-5Q) capable of predicting in-reservoir, outfall, and downstream water temperatures given tributary and meteorologic inputs. Both streamflows and water temperatures would then be available as inputs for a salmon production model (for example Salmod) to help compare the relative merits, or demerits, of the various scenarios. In this study, we apply a refined version of the Salmod model to help evaluate the potential benefits and costs of various Shasta Dam scenarios as part of the ongoing EIS evaluation. We have used streamflows and water temperatures derived from Bureau of Reclamation modeling estimates using the HEC-5Q model (more fully described in the Flow and Water Temperature section below).

The USGS has previously applied an existing salmon production model in the Sacramento River between Keswick Dam and Battle Creek. This model, Salmod, computes the effects of flow and water temperature on growth and survival of Chinook salmon. Kent (1999) first applied Salmod to the Sacramento River for fall Chinook. Kent's work was expanded to include the other Chinook races in the Sacramento and shown to produce production estimates of approximately the correct magnitude and trend (Bartholow, 2003).

Specific Objectives of the Present Study

Since the last application of Salmod on the Sacramento River, much progress has been made on many of the model's basic parameters based on continued literature review and application on the Klamath River in northern California (Bartholow and Henriksen, in press.) These new parameter estimates have been incorporated for the Sacramento River. For this study, we also extended the previous study area (which terminated at Battle Creek) to the Red Bluff Diversion Dam's inundation zone, a reach where water temperatures may be more of an issue for spawning and rearing salmon.

Given the revised Salmod model parameters, our specific objective has been to exercise the model to estimate the effects of alternative water temperature and flows for the various Shasta Dam scenarios. Effects have been measured by estimates of overall production for each of the four races of Chinook salmon.

It must be clearly understood that the U.S. Geological Survey (USGS) has performed this analysis solely to assist the resource and management agencies with a framework for making informed decisions. We make no specific water management recommendations nor endorse any specific scenario.

Methods

The modeling environment, including model selection and operation, along with data requirements, sources of data and parameter values, and important assumptions are outlined in the following sections. Portions of the text were adapted from Bartholow and Henriksen (in press).

Model Selection

Salmod (Version 3.74) is a component of the Instream Flow Incremental Methodology, or IFIM (Stalnaker and others, 1995). Another component of the IFIM methodology, specifically the Physical Habitat Simulation System (PHABSIM), has been criticized (for example Conder and Annear, 1987) as demonstrating no relationship between microhabitat quantification (weighted usable area, or WUA, an index to suitable microhabitat) and fish standing crop. Yet many other researchers persist in developing and using these relationships to relate WUA and standing crop (for example Capra and others, 1995; Heggenes and others, 1996). Like Stalnaker and others (1995) and Bovee and others (1994), Orth (1987) argued persuasively that it is illogical to expect any instantaneous relationship between habitat availability and fish density to hold true. Orth outlined the hypothesis that microhabitat availability may limit fish populations, but episodically, not continuously. In addition, he notes that other factors, such as water temperature, must be included in an analysis. In effect, Orth (1987) said that the PHABSIM models were incomplete. In response, the Salmod model was constructed to integrate habitat limitations to a population through time and space, both microhabitat and macrohabitat. Note that when we refer to habitat limitations, this does not necessarily mean that freshwater habitat is the ultimate factor limiting populations. Habitat constraints may simply reduce production while other factors, such as ocean conditions or fishing pressure may be the ultimate "bottleneck."

Salmod was chosen for the Sacramento River for two reasons. First, Salmod has been applied previously on the Sacramento (Kent, 1999; Bartholow, 2003). Second, the USGS has recently completed a thorough review and update of model parameters and techniques on the Klamath River that enable a smooth transfer of relevant model parameters to the Sacramento River (Bartholow and Henriksen, in press).

General Description of Salmod

Salmod simulates population dynamics for freshwater (for example in-river) salmonids; no population dynamics are included for ocean habitat. Though the model is applicable for both anadromous and non-anadromous salmonids, this document will only discuss the anadromous life-history implementation. The model is fully described in Bartholow and others (1993 and 2001); only an outline of the model is presented here.

The model's premise is that egg and fish mortality are directly related to spatially and temporally variable micro- and macrohabitat limitations, which themselves are related to the timing and amount of streamflow and other meteorological variables. Salmod is a spatially explicit model (sensu Dunning and others, 1995) where habitat quality and carrying capacity are characterized by the hydraulic and thermal properties of individual mesohabitats, which serve 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 water temperature in a computation unit. Individual cohorts either remain in the computation unit in which they emerged or move, in whole or in part, to nearby units. Model processes include spawning (with redd superimposition), incubation losses (such as redd scour or dewatering), growth (including egg maturation), mortality due to water temperature and other causes, and movement (freshet-induced, habitat-induced, and seasonal).

The model is organized around events (Figure 1) occurring during a biological year (sometimes known as a production year or brood year) beginning with spawning and typically concluding with fish that are physiologically "ready" (for example pre-smolts) swimming downstream toward the ocean. It operates on a weekly time-step for one or more biological years. Input variables (for example streamflow, water temperature, number and distribution of adult spawners) are represented by their weekly average values. The study area is divided into individual mesohabitat[2] types (for example 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 computation units of a given mesohabitat type changes similarly in response to discharge variation.

---

[2] Microhabitat refers to small-scale physical features defining suitability for fish on a fish's scale, for example 1 meter. In contrast, mesohabitat refers to the character of the channel that defines microhabitat, for example tens of meters.

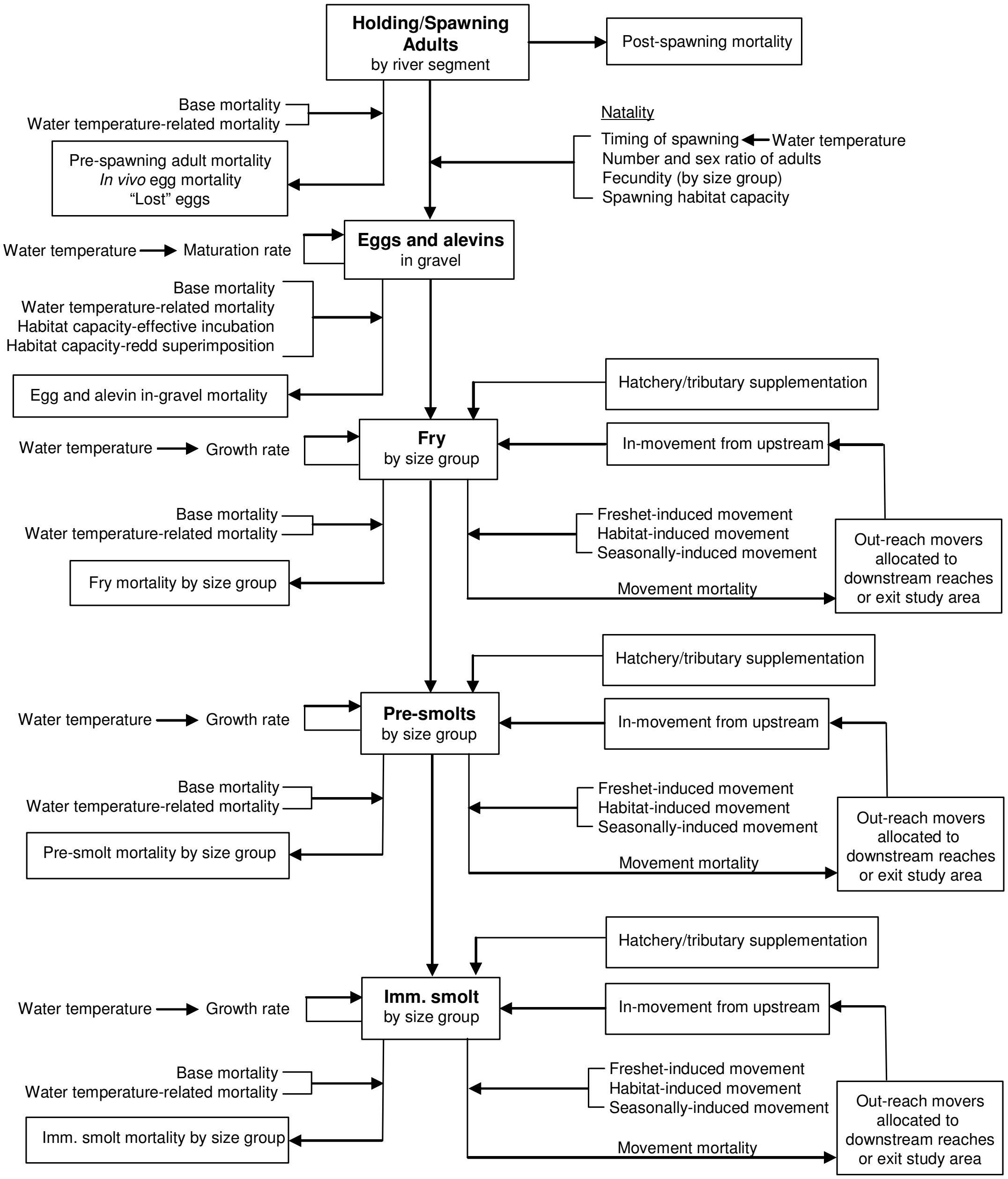


Figure 1. Conceptual illustration of the variety of factors important in controlling salmon production throughout Salmod's biological year.

Fish cohorts are tracked by life stage and size class within the spatial computation units. Streamflow and habitat type determine available habitat area for a particular life stage for each time-step and computation unit. Habitat area (quantified as weighted usable area, or WUA) is computed from flow:microhabitat area functions developed empirically or by using the Physical Habitat Simulation System (PHABSIM; Milhous and others, 1989) or similar model. Habitat capacity for each life stage is a fixed maximum number (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 computation unit is calculated for each time-step on the basis of streamflow, habitat type, and available microhabitat. Fish in excess of the habitat's capacity must move to seek unoccupied habitat elsewhere. Fish from outside the model domain (from stocking, hatchery production, or tributaries) may also be added to the modeled stream at any point in their life cycle.

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

Data and Parameter Sources for Salmod

There are three primary sources for initial parameter values for Chinook modeling on the Sacramento River. The first is from the Trinity River flow evaluation (U.S. Fish and Wildlife Service and Hoopa Valley Tribe, 1999), which in turn was an outgrowth of the work done by Williamson and others (1993) and Bartholow and others (1993). These values were reinforced by Kent (1999) and Bartholow (2003) who applied Salmod for Chinook salmon on the Sacramento River downstream from Shasta Dam. 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 available to represent the life-history of Sacramento River Chinook. Where relevant, significant assumptions are included when data are borrowed from other species, locales, or races. A summary of the important model input values and assessment of their relative certainty or uncertainty is also provided.

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

There are two things that may enhance the readers' understanding of this report. The first is patience; there is a fundamental difficulty inherent in explaining a complex model that makes it hard to understand some portions of the model until other portions have been explained. The second is to understand that data input for many of the parameters are sets of paired values. For example, the thermal mortality values are described by a set of values for the temperature and corresponding life stage mortality rate (for example temperature_1, mortality rate_1, … temperature_n, mortality rate_n). Salmod always performs a piece-wise interpolation between user-specified values to derive intermediate results, or if outside the range of supplied values, extends but does not extrapolate the terminal values.

The Salmod software and input files for the Sacramento River are available from the authors.

Definition of Model Life-history Structure

Life Stage and Size Classes

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. We refer to smolts 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 1 lists the class attributes chosen for the Sacramento River and is a modification of the categorization used on the Trinity and Klamath Rivers.

Table 1. Life stage and size class naming and break points. [mm, millimeters]

Salmod life stage	**Sometimes known as**	**Development index for eggs, Length class (mm) for juveniles**		
			Min	**Max**
Eggs	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

Weight:Length Data

Kent (1999) used a formula based on a cubic regression of fork length and wet weight developed for naturally reared fall Chinook salmon with lengths between 30 and 100 mm. A cubic regression was used because the length and weight relationship for fish is approximately cubic (Busacker and others, 1990). Accordingly:

$$WW(g) = -0.67 + 0.0282FL - 0.000491FL^2 + 0.0000141FL^3 \quad \text{(R unspecified)}$$

where WW = wet weight (grams), and
FL = fork length (millimeters).

Figure 2 contrasts weight:length relations for three California rivers for the length ranges from which the data were derived. Variability in the wet weight of individual fish of the same fork length may be due to true variation in weights or may simply be explained by differences among individuals in fullness of the stomach or presence of water in the buccal (mouth) cavity. Nonetheless, one might reasonably conclude that Sacramento and Klamath Chinook salmon have better condition factors than those from the Trinity River, at least for the time periods from which these fish were collected and relations developed. Klamath fish may be slightly heavier than Sacramento fish of the same length, but it has also been noted that diseased juveniles (often found on the Klamath) can appear to have higher condition factors (Nick Hettrick, U.S. Fish and Wildlife Service Arcata, written comm., 2006).

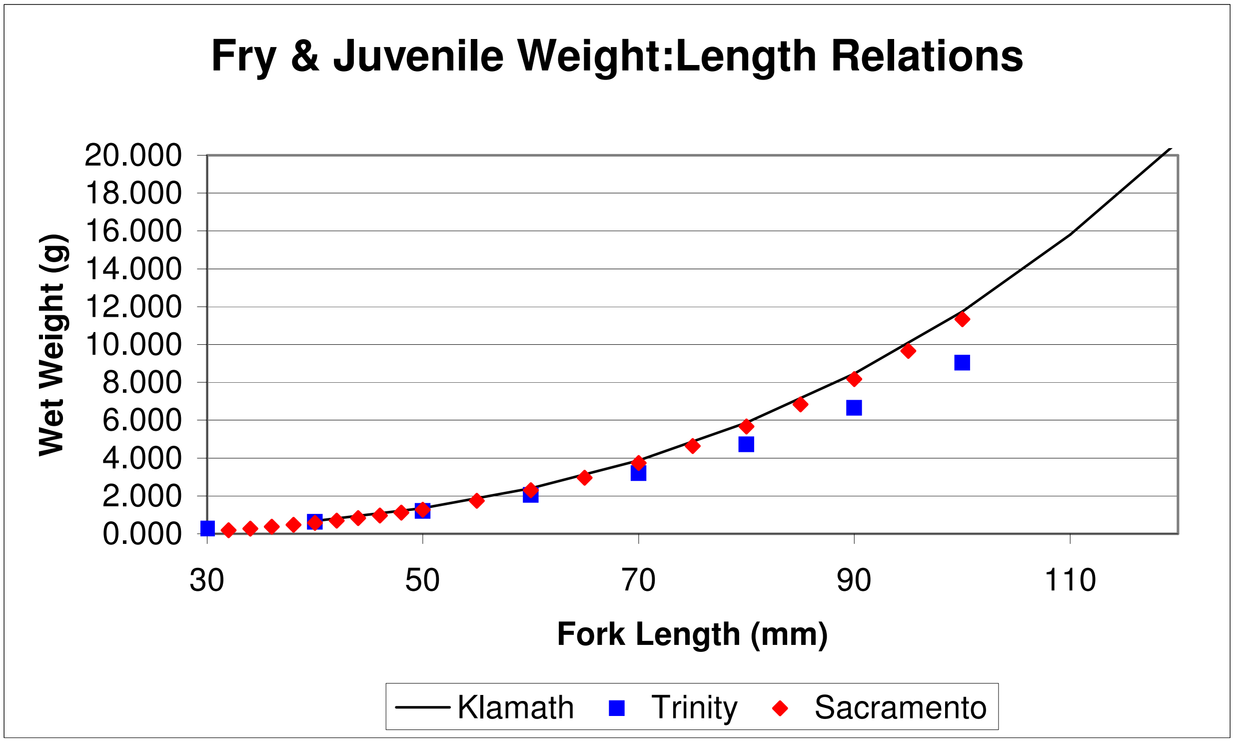


Figure 2. Weight:length relations for the Sacramento and other rivers. Data are from Bartholow and Henriksen (in press)

The weight: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 exception to this is if fish lose weight; if so, they retain their previous length, but must regain lost weight to add length. The weight:length relationship supplied to Salmod for the Sacramento River is detailed in Table 2.

Table 2. Weight:length relationship for Sacramento River fall Chinook salmon. The number of decimal points reflects the need to convert back and forth accurately and should not be construed to imply precision. [g, grams; mm, millimeters]

Weight (g)	Fork length (mm)	Weight (g)	Fork length (mm)
1.112	48	11.34	100
1.275	50	15.258	110
1.742	55	20.008	120
2.3	60	40.1	150
2.961	65	92	200
3.734	70	310.5	300
4.632	75	1437.5	500
5.663	80	3944.5	700
6.839	85	5888	800
8.17	90	12000	900
9.667	95		

General Biological Year Timing

Salmod is a weekly time-step model that, when used for an anadromous species with a single season in freshwater, most frequently begins with the onset of spawning and continues through the duration of outmigrating juveniles. For the Sacramento River, four distinct runs of Chinook are of concern, each with different life-history timing. Though it is theoretically possible to construct a single Salmod model incorporating all runs (each as a separate "species"), it is advisable not to let the spawning season for any "species" span two production years. For this reason, we constructed four distinct Salmod data sets, each with different simulation timing and each uniquely named.

Sacramento River Chinook life-history timing is well illustrated by Vogel and Marine (1991). Figure 3 and its corresponding table were derived from this source and become the essentially fixed timing template for the model's treatment of each race's biological year. Some compromises were necessary to best fit the race-specific timing into the capabilities of the model. Not all sources may agree with Vogel and Marine. For example, Frank Fisher created a "Race Designation Chart" (unpublished) that tends to show a much more protracted rearing period than Vogel and Marine. In addition, Healey (1994) argues that the various runs in the Sacramento River have no unique phenotype but rather a gradation of characteristics that we can relate to and name. Others may argue that there is no true run of spring Chinook that spawns in the main stem. For this study, however, we have used Vogel and Marine (1991). We have also assumed that most of the juveniles of each race will emigrate as ocean-type Chinook if they are physiologically ready, though stream-type Chinook likely exist in some cold-water tributaries, such as Deer and Mill Creeks, and even Butte Creek on occasion (Brannon and others, 2004) and are shown to pass Red Bluff in small numbers (for example Poytress, 2005).

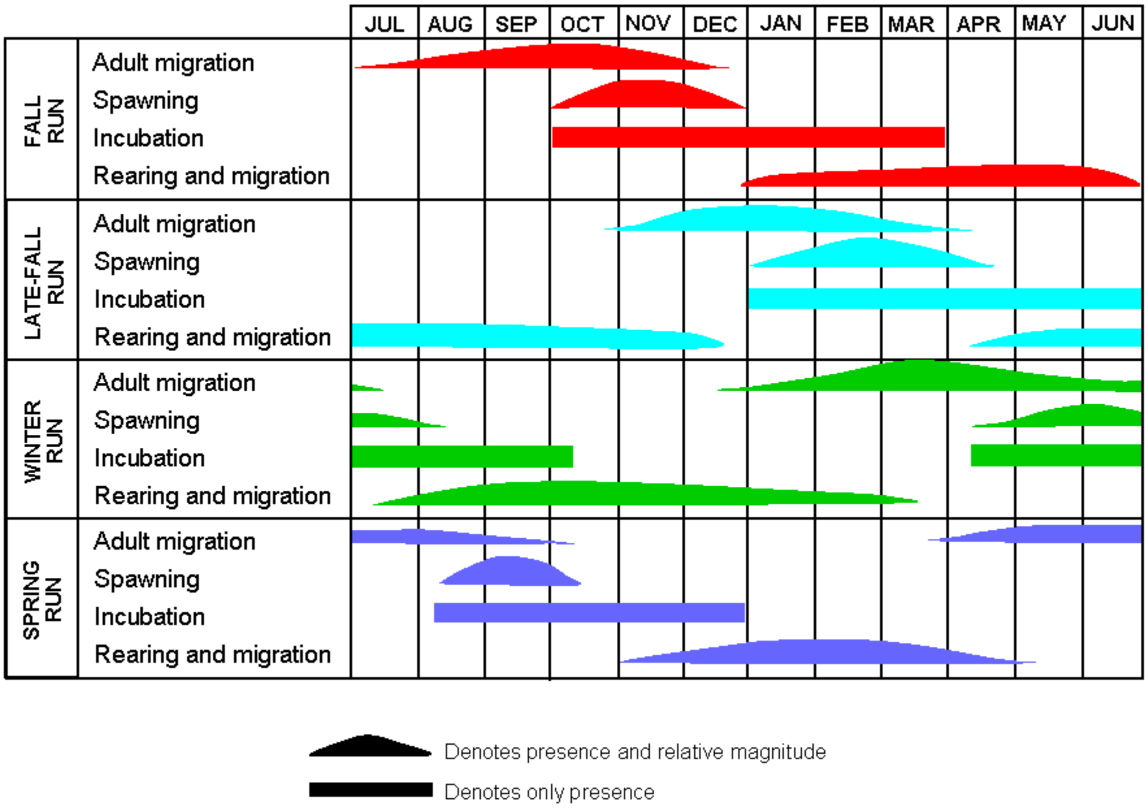


Figure 3. Approximate timing of the various races of Chinook salmon from Vogel and Marine (1991).

Simulation time-steps referenced in Salmod's input files are simply chronological week number (Table 3). Note that simulation processes are initiated on the first day of the week, but simulation results are tabulated on the last day. This can be a cause for confusion when reviewing the output.

Table 3. Correspondence between Salmod's weekly time-step and the biological year for each of the four races of Chinook.

Simulation week	Fall run	Late-fall run	Winter run	Spring run
1	2-Sep	3-Dec	4-Feb	6-May
2	9-Sep	10-Dec	11-Feb	13-May
3	16-Sep	17-Dec	18-Feb	20-May
4	23-Sep	24-Dec	25-Feb	27-May
5	1-Oct	31-Dec	4-Mar	3-Jun
6	8-Oct	7-Jan	11-Mar	10-Jun
7	15-Oct	14-Jan	18-Mar	17-Jun
8	22-Oct	21-Jan	25-Mar	24-Jun
9	29-Oct	28-Jan	1-Apr	1-Jul
10	5-Nov	4-Feb	8-Apr	8-Jul
11	12-Nov	11-Feb	15-Apr	15-Jul
12	19-Nov	18-Feb	22-Apr	22-Jul
13	26-Nov	25-Feb	29-Apr	29-Jul
14	3-Dec	4-Mar	6-May	5-Aug
15	10-Dec	11-Mar	13-May	12-Aug
16	17-Dec	18-Mar	20-May	19-Aug
17	24-Dec	25-Mar	27-May	26-Aug
18	31-Dec	1-Apr	3-Jun	2-Sep
19	7-Jan	8-Apr	10-Jun	9-Sep
20	14-Jan	15-Apr	17-Jun	16-Sep
21	21-Jan	22-Apr	24-Jun	23-Sep
22	28-Jan	29-Apr	1-Jul	1-Oct
23	4-Feb	6-May	8-Jul	8-Oct
24	11-Feb	13-May	15-Jul	15-Oct
25	18-Feb	20-May	22-Jul	22-Oct
26	25-Feb	27-May	29-Jul	29-Oct
27	4-Mar	3-Jun	5-Aug	5-Nov
28	11-Mar	10-Jun	12-Aug	12-Nov
29	18-Mar	17-Jun	19-Aug	19-Nov
30	25-Mar	24-Jun	26-Aug	26-Nov
31	1-Apr	1-Jul	2-Sep	3-Dec
32	8-Apr	8-Jul	9-Sep	10-Dec
33	15-Apr	15-Jul	16-Sep	17-Dec
34	22-Apr	22-Jul	23-Sep	24-Dec
35	29-Apr	29-Jul	1-Oct	31-Dec
36	6-May	5-Aug	8-Oct	7-Jan
37	13-May	12-Aug	15-Oct	14-Jan
38	20-May	19-Aug	22-Oct	21-Jan
39	27-May	26-Aug	29-Oct	28-Jan
40	3-Jun	2-Sep	5-Nov	4-Feb
41	10-Jun	9-Sep	12-Nov	11-Feb
42	17-Jun	16-Sep	19-Nov	18-Feb
43	24-Jun	23-Sep	26-Nov	25-Feb
44	1-Jul	1-Oct	3-Dec	4-Mar
45	8-Jul	8-Oct	10-Dec	11-Mar
46	15-Jul	15-Oct	17-Dec	18-Mar
47	22-Jul	22-Oct	24-Dec	25-Mar
48	29-Jul	29-Oct	31-Dec	1-Apr
49	5-Aug	5-Nov	7-Jan	8-Apr
50	12-Aug	12-Nov	14-Jan	15-Apr
51	19-Aug	19-Nov	21-Jan	22-Apr
52	26-Aug	26-Nov	28-Jan	29-Apr

Physical Data

Study Area

The study area for this analysis is shown in Figure 4. It covers an 85-km (53-mile) stretch of the Sacramento River from Keswick Dam to just upstream from the Red Bluff Diversion Dam at a latitude of approximately 40.5°N. 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 RBDD is operated with flashboards that alter the inundation pool's hydraulics. This pool has not been modeled for habitat value as far as we know.

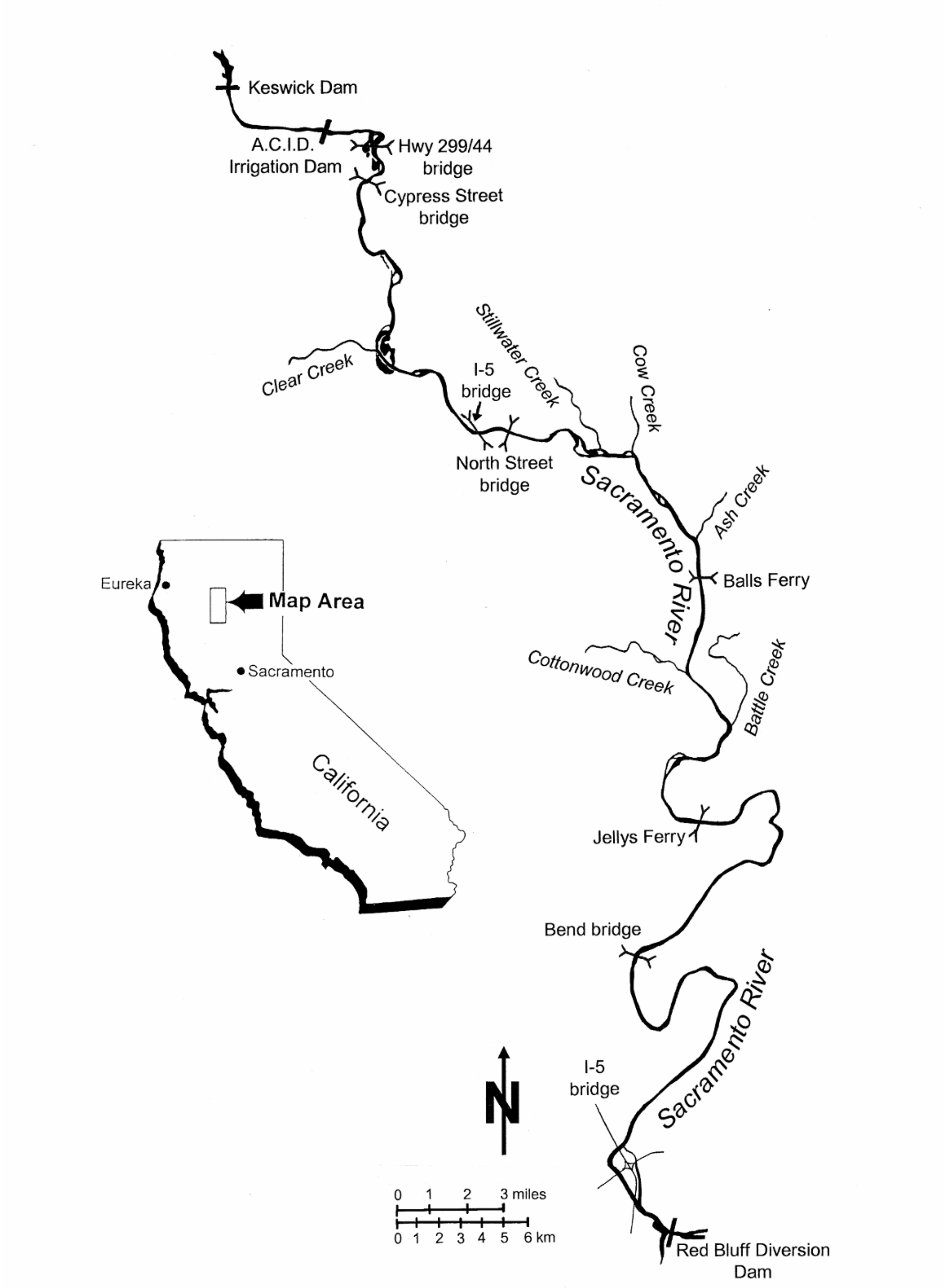


Figure 4. Salmon production model study area in northern California, ranging from Keswick Dam to the Red Bluff Diversion Dam inundation pool. Shasta Dam lies approximately 14.5 kilometers (9 miles) upstream from Keswick Reservoir, off of this detailed map.

Flow and Water Temperature Data

Flow (ft^3/s) and water temperature (°C) time series values derived from the HEC-5Q model were received from the Bureau of Reclamation for each scenario analyzed (Research Management Associates, 2003). Data came in the form of a database of values for each day corresponding to the weekly average conditions for that day forward. Data covered the period 10/01/1921 through 09/30/94, a total of 73 water years. We extracted data from this database appropriate for each race and each scenario. Because each race has an individually defined biological year (Figure 3), decisions on when to begin the record for each race were made to reduce potential confusion by the reader. Table 4 illustrates how these data were organized by calendar year.

One potential disadvantage to the approach we used is for the winter run Chinook. Their simulated biological year begins in February and ends in January. Salmod will report the results for that biological year as of the January calendar year even though the bulk of the winter run's outmigration may have occurred the previous calendar year. Another consequence of our decision is that the Salmod model can only be run for 71 biological years (1923 to 1993) because some data values at the beginning and end of the record cannot be used, given the staggered life-history and the desire to report results as consistently as possible.

Table 4. Illustration of how flow and temperature data were extracted from the HEC-5Q model database and "line up" across the four Chinook races. Month 10 is October. [cal, calendar]

Month	Initial cal. year	Fall	Late fall	Winter	Spring	Month	Last cal. year
10	1921					10	1991
11	1921					11	1991
12	1921					12	1991
1	1922					1	1992
2	1922			Begin		2	1992
3	1922			v		3	1992
4	1922			v		4	1992
5	1922			v		5	1992
6	1922			v	Begin	6	1992
7	1922			v	v	7	1992
8	1922			v	v	8	1992
9	1922	Begin		v	v	9	1992
10	1922	v		v	v	10	1992
11	1922	v		v	v	11	1992
12	1922	v	Begin	v	v	12	1992
1	1923	v	v	End	v	1	1993
2	1923	v	v		v	2	1993
3	1923	v	v		v	3	1993
4	1923	v	v		v	4	1993
5	1923	v	v		End	5	1993
6	1923	v	v			6	1993
7	1923	End	v			7	1993
8	1923		v			8	1993
9	1923		v			9	1993
10	1923		v			10	1993
11	1923		End			11	1993
12	1923					12	1993
…	…					1	1994
						…	…

Note that this modeling study did not deal directly with flow ramping. We have been told (Stephanie Theis, Bureau of Reclamation contractor, Sacramento, 2006) that the ramping criteria are expected to minimize or eliminate impacts to steelhead and spring-run Chinook salmon fry and juveniles from stranding and dewatering. Ramping flows down occurs primarily at night when fish typically are more active and less likely to become isolated in pools or side channels. In addition, releases are reduced at slow rates over several nights, allowing adequate opportunities for fish to pass from shallow, near-shore areas and pools into the main stem of the river. Stranding of winter-run Chinook salmon fry is not expected to be significant since large flows from Shasta Dam are usually stabilized by May. Regardless of the expectations, with Salmod's weekly flows, potential ramping effects are not considered.

Mesohabitat Sequence and Segmentation

Carefully distinguishing microhabitat and mesohabitat is important to understand this topic. 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 (for example 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 tend to respond similarly to changes in flow. Morhardt and others (1983) argued that collecting data for a PHABSIM microhabitat study was best done at the mesohabitat unit (also known as a channel geomorphic unit) level where microhabitat is characterized by multiple samples of each mesohabitat type within the each sub-segment. Salmod carries this process further by retaining the exact sequence and length of each mesohabitat type as computation units within the model.

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 computation 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. Though the flows and temperatures are supplied as separate input files, the list at the end of the habitat sequence denotes which computation units belong to which flow and temperature segments. Though flow and temperature segments need not be congruent with each other, they were for this application.

We started with the stream descriptions developed by Jason Kent (1999). His habitat description extended from Keswick Dam to Battle Creek, but the USGS contracted with the Sacramento office of the USFWS to extend the mesohabitat description from Battle Creek to the inundation pool of Red Bluff diversion dam. We did not go all the way to the dam because the inundated habitat has not been satisfactorily measured hydraulically and the flash boards are in place only intermittently. Thus, our study area terminated at the downstream end of the free-flowing river.

It was apparent that the mesohabitat delineation compiled by Kent and the new one developed by the USFWS overlapped slightly. To resolve this overlap, the coordinates for the beginning and end of the Battle Creek to Red Bluff Lake section of the river were measured from the habitat map provided by Mark Gard using ARCGIS (v. 9.0), and the distance from Keswick Dam to the beginning of the Battle Creek to Red Bluff Lake section was computed using Maptech Terrain Navigator software. These distances were used to determine the overlap between the upper and lower river descriptions. The old upper section computation units contained in the overlap were removed as appropriate. The lower section computation units were then added to the remaining upper section units.

Next, the newly described habitat units from Battle Creek to Red Bluff Lake were evaluated and converted to a sequential list of mesohabitats. However, 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. Though the habitat was realistically described by the USFWS, Salmod is not capable of representing this level of habitat complexity, complicating the translation process.

Fifty-six habitat polygons were processed in sequence from the most upstream polygon to the most downstream polygon. River length (meters) was measured for each habitat polygon representing a distinct segment of the river. This was done by tracing the centerline of the river from the upstream boundary to the downstream boundary by using the measurement tool of ARCGIS v. 9.0. A single computation unit having the length measured was thus created for river segments containing a single habitat polygon.

For those segments containing habitat mosaics, we followed a multi-step process to divide the reach into sequential computation units. The total area for the reach was computed as the sum of the habitat areas for all constituent polygons. The length for each computation unit was computed as the ratio of the habitat polygon's area to the reach area times the reach length. Computation units were ordered according to the upstream to downstream position of their respective habitat polygons. Where internal polygons were not near the edge of the river reach, the parent polygon was split, their areas estimated, and computation units were created with the parent units on the upstream and downstream side of the internal units. Side channels were treated as if they were internal to the river reach and added as sequential computation units.

In total, sixty-one computation units were created from the original fifty-six habitat polygons, covering 22.27 miles of the river. This process preserved each unique habitat type and continues to reflect 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.

A table of flow and temperature segment descriptions was received from BOR (Russ Yaworsky, written comm., 2006). These segments were developed from Reclamation's HEC-5Q model application and reflect approximate locations where tributaries are accounted for or other "compliance" points (Table 5). Within each segment, flows and temperatures are assumed to be homogeneous. The ACID diversion is the only major diversion within the study area. Balls Ferry, Jellys Ferry, and Bend Bridge are temperature compliance points on the Sacramento River.

Table 5. Flow and water temperature segmentation for the study area.

Segment number	Length (miles)	Flow and temperature segments
1	3.5	Keswick Dam to ACID Diversion Dam
2	2.0	ACID 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

We used this table to develop estimates of river kilometers to assign the flow and water-temperature segment boundaries. This was accomplished by measuring the distances for each named segment on USGS topographic maps using the Maptech Terrain Navigator software.

These distances were compared with delineated computation unit boundaries. Some of the new or previously existing computation units were split in two so that the flow and temperature segment boundaries approximately coincided with computation unit boundaries.

Finally, all computation units greater than 500 meters long were split so that the maximum length of any computation unit was 500 meters. This was done because Salmod moves fish from center to center of adjacent computation units. Long computation units might result in unrealistically high movement mortality. Constraining the maximum computation unit length overcomes, or at least minimizes, this potential problem. In total, the stream habitat description resulted in 279 computation units from Keswick to the Red Bluff inundation pool where we truncated the stream description, approximately 85 km in length.

Assigning Habitat Descriptions to Computation Units

In Salmod, each mesohabitat must have a corresponding estimate of the amount of weighted usable area (WUA) available throughout a range of flows for each life stage. Kent (1999) had compiled estimates of WUA for fall Chinook for each mesohabitat type from hydraulic data collected in a 1990's study by the California Department of Water Resources but updated to include new habitat suitability criteria from the USFWS. When Bartholow (2003) expanded the analysis to include the other three races, he slightly modified the same scheme that Kent had developed to include new information regarding which specific computation units did or did not appear to support spawning, and for a limited amount of race-specific spawning WUA estimates, both with the assistance of Mark Gard (U.S. Fish and Wildlife Service, Sacramento). The result was a tri-part naming scheme–type:subtype:spawning or no spawning.

It was our intention to continue with this naming scheme with the expanded study area and to easily incorporate new or revised WUA estimates available from the USFWS and California Department of Fish and Game to do so. This task proved to be impossible with existing resources for several reasons: (1) the WUA estimates were not readily available for all habitat types, some of which were different from those developed by Kent (1999); (2) we had no consistent spawning/non-spawning data on a computation unit basis; and (3) the full rationale used by Kent (1999) and modified by Bartholow (2003) was not well documented. Therefore, we kept the habitat typing and WUA values used by Kent and Bartholow but chose the following method in order to best approximate habitat availability downstream from Battle Creek.

Habitat types received from the USFWS contract were: Bar Complex Riffle, Bar Complex Run, Bar Complex Glide, Bar Complex Pool, Flatwater Riffle, Flatwater Run, Flatwater Glide, Flatwater Pool, Side Channel Riffle, Side Channel Run, Side Channel Glide, Side Channel Pool. These types are defined in Table 6 along with their habitat assignment to readily available and previous applied typing, as needed.

Table 6. Definitions of habitat types received from the U.S. Fish and Wildlife Service for mesohabitats downstream from Battle Creek.

Name	Characteristics
Bar complex	Submerged and emergent bars are the primary feature, sloping cross-sectional channel profile.
Flatwater	Primary channel is uniform, simple and without gravel bars or channel controls, fairly uniform depth across channel.
Side channel	Carrying less than 20 percent of total flow.
Pool	Primary determinant is downstream control–thalweg gets deeper as go upstream from bottom of pool. Fine and uniform substrate, below average water velocity, above average depth, tranquil water surface.
Glide	Primary determinants are no turbulence (surface smooth, slow, and laminar) and no downstream control. Low gradient, substrate uniform across channel width and composed of small gravel or sand/silt, depth below average and similar across channel width (but depth not similar across channel width for Bar Complex Glide), below-average water velocities, generally associated with tails of pools or heads of riffles, width of channel tends to spread out, thalweg has relatively uniform slope going downstream.
Run	Primary determinants are moderately turbulent and average depth. Moderate gradient, substrate a mix of particle sizes and composed of small cobble and gravel, with some large cobble and boulders, above-average water velocities, usually slight gradient change from top to bottom, generally associated with downstream extent of riffles, thalweg has relatively uniform slope going downstream.
Riffle	Primary determinants are high gradient and turbulence. Below-average depth, above-average velocity, thalweg has relatively uniform slope going downstream, substrate of uniform size and composed of large gravel or cobble, change in gradient noticeable.

Most of the habitat downstream from Battle Creek was bar complexes with a few side channels which, in turn, were further sub-typed and translated easily into Kent (type B or S) glides (subtype 1), runs (subtype 2), riffles (subtype 3), and pools (subtype 4). In a few cases, when there was no readily available equivalent type, we made the best assumption we could. For example, Kent (1999) had no side channel glide, so his flatwater was used in its place. For each habitat type downstream from Battle Creek, we used spawning WUA estimates from USFWS for each race (2005b). Thus, we were not able to use WUA estimates collected directly in the Battle Creek to RBDD segment of the study area except for spawning because no assuredly comparable habitat types were identified. Inspection of U.S. Fish and Wildlife Service (2005a and b) reveals that there is not likely to be much difference in at least the qualitative shape of the WUA relative to discharge curves for other life stages. However, we may not have captured the correct amount of habitat available in this segment. See the discussion and recommendations for more on this subject.

We had detailed redd counts that could have been used to delineate spawning/no spawning computation units (Mark Gard, U.S. Fish and Wildlife Service, Sacramento) as was done in the previous model application. However, because we wished to run the model using the number of spawners reflecting recovery goals, and these numbers are far higher than levels for which redd counts have recently been obtained, we assumed that all computation units with spawning habitat were spawnable. [In a few instances, when we did not have spawning area estimates for some named habitat types because there had been no documented redds, we were forced to assume zero spawning habitat. These were few in number.]

Microhabitat (WUA) Estimates for Salmod

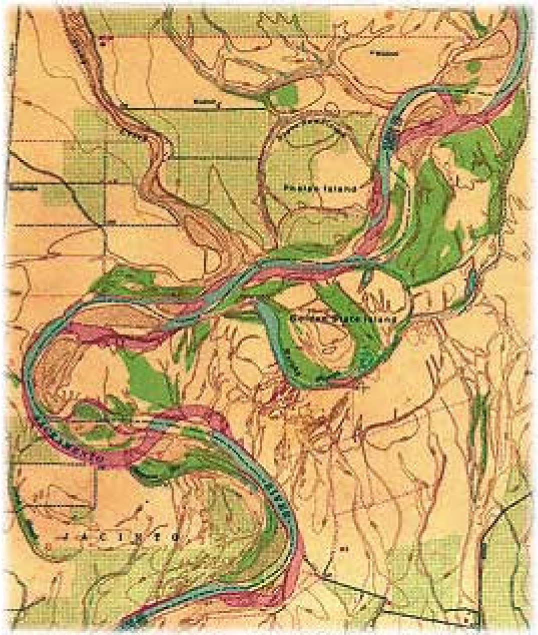
Kent (1999) and Bartholow (2003) did not have WUA estimates for egg incubation habitat. Instead, they assumed that egg incubation habitat was essentially identical to spawning habitat by making them equivalent in Salmod's WUA input file. On consultation with Mark Gard (U.S. Fish and Wildlife Service, Sacramento) it became apparent that this assumption was likely responsible for overestimating egg incubation losses due to presumed redd scour. This is because Salmod "remembers" the amount of spawning habitat available when each set of redds is constructed in each computation unit. If the egg incubation habitat declines in a unit due to changes in flow during the incubation period, Salmod assumes a proportionate loss in egg habitat. Such an assumption is reasonable when flows decline, potentially dewatering redds constructed at high flows, but the reverse is less logical. Weighted usable area for spawning peaks at relatively low flows (~2,000–5,000 ft^3/s) in the Sacramento River. If flows exceed this range and WUA decreases, Salmod would predict bed scour. But true bed scour is unlikely until very high flows are encountered, although some redd dune movement may still entomb egg pockets even with flows in the range of 5,000 ft^3/s by moving surface materials over the tops of redds, affecting their hydraulic conditions and potentially survival (Doug Killam, California Department of Fish and Game, Red Bluff, personal communication, 2006).

A more reasonable way to treat egg incubation habitat is to assume that as long as eggs are "kept wet regardless of depth" they suffer no mortality until true scouring flows occur. Because the Sacramento River channel is generally quite large, scouring flows are unlikely to occur until discharge is similarly large. As we understand it, studies are underway to quantify flows at which bed (and redd) scouring is likely to occur. In the absence of specific data, we have assumed that bed scour is likely above 50,000 ft^3/s given gravel displacement observations recorded by Bigelow (1996), and that significant bed-changing events occur above 60,000 ft^3/s. Therefore, we derived egg incubation WUA directly from the estimated spawning WUA by retaining the rising limb of the spawning curve with increasing discharge, but then holding the maximum WUA value constant with increasing flow. This is equivalent to keeping the eggs wet regardless of depth. We truncated this maximum value when flows exceed 50,000 ft^3/s linearly reducing the habitat value to zero at 60,000 ft^3/s due to increasing probability of redd-destroying bed scour or entombment.

Zero habitat above 60,000 ft^3/s assumes that redd scour or entombment causes 100 percent egg mortality, an assumption for which we have little guidance. Lapointe and others (2000) estimated that scour would indeed "destroy" a redd, but they also estimated that flooding would scour a maximum of only 20 percent of a Canadian Shield stream. However, their method only considered "net scour", that is, what had changed from pre- to post-flood (Bob Milhous, U.S. Geological Survey, oral comm., 2006). Such a technique risks ignoring the during-flood maximum scour extent. Montgomery and others (1999) speculate much higher mortality when scouring occurs at only modest egg burial depths, for example 80 percent at 30 cm. Note that Salmod's weekly time-step may underestimate the frequency of scour from daily peak flow events, especially if those flows were derived from Calsim's monthly flow model.

There are two assumptions to note regarding our treatment of physical micro/ mesohabitat. First, in assessing the effects of alternative flows and water temperatures on different life stages of salmon, we are making the assumption that they do not use–and compete for–the same microhabitat at the same time, an assumption supported by Chapman and Bjornn (1969), Fraser (1969), and Mundie (1974). Although more than one juvenile life stage (for example fry and pre-smolts) of more than one race may be present in the Sacramento River at the same time, juvenile Chinook salmon use progressively deeper and faster water as they grow (Chapman and Bjornn, 1969). Therefore, it is reasonable to assume that there is minimal competitive interaction. The same holds true with the assumption that juveniles are not competing with those of other species (for example steelhead). Obviously, these are ecological niche assumptions that could be strengthened or challenged by additional research.

Second, the quantification of WUA as a function of discharge is static. That is, we are assuming that none of the flows we simulate result in changes to the channel geometry, substrate composition (gravel quantity or quality), or cover availability. We know that the Sacramento River does change its channel morphology (Figure 5), but the assumption we are making is that such changes for this application are tantamount to dynamic equilibrium, that is, that habitat types remain in approximately the same proportion before and after channel-changing events.



Credit: US Geological Survey

Figure 5. Illustration of channel change along the main stem Sacramento River, best viewed in color. Source is obscure, but see *http://www.forester.net/ec_0005_river.html* and http://www.sacramentoriverportal.org/big_chico/1_40.pdf.

Model Processes

Spawning

Spawner Characteristics

Salmod requires the specification of the number and attributes of adults to "seed" the model. Using a recommendation from California Department of Fish and Game biologists (supplied by Jim DeStaso, written comm., 2006), we initialized model runs with main stem production goals for each race upstream from RBDD as shown in **Table 7**. We used a sex ratio of 48 percent spawning females to all other returning adults or grilse from Kent (1999).

Table 7. Number of adult spawners used to seed the Salmod model (ARFP Goals) compared with recent and older main stem estimates.

Source	Fall	Late fall	Winter	Spring
ARFP Goals[1]	230,000	44,000	110,000	59,000
Avg. 2000–2004[2]	58,289	15,431	6,500	332
Average in-river 1967–1991[3]	48,240	11,768	14,246	9,748

1. Anadromous Fish Restoration Program Core Group (1995).
2. From GrandTab spreadsheet.
3. From Stephanie Theis, contractor for Bureau of Reclamation.

In part we decided to use these numbers rather than an average for the last 5 years (as an example) because Salmod model may be inappropriate in situations where the number of spawners is quite small. Defining "quite small" is open to question, but we have in the past mentioned the number 500. Salmod relies on being able to treat many rate values (for example base mortality) as average values. When the number of fish in each cohort is small, random events (attributable to either environmental stochasticity or individual fish variability) not captured by the model can play a larger, more stochastic role in survival than what Salmod "expects." When spawner numbers are low (for example spring Chinook per the current GrandTab spreadsheet numbers), we would encourage even more attention to model uncertainty than usual and suggest that other models, such as population viability analysis (PVA), might be more appropriate than Salmod. However, it is unclear whether PVA would include detailed enough provision for altered flows and water temperatures to distinguish among scenarios.

Fecundity

Salmod uses a simple relationship for the number of eggs per gram of spawning female weight. Kent (1999) stated that the ratio he used was taken from the records of the Coleman National Fish Hatchery Lot History Reports from the hatchery's annual reports for fiscal years 1970–1997. This value is currently scaled to 5,000 eggs for a 12-kg fish.

We assumed Kent was referring to fall Chinook. The National Marine Fisheries Service (no date) has noted that winter run Chinook have a lower fecundity (average of 3,353 eggs per female) than most other Chinook populations, including Sacramento River fall-run Chinook (average of 5,498 eggs per female). Because of this potentially lowered reproductive potential, we reduced winter run fecundity to 60 percent of that of the other races.

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 already occupied by pre-existing redds. The model does not allow superimposition of redds created within one weekly time-step; in effect, this means that redds are defended for one week.

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 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 any previously deposited eggs. The egg pocket area is typically a value much smaller than the total area of disturbance. We chose to use a value of 4.5 m^2 (Bartholow, 2003) after consultation with Mark Gard (U.S. Fish and Wildlife Service, Sacramento).

Salmod can simulate superimposition by using three distinct probability algorithms. For this application, we initially chose the "random" option, signifying that current spawners neither seek nor avoid previously constructed redds in agreement with Bartholow's (1996) recommendation. However, we subsequently used the "avoidance" option and reduced the assumed redd egg pocket area to 2 m^2 in deference to California Department of Fish and Game's concerns. These changes, in effect, allow more spawners to use the same amount of spawning habitat with less superimposition.

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. Required data include the number of adults spawning in each section of river, the proportion of female spawners to non-spawners, and their weights–information typically available from carcass and/or redd counts. We used the values in **Table 8** to seed the study area for each simulation year so that we would be able to clearly distinguish the effects of flow and water temperature, as opposed to escapement, in estimating salmon production.

Note that we have assumed that the spatial distribution of spawners is essentially the same with higher spawner numbers as it has been in the recent past with lower returns. This may or may not be true. It might be reasonable to speculate that higher numbers of spawners would "spread out" longitudinally, but lacking data on this phenomenon, we have simply used current distribution data.

Table 8. Assumed distribution of spawners in eight spawning segments throughout the study area. Original location data covering years 2001 to 2005 was from data supplied by John Hannon (Bureau of Reclamation, Sacramento, written communication, 2006) and included redd counts downstream from Red Bluff diversion dam, ignored here. We also assumed that there were no redds in the Red Bluff inundation zone. [m, meters; A.C.I.D., Anderson Cottonwood Irrigation Diversion]

			Proportion Spawning				**Number Spawning**			
Spawning segment number	**Description**	**Cumulative Distance from Keswick (m)**	**Fall**	**Late fall**	**Winter**	**Spring**	**Fall**	**Late fall**	**Winter**	**Spring**
1	Keswick to A.C.I.D.	5,791	0.103	0.345	0.418	0.045	23,779	15,167	45,983	2,668
2	A.C.I.D to Highway 44 Bridge	9,025	0.062	0.153	0.205	0.191	14,368	6,725	22,504	11,266
3	Highway 44 Br. to Airport Rd. Br.	28,810	0.111	0.228	0.354	0.317	25,424	10,018	38,933	18,678
4	Airport Rd. Br. to Balls Ferry Br.	41,411	0.192	0.183	0.019	0.176	44,269	8,031	2,109	10,377
5	Balls Ferry Br. to Battle Creek.	49,207	0.129	0.056	0.001	0.106	29,627	2,472	157	6,226
6	Battle Creek to Jellys Ferry Br.	56,538	0.188	0.021	0.001	0.151	43,355	928	63	8,894
7	Jellys Ferry Br. to Bend Bridge	71,413	0.136	0.010	0.002	0.015	31,248	432	252	889
8	Bend Bridge to Red Bluff inundation zone	84,828	0.078	0.005	0.000	0.000	17,931	227	0	0
	Totals		1.0	1.0	1.0	1.0	230,000	44,000	110,000	59,000

Spawn timing in Salmod is set to occur regularly within a certain time window and is not specifically a function of streamflow or habitat availability, though it does depend on water temperature being within a certain range. If outside the specified bounds, fish that are ready to spawn will wait for the next time-step and reevaluate the temperature. Some biologists believe that spawn timing may be more a function of habitat availability rather than water temperature. Though spawning in Salmod does not directly respond to a habitat cue, limited spawning habitat will result in the spawners above the spawning habitat's capacity shedding their eggs or dying unspawned. Thus, Salmod does indirectly consider habitat availability.

The model does not account for "green" spawners directly, but does so indirectly by allocating spawning activity through time based on "new" redds identified in the redd counts. Thus, it does not matter if spawning occurs only in one week or is spread out over two months or more. The model is told what proportion of adults is "ready" to spawn each week of the designated period. These proportions will hold unless other things preclude spawning, such as temperatures being too high–they wait–or not enough spawning habitat to go around even with superimposition–the adults shed their eggs and die. Adult mortality will be discussed later, but adults may suffer pre-spawn mortality from various causes, for example high water temperatures.

Spawn timing in this model application (**Table 9**) was identical to Bartholow (2003) and directly mimics the overall phenology shown in Figure 3.

Table 9. Date and fraction of adults converted to spawners in each week of their respective spawning periods.

Spawning week	**Fall-run**		**Late-fall-run**		**Winter-run**		**Spring-run**	
1	1-Oct	0.02	7-Jan	0.02	15-Apr	0.02	12-Aug	0.12
2	8-Oct	0.06	14-Jan	0.06	22-Apr	0.06	19-Aug	0.13
3	15-Oct	0.12	21-Jan	0.12	29-Apr	0.12	26-Aug	0.15
4	22-Oct	0.16	28-Jan	0.16	6-May	0.16	2-Sep	0.16
5	29-Oct	0.20	4-Feb	0.20	13-May	0.20	9-Sep	0.20
6	5-Nov	0.13	11-Feb	0.13	20-May	0.13	16-Sep	0.08
7	12-Nov	0.08	18-Feb	0.08	27-May	0.08	23-Sep	0.06
8	19-Nov	0.07	25-Feb	0.07	3-Jun	0.07	1-Oct	0.05
9	26-Nov	0.06	4-Mar	0.06	10-Jun	0.06	8-Oct	0.05
10	3-Dec	0.05	11-Mar	0.05	17-Jun	0.05		
11	10-Dec	0.04	18-Mar	0.04	24-Jun	0.04		
12	11-Dec	0.01	25-Mar	0.01	1-Jul	0.01		
Total		1.00		1.00		1.00		1.00

Egg Development and Juvenile Growth

Egg Development Rate

After deposition, eggs incubate and hatch in approximately 6–12 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 100 percent of the development accumulation is reached. Crisp's (1981) quadratic equation was used to calculate each day's thermal contribution from deposition to hatch. The resulting rate values were decreased to 60 percent 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 6. This function shows that eggs will mature more rapidly at 10°C than at 2°C. Note that thermal accumulation begins with egg deposition and does not account for any ova maturation that may have occurred in vivo.

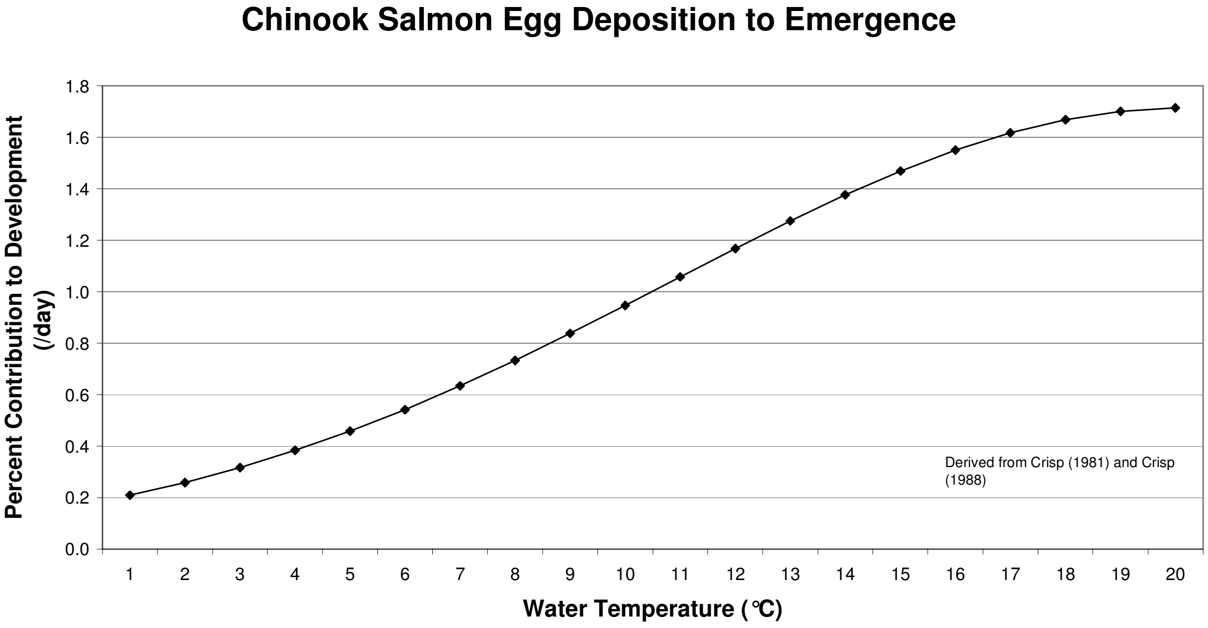


Figure 6. Egg and alevin development rate as a function of mean weekly water temperature. Each week adds to the percent development until 100 percent is reached.

Minimum Emergence Temperature

Salmod does not allow fry to emerge from the gravel until mean weekly water temperature exceeds a user-specified threshold. Previous applications have used a minimum of 8°C (46.4°F) based on work for Atlantic salmon (Jensen and others, 1991), though it is known that in-gravel feeding for Chinook alevins may still be underway (Heming and others, 1982). Verifying this relationship is problematic on the Sacramento River because trapped fry may have originated in warmer, spring-fed tributaries, biasing any estimate of true emergence temperature. Bartholow and Henriksen (In press) carefully examined a variety of data sources on the Klamath River and concluded that an emergence value around 7° or 8°C was not unreasonable.

We have consulted with others on this issue and opinions vary. Thomas Quinn (University of Washington, written comm., 2006) believes there may indeed be a threshold emergence temperature, though it might vary from river to river or area to area. He cites anecdotal information related to ice-out conditions and to late-season temperatures being the best predictor of emergence timing. Others are not so sure. Nick Beer (also University of Washington, written comm., 2006) believes that the suite of simultaneous environmental cues is tricky to decouple, but most likely fish will synchronize spawn timing to “optimize” production and development rate is purely mechanistic. Ernie Brannon (University of Idaho, written comm., 2006) says that he knows of no situation in the field or laboratory where there was an emergence threshold below which emergence would not occur. However, he also stated that, unlike other species, Chinook can feed in the gravel and remain there after their yolk is absorbed "if conditions require it."

Because of this uncertainty, we lowered the minimum emergence temperature of 8°C that we used previously to 6°C (42.8°F) until more main stem-specific evidence may be brought to bear on the issue. Salmod has no upper temperature threshold. If temperatures are too hot, fry will die due to thermal mortality.

Emergent Length

Eggs incubate after deposition and hatch after 6–12 weeks, depending on water temperatures. Alevins remain in the gravel for an additional period, living off the still-attached yolk sac. The average weight of a fry on emergence from the gravel was given by Kent (1999) as 0.275 g, 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 is the value used for this application.

Juvenile Growth Rates

Growth rates for juvenile fish are important because the size fry and pre-smolts achieve provides a competitive advantage to all subsequent life stages, being correlated with survival, smoltification, and reproductive success (Dill and others, 1981; Holtby and Scrivener, 1989; Quinn and Peterson, 1996). Growth rate is the most frequently reported measure of fish health (Sullivan and others, 2000), as it appears to integrate the full range of physiological responses to water temperature. In Salmod, growth is (almost) solely a function of mean weekly water temperature. Although the weekly time-step has been questioned regarding its adequacy in handling thermal mortality, a mean weekly temperature approach for growth appears well justified. Several authors have investigated the effects of fluctuating temperatures on growth. Fortunately, a time-weighted mean provides essentially the same results as integration over much smaller time increments (Sullivan and others, 2000).

Growth as a function of water temperature for juvenile life stages was obtained from Shelbourne and others (1973) and is the same function used on the Trinity and Klamath Rivers. Note that this function (Figure 7) assumes a constant food supply with juveniles fed to excess. We do not know whether the Sacramento River downstream from Keswick is considered nutrient rich, but simulated growth results from Bartholow (2003), at least for fall Chinook, did not suggest that the Salmod model was either over- or underestimating juvenile growth. The growth rates we use are consistent with findings from Marine and Cech (2004) who did not observe significant reductions in juvenile growth rates until daily temperatures, either means or maxima, exceeded 20°C (68°F).

There is one exception to the statement that growth is solely a function of water temperature. Salmod can control whether fish that are forced to move due to a habitat/density constraint will be allowed to grow or not. There is scant literature to support one view or the other, but Titus and Mosegaard (1991) concluded that newly emerged trout fry that successfully established feeding territories grew well in contrast to those forced into downstream movement. In fact, they characterized the emigrants as "starved" on the basis of otolith measurements. For this reason, we have set Salmod to allow growth only for juveniles not forced to move, the assumption being that energy is preferentially expended by movers in search for new territory and is not available for growth. In contrast, we set Salmod to allow growth during volitional seasonal downstream movement (discussed in the following section) as reported by Mikulich and Gavrenkov (1986).

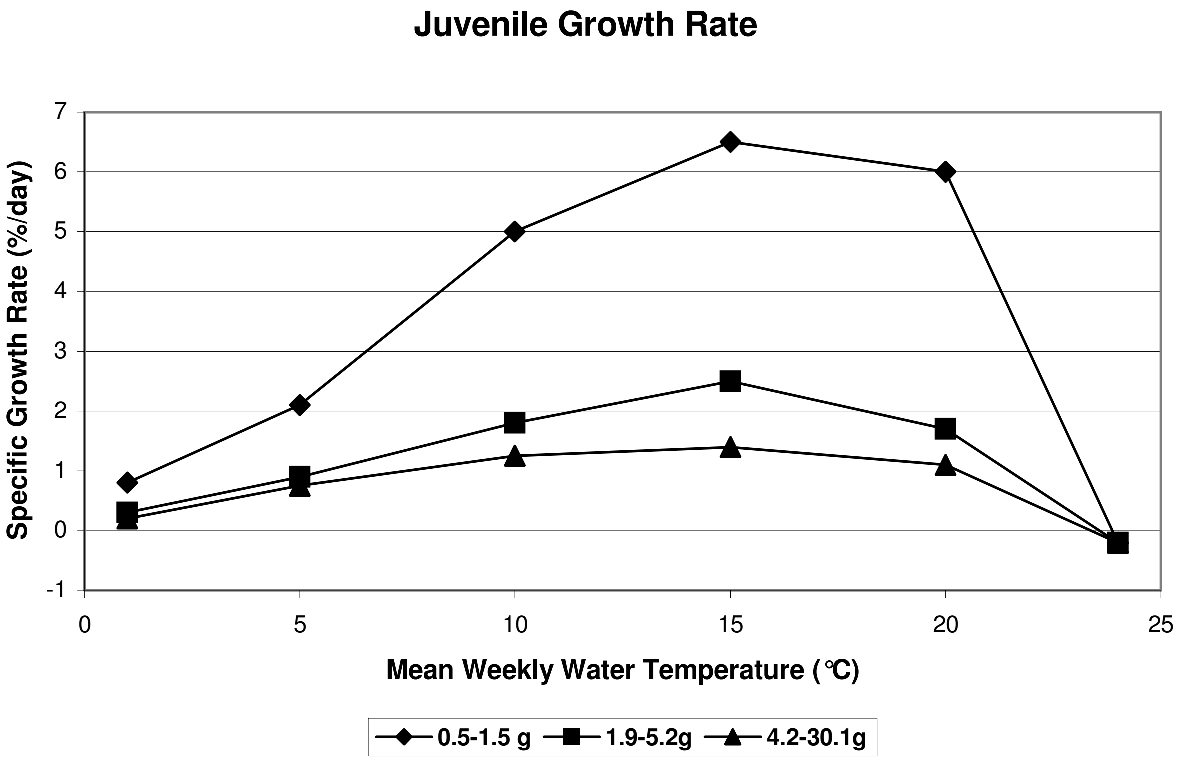


Figure 7. Juvenile growth rates for different weight fish (grams) as a function of mean weekly water temperature. Values are from Shelborne and others (1973).

Movement and Associated Mortality

Freshet Movement

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

Freshet movement was used initially in the model for the Trinity River but was discontinued due to lack of direct evidence for movement stimulus and is currently disabled for the Sacramento River.

Note that a corollary to the previous discussion is that a lack of freshet stimulations may "encourage" juveniles to remain longer in freshwater than they might otherwise do (Irvine, 1986). Future application of Salmod should more closely examine the evidence for or against simulating freshet-induced movement.

Seasonal Movement Timing and Attributes

Salmod moves juveniles a specified distance downstream through a specified time period. The assumption is that these fish are physiologically "ready" and that some combination of external timing cues (water temperature, discharge, and so forth) trigger downstream volitional movement of (pre)smolts (McDonald, 1960; Bjornn, 1971).

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 race. However, we found that under many circumstances, with the larger number of adult spawners and generally cooler 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, we lengthened the outmigration period to extend throughout the biological year, as shown in **Table 10**. Through the outmigration period, the proportion of each life stage actively moving was assumed to increase through time from 30 to 95 percent, while the corresponding mortality rate associated with this movement was assumed to decrease through time from 1.5 to 1 percent, a lower rate than we had previous used because higher rates had been questioned on the Klamath River.

Table 10. Time windows for outmigration for pre-smolts and immature smolts.

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

Note that Salmod does not adjust movement distance based on the river's discharge, as has been documented for the Columbia and Snake Rivers (Berggren and Filardo, 1993). This is an area of potential improvement in the model, though we would need reasonable estimates of travel time relative to discharge for the juvenile life stages. Movement rates found by Berggren and Filardo (1993) would not be applicable because in that study, movement rates were computed for fish moving through impoundments.

Base Mortality Rates

Base, or background, rates of mortality cover all causes of death not otherwise modeled by Salmod. For example, "normal" or "background level" predation fall into this category, as would mortality due to chronically low dissolved oxygen egg survival, unscreened diversions, and the like. The fractional rates we used came from the calibrated Trinity River model and are identical to those used previously on the Sacramento River (Bartholow, 2003). The weekly base mortality rates were: eggs, 0.035; fry, 0.025; pre-smolts, 0.025; and immature smolts, 0.025. The adult rate was 0.002 based on judgment.

Thermal Mortality Rates

Thermal effects on salmon have long been recognized as important on the Sacramento River as described in the Introduction. Thermal concerns span the range from (1) physiological changes, including direct or indirect mortality, growth rate, embryonic development, and susceptibility to parasites and disease; (2) changes to behavior, including seeking special habitat such as thermal refugia, altering feeding activity, shifting fish spatial distributions, and altered 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. Most of the temperature focus on West Coast rivers has been on high temperatures, with both the Central Valley of California and the Columbia River getting the largest share of attention. However, there is growing concern on East Coast rivers as well as selected interior habitats, for example Ozark and Appalachian Mountains.

Thermal mortality values for Salmod are meant to reflect 7-day exposure-related effects of water temperature. Acute mortality is generally defined as anything up to 96 hours, but Salmod’s 7-day (168-hour) time-step encompasses both acute and longer-term (chronic) mortality. The reason that Salmod uses mean weekly water temperatures instead of maximum daily temperatures is that there is a growing consensus that chronic, sublethal 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 and others, 1999). Brett (1956) concludes that sublethal thermal stress is as decisive as lethal temperatures to survival. Sub-lethal effects are also associated with sub-optimal growth rates, reduced swimming performance and associated predation, increased disease risk, and impaired smoltification (U.S. Environmental Protection Agancy, 2003, Marine and Cech, 2004).

Salmod deals with thermal mortality by life stage, that is 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; if an adult female dies for any reason, her eggs also die.)

Egg Thermal Mortality Rates

The basis for egg and embryo (including in vivo egg) mortality rates used in Salmod was work done by the U.S. Fish and Wildlife Service and the Bureau of Reclamation to evaluate the effectiveness of adding temperature control to Shasta Dam on the Sacramento River. For this project evaluation, Bureau of Reclamation (1991) built a salmon mortality model parameterized with values supplied by the U.S. Fish and Wildlife Service (Richardson and Harrison, 1990) in collaboration with the California Department of Fish and Game. The exact origin of the rate values supplied by Richardson and Harrison is somewhat obscure, but they cite Hinze and others (1956) and Boles (1988), among others.

Unfortunately, the USFWS calculated what is called "crude" mortality rates because for most, but not all, of the rates they presented (Table 11), they took the percent mortality and divided it by the number of days in the reference period to get the average daily mortality. Crude mortality rates would not be correct for Salmod or similar models because the model's mortality rates operate sequentially. For example, the egg mortality rate given by Richardson and Harrison (1990) for a temperature of 61°F is 80 percent at 15 days. Using their "crude" averaging method resulted in an average daily rate of 5.33 percent (they report 5.3 percent). But if one applied such a crude rate for 15 consecutive days, the resulting mortality rate would be:

$$15 \text{ day mortality } (M_{15}) = 1 - (1 - 0.0533)^{15} = 1 - 0.44 = 0.56$$

far different from the 80 percent they expected and Salmod requires.

We have corrected the values reported by Richardson and Harrison (1990) using a formula to calculate what is called an "absolute" or "instantaneous" mortality rate and then converting those rates to the reference time period, namely one week for Salmod. Continuing with the same example for illustration, we use:

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

where n is the number of days in the reference period. Thus we have:

$$M_1 = 1 - (1 - M_{15})^{1/15} = 1 - (1 - 0.8)^{1/15} = 1 - 0.898 = 0.102$$

Then a seven-day mortality rate would be calculated as:

$$M_7 = 1 - (1 - 0.102)^7 = 1 - 0.472 = 0.528$$

Regrettably, the 100 percent mortalities for temperatures over 62°F given in Richardson and Harrison (1990) present a challenge for this technique. The best we can do is to assume a 1 percent survival for mathematical convenience. Thus a single-day mortality rate that would result in 99 percent mortality at 12 days could be calculated as:

$$1 - (1 - M_1)^{12} = 0.99$$
$$1 - M_1 = 0.01^{1/12}$$
$$M_1 = 1 - 0.6812 = 0.3187$$

We also averaged the mortality rates Richardson and Harrison (1990) used for eggs and sac fry (embryos) to be consistent with the combined life-history simulated in Salmod for the Sacramento River. This was done by first calculating the absolute weekly mortality rate for both egg and sac-fry. We then averaged these two rates by taking the geometric mean of their respective survival rates (analogous to what we were doing above). We have complicated this somewhat by weighting the two survival rates by their respective durations. That is, the egg stage lasts about 2/3 of the whole egg-alevin life stage whereas the sac-fry stage lasts about 1/3. Thus, these two survival rates were weighted accordingly. This method assumes independence, which is probably not true, but we do not know a better alternative.

With one exception, the last column of Table 11 then records the in-gravel egg mortality rates used in the model. Richardson and Harrison (1990) did not evaluate temperatures below

13°C (55.4°F), but Combs and Burrows (1957) supply relevant data for egg mortality under low constant water temperatures (Figure 8). Data from their study indicate substantial mortality below about 4.5°C (41°F). However, these low temperatures do not appear to occur on the Sacramento River, making them irrelevant for this analysis.

Note that the Bureau of Reclamation may have updated their salmon mortality model with the revised egg mortality rates shown in table 11 (Russ Yaworsky, Bureau of Reclamation, oral comm., 2006).

Table 11. Calculation of mean weekly mortality rate as a function of mean daily water temperature (diel fluctuations of 3°F) for Chinook salmon. Values on the left side of the table were given by Richardson and Harrison (1990); those shaded on the right are our replacement calculations. [Temp, temperature; °F. degrees Fahrenheit; °C, degrees Celsius; %, percent; frct, fraction, <, less than; NA, not applicable]

Temp (°F)	Temp (°C)	Given egg mortality (%/days)[1]	Given egg avg. mortality (%/day)	Given sac-fry mortality (%/days)	Egg mortality (frct/day)[3]	Sac-fry mortality (frct/day)	Egg mortality (frct/week)	Sac-fry mortality (frct/week)	Geometric mean mortality (frct/week)
<56	13.33	Natural[2]	0.00	Natural	0.000	0.000	0.000	0.000	0.000
57	13.89	8 / 24	0.40	Natural	0.003	0.000	0.024	0.000	0.016
58	14.44	15 / 22	0.70	Natural	0.007	0.000	0.050	0.000	0.034
59	15.00	25 / 20	1.25	10 / 14	0.014	0.007	0.096	0.051	0.081
60	15.56	50 / 12	4.16	25 / 14	0.056	0.020	0.333	0.134	0.272
61	16.11	80 / 15	5.30	50 / 14	0.102	0.048	0.528	0.293	0.460
62	16.67	100 / 12	8.30	75 / 14	0.319	0.094	0.932	0.500	0.867
63	17.22	100 / 11	9.00	100 / 14	0.342	0.280	0.947	0.900	0.934
64	17.78	100 / 7	14.00	NA	0.482	NA	1.000	NA	1.000

[1]. Percent mortality for the number of days indicated.

[2]. Natural implies not elevated above normal background levels.

[3]. Mortality expressed as a fraction.

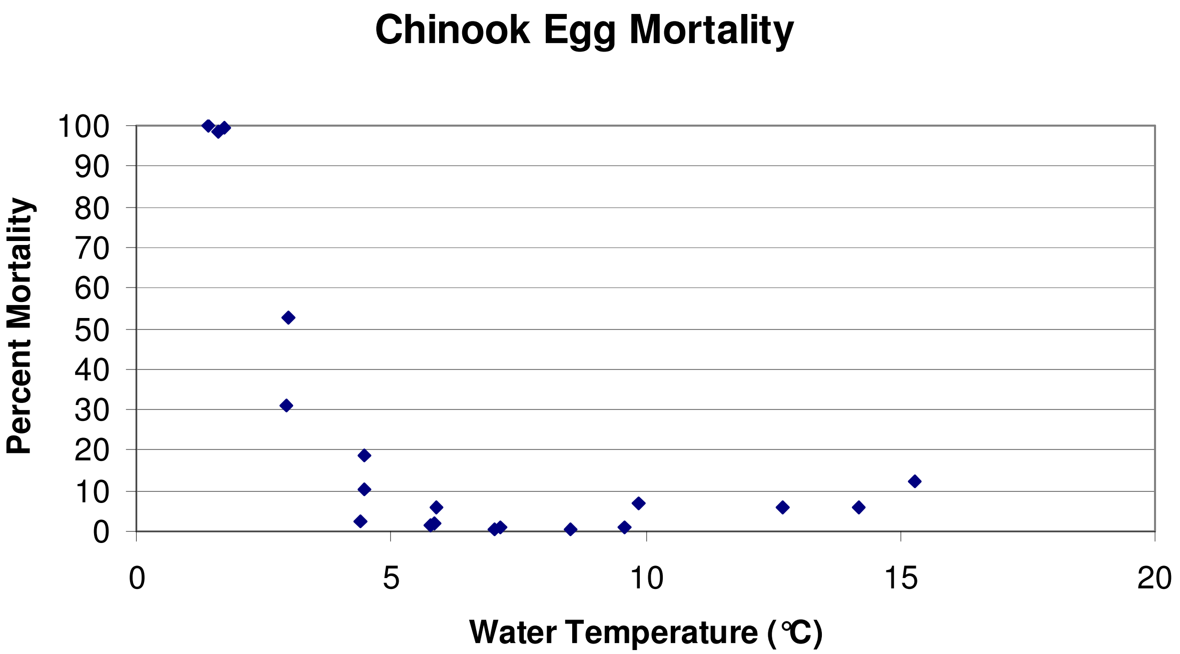


Figure 8. Egg mortality from low constant water temperatures, from Combs and Burrows (1957).

In Vivo Egg Mortality

Donaldson (1990) compiled an extensive list of likely potential effects of stressors (not just water temperature) on sexually maturing adults, including changes in gonad development, changes in the endocrine control system, and changes in gametes, all of which may reduce reproductive success or ultimate recruitment. In Salmod, these effects due to temperature have been lumped into the in vivo egg mortality category. In previous model applications, Salmod has been parameterized using an in vivo mortality rate as a function of water temperature identical to the rate used for in-gravel eggs.

Though not cited by the USFWS, probably the strongest evidence for in vivo gamete mortality has been presented by Billard (1985, his figure 7) citing his own published work (but in French), Berman (1990), Berman and Quinn (1991) and Leitritz and Lewis (1980). Berman held adult spring Chinook salmon at 14°C and 19°C. The group held at 19°C produced a greater number of pre-hatch mortalities and developmental abnormalities as well as smaller eggs and alevins. As with Berman and Quinn (1991), sample size was too small to permit statistical analysis, and disease was an issue. Leitritz and Lewis (1980, p. 33) dealt primarily with hatchery methods, stating that young rainbow trout should be reared at around 15.5°C (60°F) for good growth, but then maturing rainbows (including Chinook) should be held at water temperatures not exceeding 13.3°C (56°F), and preferably not above 12.2°C (54°F), for a period of at least 6 months before spawning. Flett and others (1996) speculated that low egg survival of coho swimming through warm lake surface water to spawn in tributaries was due to “overripening” in females exposed to high, but not lethal, temperatures. Unfortunately, exact thermal exposure was unknown. Smith and others (1983) showed that cutthroat trout (*Salmo clarki lewisi*) whose holding temperatures ranged from 2 to 10°C produced better quality eggs than those fish held at a constant 10°C, but the water sources were different.

Because there is a considerable body of published literature that suggests that there is a real in vivo thermal effect, we have chosen a compromise. We will assume that the in-gravel egg thermal mortality rates apply for in vivo eggs, but we will also assume that adults are behaviorally capable of buffering themselves (and their eggs) from the warmest in-river temperatures. For lack of any other value, we will use the 2.5°C difference found by Berman and Quinn (1991) for the Yakima River in Washington. Because of the uncertainty, this topic should be a priority for future research on the Sacramento River.

Juvenile and Adult Thermal Mortality Rates

Thermal mortality rates for juvenile and adult life stages were derived from Baker and others (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). This value is slightly lower than well-recognized laboratory data with established acclimation temperatures but is pragmatically estimated in the field from trawl runs two to five days after hatchery releases. One can use the Baker and others (1995) data to estimate a survival curve from a quasi-likelihood function the authors fitted:

$$\text{Survival rate} = \frac{1}{1 + e^{-a-bT}}$$

where a = 15.56;
b = -0.6765;
T = mean daily water temperature for the sampling period.

This method is appealing because it avoids problems associated with applying laboratory results to field situations and has an exposure period roughly equal to Salmod's. We are assuming that mortality rates for juveniles derived from Baker at al. (1995) also represent adult thermal mortality.

Though there are other data sets in the literature for adults, we wanted to retain the best estimate from field methodology. However, as has been discussed for in vivo eggs, adults may also be buffered from ambient thermal mortality. As mentioned previously, the study by Berman and Quinn (1991) demonstrated that adult spring 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. Though their study was for the Yakima River, at least some areas of cool-water refuges generally associated with tributary mouths are likely to exist in the Sacramento River. For example, Resource Management Associates, Inc. (2003) identified Battle Creek, Paynes Creek, and Antelope Creek as “cool,” and Clear Creek, Chum Creek, Cow Creek, Bear and Ash Creeks, Cottonwood Creek, Mill Creek, Deer Creek, Pine Creek, and Big Chico Creek as “moderate.” To be consistent with our in vivo mortality compromise, we have chosen to buffer adults by using the same 2.5°C value. In other words, the model would treat an ambient water temperature of 17.5°C as if it were only 15°C for adults in calculating thermal mortality. The mortality curves we used are shown in Figure 9.

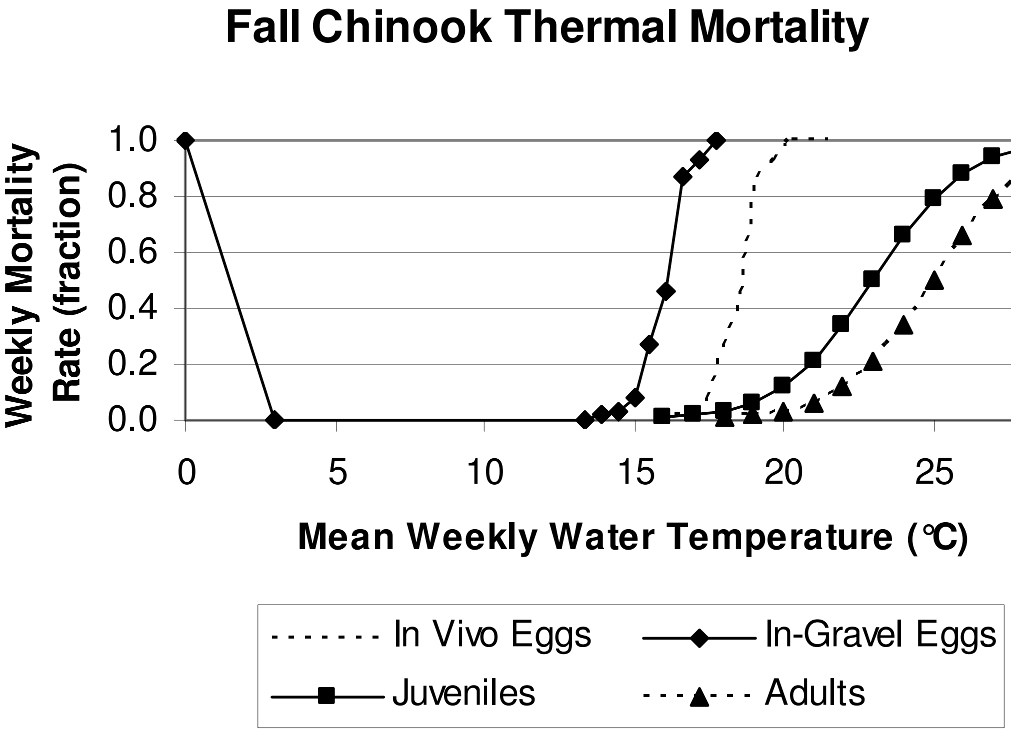


Figure 9. Mortality as a function of mean weekly water temperature used in Salmod simulations. See text for a description of data sources and assumptions. Mortality values used for in vivo eggs and adults have been shifted to the right by 2.5℃ to reflect assumed adult behavioral "thermoregulation."

Verification of Thermal Mortality Rates

Because Salmod can be sensitive to thermal mortality rates for all life stages, it was appropriate to seek independent verification. Representative values from the literature are provided below. In general, the authors are referring to constant temperature experiments, but occasionally their metrics are not specific:

Healey (1977) examined egg-to-fingerling mortality at the Coleman National Fish Hatchery and concluded that main stem Sacramento River temperatures should not exceed 14.2°C (57.6°F) to prevent abnormally high (about 80 percent) mortality.

Boles (1988) reviewed thermal requirements for each Chinook life stage. Though not quantified in a manner suitable for direct comparison, his findings include the following: (1) adults held at temperatures in excess of 15.5°C (60°F) exhibited "poor" survival and "reduced" egg viability; (2) eggs incubated at temperatures in excess of 15.5°C (60°F) suffer "high" mortality; (3) eggs incubated in the range of 12.8 to 14.2 (55 to 57.5°F) experienced sac-fry mortality in excess of 50 percent; (4)fingerlings appear to survive an upper lethal temperature of approximately 25.8°C (78.5°F) for long-term exposure.

Marine (1992) explored a wide variety of thermal effects with an emphasis on adults and their progeny. His findings are summarized in Table 12.

Table 12. A compilation of published information and summary of the observed relationships between water temperature and various attributes of spawning performance in Chinook salmon, with inferences on the sublethal elevated temperature range, derived from the scientific literature, agency reports, and interviews with fishery biologists and hatchery workers. Reproduced from Marine (1992). [℉. degrees Fahrenheit; ℃, degrees Celsius; <, less than; >, greater than]

Temperature range	Effect on adult salmon and reproduction	Sources cited by Marine
< 6°C (< 42.8°F)	Increased adult mortality, retarded gonad development and maturation, infertility.	Leitritz and Lewis (1976); Piper and others (1982).
10°C–18°C (50–64.4°F)	Physiological and behavioral optimum temperature range for non-gravid adult salmon.	Coutant (1977); Piper and others (1982); Raleigh and others (1986).
6°C–14°C (42.8–57.2°F)	Optimal pre-spawning broodstock survival, maturation, and spawning temperature range.	Leitritz and Lewis (1976); Piper and others (1982).
15°C–17°C (59–62.6°F)	For chronic exposure, inferred range of incipient sublethal elevated water temperature for broodstock, increased infertility, and embryonic developmental abnormalities.	See text for derivation of this temperature range.
17°C–20°C (62.6–68°F)	For chronic exposure, incipient range of upper lethal water temperature for pre-spawning adult Chinook salmon (primarily derived from observations of captive broodstock).	Hinze and others (1956); Rice (1960); Bouck and others (1977); Berman (1990); and personal communications (see text).
13°C–27°C (55.4–80.6°F)	Increased pathogenesis of many of the important salmonid disease organisms with potential for impairing reproduction in Chinook salmon.	Fryer and Pilcher (1974); Becker and Fujihara (1978); Post (1987).
25°C–27°C (77–80.6°F)	Range of highest elevated temperatures observed to be transiently passed through during migrations or tolerated for short-term by adult Chinook salmon.	Moyle (1976); Piper and others (1982); Department of Water Resources (1988).

Myrick and Cech (2001) provide a recent comprehensive review for Central Valley salmon. They conclude that eggs can survive between 1.7 and 16.6°C (35.1–61.9°F), but with increased mortality below 4°C (39.2°F) or above 12°C (53.6°F). The chronic upper lethal level is approximately 25°C (77°F) with higher temperatures, up to 29°C (84.2°F), tolerated for short periods. Marine and Cech (2004) provide the latest information for juveniles. They conclude that juvenile fall Chinook salmon can withstand chronic (more than 60 day) exposure to temperatures in the range 21–24°C (69.8–75.2°F) (with diel fluctuations) and even grow when fed without limit, albeit at reduced rates. At these temperatures, smoltification was impaired, and the smaller fish were at increased vulnerability to predation. Fish reared at 17 to 20°C (62.6 to 68°F) grew well, but experienced variable smoltification impairment and higher predation rates than fish reared at 13 to 16°C (55.4 to 60.8°F). Although Marine and Cech (2004) conclude that the Baker and others (1995) results likely represented indirect thermal effects as opposed to direct upper incipient lethal thermal effects, for Salmod's purposes, the distinction is unimportant because thermal mortality covers both direct and indirect effects.

Olson and Foster (1955) showed that Columbia River Chinook eggs suffered a total of 79 percent mortality through the fingerling stage if initial incubation temperatures were 18.4°C (65.2°F), but only 10.4 percent mortality if the temperature was 16°C (60.9°F). The latest compilation of information appears in information assembled in support of thermal criteria developed by the U.S. EPA primarily for use in Total Maximum Daily Load (TMDL) analyses (Poole and others, 2001). This compilation drew heavily from the work of McCullough (1999) and is summarized in Table 13.

Table 13. Estimates of thermal conditions known to support various life stages and biological functions of anadromous salmon. These numbers do not represent rigid thresholds, but rather represent temperatures above which adverse effects are more likely to occur. In the interest of simplicity, important differences between various species of anadromous salmon are not reflected in this table. Likewise, important differences in how temperatures are expressed are not included (for example instantaneous maximums, daily averages, and so forth). Adapted from Poole and others (2001). [°C, degrees Celsius; °F, degrees Fahrenheit; >, greater than; <, less than]

Consideration	**Anadromous Salmon**	
Temperature of common summer habitat use	10–17°C	50–62.6°F
Lethal temperatures (one week exposure)	Adults: >21–22°C Juveniles: >23–24°C	>69.8–71.6°F >73.4–75.2°F
Adult migration	Blocked: >21–22°C	>69.8–71.6°F
Swimming speed	Reduced: >20°C Optimal: 15–19°C	>68°F 59–66.2°F
Gamete viability during holding	Reduced: >13–16°C	>55.4–60.8°F
Disease rates	Severe: >18–20°C Elevated: 14–17°C Minimized: <12–13°C	>64.4–68°F 57.2–62.6°F <53.6–55.4°F
Spawning	Initiated: 7–14°C	44.6–57.2°F
Egg incubation	Optimal: 6–10°C	42.8–50°F
Optimal growth	Unlimited food: 13–19°C Limited food: 10–16°C	55.4–66.2°F 50–60.8°F
Smoltification	Suppressed: >11–15°C	>51.8–59°F

Finally, a relatively new report (Richter and Kolmes, 2005) synthesizes numeric water temperature criteria on a mean weekly basis as follows: spawning and incubation, 10°C (50°F); juvenile rearing, 15°C (59°F); adult migration, 16°C (61°F); smoltification, 15°C (59°F). So, in short, there does not appear to be any information that provides more temperature dose-response quantification than that developed from Richardson and Harrison (1990), Combs and Burrows (1957), and Baker and others (1995) with the modifications we have applied. However, it is apparent that much of the emphasis has been on developing thermal standards (thresholds), not examining exposure-related mortality. To corroborate the estimates we derived from Baker and others (1995) we examined the more “classic” approach to calculate mortality given exposure time and acclimation temperature. Armour (1991) summarizes parameters for an equation that, if evaluated to be greater than 1.0, mortality is expected to occur:

$$1 \geq \frac{\text{minutes}}{10^{[a + b\ (\text{temperature}^\circ\text{C} + 2^\circ\text{C})]}}$$

where $a = 22.9065$ and $b = -0.7611$ for an acclimation temperature of 20°C (68°F)

Using this equation and a weekly exposure (10,080 minutes), a temperature of 23°C (73.4°F) is expected to result in 50 percent mortality, in remarkably exact agreement with the Baker and others (1995) formula (see Figure 9). Thus, using multiple lines of evidence, relevant data and accepted methods point to the conclusion that the relationships given in Figure 9 are acceptable for modeling.

Uncertainty in thermal mortality rates

Having said that we are comfortable with our initial compilation of mortality rates, we also acknowledge room for evaluation and adjustment. Let us briefly revisit both the egg and juvenile/adult criteria.

Eggs

It well could be that the egg mortality rates derived from hatchery studies are too high at moderate temperatures because eggs, and presumably embryos, remain buried in approximately 10–30 cm of gravel and may be buffered from in-channel water temperatures that would otherwise be too hot, or too cold, for optimum survival. Shepherd and others (1986) showed that intragravel temperatures approximately 10 cm into the streambed cause parallel but lagged and buffered heating and cooling trends in infiltration-source intragravel water compared with surface water. Such waters were generally 0.5–1.0°C warmer in winter and 0.5–1.5°C cooler in summer, with crossovers around March and October. Hannah and others (2004) showed that in-gravel incubation temperatures were, on average, 1.97°C warmer than water column temperatures in a coastal Scottish salmon stream. However, Geist and others (2002) found that Chinook, unlike chum salmon (*Oncorhynchus keta*), in the Columbia River tended to spawn in zones of downwelling water where, presumably, a redd’s thermal environment would be more like that of the main river. We have chosen to assume (per Geist and others, 2002) that intragravel egg temperatures are likely to be little different from main channel water temperatures. This may be an appropriate area for research in the future.

Juveniles and Adults

There may be problems using the Baker at al. (1995) technique applied previously. The data were collected from fall run hatchery fish traversing the sometimes-brackish waters of the Sacramento bay-delta system. Fish recoveries were made from mid-water trawls that may bias the interpretation for fish not actively (or passively) outmigrating. There are a variety of mathematical assumptions implicit in the curve fitting that Baker and others (1995) did. Exposure times were not uniform and may or may not conform to Salmod's weekly time-step. Finally, the data represent only smolts, yet we have applied the results to all juvenile and adult life stages. In spite of these limitations, we feel that this approach is a step forward from the more simplistic habitat suitability index (HIS)-type method used in some previous Salmod applications and helps avoid using unmodified laboratory-derived data in real world applications (Ligon and others, 1999).

There has always been speculation that California's southerly salmon stocks may exhibit higher thermal thresholds than other West Coast stocks. However, during the course of our literature review, we found no conclusive evidence that this is true. McCullough (1999) investigated the issue of stock-specific thermal adaptation as part of his comprehensive review and found that, although there are well recognized genetic adaptations to temperature that appear to tailor the fitness of stocks to their environment, absolute differences are small, generally attributable to morphological distinctions, and never result in a conclusion that thermal standards should be stock specific. Myrick and Cech (2001) comment that Central Valley Chinook salmon, despite their southerly distribution, do not appear to have any greater thermal tolerance than more northerly races. Further, thermal tolerance is a function of acclimation history that is, of course, an implicit consequence of each unique physical setting and time series of thermal exposure.

In sum, we feel comfortable that we have identified suitable sets of thermal mortality rates for each of the Chinook life stages, at least initially. Remaining uncertainty leaves some room for adjusting those rates, up or down, as we learn and adapt the model. Further research would be welcome.

Habitat Capacity

Salmod assumes a relatively fixed "capacity" per unit of available physical habitat for adult and juvenile fish (Chapman, 1962, 1966; Mesick, 1988; Beechie and others, 1994; Burns, 1971). Capacity is computed by knowing the flow in each computation unit, translating that 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 computation unit.

In previous Salmod applications, we have used either the maximum number of fish or maximum biomass per unit area. On the Trinity River, for example, the biologists preferred the maximum number because it best matched the data they had collected from systematic snorkel observations. Kent (1999) subsequently applied the Trinity River derived values to the initial Sacramento River model but did not calibrate the model. In an earlier study (Bartholow, 2005), I used the maximum biomass approach rather than numbers of individuals because I believed that (1) it is more consistent with what we understand in terms of bioenergetic requirements, (2) measuring density with numbers per unit area has the problem that two individuals of different body size should not count equally, and (3) because biomass increases as fish grow in length and weight, such growth would result in a somewhat constant "pressure" for some individuals to move (Grant and Kramer, 1990; Bohlin and others, 1994; though see Grant and others, 1998, for a critique). An approach used in France is to choose the median biomass per unit area.

Regardless of the technique used, it is apparent that one can obtain vastly different density estimates in different riverine settings, and great care must be used if one transfers site-specific density values from another river to the Sacramento River unless verified. Density estimates described by Grant and Kramer (1990) were largely from small, "natural" streams; the Sacramento River with its in-line reservoir is anything but natural and small. Further, Salmod assumes that maximum habitat capacity is per unit of ideal habitat (WUA), and the quality of ideal habitat may not be transferable from small streams to large rivers (Grant and others, 1998). The factor most likely to influence the "currency," and therefore lack of transferability from one stream to another, is food availability because food productivity is thought to directly affect minimum territory size (Grant and others, 1998). For example, Allen (1969) cites an average salmonid density of 1.7 g/m^2 for New Zealand rivers, an order of magnitude smaller than the values from Grant and Kramer (1990). Hume and Parkinson (1987) cite stocking densities as low as 0.3–0.7 fry/m^2 in low productivity British Columbia streams.

Mark Gard (U.S. Fish and Wildlife Service, Sacramento) supplied revised site-specific maximum density estimates for the Sacramento River that were used in the previous model application. These were based on observations (actually 90 percent of absolute maximum observed) of 106 fry smaller than 60 mm and 200 juveniles larger than 60 mm. In the previous application, I used an average weight of 0.94 gram for fry, resulting in approximately 100 g per unit WUA, but experimentation with the current model suggested that it was likely overestimating fry habitat-induced mortality. On reflection, fry can be anywhere from 30 to 60 mm, totaling from 20 to 240 g/m^2 depending on their length, so we chose to increase the maximum biomass density to 250 g/m^2 for this application, in part because California Department of Fish and Game was wary of putting undue emphasis on juvenile habitat limitations, and the previous model (Bartholow, 2003) was viewed as likely underestimating production. **Table 14** reflects the maximum biomass for each life stage used in this Sacramento River application, identical to what was used previously by Bartholow (2003) as corrected by Mark Gard (U.S. Fish and Wildlife Service, Sacramento).

Table 14. Maximum biomass per unit WUA for each life stage used in the Sacramento River application.

Life stage	Maximum grams/square meter/WUA
Fry	250
Pre-smolts	1162
Immature smolts	1162
Adults	52.58

Habitat-Induced Movement Rules

In the event that fry in a computation unit exceed the computed habitat capacity, we set Salmod to first move the most recent arrivals out of that computation unit under the supposition that moving, non-territorial fry are more likely to continue to move. In contrast, the model moves the more territorial pre-smolts and immature smolts with the lowest condition factor first, assuming that more robust fish have a territorial advantage. These two methods operate only within in a life stage category, that is, fry only compete with fry, and so forth. It is possible to set Salmod to be even more size selective within a life stage. In other words, one could move the smallest, most recently arrived fry first, but we have not done so for this Sacramento River application as it does not appear to affect the results significantly. On the Sacramento River, all habitat-induced movement is set to be downstream only.

Distance Moved Mortality Rate

There is a mortality rate associated with habitat-constrained movement–the farther fish must travel to encounter unoccupied habitat, the greater their mortality. Though there are a variety of ways to quantify this mortality in Salmod, we find it conceptually easiest to specify the maximum distance that can be moved in one week before 100 percent mortality, linearly interpolating back to zero mortality at zero distance, though it is possible to describe any curvilinear function one can support or hypothesize.

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

Exogenous Production

Chinook salmon production in the Sacramento River downstream from Keswick is not isolated to the main stem. Several tributaries and two hatcheries (Battle Creek and Livingston Stone) also produce fish that supplement main stem production, with those fish entering the main stem at specific locations during specific time periods. If specified in Salmod, these additional tributary fish contribute to production along with main stem fish, undergoing all simulated main stem events. It should be understood that these tributaries are not simulated as individual streams; rather, the exogenous production has been simulated as constant for each year just like adult main stem spawners.

For this application, we compiled hatchery production information for the period 1992 to 2004. Releases were, however, inconsistent between the hatcheries, with some releases made at downstream locations different from their hatchery stream. Because of these inconsistencies, and because most of the releases appeared to be made in a manner that deliberately avoids the peak outmigration period (presumably to avoid the possibility of competition for food and space with natural fish), we have not included hatchery production in this application.

We received a summary of weekly production estimates from Clear Creek, 1998 to 2004, from Matt Brown (U.S. Fish and Wildlife Service, Red Bluff). The data had been divided into four average weekly time series, one for each "race." But according to Mr. Brown, the four categories represented fish length instead of true race. By far the majority of fish were nominally classified as fall Chinook, with the other "races" representing less than 2 percent of the "fall" fish. We computed an average length for each weekly cohort based on the length:weight conversion formula given previously and scaled the numbers of fish in an attempt to better match the relative production between main stem and tributaries. Because we did not receive similar Battle Creek production estimates in time, we simply duplicated the Clear Creek values when we added these "fall" fish to Salmod's input files as shown in Table 15. We did not do this for the other races because the number of fish of the other races from Clear Creek was comparatively small.

Table 15. Scaled number of "fall" Chinook added to the fall Chinook Salmod model to represent tributary production.

Date	Week #	# of Fish	Weight (g)
12/3	14	9,447	0.192
12/10	15	7,972	0.192
12/17	16	10,812	0.233
12/24	17	46,895	0.320
12/31	18	86,050	0.320
1/7	19	134,149	0.367
1/14	20	188,462	0.367
1/21	21	493,681	0.415

1/28	22	472,797	0.415
2/4	23	337,226	0.415
2/11	24	300,265	0.415
2/18	25	385,796	0.466
2/25	26	235,752	0.466
3/4	27	197,219	0.466
3/11	28	128,375	0.519
3/18	29	75,703	0.633
3/25	30	61,695	0.756
4/1	31	20,947	0.890
4/8	32	26,171	0.961
4/15	33	13,945	1.362
4/22	34	12,134	1.846
4/29	35	12,506	2.300
5/6	36	12,945	2.424
5/13	37	14,730	2.424
5/20	38	15,144	2.424
5/27	39	5,492	2.424
6/3	40	2,592	2.683
6/10	41	1,374	3.106
6/17	42	830	3.106
6/24	43	1,023	3.570
7/1	44	513	4.078

Conceptually, tributaries enter the simulation model's virtual river at one computation unit. Adding one week's tributary contribution to a single computation unit would result in disproportionate crowding in that unit. An alternative would be to distribute these fish for a distance equal to one week's travel time downstream, but this would essentially permit distribution throughout most of the study area. We chose a compromise by assuming that tributary fish would be distributed throughout a 5-km "mixing zone" downstream from each tributary. Juveniles entering the main stem are treated just like main stem cohorts; if they are moving seasonally, they will continue to do so.

Summary of Model Parameters and Variables

Obviously Salmod has many input requirements. To the degree possible, we have endeavored to derive evidence-based inputs from Sacramento River-specific sources. However, some values were derived from literature sources, previous model applications, and assumptions. Table 16 summarizes these values and where appropriate shows which ones have been changed from the previous application (Bartholow, 2003).

Table 16. Summary of important model structural elements, parameters, variables, and potential calibration data, with notes on their origin and status.

Element, parameter or variable	Sacramento-specific	Differs from previous application	Status
Study area	Yes	Yes	Fixed at present; Keswick to Red Bluff inundation pool.
Flow and temperature segments	Yes	Yes	Fourteen segments, matched to hydrology and thermal attributes of the river.
Flow and water	Yes	Yes	Comes from Calsim/HEC-5Q. Calsim deals in monthly flows

Element, parameter or variable	Sacramento-specific	Differs from previous application	Status
Temperature values			that have been disaggregated to daily by Bureau of Reclamation and subsequently aggregated by Reclamation and USGS to weekly means. These transformations may mask peak flows or temperature events. Scenarios are all synthetic, essentially eliminating the opportunity to field verify model results. Water temperature model (HEC-5Q) also contains uncertainty and known seasonal biases (RMA, 2003).
Mesohabitat typing data and sequence	Yes	Yes	Derived from detailed habitat mapping.
PHABSIM WUA quantification	Yes	No	Available, with assumptions. Differences in methods between Kent, Cal DWR, and USFWS as interpreted by USGS.
Biological year timing	Yes	No	Good.
Life stage nomenclature and size class breakpoints	Yes	No	Good.
Weight:length relationship	Yes	No	Well defined.
Spawning spatial and temporal distribution	Yes	Yes	Well defined, but using multi-year average.
Spawning temperature window	No	Yes	Well defined from literature.
Spawner density and characteristics	Yes	Yes	Reflects race-specific goals.
Fecundity	Yes	Yes, for winter run only	From Coleman Hatchery and literature.
Redd area and superimposition	Yes	Yes	Well defined, but deliberately reduced estimated superimposition by reducing redd area, using “avoidance” option, and allowing spawning in computation units without recorded redds.
Egg development rate	No	No	From reliable literature.
Emergent length	Yes	No	From field measurements
Minimum emergence temperature	No	Yes	Reasonable estimate, but called into question on the Klamath River.
Juvenile growth rates	No	No	Well-defined literature values that have worked well on this river.
Freshet movement attributes	Not used on Sacramento River	No	Largely stable flows in dry years may precluded measurement–monitor.
Seasonal movement timing and attributes	Yes for timing but no for distance	Yes	Not well defined.
Base mortality rates	No	No	Values derived from Trinity River.

Element, parameter or variable	Sacramento-specific	Differs from previous application	Status
Thermal mortality rates	Partly	Yes	Composite values from multiple literature sources.
Habitat capacity	Partial	Yes for fry; No for other life stages	Based on extensive sampling.
Habitat capacity movement rules	No	No	Literature and previous model based.
Distance moved mortality rate	No	Yes	Derived initially from Bill Snider, but adjusted.
Exogenous production	Yes	Yes	Derived from Clear Creek; assumed Battle Creek was identical to Clear Creek; other tribs and hatchery ignored.

Sensitivity Analysis

Salmod is a mathematical model constructed from a series of variable inputs, equations, and parameters that describe and quantify Chinook salmon production potential on the Sacramento River downstream from Keswick Dam. Variables are defined as those external driving factors (flow, water temperature, and spawner seeding density) that vary from time step to time step or year to year. Parameters are essentially fixed values controlling internal model computations. It is important to understand uncertainties in both model variables and parameters, but in this initial sensitivity analysis (SA) we are primarily targeting model parameters. Though we deal with spawner seeding here, sensitivity to flow and temperature variability will be addressed in another stage of the analysis.

Model parameters are subject to many sources of uncertainty including errors of measurement, absence of information, and poor or partial understanding of important biological mechanisms. These limitations necessarily tax our confidence in model predictions. Good modeling practice requires that the modeler provide an evaluation of his or her confidence in the model, a portion of which involves assessing uncertainties associated with all model inputs.

Sensitivity analysis is one tool that can be used to:

- Apportion the relative variation in model output to variation in model inputs, qualitatively or quantitatively
- Identify those parameters in the greatest need of additional empirical data collection
- Identify factors that may prove useful in subsequent model calibration
- Identify insensitive variables that require little further attention
- Establish defensibility in the sense that reviewers are increasingly asking for sensitivity analysis as a component of a thorough modeling analysis.

Sensitivity Analysis Methods

These are the general steps followed in conducting a SA for Salmod on the Sacramento River:

1. Specify the model output of interest. It is important to select only one or a few of the many outputs produced by a model and identify this as the output of interest. In our case, the key value chosen was the total annual number of Chinook outmigrating downstream from Red Bluff. Though we could have chosen biomass, we elected to choose numbers of fish because we felt that this would be

more widely understood by all stakeholders, and we relied on this metric during subsequent modeling analysis.

2. Select the inputs of interest from the full suite of possibilities, focusing on the most likely sensitive factors. Salmod has literally many hundreds of input values. If every single value were subject to variation, it would be very difficult to make sense of the voluminous results. For this reason, we grouped values into sets that were subsequently treated as single factors. For example, Salmod has a set of x,y coordinates that describe the relationship between mean weekly thermal exposure and mortality rate for each life stage. Rather than test the sensitivity of each coordinate pair, we shifted the whole set of coordinates "left and right" by 2°C for each life stage.

3. Choose the amount of variability for the selected factors. There is no single standard technique in performing a sensitivity analysis. Parameter variation is typically specified either as proportionate (for example ± 10 percent) or through a "reasonable range" (for example, from a low to high "probable" or "expected" value). We have chosen the reasonable range approach for most parameters, but we also used the proportionate approach when we could not clearly identify the reasonable range. Note that using both techniques can result in measures of sensitivity that are difficult to compare. For example, adjusting the calendar date of downstream pre-smolt migration by ±1 week may not be directly comparable to varying the temperature that initiates spawning by ±2°C because the units of variation differ. In addition, it should be clear that we may have overestimated the variability range for some parameters and underestimated the range for others, regardless of the approach. A comprehensive list of parameters and the variability assigned to them is given in **Table 17**.

Table 17. Considerations in choosing sensitivity variation range for each important model constituent. [5, percent; ±, plus or minus; WUA, weighted usable area; NA, not applicable]

Structural elements	Uncertainty	Sensitivity range
Study area	Downstream fate (including estuary and ocean) are considerable.	None
Flow and temperature segments	Considered minor; segments, well matched to hydrology and thermal characteristics of the river.	None
Mesohabitat typing data and downstream sequence	Derived from detailed habitat mapping. Any misclassifications considered random.	None
Life stage nomenclature and length class breakpoints	Considered minor. Some investigators may use slightly different values.	None
Initiation of biological year	Some adults may be in study area somewhat prior to model initiation.	None
Hatchery supplementation	Not included at this time.	None
Tributary supplementation	Is not dynamic across years/conditions. Fall Chinook only. Numbers.	±10 percent
	Weight.	±10 percent

Driving environmental variables	Uncertainty	Sensitivity range
Flow and water temperature values	All values from other simulations. Aggregation to weekly time-step masks peaks.	None.
Parameters	**Uncertainty**	**Sensitivity range**
Q:WUA quantification (life stage-specific)	Considerable. Magnitude (y-axis).	0.5 to 2 times
	Unknown. Flow-dependence (x-axis).	Did not vary
Weight:length relationship	Agrees well with other rivers.	None
Spawning initiation temperature	Annual temperatures are generally constrained on the Sacramento River.	± 2°C “shift”
Spawning spatial and temporal distribution	Well defined, but using multi-year average for all attributes. Distribution through study area.	None
	Initiation timing (x-axis).	± 1 week
	Duration or “peakedness” (x-axis).	± 1 week
Spawner density and characteristics	Number of adults.	± 10 percent
	Sex Ratio (actually spawners to non-spawner ratio).	± 10 percent
	Size (weight).	± 10 percent
Fecundity	Could perhaps improve based on more current estimates.	± 10 percent
Redd area	From measured data, but adjusted to minimize superimposition.	± 10 percent
Superimposition option	Set to Avoidance to minimize superimposition.	Random/ Avoidance
Egg development rate	Some uncertainty in hatch to emergent timing.	± 2°C “shift”
Emergent length (weight)	34mm; contains both uncertainty and variability.	± 10 percent
Minimum emergence temperature	Literature derived, but for Atlantic salmon. Has been called into question on the Klamath River. Lowered to 6°C.	± 2°C “shift”
Juvenile growth rates (life stage-specific)	Some uncertainty because values derived from ad lib feeding.	± 2°C “shift”
Freshet movement attributes (life stage-specific)	Trigger.	NA
	Distance moved.	NA
	Mortality.	NA
Seasonal movement attributes (Life stage-specific)	Initiation timing and subsequent duration.	± 1 week
	Distance moved.	± 10 percent
	Mortality–much uncertainty.	± 10 percent
Base mortality rates (life stage-specific)	Much uncertainty.	± 10 percent
Thermal mortality rates (life stage-specific)	Uncertainty due to many causes.	± 2°C “shift”
Habitat capacity (juvenile life stage-specific)	Uncertainty from multiple causes.	0.5 to 2 times
Habitat capacity movement rules	Several assumptions, but considered fixed assumption of the model.	None
Habitat-related distance moved mortality rate (Life stage-specific)	Much uncertainty. Will vary only the distance to 100 percent mortality.	0.5 to 2 times

4. Choose variation technique. The simplest and most common sensitivity analysis varies one parameter at a time, executing the model repeatedly to quantify any differences in key model outputs. The next level of complexity calls for variation of more than one parameter at a time, typically from a joint probability distribution that attempts to describe how the parameters might vary in tandem. However, it is often the case that such a joint probability distribution is itself unknown. We chose the single factor approach due to its simplicity. Under the presumption that all uncertain factors are susceptible to "correct" determination, and have the same cost to remove uncertainty, this so-called first-order sensitivity analysis identifies the factor(s) most deserving of better field or experimental measurement.

5. Generate a matrix showing the maximum sensitivity in model outputs from parameter variation. Again, we have chosen a simple design. We begin with the base simulation that contains our current best estimate of parameters. Then we make two other simulation runs, one with the high estimate and one with the low. Computing the biggest absolute change in outmigrant numbers (high minus base or low minus base) provides a measure of the maximum sensitivity for this parameter. In addition, having three points for each parameter (high, base, and low) enables us to examine whether variation in each parameter causes a linear or non-linear response. We do not discuss this last point further here.

6. Repeat Step 5 for a variety of year types. Following the philosophy of looking for the maximum possible sensitivity, we also wanted to make sure that we examined a variety of different year types, from wet to dry and hot to cold. After examining the range of conditions (Figure 10) we chose four specific years: wet-cold 1974, wet-average 1938, dry-average 1936, and dry-hot 1934. As before, we chose the maximum sensitivity for each parameter across all nine year types.

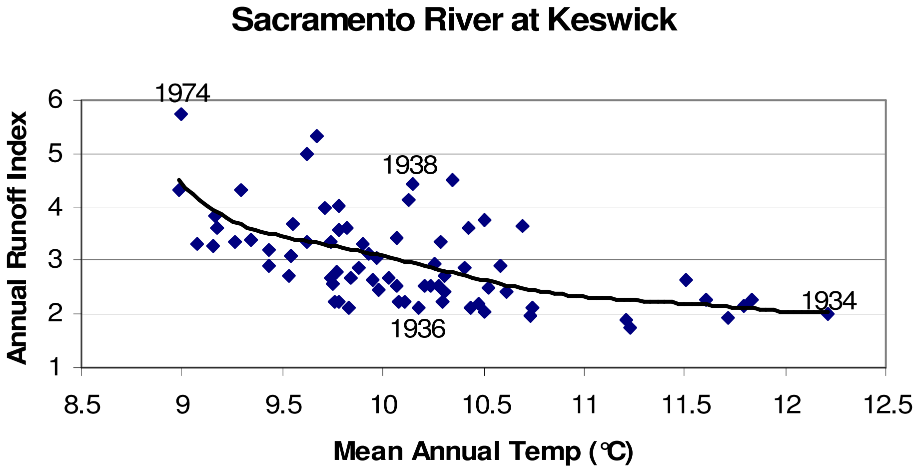


Figure 10. Individual water years being analyzed arrayed according to total annual runoff and mean annual water temperature downstream from Keswick Dam. Solid line is simple polynomial fit, and four labeled points are the water years selected for sensitivity study.

7. Repeat across all four races of Chinook.

To summarize, we chose the maximum parameter sensitivity across three different cases: base compared with high and low parameter estimates, and then across four year types, all for each Chinook race.

Sensitivity Analysis Findings

The following figures summarize the findings. We have displayed each parameter's relative sensitivity by scaling all sensitivity values to a maximum value of 100, where 100 represents the largest change from baseline conditions for each race independently. Those parameters rated as highly sensitive essentially demand extra scrutiny. Parameters of lesser sensitivity are still important but are not likely to dominate Salmod's predictive ability. Parameters with low sensitivity warrant little scrutiny at this time.

Though there were a few distinct race-by-race differences apparent from this analysis, it is also possible to develop some generalities. One factor that stands out across all races is fry habitat (or capacity). This should not be too surprising given the inherent uncertainty with these parameters (Gard, 2005) and because the results reflect our liberal 0.5 to 1.5X weighting, higher than for most other parameters. To a large degree, all stocks also showed some sensitivity to the maximum distance fry can move before suffering 100 percent mortality. This is a logical correlate. Fry growth rate also stands out as a "blip" across all races, although far less important.

Beyond these few similarities, the individual race differences are important. The fall run showed sensitivity to spawning WUA and the parameter describing the distance fry are forced to move to find available habitat before 100 percent mortality. The late fall run, for whatever reason, showed sensitivity to more parameters than the other races. Late fall fish were also sensitive to spawning WUA and fry movement distance, but to this list one must add pre-smolt and immature smolt seasonal movement parameters. Other parameters dealing with spawning (initiation week, spatial distribution, sex ratio, fecundity) were also of some importance. Winter and spring Chinook had the aforementioned similarities but also showed some sensitivity to egg temperature mortality and fry growth rates.

Though we did the Sacramento River sensitivity analysis somewhat differently than one on the Klamath River, we were surprised that several other factors relating directly to species life-history timing, emergence temperature, and spawning initiation week did not collectively show up as important. Bartholow (2005) had shown that timing was a key determinant in predicting relative survival for the four races of Chinook salmon in the Sacramento River. Instead, one could interpret the results as indicating most parameters fell into a moderate sensitivity range, neither outstanding nor zero.

Sensitivity analysis as such does not address the issue of model realism. In other words, one might identify a parameter that has little influence on simulated model outcomes, but if the value is "wrong," it will detract from the believability and trust in model results regardless. In addition, one must be cognizant that in complicated, multi-parameter models, errors in one parameter may be masked by errors in other parameters without significantly affecting model behavior. Should one choose an apparently sensitive parameter as a management focus, it would be wise to test that sensitivity as a hypothesis before a full-scale effort. Sensitivity analysis can also be used to address the model's internal structure. In our opinion, that is not our principal objective here. However, we must not lose sight of the fact that Salmod attempts solely to represent the freshwater dynamics and is not a full life-cycle model.

It is also important to remember that sensitivity analysis does not in any way identify parameters that are wrong. The model may well be, and should be, sensitive to parameter changes. A different form of sensitivity analysis that could be pursued is what might be called the ultimate sensitivity analysis where one would examine how parameter variation might lead to a change of decision in using the model. This would require much additional work, but certainly what we have been doing is a sensitivity analysis of the variables, flow and water temperature, and how that variation may have had an effect on historical salmon production.

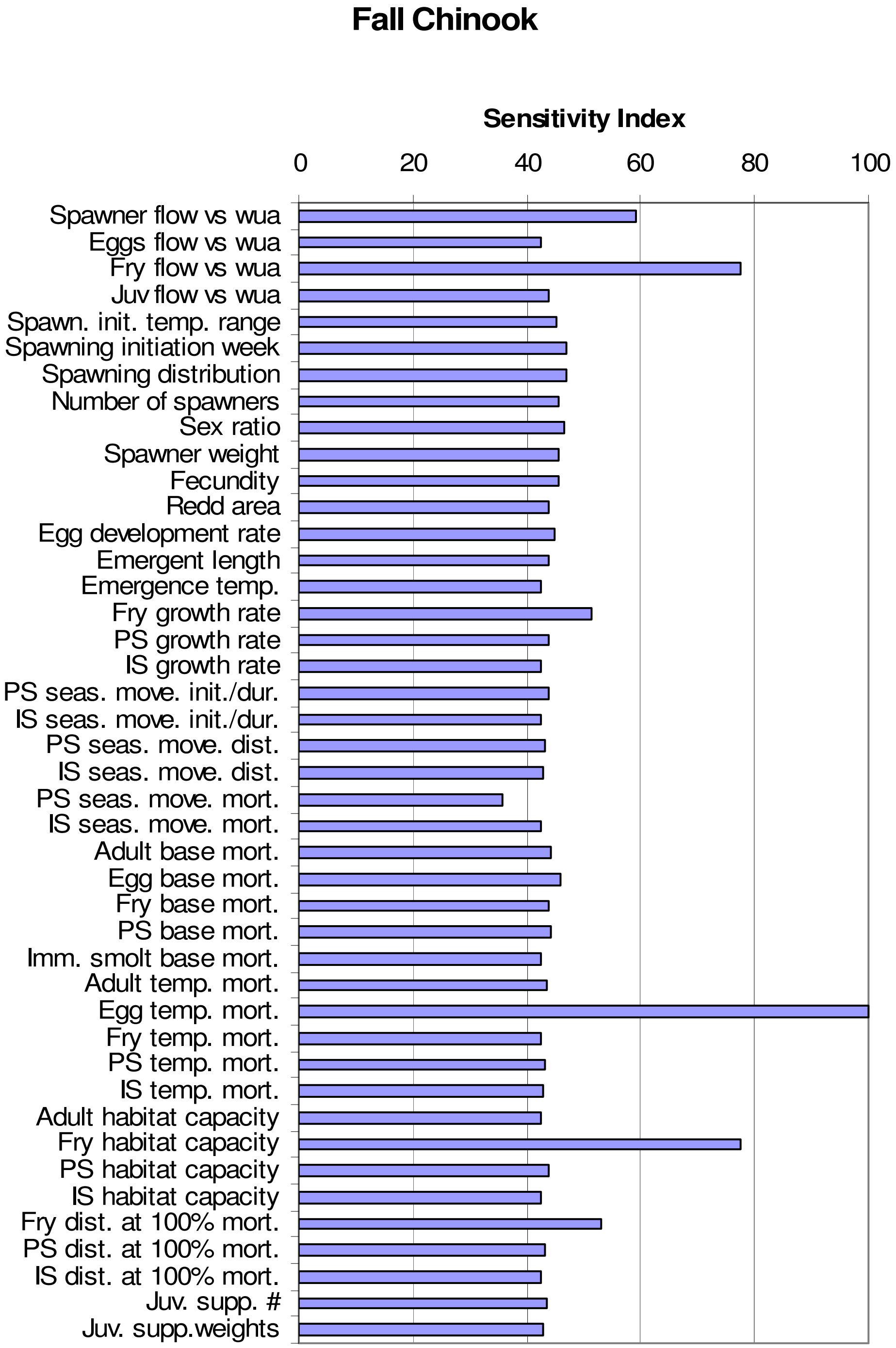


Figure 11. Sensitivity analysis results for fall Chinook arranged from most sensitive at the top to least sensitive at the bottom.

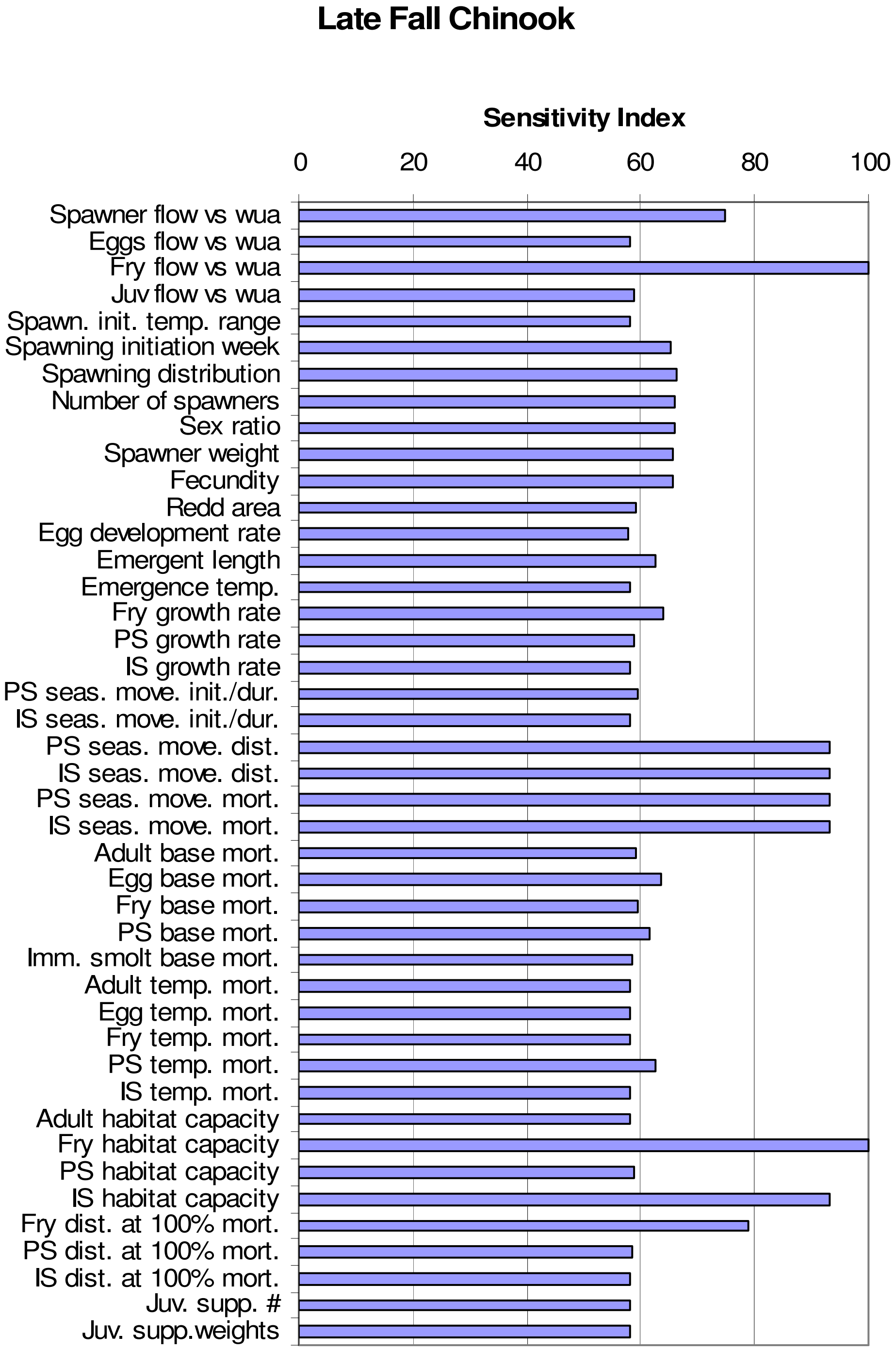


Figure 12. Sensitivity analysis results for late fall Chinook arranged from most sensitive at the top to least sensitive at the bottom.

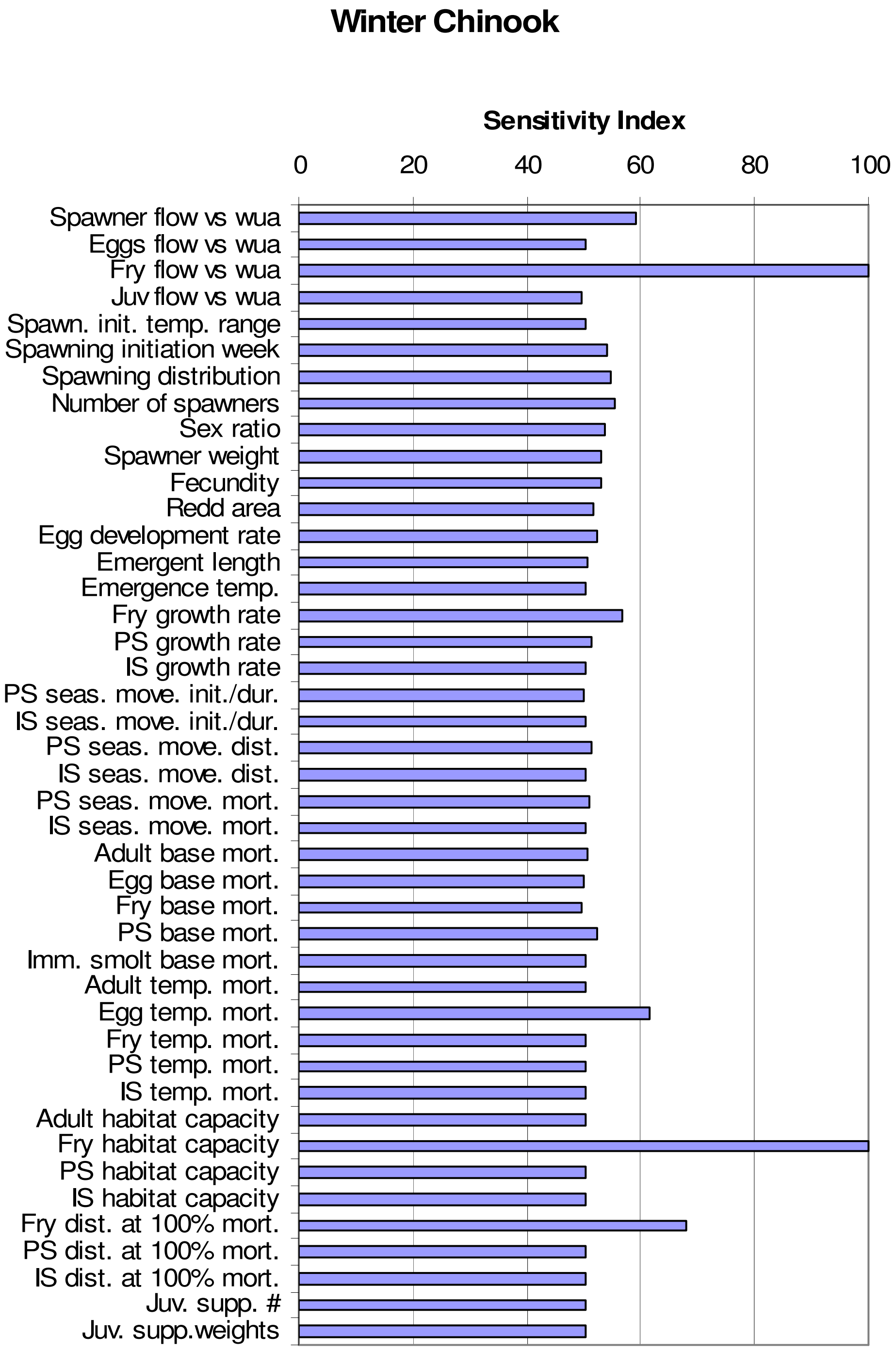


Figure 13. Sensitivity analysis results for winter Chinook arranged from most sensitive at the top to least sensitive at the bottom.

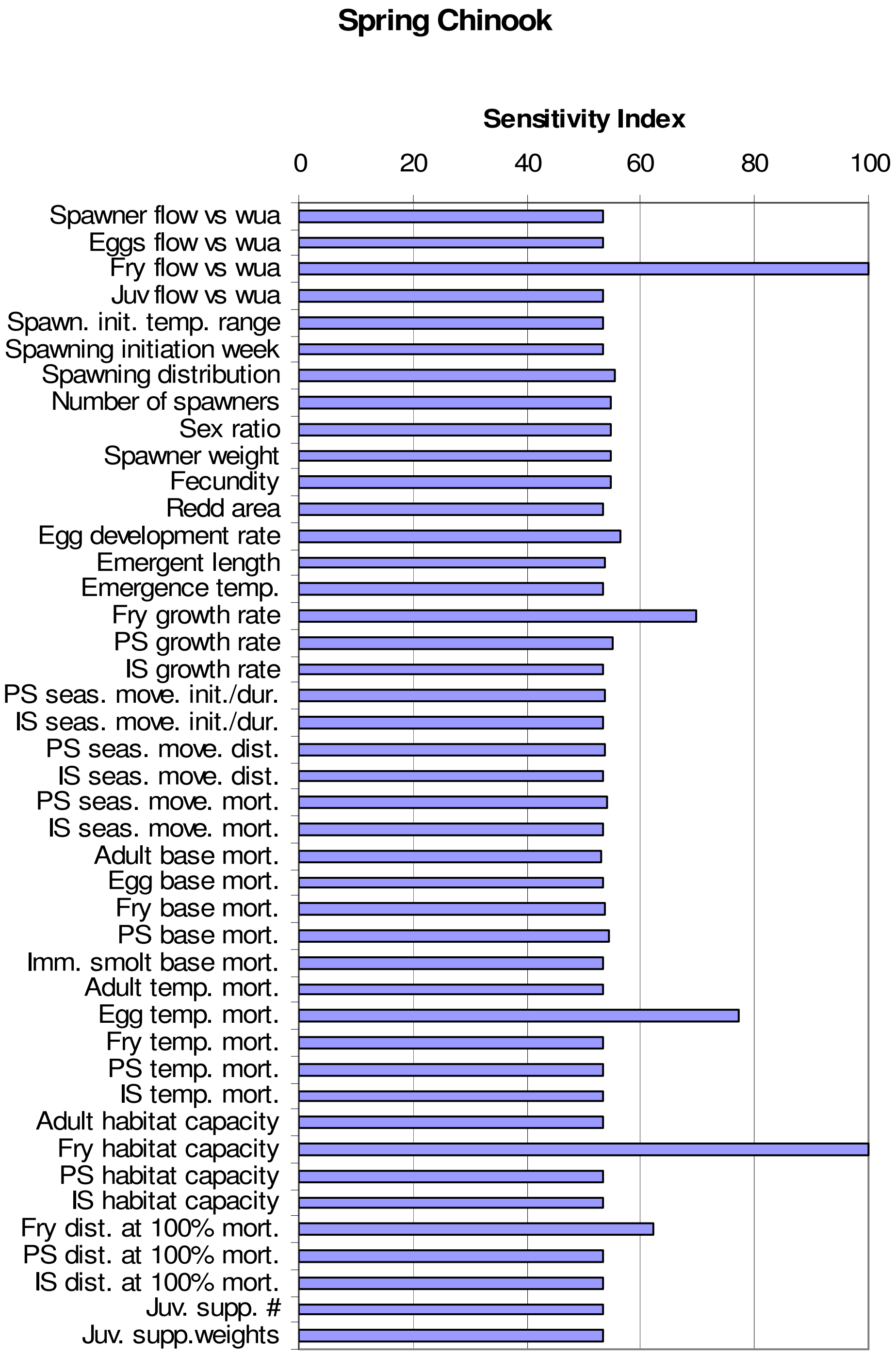


Figure 14. Sensitivity analysis results for spring Chinook arranged from most sensitive at the top to least sensitive at the bottom.

Interpreting Model Results

Because no true calibration has been completed for this Salmod model application, the reader is urged to remember that simulated outmigration numbers and their attributes are best used not as absolute values, but rather as relative values (Prager and Mohr, 1999). Even if the model were fully calibrated, measurements for outmigrating salmon are imprecise and subject to poorly understood biases. Further, because this is not a full life cycle model including complex estuarine and ocean dynamics, nothing is known about what happens to salmon successfully migrating downstream from Red Bluff, where other density-dependent phenomena may constrain the populations. Salmod is clearly not an ecosystem model (sensu Link, 2002) but instead a single species model whose "predictions" are limited to that target species.

Uncertainty Inherent in Model Results

Models can be misused (Radomski and Goeman, 1996; Schnute and Richards, 2001). We have spoken at some length about the uncertainty and assumptions bound up in this application. Parameter values have come from a variety of sources representing studies in different locations and river settings, have been "extrapolated" across salmon runs, and in some cases, borrowed across species. One must be forever critical of what has been published. We are rather fond of a statement from Healey and Heard (1984), to wit: "Much of the work that has been done … is tantalizing rather than conclusive. Most of the studies were undertaken to describe consequences rather than to test specific hypotheses …. Unfortunately, sampling and analysis methods were sometimes inadequate and replication was usually insufficient."

Model formulations are inexact approximations of the processes we believe to be governing populations, not necessarily the "truth." Models act as metaphors of reality and also as filters to isolate a signal from background noise in the data. Three types of potential errors are inherent in fisheries models that frustrate this signal extraction (Schnute and Richards, 2001). The first is process error, referring to the model's inability to capture the full range of dynamism in birth, death, and growth rates. The second is measurement error, referring to our inability to precisely measure what it is we are trying to model. The third element is model uncertainty, referring in the authors' context to our occasional inability to know whether the model does in fact cover the full range of possible phenomena that may occur to a fish stock. Collectively, these three types of potential errors indicate that there may be multiple, equally valid explanations to account for what we believe we have witnessed. As has been pointed out by modelers investigating the dynamics of fall Chinook in the ocean, relationships can be spurious and fail with the addition of new data, relationships can be real, but environmental or recruitment stochasticity masks the relationship, or relationships may not be stationary, but change over time for unclear reasons, making that relationship exceedingly difficult to determine (Prager and Mohr, 1999).

Suggested remedies to these problems include vigilant skepticism, continued data collection to "disprove" the model, applying common sense, and implementing precautionary management strategies that are robust to fish stock failure (Schnute and Richards, 2001).

Drawing Inferences from Model Results

Walters (1986) reasons that we are always in the mode of needing to make policy choices, even when field experimentation is impossible or extremely difficult. Thus, choices will continue to be made based on inference. Inference is fine as long as we make our assumptions explicit–and that is what a model is all about. The Achilles heel, however, is that our assumptions, however carefully considered, may still be wrong (Schnute and Richards, 2001). For this reason, Walters (1986) further argues that there should always be an opportunity to rethink, revise, and expand the model.

With this in mind, we have given some thought to the evolutionary progression of model development and application (Table 18) that shows that modeling, like any investigation, moves from general and suggestive to specific and credible (Holling and Allen, 2002). The reader will notice from Table 18 that validity is always provisional rather than essential for model utility (Rykiel, 1996). In our estimation, Salmod for the Sacramento River is currently cycling between Stages 3 and 6, indicating that one can begin to evaluate management issues as long as one is clear that the model remains a hypothesis and skepticism is promoted. We believe the model rests on a sound theoretical footing, and most, but not all, of its parameters are tied to sound empirical data.

Table 18. Progression of model development and application stages.

Model development stage	Attributes	Model capabilities may be used in decisions to:
(9+) Repeated calibration/ verification loop	Confidence-driven	Refine estimate of uncertainty/ Evaluation is ongoing/ Model becomes ever more trustworthy
↑	↑	↑
(8) Verification	Understanding-driven	"Confirm"/strengthen/predict/or falsify; Continue to accumulate evidence; Uncertainty is poorly defined
↑	↑	↑
(7) Calibration	Knowledge-driven	"Suggest" (assuming model is "calibratable"); Gain precision
↑	↑	↑
(6) Parameterized using best river-specific data	"Fact"-driven	"Imply or Infer" Can begin to explore "solutions" to issues, but must be clear that model remains a hypothesis
↑	↑	↑
(5) Testing	Plausibility?	Question perceptions; Gain insight by identifying patterns Revise data and implementation
↑	↑	↑
(4) Parameterized from literature or general knowledge	Data-driven	"Deduce" based on estimates and assumptions; Continue consensus building on model structure and expected behavior; Gain realism
↑	↑	↑
(3) Formalization and implementation	Box-and-arrow-driven	Stimulate concrete thought about variables, relationships, constraints, temporal and spatial scale, and so forth; Speculation
↑	↑	↑
(2) Conceptual formulation	Hypothesis-driven	"Reason"
↑	↑	↑
(1) Opinion	Experience-driven	No real model

Simulation Results

Habitat Availability

Salmod may be used to calculate aggregate microhabitat availability throughout the entire 85-km study area by summing the WUA values times the total reach length for all computation units, assuming that accretions were at a median level throughout the Keswick to RBDD study reach. The resulting curves for each life stage for spring Chinook are shown in Figure 15; the other races would be quite similar. These curves indicate that spawning habitat is the most likely to become limiting at high flows, whereas juvenile habitat remains relatively constant throughout the range shown. Incubation habitat does not decline with increasing flow due to our assumption that the eggs must simply remain wet, though scouring flows would begin to eliminate incubation habitat starting at 50,000 (Bigelow, 1996; not shown on the graph). These curve shapes are not unexpected given what has been defined by Gard (1995a and b), but please note that the graph ignores the fact that neither fish habitat nor the number of adult spawners is homogeneous throughout the study area.

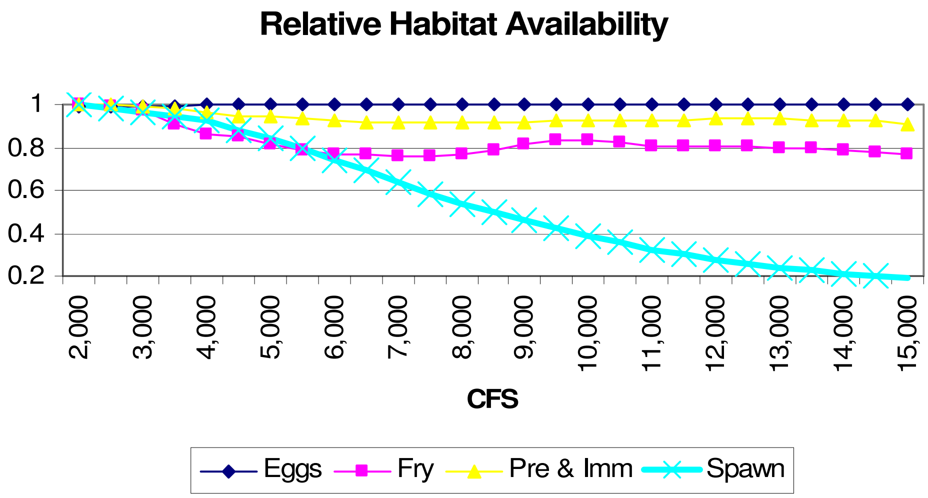


Figure 15. Relative gross habitat availability as a function of discharge through the entire study area for spring Chinook. The graph assumes median accretions throughout the study area and ignores all effects due to water temperature.

Production Potential by Scenario

Depending on one's point of view, figure 16 is either very telling or anticlimactic. Our view is that this figure, along with figure 17, sums up the results about as well as anything. What figure 16 shows is that predicted differences among the alternatives for each race are minor. This is true whether one looks at the minimum, maximum, average, median, or other measures of central tendency. One interesting feature from this graph is that, at the high escapement levels simulated, absolute maximum production is little more than the median, indicative of the predicted ceiling on stock-recruit relationship. Another way to say this is that the median production is far higher than the average because the average is brought down by the occasional production "busts." Relative production across the four life-history patterns is also clearly communicated from this figure. The vast majority of the difference in relative production is due to the assumed adult escapement levels of each race. Though we have been looking at production as measured by numbers of surviving fish, it is also possible to examine production based on either biomass or average length. A cursory examination revealed much the same story for either of these two metrics as numbers, so we will limit the material we present to numbers.

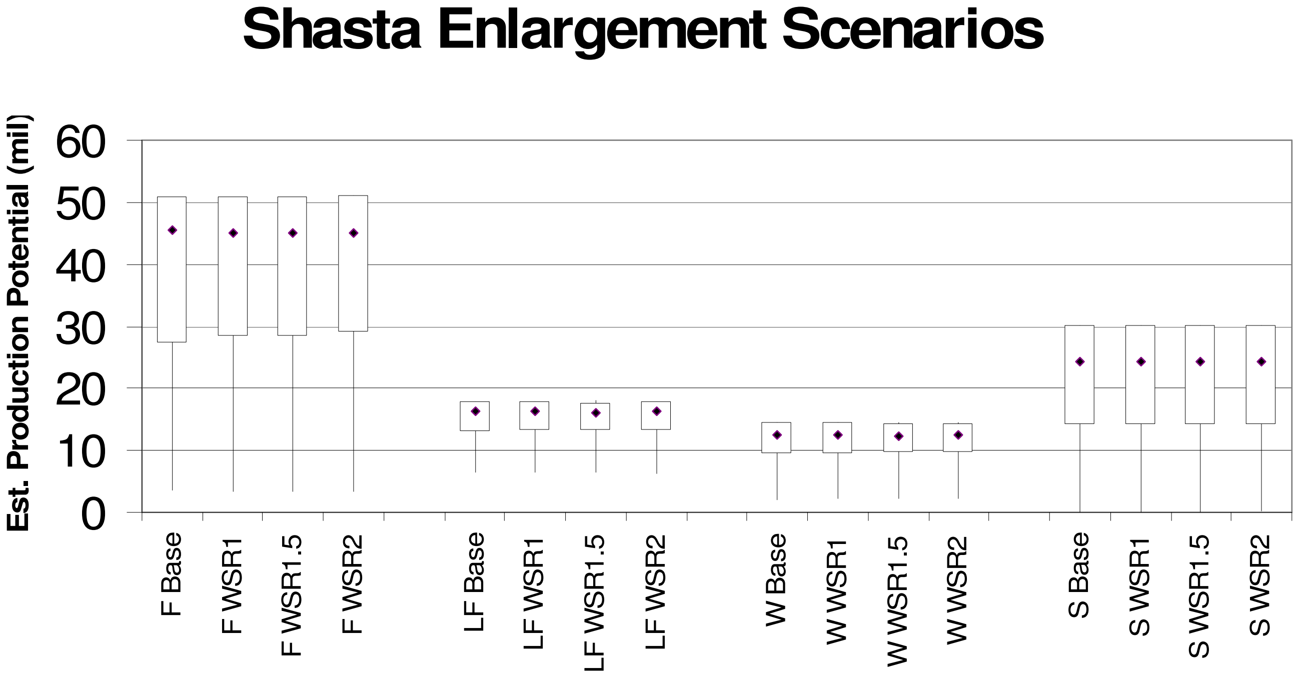


Figure 16. Estimated production potential (millions of fish) for the various scenarios for fall (F), late fall (LF), winter (W), and spring (S) runs (or life-history patterns). Tails (not always visible) represent absolute maximum and minimum production across the years simulated. Diamonds represent median production. The box represents the average plus or minus the standard deviation.

Table 19. Values used to construct figure 16 for fall (F), late fall (LF), winter (W), and spring (S) runs, in millions of fish. Maximum and minimum values are absolutes across all simulation years. SD is the standard deviation.

Scenario	Maximum	Average +1 SD	Median	Average - 1 SD	Minimum
F Base	49.69	50.96	45.49	27.31	3.55
F WSR1	49.80	50.86	45.03	28.24	3.38
F WSR1.5	49.82	50.87	45.02	28.26	3.30
F WSR2	50.30	51.05	45.00	28.90	3.26
LF Base	17.95	17.85	16.26	12.99	6.39
LF WSR1	17.85	17.77	16.27	13.14	6.43
LF WSR1.5	18.00	17.72	16.15	13.12	6.43
LF WSR2	17.70	17.79	16.26	13.20	6.35
W Base	14.61	14.46	12.54	9.35	2.12
W WSR1	14.23	14.42	12.51	9.44	2.17
W WSR1.5	14.42	14.23	12.36	9.55	2.27
W WSR2	14.48	14.23	12.44	9.57	2.25
S Base	29.69	30.13	24.35	14.11	0.02
S WSR1	29.29	30.02	24.34	14.10	0.08
S WSR1.5	29.98	30.13	24.35	14.05	0.10
S WSR2	29.48	30.03	24.41	14.08	0.12

While figure 16 correctly shows the similarity among the scenarios, figure 17 better illustrates the differences. This graph is “better” because it quantifies differences based on percentage changes rather than absolute changes, something more appropriate for an uncalibrated model. One should note two things from this graph. The first is that all predicted differences are less than 2 percent and most less than 1 percent. The second thing is that only fall run fish seem to benefit from raising Shasta Dam. The other three life-history patterns are little affected, perhaps showing some slight benefits or some slight drawbacks depending on the exact scenario.

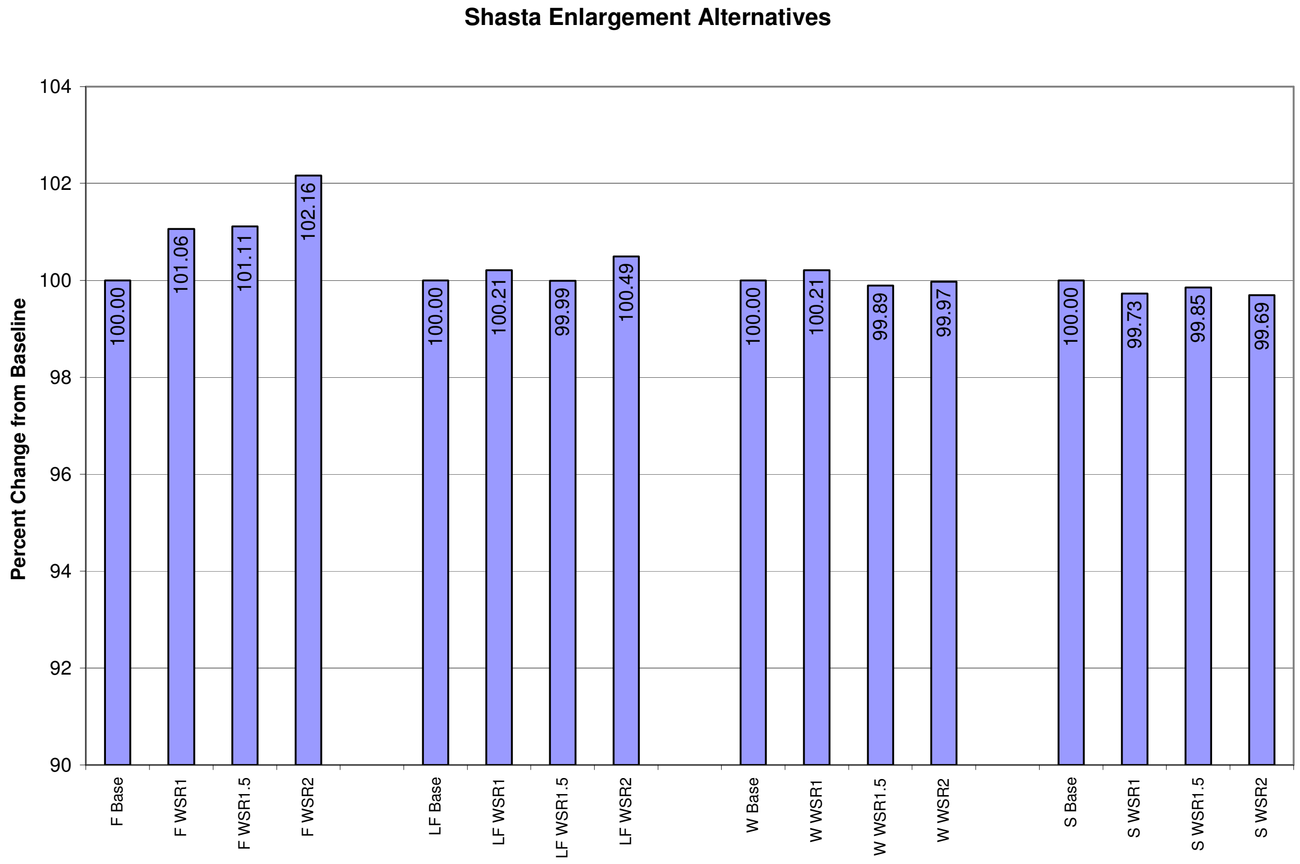


Figure 17. Predicted percentage differences from the baseline condition among the scenarios for fall (F), late fall (LF), winter (W), and spring (S) runs (or life-history patterns). The y-axis has been deliberately truncated to highlight small differences.

Looking at averages, however, obscures much of the underlying dynamic. Figure 18 compares the WSR2 estimated production with the baseline. It is clear that the enlarged reservoir scenario is predicted to partially mitigate production in at least four of the five worst years, typically those when the reservoir runs out of cool water. Similar results would be seen if the other races were examined. Figure 18 also shows why the whisker plot in figure 16 has the shape that it does, namely relatively high and narrow-ranging average production, but the occasional “busts” resulting in the tails of the distributions. It also shows that, in this case, although predicted baseline production minima are avoided with the WSR2 scenario, the baseline’s maxima are also not quite equaled. This phenomenon was typical across the four races; namely, the larger the reservoir is expanded, the more moderate the predicted differences between the minimum and maximum production and the smaller the coefficient of variation computed across all simulation years. These changes are not major but are worth mentioning.

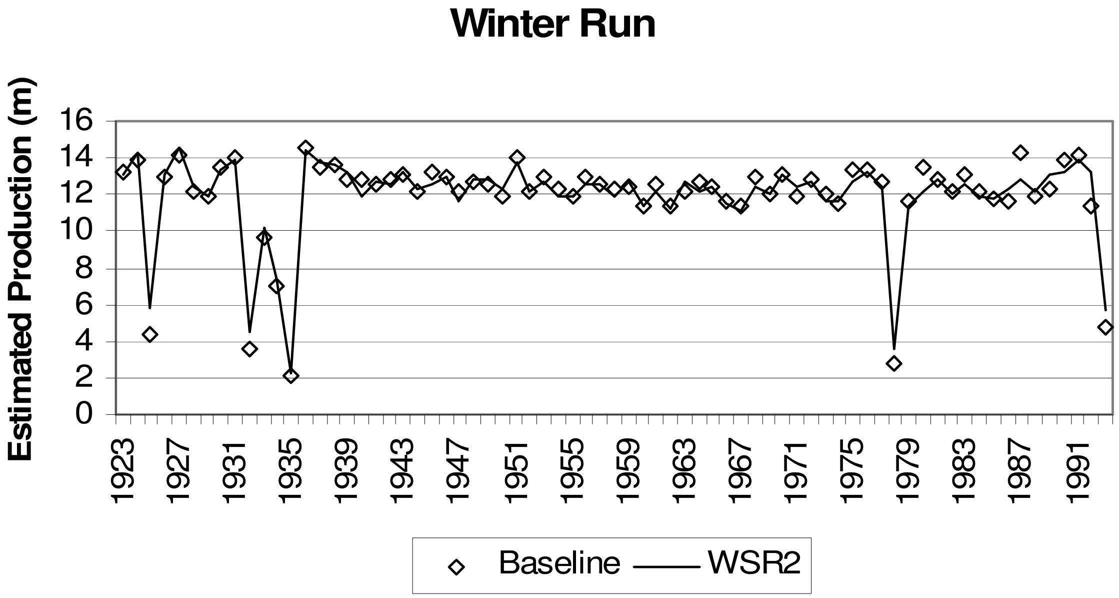


Figure 18. Time series of estimated production (m, millions) for the winter run comparing only the baseline and WRS2 scenario. Production is generally enhanced in otherwise poor years, but slightly depressed in most years.

Table 20. Values used to create figure 18 for winter run Chinook.

Year	Baseline	WSR2	Percent difference
1923	13,272,406	13,055,535	-1.63
1924	13,947,751	14,220,446	1.96
1925	4,395,081	5,752,135	30.88
1926	12,916,247	13,147,814	1.79
1927	14,104,954	14,480,721	2.66
1928	12,150,651	12,436,636	2.35
1929	11,890,807	11,871,801	-0.16
1930	13,462,314	13,290,572	-1.28
1931	14,028,268	13,949,076	-0.56
1932	3,529,026	4,489,734	27.22
1933	9,674,682	10,187,922	5.30
1934	6,959,685	7,360,305	5.76
1935	2,117,028	2,245,148	6.05
1936	14,606,761	14,413,517	-1.32
1937	13,492,304	13,714,660	1.65
1938	13,671,657	13,682,947	0.08
1939	12,782,910	13,164,952	2.99
1940	12,804,042	11,860,691	-7.37
1941	12,626,253	12,759,682	1.06
1942	12,837,338	12,568,726	-2.09
1943	13,060,326	13,243,910	1.41
1944	12,205,298	12,297,383	0.75
1945	13,257,676	12,523,143	-5.54
1946	12,943,575	12,928,937	-0.11

Year	Baseline	WSR2	Percent difference
1947	12,198,290	11,661,252	-4.40
1948	12,682,933	12,867,728	1.46
1949	12,600,652	12,854,685	2.02
1950	11,955,314	12,239,971	2.38
1951	14,045,727	13,812,945	-1.66
1952	12,231,187	12,122,159	-0.89
1953	12,980,159	12,692,318	-2.22
1954	12,250,325	11,932,232	-2.60
1955	11,844,250	11,841,031	-0.03
1956	12,915,198	12,523,773	-3.03
1957	12,619,194	12,541,223	-0.62
1958	12,261,362	11,906,238	-2.90
1959	12,446,427	12,750,825	2.45
1960	11,380,206	11,347,278	-0.29
1961	12,536,713	12,178,903	-2.85
1962	11,382,549	11,238,116	-1.27
1963	12,231,389	12,709,344	3.91
1964	12,702,139	12,223,096	-3.77
1965	12,451,971	12,449,878	-0.02
1966	11,695,962	11,467,267	-1.96
1967	11,354,916	11,144,261	-1.86
1968	12,895,330	12,387,975	-3.93
1969	12,075,260	12,017,971	-0.47
1970	13,065,495	13,051,589	-0.11
1971	11,959,505	12,400,802	3.69
1972	12,848,344	12,750,650	-0.76
1973	12,004,863	11,659,599	-2.88
1974	11,500,341	11,665,465	1.44
1975	13,315,383	12,633,491	-5.12
1976	13,402,793	13,284,997	-0.88
1977	12,672,808	12,372,468	-2.37
1978	2,741,813	3,588,861	30.89
1979	11,660,224	11,414,610	-2.11
1980	13,468,160	12,153,733	-9.76
1981	12,819,061	12,810,627	-0.07
1982	12,197,708	12,082,250	-0.95
1983	13,032,882	12,571,998	-3.54
1984	12,111,086	11,842,825	-2.22
1985	11,737,224	11,797,979	0.52
1986	11,656,741	12,244,488	5.04
1987	14,338,566	12,791,834	-10.79
1988	11,903,044	12,108,344	1.72
1989	12,254,371	13,146,932	7.28
1990	13,823,932	13,275,386	-3.97
1991	14,108,678	13,906,646	-1.43
1992	11,324,482	13,165,784	16.26
1993	4,782,983	5,646,349	18.05
Average	11,904,295	11,900,346	1.23

Causes of Mortality

The four races benefit in aggregate from reduced thermal mortality. This should be expected given one of the specified benefits a larger reservoir; namely, more carryover storage resulting in a larger volume of cool water from which to draw in low-water/high-temperature years (Hanna, 1999). Adding together the major sources of mortality attributable to water temperature (potential progeny of adult females, in vivo egg, egg, and juvenile), thermal mortality is reduced by about 7.5 percent for fall fish, 8.9 percent for late fall, 10 percent for the winter run, and 9.6 percent for the spring life-history pattern. If water temperature alone were the concern, reservoir enlargement should be seen on average as entirely positive.

So if an enlarged reservoir can help in years when cool water is at a premium, what is happening in others years to bring the average production back down? As you might imagine, it is the variety of habitat influences, including both microhabitat and macrohabitat. The relative importance of these other factors varies among the races, but can be summarized as follows: Though fall Chinook benefit from reductions in egg mortality (including in vivo, superimposition, temperature, and incubation), these benefits are partially offset by mortality related to fry-rearing habitat limitations. Late fall fish are essentially the same as fall fish, but they do not benefit as strongly from reductions in in vivo and other thermal egg mortality. Winter fish benefit from reduced egg thermal and incubation mortality, but these gains are offset by significant reductions in spawning habitat availability. The spring run benefits from reductions in egg mortality but is negatively affected by reductions in fry-rearing habitat. Increased flows in the summer are predicted to degrade spawning habitat availability for summer-spawning races, but more stable flows in the fall and winter are predicted to improve survival for other life stages. Some years in the time series are predicted to get much worse and some much better, yet the average (or median) production is not predicted to change much at all.

Discussion

Is it reasonable to believe that Salmod can accurately estimate such small differences in production? This is a very relevant question, but before we attempt to answer it, let’s look at three important considerations. First, we are unsure how to quantify the “confidence interval” for the model predictions on the Sacramento River. The model has not been calibrated, so we have no goodness-of-fit metrics to fall back on except that the model has been called “in the ballpark” (Bartholow, 2003) which does nothing to answer the question we have posed. Bradford (1995) compiled representative egg-to-fry and egg-to-smolt survival ratios for several studied Chinook streams; these averaged 3–4 percent. Comparable Salmod survival egg to outmigrant survival rates down to Red Bluff average 7 to 14 percent depending on the race. Of course, the reputedly perilous Delta still lies ahead of these outmigrants. Second, we recognize that Salmod can display some apparent “noise.” By this we mean that small changes in any of the driving inputs (discharge, temperature, number of adult spawners) can result in what seem to be small oscillations in simulated production. There are many reasons for this, but suffice it to say that the model contains certain thresholds (for example temperature of emergence, discharge initiating redd scour) and properties of dealing only with integer numbers of fish (for example what if one spawning female dies?) that can induce ostensibly non-linear oscillations in the results. Third, our original design criterion for Salmod was to be able to detect production differences greater than 25 percent (Williamson, 1993). Obviously, average predicted differences in this case are well within this design tolerance. Given these considerations, our conclusion is that any production differences, if true, probably would not be detectable in the field even through a long-term, rigorous statistical analysis (Korman and Higgins, 1997).

What caveats might we offer regarding this analysis? We have attempted to lay out the variety of assumptions that we have made and will not repeat them here. However, it is important to remember that we have endeavored to predict the production response resulting from several flow and temperature scenarios. These scenarios are solely model characterizations of what alternative futures might be on the Sacramento River. These models, just like Salmod, will have known and unknown biases and uncertainties. Even if these scenarios are good caricatures of possible alternative futures, actual day-to-day or week-to-week operation will certainly be different from any specific scenario. Ramping rates, TCD malfunctions, and the whole host of Murphy's Laws will tend to influence actual production. Further, Salmod has a distinct geographic boundary below which nothing is stated regarding survival rates of either adults or juveniles. Delta and ocean conditions are a black box in this regard. Finally, as mentioned earlier, Salmod is not an ecosystem model. Just because this model indicates some changes (both positive and negative) for Chinook does not mean that one would not want altered flows during certain times of the year. As examples, channel-forming flows leading to gravel recruitment or substrate cleaning is an often-cited goal (see *http://science.calwater.ca.gov/pdf/eco_restor_sac_river.pdf*) or salinity control in the Delta. A larger Shasta reservoir would have a longer hydraulic retention time, likely processing nutrients differently (Ahearn and others, 2005) with potential consequences for its food web dynamics (Saito and others, 2001). We have only simulated four races of a single species. Whatever changes may occur, they will likely benefit some organisms while being detrimental to others.

Did we see anything in the modeling results that was disquieting? Following earlier modeling efforts (Bartholow, 2003), the four race-specific models we applied concentrated attention on pre-smolt and immature smolt outmigrants (greater than 60 mm) under the widely believed assumption that their subsequent downstream and ocean survival is better than that for fry (smaller than 60 mm). However, when simulating such a broad range of thermal and hydrologic conditions over 70+ years, we found that under certain circumstances, some juveniles were still in the virtual river at the end of the 52-week biological year as if they were stream-type Chinook. In part, this may be an unrealistic artifact of the way the models were put together and perhaps could be cured in future applications. The 6°C emergence temperature may be too high, the annual timing we used may be incorrect, or some combination of factors. Regardless, we took explicit steps to "flush" the larger fish (greater than 60 mm) down to Red Bluff but did not do so for fry so we could observe what seemed to be happening in the models more closely. Assuming that some of these "residual" fry may survive to subsequently outmigrate, either as young of year (YOY) or as yearlings, we may have slightly underestimated average production (less than 1 percent difference). We believe that the conclusions of the study relative to production potential remain as described. However, we feel compelled to mention that we also saw a trend in a greater number of these "residual" fish as the simulated reservoir became larger and water temperatures became colder. These colder temperatures delayed the "normal" egg incubation period such that fry emerged slightly later or grew slightly slower, resulting in more fish less than 60 mm after 52 weeks. This may or may not be a concern in managing the river to promote stock recovery.

Is it heretical to suggest the possibility of increasing water temperatures to a point that might violate existing downstream standards such as the 2004 NOAA Biological Opinion on Operational Criteria and Plan (OCAP)? Perhaps. Yet in our defense we have been trying to objectively quantify the tradeoff between thermally induced mortality and growth. This model predicts that cooler water temperatures will often reduce adult, egg, and juvenile thermal mortality, but at the cost of lengthening the egg incubation and juvenile growth periods for survivors. Lengthening this development window also lengthens the cumulative exposure to "base" and other potential mortality sources. We are not alone in our opinion. Brannon and others (2004) has stated that "Most concerns about temperature in the ecological literature seem to be identified with increases in the lethal extremes. However, the far more profound impacts of temperature are related to the changes that occur well within the tolerance range of the species. A change in the mean incubation temperature of 1°C, for example, can alter the period of incubation and emergence by more than a month." At latitude 40.5°N. the upper Sacramento River would be expected to have "natural" mean April-September temperatures approaching 18°C, in contrast to the McCloud and Pit Rivers that tend to peak about 15°C with a mean closer to 13°C (Brannon and others, 2004, figures 16 and 17). With the TCD in place currently, the Sacramento River downstream from Keswick reaches a maximum average of about 12.5°C and an average maximum of 17.5°C.

Is it possible to use Salmod to "define" an optimum thermal regime? In fact, we did attempt to estimate a "globally optimum" water temperature regime across the four race models. We did this by constructing special software that repeatedly re-ran the simulation models, randomly varying the weekly thermal regime ±1°C around the median water temperature regime associated with the 18.5-foot dam extension. We used median flows for all runs and retained the average longitudinal heat flux and discharge accretions. We ran this simulation model over 28,000 times and compiled two averages of the best 10 regimes, one representing the best overall percentage improvement from the median temperatures and one representing the best absolute improvement in numeric production. The results are shown in Figure 19 where these two average regimes have been smoothed to reduce their inherent jaggedness. Though there are obvious problems in the smoothing, the results are instructive. Most apparent is that both of the "ideal" thermal regimes generally lie within the ±1° search tolerance, indicating that the starting water temperatures were, on average, very good for these fish. The exception is in mid-winter when this envelope indicates that warmer temperatures would be "preferred." Somewhat warmer spring water temperatures would also be beneficial, while late summer water temperatures could be cooler. Even very small changes extending over several weeks can add up to large differences in development and growth. However, some temperature alterations may simply be impossible for Shasta Lake. According to Russ Yaworsky, for about 4 months of the year (December to March), little can be done to provide warmer temperatures from the TCD such that Shasta cannot deliver the "best" regime all the time. We should not let existing regulatory requirements preclude innovative operations if the evidence supports a change, but we have not taken the opportunity to further explore this interesting question.

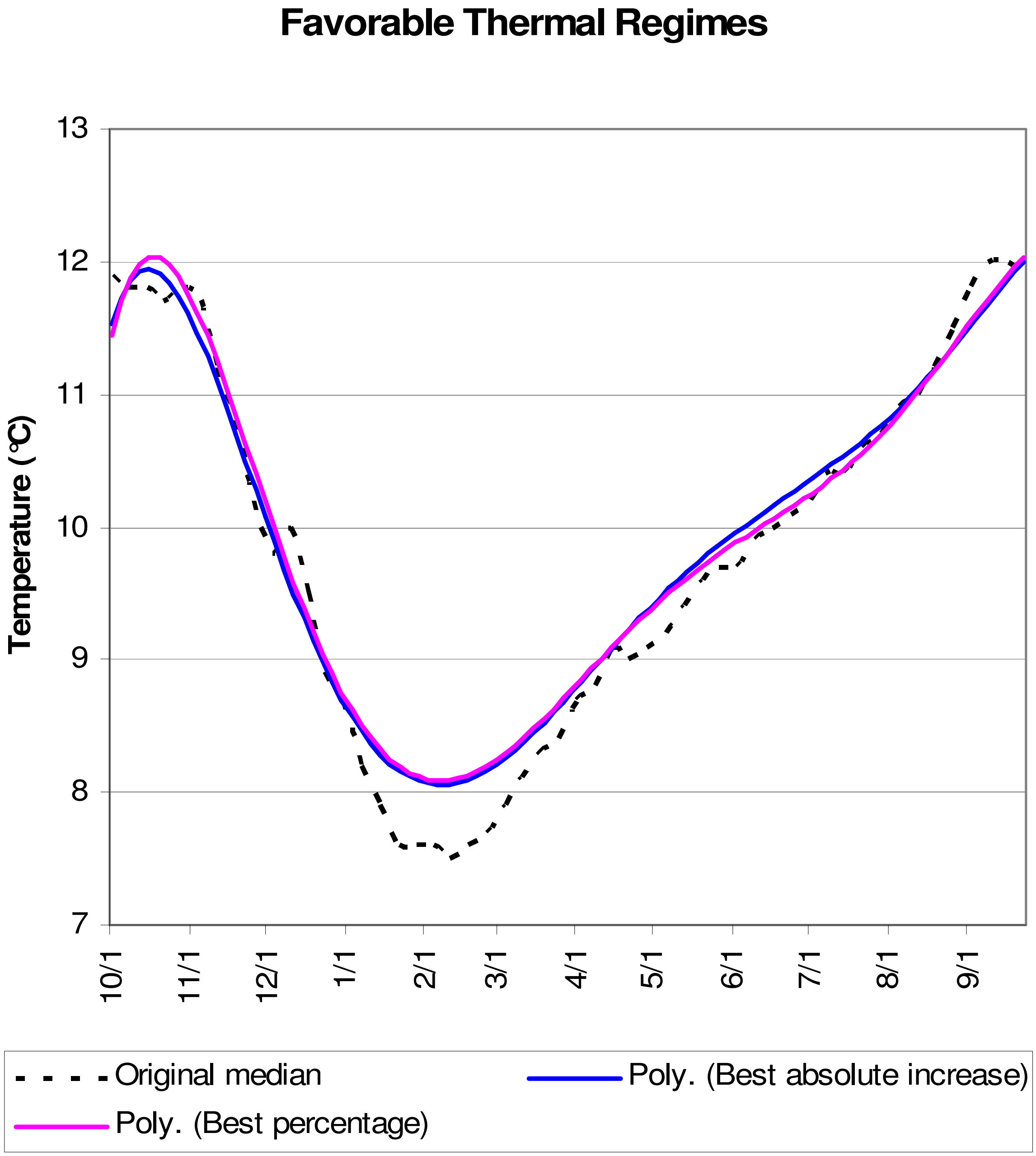


Figure 19. Idealized annual (52-week) thermal regimes compared to the median 18.5-foot dam water temperatures. See text for a description of how these regimes were developed.

Figure 19 also interestingly indicates that maintaining seasonality remains important. It's not like a hatchery where it may be advisable to target relatively constant temperatures, at least for a specific race of fish. In the river, trying to accommodate all four races in our case, seasonality apparently needs to be maintained. Note that we can say nothing here about the need, if any, for a daily temperature range; Salmod's weekly time step does not account for daily variability.

If we can do this for water temperatures, can the same thing be done to define an "optimum" flow regime? The answer is "Maybe." We attempted to follow the same procedure that we used for water temperatures, but instead varying the flows ±1,000 ft^3/s about the median conditions. Initially, the results were confounding. Unlike the temperature results given above, the resulting "optimal" flow regime was highly jagged and not a "regime" in the strict sense of the word. We have developed a hypothesis to explain these results that seems at least plausible. Figure 15 shown above indicates very small "bumps" and "dips" in the curves describing the relationship between flow and habitat availability. What appears to explain the jaggedness in the identified favorable flow regime is entirely related to the bumps and dips in the WUA curves. Adjusting flows up or down just slightly can "hit" those bumps just right. Further, though Keswick releases are relatively "smooth" from week to week, tributary accretions downstream from Keswick show a clear seasonal pattern that differs substantially from Keswick's and are "lumpy" in their own right. Add the non-homogeneity of habitat availability and you have a recipe for the optimizer to "adjust" the flows up and down in seemingly unpredictable ways to try to hit the high points in habitat availability. Are those bumps and dips in the habitat availability curve real or simply an artifact of the field surveying and modeling? We are generally suspicious of unexplainable undulations in the WUA curves, but there are potential explanations related to historical, non-random flow regimes that tend to create "benches" or "shelves" along the margins of the river and patterns of deposition in gravel bars related to spawning. If these benches and bars are not random, then just flooding a group of vegetated shelves to a small depth can create abundant juvenile habitat. Of course, if Shasta Dam were raised and a new flow regime instituted, those shelves would change and the habitat availability curves might need to be updated.

Specific Responses to California Department of Fish and Game Comments

The California Department of Fish and Game (CDFG) offered some comments on the evaluation of Shasta Dam enlargement alternatives in a letter to Jim DeStaso dated February 3, 2006. We very much appreciate the comments specific to using Salmod as part of this evaluation and herein we attempt to address several of CDFG's concerns.

(1) California Department of Fish and Game was concerned that existing winter run production data show good correlation with returning adult spawners, suggesting that physical habitat may not be limiting in the manner addressed by Salmod. We understand this logical concern and agree that adult escapement (perhaps controlled by ocean conditions, fishing, or other factors) is likely very highly correlated with production (Milner and others, 2003), especially when escapement numbers are low, something that has been documented by Kope and Botsford (1990) and further explored by Martin and others (2000). Salmod indeed confirms that estimated production is very highly correlated with adult escapement, at least up to some level of returning adults (**Figure 20**).

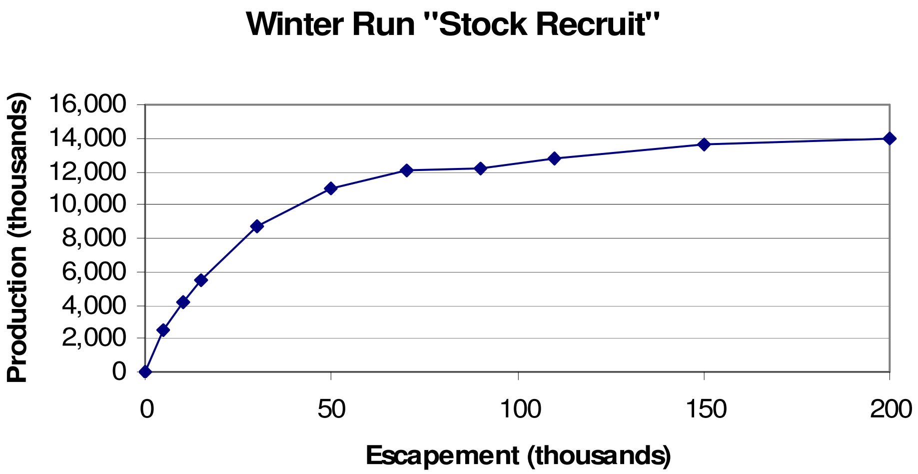


Figure 20. Simulated relationship between spawner abundance and estimated production for winter run Chinook on the Sacramento River.

However, Salmod's task in this evaluation was to help assess the degree to which altered flows and water temperatures might or might not affect Chinook freshwater production. We did this by considering the effects potentially induced by microhabitat and or macrohabitat. In this sense, it may be more appropriate to say that Salmod is considering those factors that reduce production rather than ultimately limit production. We are unaware of how this kind of flow and temperature scenario evaluation might be done considering spawner density alone.

We would add that it seems clear that the Sacramento River likely is subject to many habitat-related problems cited by Moyle (2002), specifically loss of flood-plain rearing habitat by diking and draining, predation of juvenile salmon by nonnative fish such as striped bass, competition from hatchery fish, and siltation of spawning areas. In a review of salmonid freshwater population regulation, Milner and others (2003) stated that the "evidence for density-dependent regulation of abundance in the salmonid lifecycle is overwhelming." Salmod may or may not be correct in accounting for cumulative habitat-related production limitations, but we certainly believe that these limitations cannot be ignored.

(2) California Department of Fish and Game was concerned that habitat preferences may not have been correctly considered in the habitat quantifications used in Salmod. We make no judgment on this specific issue. We are using the best information we could gather as collected by DWR and USFWS (which appear to agree fairly well) and assume that the habitat suitability criteria (HSC) were collected properly. We agree that habitat studies continue to evolve and that continued field research, and better understandings of the available data, may result in improved habitat quantification.

(3) California Department of Fish and Game suggested using a modification of how HSC criteria are handled in PHABSIM (or similar simulation technique such as 2-D modeling). We are not in the best position to judge on this issue. Again, the USFWS should be the principal contact to discuss the evidence for or against such a modification. This is not a Salmod issue–except in the need for the best input data available.

(4) California Department of Fish and Game questioned whether juveniles of the four races are completely segregated in their habitat use. CDFG believes that modeling the four races independently implies a purely sequential use of habitat without spatial and temporal overlap among the races. We agree that this model, like all models, is a simplification and to the degree that this concern is valid, it strengthens the argument for habitat-based limitations. But we wonder if we have made it clear that we

only assumed segregation by juvenile size class? In other words, does a 60-mm fall fish coexist with a 60-mm spring fish at the same depth and velocity? Perhaps some do, especially when tributary fish intermingle with main stem origin fish; we do not know. Moyle (2002) and Milner and others (2003) state clearly that segregation of microhabitat use is the usual pattern for salmonids, with niche segregation being strongly related to fish size regardless of species. We have made the recommendation (see below) that this model simplification be more closely evaluated.

(5) California Department of Fish and Game is concerned that model predicted superimposition may be too high and without obvious merit. We cannot comment on CDFG's field observations but instead fall back solely to what the current input data seem to imply. Salmod predicts that there is not enough high quality spawning habitat (proper depth, velocity, clean substrate quality) to support thousands of 4.5-m^2 redd egg pockets without significant overlap. Looking outside of the modeling framework, a report from the USFWS (2005, Appendix 1) shows that the maximum spawning area available in the Red Bluff to Battle Creek segment is 179,530 m^2 (1,813,440 ft^2) at a discharge of 4,750 ft^3/s. If an egg pocket averages 4.5 m^2, this total area would allow a maximum of about 39,900 redds with zero superimposition. Changing flow conditions through the spawning period might allow additional redds, but some of this total area might also be in small pockets less than 4.5 m^2 and thus incapable of supporting a single redd. Even if the spawning area upstream from Battle Creek were twice as abundant, there would be room for only about 120,000 redds in the Keswick to RBDD area during one race's spawning period blessed with continuously optimum flow conditions.

We note that gravel has been added to the main stem Sacramento River and has been mentioned as a potential limiting factor for larger winter run populations by NMFS (http://swr.ucsd.edu/hcd/ch3.pdf). Bigelow (1996) stated that "loss of gravel is believed to be a major contributing factor to declining Chinook salmon … productivity in the Upper Sacramento River downstream from Keswick Dam. … Spawning gravel depletion has been most severe in the stretch … from Keswick Dam … to the mouth of Cottonwood Creek. … Historically, gravel in this river reach had been recruited from upstream from Shasta Dam or by bank erosion." In addition we note that researchers from Stillwater Sciences have stated that they "are of the strong opinion that spawning habitat is limiting, primarily upstream of Cottonwood Creek (RM 273.5), which provides the first source of significant sediment supply. We think that there is significant redd superimposition occurring in the upper reaches, for all the runs" (Michael Fainter, Stillwater Sciences, written comm). We must await the release of their final report to examine the evidence for or against this opinion.

We certainly acknowledge ample opportunity for error: spawning habitat availability may have been underestimated or mesohabitats that do not support spawning (from redd counts) may be overestimated. The four race-specific models generally predict a relatively constant annual amount of superimposition mortality depending on the race, so we do not believe any error in estimating superimposition would change the overall rank order of one scenario relative to another, but this could be tested. Nonetheless, because of the expressed concerns, we took explicit steps to minimize predicted superimposition. In the long run, this should be an area of investigation. The bottom line, however, is that we believe it unlikely that a better description of spawning habitat would change the basic conclusions from this study, namely, that predicted effects of the various scenarios are minor.

(6) California Department of Fish and Game expressed the concern that water temperatures should always adhere to the "precautionary principle" and recommended careful examination of all water (and meteorological) year types in the evaluation. We agree with the concern and have covered a wide range of year types, from 1923 to 1994. But we also feel compelled to point out that this model suggests that one might expect a marginal gain in production with temperatures that may be warmer during certain times of the year than the specific regulatory standards currently in place. This

conclusion appears to result from reduced stream residency time due to accelerated incubation and growth, which more than offsets slightly increased thermal mortality. We recognize that this conclusion may be heretical and understand that there well may be other reasons for the regulatory thermal standards than this model currently considers, particularly in some annual circumstances when cool water is limited, or if warmer temperatures enhance predation by warm-water species. We note, however, that the precautionary principle must be reconciled with the conclusions of U.S. Fish and Wildlife Service (1999) that stated that because mortality increases non-linearly with increasing constant temperature above a threshold, slightly elevated temperatures over a long period may result in lower mortality than spikes of high temperature if cold water is exhausted. Since raising summer temperatures slightly will reduce the probability of running out of cold water in the fall, which philosophy is the more precautionary?

Having said this, we should note that unlike the previous Sacramento River analysis, we did reduce in vivo egg mortality due to concerns expressed in Klamath River modeling (Bartholow and Henriksen, in press). We continue to advocate that in vivo egg mortality is in need of careful research and the model adjusted to reflect the findings.

(7) California Department of Fish and Game stated that the Salmod model needs validation on the Sacramento River. We agree and have encouraged model skepticism. This does not mean that we believe Salmod is not based on sound principles and that growth and overall production appear to be "in the ballpark." But it does mean that the underlying mechanisms in the model may not be correct. Much more needs to be done, especially to make quantitative rather than qualitative predictions. (USGS researcher Sam Williamson may be interested in pursuing a detailed a calibration effort.)

(8) California Department of Fish and Game expressed the concern that hatchery-origin returning adult spawners somehow confound Salmod results, particularly upstream from Battle Creek. This concern may simply be a misunderstanding arising from a statement in our original modeling work. The previous statement was meant to reflect the difficulty in distinguishing hatchery and natural juvenile outmigrants at Red Bluff, not adult spawners. The number of adult spawners in the previous model application was derived solely from redd counts without regard to natal origin.

(9) California Department of Fish and Game would like tributary production to be included in the model. We agree, and have made a first attempt to do so in this application. We note, however that we are unsure whether adding tributary production is likely to make much difference in ranking the various scenarios. Instead, adding tributary fish may tend to obscure scenario evaluation for main stem-origin juveniles.

(10) California Department of Fish and Game wanted to combine spring and fall fish given a concern that the spring run might not be a distinct run at all, but rather just a "shoulder" of the fall run. It might be possible to combine the runs as suggested; we did not do so for two reasons. First, preliminary modeling suggested qualitatively different responses for fall and spring runs to the dam-raise scenarios. Fall run seemed to improve slightly, but fish with a spring-run timing pattern did not. Thus if the runs were lumped, which one may certainly do in simply summarizing the results, we would still conclude that the spring "shoulder" of the fall run would be expected to suffer slightly. In addition, since there is an existing NMFS recovery goal for main stem spring run Chinook, we believed it would be best to segregate the runs as we have. If there is indeed no true spring run in the main stem, then these results may safely be ignored.

(11) California Department of Fish and Game expressed the sentiment that this analysis should draw on experience from the ongoing analysis for the Trinity River. We have generally kept abreast of activity in the Trinity Basin and, in fact, are actively sharing experiences gained with all participants.

(12) California Department of Fish and Game wishes the model domain to be expanded to the Delta. We concur that downstream phenomena should be a concern, but detailed habitat descriptions simply are not available to accomplish this task with Salmod. Further, it is not clear whether Salmod would actually be the right tool for analyzing Delta phenomena.

(13) California Department of Fish and Game expressed a desire to use the Instream Flow Incremental Methodology (IFIM), consider other factors, and use other tools such as C-Pop and the Indicators of Hydrologic Alteration (IHA) when making flow (and temperature) recommendations. We concur that scenario evaluation would likely benefit by applying multiple tools, especially if all stakeholders agree that IFIM and various related tools are applied properly. Furthermore, we emphasize again that Salmod is not an ecosystem model. Other considerations must be brought to the table in making water (and temperature) allocation decisions. In addition, we did supply results (Appendix A) from the latest generation of IHA (called Hydrologic Assessment Tools). These results did not compare the scenarios with a "true" (pre-development) baseline. Undoubtedly, if such a comparison were made, changes to both the flow and temperature regimes would be substantial.

Recommendations for Further Study and Development

There will always be opportunities to improve this model. We did very little during the course of this scenario evaluation other than apply the model with slightly revised parameters. The timeline was too short and resources too limited. If the Bureau of Reclamation and other stakeholders wish to continue to refine this modeling in the future, we have several recommendations for improving both the trustworthiness of the results and the process we have used.

It appears that there has been an explosion of data availability for Chinook salmon in the Sacramento River Basin (CALFED, 1998), far more than what was available for either Kent (1999) or Bartholow (2005). These new data have opened excellent possibilities for model parameter review and calibration, as well as raising new questions about such things as whether spring Chinook do or do not spawn in substantial numbers in the main stem and whether spawning habitat might be limited at high escapement levels. It is often a trying task for modelers far removed from the "action" to be able to locate the best, most recent and reliable data, know what their assumptions and limitations are, and synthesize them into forms suitable for modeling. What may look reasonable to a modeler might not to someone intimately familiar with the field data. Therefore, we recommend that the Bureau of Reclamation organize a series of workshops where the various local data collection agencies come together to critically review existing model parameterization, bring together the best evidence for parameter revisions, and collectively agree on the "best" data to go forward with and use for model calibration. Model revisions should also be considered. This would be a long task requiring a substantial commitment from the various stakeholder agencies, but we believe the payoff would be substantial. Benefits would likely accrue not just in the context of EIS evaluations, but perhaps even more in the context of data sharing across agencies, development of a common language and understanding (for example how juveniles are classified in the tributaries), and eventually greater use in evaluating potential "fish friendly" water-management scenarios. We know that this kind of collaboration is taking place to some extent now, but believe it could be strengthened in the future using an agreed-upon model (not necessarily Salmod) as a common focal point.

Beyond this basic suggestion, there are some specific categories of data that need attention. Foremost is the habitat quantification. Not only were these data shown to be sensitive in this model application, but also we were unable to use all of the latest data now available from the USFWS. In fact, we would recommend that the USFWS be contracted to assemble the requisite mesohabitat and WUA input files as they are most knowledgeable about just what the output from their models represent, how best to assign WUA to the various mesohabitat types, and how to designate individual computation units as either spawning or non-spawning at various escapement levels, all on a race-by-race basis.

We believe that the potential for and degree of in vivo egg mortality remains poorly documented. This form of mortality, if it actually occurs, could be significant, especially in evaluating alternative thermal regimes. As mentioned elsewhere, however, clearly established proof of in vivo egg mortality in the field seems lacking and was the reason why this analysis reduced otherwise high in vivo mortality rates. Are adult females capable of avoiding high measured water temperatures otherwise assumed to be uniform throughout the channel or not? If not, do the pre-deposition eggs suffer large losses either as eggs or as fry? This would be an excellent research project.

There are also some areas where the Salmod model (if to be applied in the future) must be improved. Salmod estimates incubation losses in proportion to any incubation habitat losses that occur from the time of redd creation. It might be possible to use USFWS modeling results known as "effective spawning habitat" to more realistically estimate redd dewatering at channel margins. We should explore the feasibility of incorporating effective spawning estimates and make a determination whether it would be possible, cost effective, and truly more realistic to change the Salmod model. In addition, we found it difficult in this analysis to rapidly compare one set of simulation results with another. Often, differences from one scenario to another were quite small, and it was problematic to track down the exact causes of the differences. Some changes to the modeling environment might substantially improve this process, both saving time and aiding insight into limiting factors. In particular, we believe it would be beneficial to be able to plot mortality rates in addition to raw numbers of fish for each mortality source. Last, the Sacramento River has been the only study area where we have applied Salmod for more than one race/species at a time. Though some advantages remain in keeping these models separate, there may also be some advantages to combining them all in a single simulation model. This might be especially true in exploring whether there might indeed be any competition for habitat among the various races. Again, this possibility should be explored for feasibility and practicality.

References

Allen, K.R., 1969, Limitations on production in salmonid populations in streams: Pages 3–18 *in* H.R. MacMillan Lectures in Fisheries–Symposium on salmon and trout in streams, Institute of Fisheries (T.G. Northcote, ed.), University of British Columbia, Vancouver, 388 p.

Ahearn,D.S., Sheibley, R.W., and Dahlgren, R.A., 2005, Effects of river regulation on water quality in the Lower Mokelumne River, California. River Research and Applications, V. 21, p. 651–670.

Anadromous Fish Restoration Program Core Group, 1995, Working paper on restoration needs, Habitat restoration actions to double natural production of anadromous fish in the Central Valley of California, volume 3, table 3-xa-1: Available on the Internet at *http://www.delta.dfg.ca.gov/afrp/documents/WorkingPaper_v3.pdf*

Armour, C.L., 1991, Guidance for evaluating and recommending temperature regimes to protect fish: U.S. Fish and Wildlife Service, Biological Report, V. 90, No. 22, 13 p.

Baker, P.F., Speed, T.P., and Ligon F.K., 1995, Estimating the influence of temperature on the survival of Chinook salmon smolts *(Oncorhynchus tshawytscha)* migrating through the Sacramento-San

Joaquin River delta of California: Canadian Journal of Fisheries and Aquatic Science, V. 52, p 855–863.

Bartholow, J., 2003, Modeling Chinook salmon with Salmod on the Sacramento River, California: Project completion report, Revised, 97 p. plus appendix. (Available on request.)

Bartholow, J., Heasley, J., Sandelin, J., Coughlan, B.A.K., Laake, J., and Moos, A., 2001, Salmod: A population model for Salmonids: User's manual. Version W3: USGS/FORT Internal Publication, 76 p. Also available over the Internet at http://www.fort.usgs.gov/products/Publications/4046/4046.asp.

Bartholow, J.M., Hanna, R.B., Saito, L., Lieberman, D., and Horn, M., 2001, Simulated limnological effects of the Shasta Lake temperature control device: Environmental Management V. 27, No. 4, p. 609–627.

Bartholow, J.M., 1996, Sensitivity of a salmon population model to alternative formulations and initial conditions: Ecological Modeling, V. 88, Nos. 1–3, p. 215–226.

Bartholow, J.M., 2005, Modeling Chinook salmon with Salmod on the Sacramento River, California: Hydroecologie Appliquee, V. 14, No. 1, p. 193–219.

Bartholow, J.M., and Henriksen, J.A., 2006 In press, Assessment of factors limiting Klamath River fall Chinook salmon production potential using historical flows and temperatures: USGS Open File Report.

Bartholow, J.M., Laake, J.L., Stalnaker, C.B., and Williamson, S.C., 1993, A salmonid population model with emphasis on habitat limitations: Rivers, V. 4, No. 4, p. 265–279.

Beechie, T., Beamer, E., and Wasserman, L., 1994, Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration: North American Journal of Fisheries Management, V. 14, p. 797–811.

Berggren, T.J., and Filardo, M.J., 1993, An analysis of variables influencing the migration of juvenile salmonids in the Columbia River Basin: North American Journal of Fisheries Management, V. 13, p. 48–63.

Berman, C.H., 1990, The effect of elevated holding temperatures on adult spring Chinook salmon reproductive success: Masters Thesis, Seattle, University of Washington, 90 p.

Berman, C.H., and Quinn, T.P., 1991, Behavioral thermoregulation and homing by spring Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), in the Yakima River: Journal of Fish Biology, V. 39, p. 301–312.

Bigelow, P.E., 1996, Evaluation of the Sacramento River spawning gravel restoration and winter-run Chinook salmon redd survey, 1987–1993, Final report: U.S. Fish and Wildlife Service, North Central Valley Fish and Wildlife Office, Red Bluff, California, 110 p.

Billard, R., 1985, Environmental factors in salmonid culture and the control of reproduction, *in* Iwamoto, R.N., and Sower, S., eds., Salmonid reproduction, An international symposium: Bellevue, Washington, October 31-November 2, 1983, p. 70–87, Washington Sea Grant Program, Seattle, Wash.

Bjornn, T.C., 1971, Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density: Transaction of the American Fisheries Society, V.100, No. 3, p. 423–438.

Bohlin, T., C. Dellefors, U. Faremo, and A. Johlander. 1994. The energetic equivalence hypothesis and the relation between population density and body size in stream-living salmonids. Am. Nat., 143(3):478–493.

Boles, G., 1988, Water temperature effects on Chinook salmon (*Oncorhynchus tshawytscha*) with emphasis on the Sacramento River, A literature review: California Department of Water Resources, Northern District, 42 p.

Bovee, K. D., Newcomb, T.J., and Coon, T.J., 1994, Relations between habitat variability and population dynamics of bass in the Huron River, Michigan. National Biological Survey Biological Report 22, 79 p.

Bradford, M.J., 1995, Comparative review of Pacific salmon survival rates: Canadian Journal of Fisheries and Aquatic Science, V. 52, p., 1327–1338.

Brannon, E.L., Powell, M.S., Quinn, T.P., and Talbot, A., 2004, Population structure of the Columbia River Basin Chinook salmon and steelhead trout: Reviews in Fisheries Science, V. 12, p. 99–232.

Brett, J.R., 1956, Some principles in the thermal requirements of fishes: The Quarterly Review of Biology, V. 31, p. 75–87.

Bureau of Reclamation (USBR), 1991, Appendixes to Shasta outflow temperature control, planning report/environmental statement, Appendix A: Bureau of Reclamation, Mid-Pacific Region. 176 p. Originally issued in November 1990, revised May 1991.

Burger, C.V., Wilmot, R.L., and Wangaard, D.B., 1985. Comparisons of spawning areas and times for two runs of Chinook salmon (*Oncorhynchus tshawytscha*) in the Kenai River, Alaska: Canadian Journal of Fisheries and Aquatic Sciences, V. 42, No. 4, p. 693–700.

Burns, J.W., 1971. The carrying capacity for juvenile salmonids in some northern California streams: California Fish and Game, V. 57, No. 1, p. 44–57.

Busacker, G.P., Adelman, I.R., and Goolish, E.M., 1990, Chapter 11–Growth, from Methods for Fish Biology, C.B. Schreck and P.B. Moyle, eds.: American Fisheries Society, Bethesda, Maryland.

CALFED, 1998, CALFED's comprehensive monitoring, assessment, and research program for Chinook salmon and steelhead in the Central Valley Rivers: http://www.iep.water.ca.gov/cmarp/groups/ecowt/workplans/chinsal/cvsast1030.doc, 41 p.

Capra, H., Breil, P., and Souchon, Y., 1995, A new tool to interpret magnitude and duration of fish habitat variations: Regulated Rivers: Research and Management, V. 10, p. 281–289.

Chapman, D.W., 1962, Aggressive behavior in juvenile coho salmon as a cause of emigration: Journal of the Fisheries Research Board Canada, V. 19, No. 6, p. 1047–1080.

Chapman, D.W., 1966, Food and space as regulators of salmonid populations in streams: American. Naturalist, V. 100, No. 913, p. 345–357.

Chapman, D.W., and Bjornn, T.C. 1969, Distribution of salmonids in streams, with special reference to food and feeding: Pages 153–176 *in* Symposium on Salmon and Trout in Streams, T.G. Northcote, ed., University of British Columbia, Vancouver, H.R. MacMillan Lectures in Fisheries.

Combs, B. D., and Burrows, R.E., 1957, Threshold temperatures for the normal development of Chinook salmon eggs: The Progressive Fish-Culturist, V. 19, p. 3–6.

Conder, A.L. and Annear, T.C., 1987, Test of weighted usable area estimates derived from a PHABSIM model for instream flow studies on trout streams: North American Journal of Fisheries Management, V. 7, p. 339–350.

Crisp, D.T., 1981, A desk study of the relationship between temperature and hatching time for eggs of five species of salmonid fishes: Freshwater Biology, V. 11, No. 4, p. 361–368.

Crisp, D.T., 1988, Prediction, from temperature, of eyeing, hatching and “swim-up” times for salmonid embryos: Freshwater Biology, V. 19, p. 41–48.

Dill, L. M., Ydenberg, R.C., and Fraser, A.G.H., 1981, Food abundance and territory size in juvenile Coho Salmon *(Oncorhynchus kisutch)*: Canadian Journal of Zoology, V. 59, p. 1801–1809.

Donaldson, E.M., 1990, Reproductive indices as measures of the effects of environmental stressors in fish: Pages 109–122 in Adams, S.M., ed., Biological indicators of stress in fish, American Fisheries Society Symposium 8, Bethesda, Maryland.

Dunning, J.B. Jr., and six others, 1995, Spatially explicit population models, Current forms and future uses: Ecological Applications, V. 5, No. 1, p. 3–11.

Flett, P.A., Munkittrick, K.R., Van Der Kraak, G., and Leatherland, J.F., 1996, Overripening as the cause of low survival to hatch in Lake Erie coho salmon (*Oncorhynchus kisutch*) embryos: Canadian Journal of Zoology, V. 74, p. 851–857.

Fraser, F.J., 1969, Population density effects on survival and growth of juvenile coho salmon and steelhead trout in experimental stream-channels: Pages 253–266 *in* T.G. Northcote, editor. Symposium on salmon and trout in streams, H.R. MacMillan lectures in fisheries, University of British Columbia, Vancouver, Canada, 388 p.

Gard, M., 1995a, Upper Sacramento River IFIM study scoping report, Appendix A: Available information: U.S. Fish and Wildlife Service, Sacramento, California, unnumbered pages.

Gard, M., 1995b, Identification of the instream flow requirements for anadromous fish in the streams within the Central Valley of California, annual progress report, fiscal year 1995, Appendix D, Sacramento River Hydrology: U.S. Fish and Wildlife Service, Sacramento, California, unnumbered pages.

Gard, M., 2001, Identification of the instream flow requirements for steelhead and fall, late-fall, and winter-run Chinook salmon spawning in the Sacramento River between Keswick Dam and Battle Creek: U.S. Fish and Wildlife Service, Sacramento, California.

Gard, M., 2005, Variability in flow-habitat relationships as a function of transect number for PHABSIM modeling: River Research and Applications, V. 21, p. 1013–1019.

Geist, D.R., Hanrahan, T.P., Arntzen, E.V., McMichael, G.A., Murry, C.J., and Chien, Y., 2002, Physiochemical characteristics of the hyporheic zone affect redd site selection by chum salmon and fall Chinook salmon in the Columbia River: North American Journal of Fisheries Management, V. 22, p. 1077–1085.

Godin, J.J., 1981, Migrations of salmonid fishes during early life-history phases, daily and annual timing: Pages 22–50 *in* Salmon and Trout Migratory Behavior Symposium, Brannon, E.L., and Salo, E.O., eds, Proceedings of the salmon and trout migratory behavior symposium. School of Fisheries, University of Washington, Seattle, Wash., June 3–5, 1981.

Gouraud, V., Bagliniere, J.L., Baran, P., Sabaton, C., Lim, P., and Ombredane, D., 2001, Factors regulating brown trout populations in two French rivers, Application of a dynamic population model: Regulated Rivers: Research and Management, V. 17, p. 557–569.

Grant, J.W.A., and Kramer, D.L., 1990, Territory size as a predictor of the upper limit to population density of juvenile salmonids in streams: Canadian Journal Fisheries Aquatic Science, V. 47, No. 9, p. 1724–1737.

Grant, J.W.A., Steingrimsson, S.O., Keeley, E.R., and Cunjak, R.A., 1998, Implications of territory size for the prediction of salmonid abundance in streams: Canadian Journal of Fisheries and Aquatic Science, V. 55(Suppl. 1), p. 181–190.

Hanna, R.B., 1999, Model-derived guidelines for "effective" TCD operations for target temperatures below Shasta Dam and the resulting changes in the coolwater pool in Shasta Lake, final report: U.S. Geological Survey, Fort Collins, 29 p.

Hanna, R.B., 2000, Shasta Lake water quality modeling investigations for Shasta enlargement, environmental impact statement data needs, year-end report 2000, initial findings, methods and recommendations: U.S. Geological Survey, Fort Collins, Colorado, 31p.

Hanna, R.B., Saito, L., Bartholow, J.M., and Sandelin, J., 1999, Results of simulated temperature control device operations on in-reservoir and discharge water temperatures using CE-QUAL-W2: Journal of Lake and Reservoir Management, V. 15, No. 2, p. 87–102.

Hannah, D.M., Malcom, I.A., Soulsby, C., and Youngson, A.F., 2004, Heat exchanges and temperatures within a salmon spawning stream in the cairngorms, Scotland, Seasonal and sub-seasonal dynamics: River Research and Applications, V. 20, p. 635–652.

Healey, M.C., 1994, Variation in the life-history characteristics of Chinook salmon and its relevance to the conservation of the Sacramento winter-run of Chinook salmon: Conservation Biology, V. 8, No. 3, p. 876–877.

Healey, M.C., and Heard, W.R., 1984, Inter- and intra-population variation in the fecundity of Chinook salmon *(Oncorhynchus tshawytsch*a) and its relevance to life-history theory: Canadian Journal of Fisheries and Aquatic Sciences, V. 41, p. 476–483.

Healey, T. P., 1977, The effect of high temperature on the survival of Sacramento River Chinook (king) salmon, *Oncorhynchus tshawytsch*a, eggs and fry: California Department of Fish and Game, Anadromous Fisheries Branch Administrative Report no. 79–10. 7 p.

Heggenes, J., Saltveit, S.J., and Lingaas, O., 1996, Predicting fish habitat use to changes in water flow, Modeling critical minimum flows for Atlantic salmon, *Salmo salar*, and brown trout, *S. trutta*: Regulated Rivers: Research and Management, V. 12, p. 331–344.

Heming, T.A., McInerney, J.E., and Alderdice, D.F., 1982, Effect of temperature on initial feeding in alevins of Chinook salmon (*Oncorhynchus tshawytscha*): Canadian Journal of Fisheries and Aquatic Science, V. 39, p. 1554–1562.

Hinze, J.A., Culver, A.N., and Rice, G.V., 1956, Annual Report, Nimbus Salmon and Steelhead Hatchery: Inland administrative report number 56–25.

Holling, C.S., and Allen, C.R., 2002, Adaptive inference for distinguishing credible from incredible patterns in nature: Ecosystems, V. 5, p. 319–328.

Holtby, L.B., and Scrivener, J.C., 1989, Observed and simulated effects of climatic variability, clear-cut logging, and fishing on the numbers of chum salmon (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) returning to Carnation Creek, British Columbia, *in* Levings, C.D., Holtby, L.B., and Henderson, M.A., eds: Proceedings of the National Workshop on effects of habitat alteration on salmonid stocks. Canadian Special Publication Fisheries and Aquatic Sciences, V. 105, p. 62–81.

Hume, J.M.B., and Parkinson, E.A., 1987, Effect of stocking density on the survival, growth, and dispersal of steelhead trout fry (*Salmo gairdneri*): Canadian Journal of Fisheries and Aquatic Science, V 44, p. 271–281.

Irvine, J.R. 1986. Effects of varying discharge on the downstream movement of salmon fry, *Oncorhynchus tshawytscha* Walbaum: Journal of Fish Biology, V. 28, p. 17–28.

Jensen, A.J., Johnsen, B.O., and Heggberget, T.G., 1991, Initial feeding time of Atlantic salmon, *Salmo* salar, alevins compared to river flow and water temperature in Norwegian streams: Environmental Biology of Fishes, V. 30, p. 379–385.

Kent, J.J., 1999, Application and sensitivity analysis of a salmonid population model for the Sacramento River, California: Master's Thesis, Colorado State University, Fort Collins, Colorado. 79 p.

Kope, R.G., and Botsford, L.W., 1990, Determination of factors affecting recruitment of Chinook salmon *Oncorhynchus tshawytscha* in central California: Fishery Bulletin, V. 88, No. 2, p. 257–269.

Korman, J., and Higgins, P.S., 1997, Utility of escapement time series data for monitoring the response of salmon populations to habitat alteration: Canadian Journal Fisheries and Aquatic Sciences, V. 54, p. 2058–2067.

Lapointe, M., Eaton, B., Driscoll, S. and Latulippe, C., 2000, Modelling the probability of salmonid egg pocket scour due to floods: Canadian Journal Fisheries and Aquatic Sciences, V. 57, p. 1120–1130.

Leitritz, E., and Lewis, R.C., 1980, Trout and salmon culture (hatchery methods): California Fish Bulletin No. 164. Berkeley, University of California, 197 p.

Ligon, F., Rich, A., Rynearson, G., Thornburgh, D., and Trush, W., 1999, Report of the scientific review panel on California Forest Practice Rules and salmonid habitat: Prepared for the Resources Agency of California and the National Marine Fisheries Service. Sacramento, Calif. 181 p. Accessible on the Internet at http://www.krisweb.com/biblio/cal_nmfs_ligonetal_1999_srprept.pdf

Link, J.S., 2002, Ecological considerations in fisheries management, When does it matter?: Fisheries, V. 27, No. 4, p. 10–17.

Marine, K.R., 1992, A background investigation and review of the effects of elevated water temperature on reproductive performance of adult Chinook salmon (*Oncorhynchus tshawytscha*): Department of Wildlife and Fisheries Biology, Davis, University of California, October 1992. 30 p plus appendix.

Marine, K.R. and Cech, J.J. Jr., 2004, Effects of high water temperature on growth, smoltification, and predator avoidance in juvenile Sacramento River Chinook salmon: North American Journal of Fisheries Management, V. 24, p. 198–210.

Martin, C.D., Johnson, R.R., Gaines, P.D., Kisanuki, T.T., McKinney, W.R., and Null, R.E., 2000, Estimating the abundance of Sacramento River winter Chinook salmon with comparisons to adult escapement, draft final report, Red Bluff research pumping plant, report series, volume 5: U.S. Fish and Wildlife Service, Red Bluff, Calif,, draft of October 2000, 31 p. plus tables and figures. (Available on request.)

McCullough, D.A., 1999, A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon: U.S. Environmental Protection Agency, Seattle, Washington, EPA 910-R-99-010, 1999, 279 p. Available on the Internet at http://www.critfc.org/tech/EPAreport.htm

McDonald, J. 1960. The behavior of Pacific salmon fry during their downstream migration to freshwater and saltwater nursery areas: Journal of the Fisheries Research Board Canada, V. 17, No. 5, p. 655–676.

McNeil, W.J., 1967, Randomness in the distribution of pink salmon redds: Journal of the Fisheries Research Board Canada, V. 24, No. 7, p. 1629–1634.

Mesick, C.F., 1988, Effects of food and cover on numbers of Apache and brown trout establishing residency in artificial stream channels: Transactions American Fisheries Society, V. 117, No. 5, p. 421–431.

Mikulich, L.V., and Gavrenkov, Y.I., 1986, Some biological properties and feeding of downstream migrating juvenile chum salmon, *Oncorhynchus keta*, from the Southern Maritime Territory: Journal of Ichthyology, V. 26, p. 38–46.

Milhous, R.T., Updike, M.A., and Schneider, D.M., 1989, Physical habitat simulation system reference manual - Version II: Instream Flow Information Paper No. 26. Washington, DC: U.S. Fish and Wildlife Service (Biological Report 89[16]), variously paged.

Milner, N.J., Elliott, J.M., Armstrong, J.D., Gardiner, R., Welton, J.S., and Ladle, M., 2003, The natural control of salmon and trout in streams: Fisheries Research, V. 62, p. 111–125.

Montgomery, D.R., Beamer, E.M., Pess, G.R., and Quinn, T.P., 1999, Channel type and salmonid spawning distribution and abundance: Canadian Journal of Fisheries and Aquatic Science, V. 56, p. 377–387.

Morhardt, J.E., Hanson, D.F., and Coulston, P.J., 1983, Instream flow, Increased accuracy using habitat mapping: Pages 1294–1304 *in* Waterpower "83", vol. 3, Environmental impacts, An International Conference on Hydropower, Tennessee Valley Authority, Norris, Tenn.

Moyle, P. B., 2002, Inland fishes of California, revised and expanded: Berkeley, University of California Press, 502 p.

Mundie, J.H., 1974, Optimization of the salmonid nursery stream: Journal of the Fisheries Research Board Canada, V. 31, p. 1827–1837.

Myrick, C.A., and Cech, J.J. Jr., 2001, Temperature effects on Chinook salmon and steelhead, A review focusing on California's Central Valley populations: Bay-Delta Modeling Forum Technical Publication 01–1. http://www.cwemf.org/Pubs/TempReview.pdf. 57 p.

Myrick, C.A., and Cech, J.J. Jr., 2004, Temperature effects on juvenile anadromous salmonids in California’s central valley: Reviews in Fish Biology and Fisheries, V. 14, p. 113–123.

National Marine Fisheries Service, No date, Biological Opinion, the fishery management plan for commercial and recreational salmon fisheries off the coasts of Washington, Oregon, and California of the Pacific Fishery Management Council Agency, National Marine Fisheries Service, Northwest and Southwest Regional Fishery Management Divisions, Available on the Internet at http://swr.nmfs.noaa.gov/evaluat3.htm, viewed 11/2/05.

Neilson, J.D., and Banford, C.E., 1983, Chinook salmon (*Oncorhynchus tshawytscha*) characteristics in relation to redd physical features: Canadian Journal of Zoology, V. 61, p. 1524–1531.

Nickel, D.K., Brett, M.T., and Jassby, A.D., 2004, Factors regulating Shasta Lake California, cold water accumulation, a resource for endangered salmon conservation: Water Resources Research, V. 40: W05204, doi: 10.1029/2003WR002669.

Olson, P.A., and Foster, R.F., 1955, Temperature tolerance of eggs and young of Columbia River Chinook salmon: American Fisheries Society, V. 85, p. 203–207.

Orth, D.J., 1987, Ecological considerations in the development and application of instream flow-habitat models: Regulated Rivers: Research and Management, V. 1, p. 171–181.

Poole, G., and 11 others, 2001, Technical synthesis, scientific issues relating to temperature criteria for salmon, trout, and char native to the Pacific Northwest: U.S. Environmental Protection Agency, Portland, Oreg. EPA 910-R-01-007, 21 p. Available on the Internet at http://yosemite.epa.gov/R10/WATER.NSF/6cb1a1df2c49e4968825688200712cb7/bd029c92a81bf25f88256a020072a8c7/$FILE/Final_Synthesis.PDF.

Poytress, B., 2005, Memo: biweekly report (October 22, 2005–November 4, 2005): U.S. Fish and Wildlife Service, Red Bluff, Calif.. (Available on request.)

Prager, M.H., and Mohr, M.S., 1999, Population dynamics of Klamath River fall Chinook salmon, Stock-recruitment model and simulation of yield under management: National Marine Fisheries Service, National Oceanographic and Atmospheric Administration, Southwest Fisheries Science Center, Tiburon, California. 36 p.

Quinn, T.P., and Peterson, N.P., 1996, The influence of habitat complexity and fish size on over-winter survival and growth of individually marked juvenile coho salmon (*Oncorhynchus kisutch*) in Big Beef Creek, Washington: Canadian Journal of Fisheries and Aquatic Science, V. 53, p. 1555–1564.

Radomski, P.J., and Goeman, T.J., 1996, Decision making and modeling in freshwater sport-fisheries management: Fisheries, V. 21, No. 12, p. 14–21.

Resource Management Associates, Inc. (RMA), 2003 Draft, Upper Sacramento River water quality modeling with HEC-5Q, model calibration and validation, variously paged. (Available on request.)

Richardson, T.H. and Harrison, P., 1990, An analysis of fish and wildlife impacts of Shasta Dam water temperature control alternatives: December, 1990, 63 p. U.S. Fish and Wildlife Service, Sacramento, Calif. (Available on request.)

Richter, A., and Kolmes, S.A., 2005, Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest: Reviews in Fisheries Science, V. 13, p. 23–49.

Rykiel, E.J. Jr., 1996, Testing ecological models: the meaning of validation: Ecological Modeling, V. 90, p. 229–244.

Sabaton, C., Siegler, L., Gouraud, V., Bagliniere, J.L., and Manne, S., 1997, Presentation and first applications of a dynamic population model for brown trout, *Salmo trutta* L., aid to river management: Fisheries Management and Ecology, V. 4, p.425–438.

Saito, L., Johnson, B.M., Bartholow, J., Hanna, R.B., 2001, Assessing ecosystem effects of reservoir operations using food web-energy transfer and water quality models: Ecosystems, V. 4, No. 2, p. 105–125.

Saito, L., and Bartholow, J., 1997, Summary of water temperature calibration for a CE-QUAL-W2 model of Shasta Lake, California: Available over the Internet at http://smig.usgs.gov/SMIG/features_0997/shasta_w2.html.

Saltveit, S.J., Bremnes, T., and Lindas, O.R., 1995, Effect of sudden increase in discharge in a large river on newly emerged Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) fry: Ecology of Freshwater Fish, V. 4, No. 4, p. 168–174.

Schnute, J.T. and Richards, L.J., 2001, Use and abuse of fishery models: Canadian Journal of Fisheries and Aquatic Science, V. 58, p. 10–17.

Shelbourne, J.E., Brett, J.R., and Shirahata, S., 1973, Effect of temperature and feeding regime on specific growth rate of sockeye salmon fry (*Oncorhynchus nerka*), with a consideration of size effect: Journal of the Fisheries Research Board Canada, V. 30, No. 8, p. 1191–1194.

Shepherd, B.G., Hartman, G.F., and Wilson, W.J., 1986, Relationships between stream and intragravel temperatures in coastal drainages, and some implications for fisheries workers: Canadian Journal of Fisheries and Aquatic Science, V. 43, p. 1818–1822.

Smith, C.E., Dwyer, W.P., and Piper, R.G., 1983, Effect of water temperature on egg quality of cutthroat trout: Progressive Fish-Culturist, V. 45, No. 3, p. 176–178.

Stalnaker, C., Lamb, B.L., Henriksen, J., Bovee, K. and Bartholow, J., 1995, The Instream Flow Incremental Methodology, A primer for IFIM: National Biological Service Biological Science Report 29, 44 p.

Sullivan, K., Martin, D.J., Cardwell, R.D., Toll, J.E., and Duke, S., 2000, An analysis of the effects of temperature on salmonids of the Pacific Northwest with implications for selecting temperature criteria: Sustainable Ecosystems Institute. *http://www.sei.org/pub.html#reports*.

Titus, R.G., and Mosegaard, H., 1991, Selection for growth potential among migratory brown trout (*Salmo trutta*) fry competing for territories, evidence from otoliths: Canadian Journal of Fisheries and Aquatic Science, V. 48, p. 19–27.

U.S. Environmental Protection Agency (USEPA), 2003, EPA Region 10 guidance for Pacific Northwest state and tribal temperature water quality standards: EPA 910-B-03-002. Region 10 Office of Water, Portland, Oregon, April 2003, 49 p. Available on the Internet at http://www.epa.gov/r10earth/temperature.htm

U.S. Fish and Wildlife Service (USFWS), 1990, An analysis of fish and wildlife impacts of Shasta Dam water temperature control alternatives: Fish and Wildlife Coordination Act Report, U.S. Fish and Wildlife Service Region 1, Sacramento, Calif., 22 p. plus attachments.

U.S. Fish and Wildlife Service (USFWS), 1999, Effect of temperature on early-life survival of Sacramento River Fall- and Winter-run Chinook salmon: U.S. Fish and Wildlife Service Report, North Central Valley Fish and Wildlife Office, Red Bluff, Calif., 41 p.

U.S. Fish and Wildlife Service (USFWS), 2005a, Flow-habitat relationships for Chinook salmon rearing in the Sacramento River between Keswick Dam and Battle Creek: Sacramento Fish and Wildlife Office, Sacramento, California, 249 p.

U.S. Fish and Wildlife Service (USFWS), 2005b, Flow-habitat relationships for fall-run Chinook salmon spawning in the Sacramento River between Battle Creek and Deer Creek: Sacramento Fish and Wildlife Office, Sacramento, Calif., 99 p.

U.S. Fish and Wildlife Service and Hoopa Valley Tribe, 1999, Trinity River flow evaluation, final report: 307 p plus appendix.

Vogel, D.A., and Marine, K.R., 1991, Guide to upper Sacramento River Chinook salmon life-history: CH2M HILL, Redding, California. Produced for the Bureau of Reclamation Central Valley Project, 55 p. plus appendix.

Walters, C., 1986, Adaptive management of renewable resources. Macmillan Press, New York, New York, 374 p.

Williamson, S.C., Bartholow, J.M., and Stalnaker, C.B., 1993, Conceptual model for quantifying presmolt production from flow-dependent physical habitat and water temperature: Regulated Rivers: Research and Management. V. 8, No. 1&2, p. 15–28.

Acknowledgments

Many people assisted us in the endeavor and we could not have made much progress without their able assistance. Matt Brown (USFWS), James DeStaso (USBR), Michael Fainter (Stillwater Associates.), Mark Gard (USFWS), John Hannon (USBR), James Henriksen (USGS), Nick Hettrick (USFWS), Doug Killam (California Department of Fish and Game), Bob Milhous (USGS), Stephanie Theis (MHW), Sam Williamson (USGS), and Russ Yaworsky (USBR) were all generous with their time, patient explanations, and so much more. We thank them all.

Appendix A – Statistical Summary of Hydrologic and Water Temperature Indices for Shasta Alternatives

The California Department of Fish and Game suggested that the Nature Conservancy's Indicators of Hydrologic Alteration tool (IHA) (Richter, and others, 1996) could be used to assess the effects of changes either toward or away from unimpaired flow conditions. Though we have not looked at unimpaired flows or water temperatures, we have computed comparable indices for the flows and temperatures representative of Keswick discharge for the Bureau of Reclamation's baseline and three alternative scenarios.

The statistical results that follow were computed using a new iteration of the National Hydrologic Assessment Tool (NHAT) software developed by the USGS (Henriksen and others, 2006). This software computes 171 individual indices from mean (and peak) daily discharge data. Definitions for these indices may be found at the end of this Appendix. Which metrics may be of most value will depend on their known or perceived biological relevance.

We have also computed the same suite of statistics for the water temperature data, even though some of the statistics (for example those involving drainage area, about 160 mi^2 for Keswick) are meaningless for water temperature and the definitions – as given – are written for discharge. Nonetheless, the indices and some simple summary graphics are instructive. For both discharge and temperature, we did not compute the metrics for peak daily values.

The following six graphs are a good way to summarize the month-by-month flow and temperature values from one alternative to another. In all cases, the graphs represent mean daily values for water years 1922 through 1994, with the months arrayed across the x-axis from January to December. The x-axis, however, is not labeled with the month name but rather with the index name. For example, MA12 will refer to the specific index named "MA12" that will be found to correspond to median January values. Figure A-1 plots monthly changes in the monthly median discharge and upper and lower (95 and 5) percent of the monthly distribution of those medians for discharge. In other words, the software computes the median value for all Januarys in the 73-year data set as well as the 5th and 95th percentile values, then again for each month. Figure A-2 is similar, but for monthly low flows, and figure A-3 is for monthly high flows. Figures A-4 through A-6 repeats this scheme for water temperatures. These figures indicate that month-to-month changes seem small and there is generally, though not always, a regular progression in terms of increasing height of the dam enlargement.

Tables A-1 and A-2 present a full listing of the 171 individual metrics for each alternative for discharge and water temperature, respectively. Three values may be provided for each metric. They are, respectively, the low (5 percent), median, and high (95 percent) for the specific data set across all years, just as shown on the sample figures. For example, in table A-2, index DH1 indicates that the annual high water temperature in the baseline scenario ranges from 12.20°C to 18.40°C with a median of 13.24°C. For the highest dam-raise scenario, these values have been lowered to 11.44°, 18.40°, and 12.78°C respectively. In cases when it would not make sense to compute the low and high percentile values, none are given.

It is important to keep in mind that all the values being summarized are the result of simulation models, not measured flow or temperature data. Though it might be instructive to compare the indices with measured historical data, we have not done so. It is clear, we believe, that such a comparison would reveal substantial changes given the considerably altered annual hydrograph and thermal regime. Nor have we looked at flows or temperatures lower in the study area in the same manner, though in general one would expect less deviation given the influence of “normal” downstream accretions and heat flux.

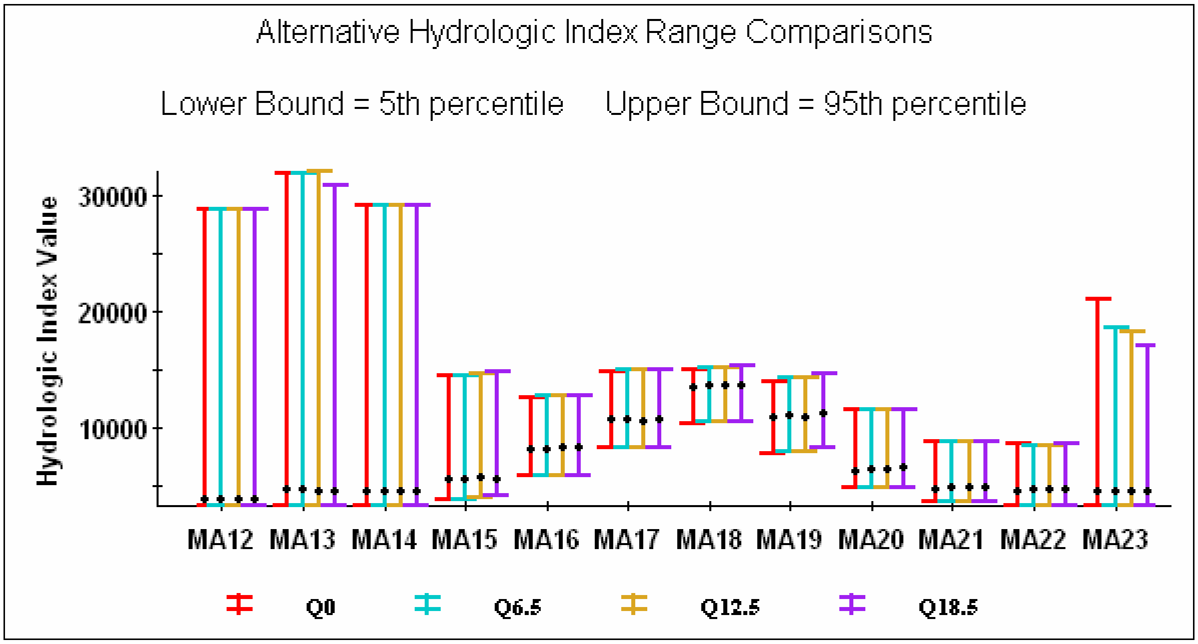


Figure A-1. Monthly differences for monthly median discharge (ft^3/s) Keswick Dam for 1922 through 1994. Y-values shown are median (dot) and 5th and 95th percentiles. The x-axis extends from January to December. Q0 is the baseline, Q6.5 is the 6.5-foot dam raise alternative, and so on.

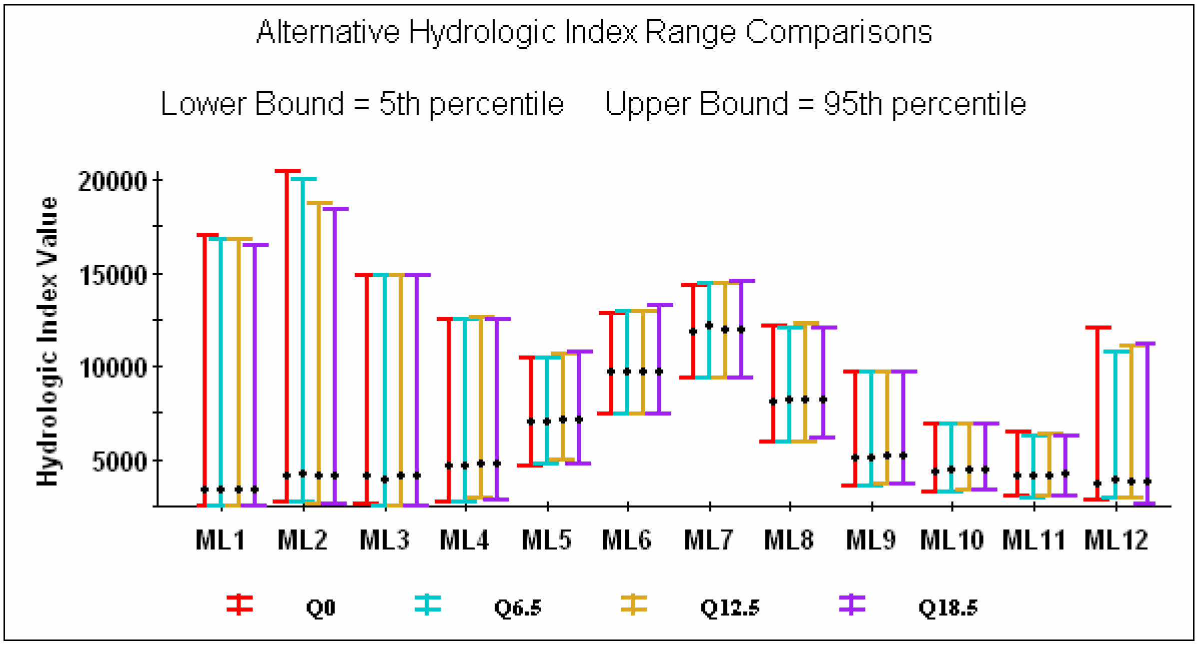


Figure A-2. Monthly differences for monthly minimum discharge (ft^3/s) Keswick Dam for 1922 through 1994. Y-values shown are median (dot) and 5th and 95th percentiles. The x-axis extends from January to December. Q0 is the baseline, Q6.5 is the 6.5-foot dam raise alternative, and so on.

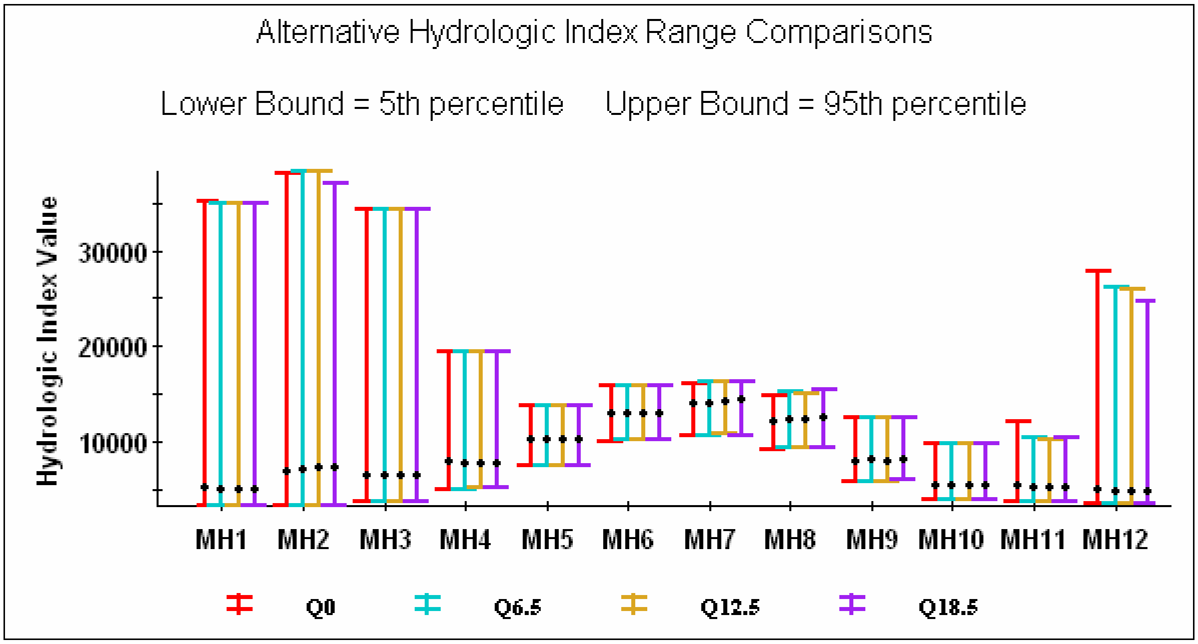


Figure A-3. Monthly differences for monthly maximum discharge (ft^3/s) Keswick Dam for 1922 through 1994. Y-values shown are median (dot) and 5th and 95th percentiles. The x-axis extends from January to December. Q0 is the baseline, Q6.5 is the 6.5-foot dam raise alternative, and so on.

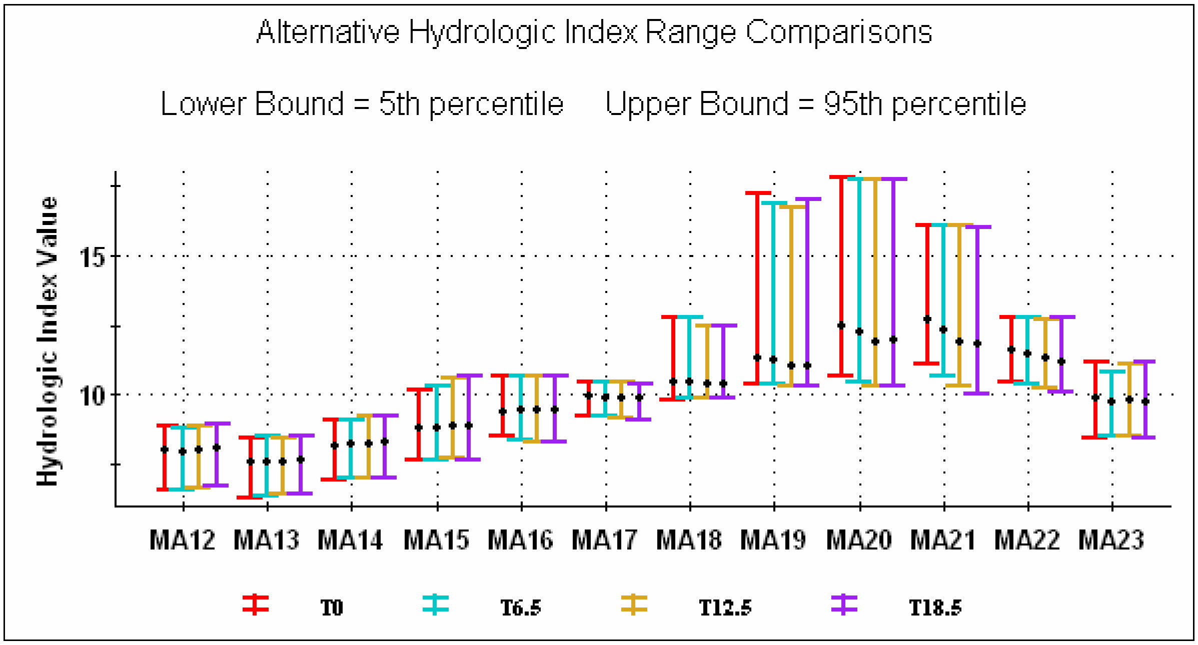


Figure A-4. Monthly differences for monthly median water temperature (℃) Keswick Dam for 1922 through 1994. Y-values shown are median (dot) and 5th and 95th percentiles. The x-axis extends from January to December. Q0 is the baseline, Q6.5 is the 6.5-foot dam raise alternative, and so on.

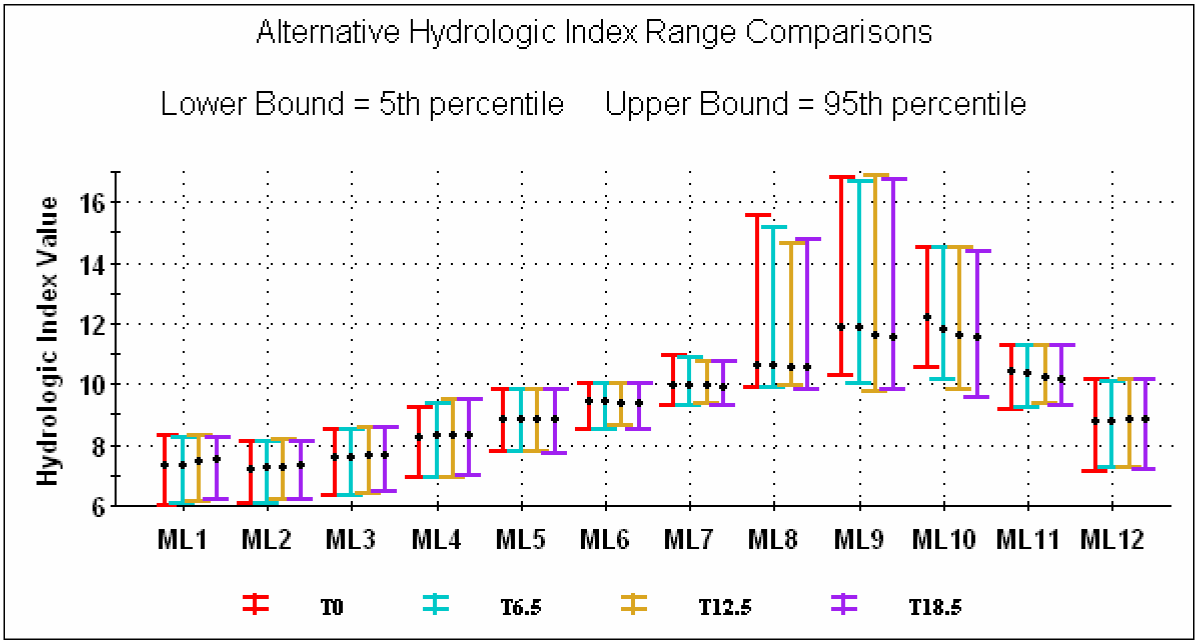


Figure A-5. Monthly differences for monthly minimum water temperature (°C) Keswick Dam for 1922 through 1994. Y-values shown are median (dot) and 5th and 95th percentiles. The x-axis extends from January to December. Q0 is the baseline, Q6.5 is the 6.5-foot dam raise alternative, and so on.

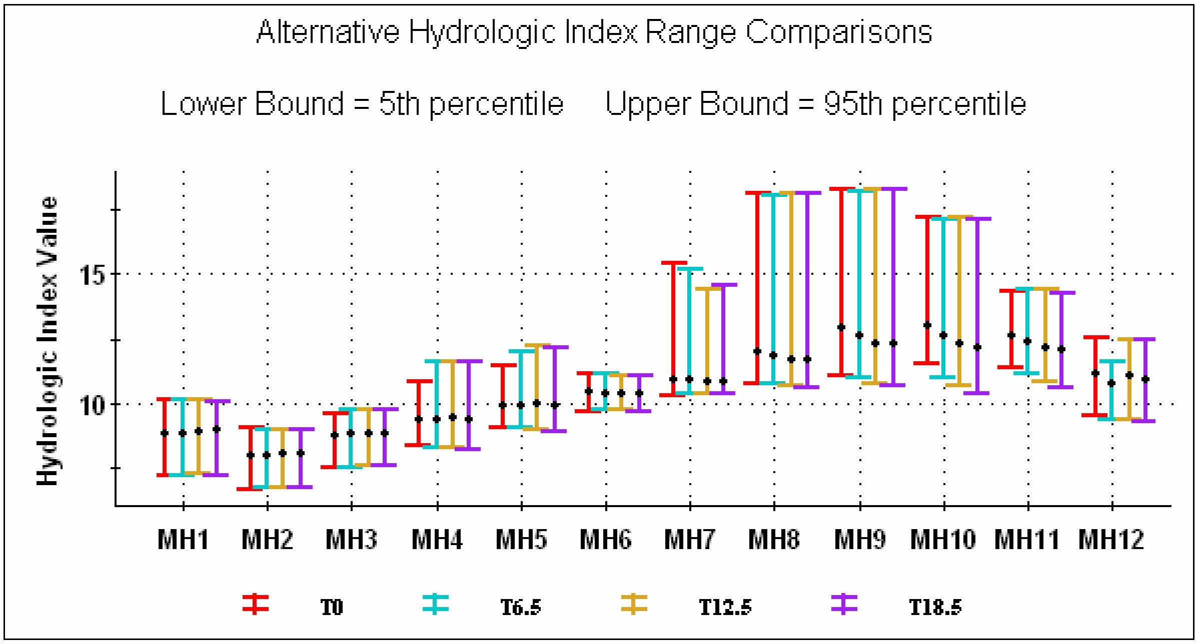


Figure A-6. Monthly differences for monthly maximum water temperature (°C) Keswick Dam for 1922 through 1994. Y-values shown are median (dot) and 5th and 95th percentiles. The x-axis extends from January to December. Q0 is the baseline, Q6.5 is the 6.5-foot dam raise alternative, and so on.

Table A-1. Indices computed from daily discharge (ft^3/s) for water years 1922 to 1994. Refer to the definitions below to interpret the values. NC means not computed.

Index	**Base**			**6.5-foot raise**			**12.5-foot raise**			**18.5-foot raise**		
	Lower Limit	Value	Upper Limit	Lower Limit	Value	Upper Limit	Lower Limit	Value	Upper Limit	Lower Limit	Value	Upper Limit
MA1	3223.78	8372.80	15957.18	3227.44	8367.51	15775.10	3224.81	8367.07	15700.01	3224.15	8353.61	15714.65
MA2	3223.78	6998.24	15957.18	3227.44	7012.92	15775.10	3224.81	7063.20	15700.01	3224.15	7024.14	15714.65
MA3	28.83	43.98	135.51	28.68	44.94	136.50	28.77	43.46	136.93	28.59	43.64	137.31
MA4	NC	5.73	NC	NC	5.71	NC	NC	5.68	NC	NC	5.68	NC
MA5	NC	1.20	NC	NC	1.19	NC	NC	1.19	NC	NC	1.19	NC
MA6	NC	4.16	NC	NC	4.18	NC	NC	4.15	NC	NC	4.16	NC
MA7	NC	2.81	NC	NC	2.82	NC	NC	2.80	NC	NC	2.79	NC
MA8	NC	2.48	NC	NC	2.47	NC	NC	2.46	NC	NC	2.46	NC
MA9	NC	0.16	NC	NC	0.16	NC	NC	0.16	NC	NC	0.16	NC
MA10	NC	0.12	NC	NC	0.12	NC	NC	0.12	NC	NC	0.12	NC
MA11	NC	0.10	NC	NC	0.10	NC	NC	0.10	NC	NC	0.10	NC
MA12	3246.97	3835.70	28741.14	3247.71	3821.07	28778.61	3246.96	3748.57	28760.46	3245.12	3822.96	28796.64
MA13	3239.46	4606.29	31769.46	3233.97	4540.99	31764.36	3233.36	4517.32	32006.86	3233.41	4517.32	30742.78
MA14	3252.90	4504.29	29052.02	3253.51	4502.12	29064.40	3253.31	4504.61	29068.65	3248.93	4502.08	29070.13
MA15	3821.57	5504.21	14453.44	3757.64	5525.81	14484.02	3970.93	5574.52	14575.64	4009.42	5506.27	14747.10
MA16	5796.61	8089.10	12526.44	5808.75	8131.37	12699.11	5795.25	8151.87	12631.88	5808.00	8149.94	12704.64
MA17	8205.75	10602.98	14707.66	8206.98	10662.05	14871.05	8211.15	10466.32	14925.97	8193.77	10674.98	14950.75
MA18	10366.23	13418.21	15032.58	10423.92	13552.93	15119.93	10418.72	13497.07	15047.77	10406.46	13557.42	15262.11
MA19	7629.75	10819.00	13985.83	7802.53	11025.97	14299.68	7922.53	10898.23	14313.86	8162.00	11085.14	14578.92
MA20	4740.44	6248.20	11582.13	4824.09	6390.98	11568.03	4832.28	6402.42	11560.71	4768.45	6441.18	11549.10
MA21	3554.59	4628.49	8798.97	3573.78	4724.36	8800.15	3574.65	4758.29	8796.44	3566.90	4794.87	8791.79
MA22	3246.25	4513.40	8543.78	3242.46	4662.00	8413.84	3243.38	4605.58	8415.66	3246.53	4650.57	8525.16
MA23	3247.27	4391.73	21059.09	3247.15	4467.68	18576.51	3247.23	4471.80	18213.38	3248.05	4466.00	16985.83
MA24	0.73	7.88	53.54	0.72	7.48	50.18	0.62	6.77	47.72	1.05	6.88	43.57
MA25	0.71	10.18	47.03	0.48	9.63	47.22	0.72	9.83	48.30	0.78	9.76	47.28
MA26	1.51	11.45	41.73	1.44	11.55	40.05	1.46	11.46	38.29	1.26	11.47	38.36
MA27	4.61	11.21	40.17	3.70	12.05	40.08	4.01	12.04	38.92	3.82	12.03	39.01
MA28	3.80	9.67	19.86	3.69	9.63	19.73	3.94	9.45	17.94	4.18	9.58	18.42
MA29	2.85	6.50	9.59	2.86	6.36	9.52	2.49	6.07	9.43	2.72	6.36	9.33
MA30	0.99	3.59	6.91	0.92	3.58	6.69	1.00	3.48	6.72	0.97	3.41	6.67
MA31	2.61	9.40	13.26	2.14	8.57	12.78	2.37	8.73	12.78	2.18	8.82	12.92
MA32	3.87	11.58	15.89	4.36	11.72	16.56	4.32	11.65	16.44	4.37	11.82	16.55

Index	Base				6.5-foot raise				12.5-foot raise				18.5-foot raise		
MA33	1.44	5.22	12.39		1.82	5.06	10.60		2.07	5.46	9.47		1.33	5.43	9.90
MA34	1.34	5.12	32.81		1.74	4.43	28.69		1.31	4.22	27.70		1.79	4.74	25.39
MA35	1.46	6.37	36.01		1.64	6.78	32.98		1.31	6.05	35.50		1.63	6.29	36.80
MA36	NC	7.20	NC		NC	7.31	NC		NC	7.32	NC		NC	7.32	NC
MA37	NC	0.91	NC		NC	0.93	NC		NC	0.93	NC		NC	0.93	NC
MA38	NC	1.53	NC		NC	1.56	NC		NC	1.57	NC		NC	1.57	NC
MA39	NC	66.90	NC		NC	66.30	NC		NC	66.10	NC		NC	65.83	NC
MA40	NC	0.19	NC		NC	0.21	NC		NC	0.22	NC		NC	0.21	NC
MA41	33.45	52.33	87.52		33.53	52.30	87.77		33.54	52.30	88.04		33.46	52.21	88.09
MA42	NC	1.57	NC		NC	1.58	NC		NC	1.59	NC		NC	1.57	NC
MA43	NC	0.47	NC		NC	0.44	NC		NC	0.44	NC		NC	0.42	NC
MA44	NC	0.77	NC		NC	0.75	NC		NC	0.74	NC		NC	0.71	NC
MA45	NC	0.07	NC		NC	0.07	NC		NC	0.08	NC		NC	0.08	NC
ML1	2500.00	3311.68	16995.75		2500.00	3382.34	16781.47		2500.00	3356.86	16755.79		2500.00	3374.03	16494.62
ML2	2716.18	4137.52	20424.47		2693.12	4172.56	20022.03		2650.38	4110.30	18754.15		2654.69	4110.29	18335.16
ML3	2564.61	4062.91	14827.60		2541.98	3866.89	14803.19		2521.64	4117.72	14799.69		2526.29	4105.65	14791.68
ML4	2735.73	4632.67	12517.49		2749.88	4691.55	12508.22		2887.10	4717.59	12562.96		2874.03	4707.99	12495.39
ML5	4679.57	7019.77	10444.34		4723.53	7016.30	10483.43		4996.55	7132.43	10646.07		4786.48	7157.71	10737.78
ML6	7468.70	9676.18	12853.86		7461.24	9652.02	12959.63		7470.19	9661.92	12941.27		7473.93	9738.24	13200.35
ML7	9349.12	11805.49	14299.76		9323.61	12186.25	14374.41		9321.76	11989.40	14385.16		9318.31	11988.34	14494.22
ML8	5913.16	8036.25	12120.14		5888.09	8135.83	12104.34		5926.14	8161.04	12230.87		6150.94	8224.66	12083.21
ML9	3558.05	5101.10	9737.72		3587.92	5108.63	9726.62		3729.33	5155.60	9733.58		3665.75	5195.35	9711.28
ML10	3259.53	4352.24	6878.65		3285.63	4408.96	6886.44		3340.81	4411.41	6916.43		3331.76	4457.82	6878.43
ML11	3044.36	4100.87	6461.17		2968.78	4119.58	6301.66		3061.41	4159.68	6396.77		3050.77	4237.50	6293.97
ML12	2785.54	3719.74	12087.64		2949.05	3888.32	10728.23		2923.18	3817.21	11104.91		2556.69	3766.41	11211.01
ML13	NC	55.18	NC		NC	54.81	NC		NC	54.36	NC		NC	54.17	NC
ML14	0.25	0.47	0.74		0.27	0.48	0.76		0.27	0.48	0.76		0.26	0.49	0.78
ML15	0.20	0.42	0.58		0.22	0.42	0.59		0.22	0.41	0.58		0.22	0.41	0.59
ML16	0.25	0.47	0.74		0.27	0.48	0.76		0.27	0.48	0.76		0.26	0.49	0.78
ML17	0.23	0.47	0.68		0.25	0.47	0.68		0.25	0.48	0.68		0.25	0.47	0.71
ML18	NC	28.92	NC		NC	28.08	NC		NC	28.74	NC		NC	28.75	NC
ML19	20.35	41.62	57.69		21.78	42.17	58.62		22.00	40.66	57.94		22.18	40.97	59.32
ML20	NC	0.90	NC		NC	0.91	NC		NC	0.91	NC		NC	0.91	NC
ML21	NC	21.12	NC		NC	21.25	NC		NC	21.31	NC		NC	21.32	NC
ML22	14.69	18.75	26.44		15.63	19.07	26.78		15.63	19.10	27.39		15.63	19.21	28.20
MH1	3330.17	5153.05	35089.98		3330.03	4906.86	35001.60		3309.37	4944.92	35004.50		3311.86	4942.45	34978.70

Index	Base				6.5-foot raise				12.5-foot raise				18.5-foot raise		
MH2	3271.49	6866.97	38168.07		3260.23	7072.91	38310.68		3263.04	7168.31	38288.47		3273.84	7168.31	36993.98
MH3	3733.22	6439.75	34286.34		3728.78	6416.41	34386.00		3739.24	6461.42	34400.50		3762.51	6504.31	34392.75
MH4	4941.99	7826.38	19509.92		4982.42	7674.88	19501.94		5173.97	7733.65	19495.84		5143.22	7648.33	19489.69
MH5	7495.11	10122.66	13728.34		7493.93	10246.04	13720.12		7493.53	10222.05	13731.35		7485.08	10262.14	13706.39
MH6	10027.73	12835.78	15843.47		10086.90	12890.82	15814.65		10157.31	12883.45	15772.24		10088.04	12951.20	15821.73
MH7	10663.95	14000.75	16082.25		10688.66	14039.18	16182.40		10743.03	14209.41	16190.25		10683.04	14481.87	16196.12
MH8	9208.21	12048.61	14813.39		9447.75	12349.58	15153.50		9272.03	12281.52	14923.70		9269.35	12443.73	15405.24
MH9	5852.13	7885.27	12589.49		5788.58	8004.08	12575.48		5853.25	7965.39	12568.78		6046.33	8068.40	12556.60
MH10	3917.56	5329.22	9851.91		3928.27	5323.54	9840.49		3883.60	5353.64	9836.60		3885.17	5353.75	9829.77
MH11	3600.13	5442.56	12078.22		3643.16	5145.71	10444.31		3586.68	5190.92	10213.75		3596.49	5134.26	10442.11
MH12	3428.57	4850.94	27872.17		3428.56	4812.81	26055.24		3405.67	4799.60	25855.78		3410.92	4798.82	24742.06
MH13	NC	66.80	NC		NC	66.30	NC		NC	66.19	NC		NC	65.93	NC
MH14	1.82	2.63	5.10		1.81	2.60	5.06		1.79	2.58	5.20		1.83	2.60	4.88
MH15	NC	4.55	NC		NC	4.54	NC		NC	4.53	NC		NC	4.51	NC
MH16	NC	2.03	NC		NC	2.03	NC		NC	2.01	NC		NC	2.04	NC
MH17	NC	1.55	NC		NC	1.56	NC		NC	1.54	NC		NC	1.55	NC
MH18	NC	4.62	NC		NC	4.52	NC		NC	4.53	NC		NC	4.49	NC
MH19	NC	1.05	NC		NC	1.11	NC		NC	1.14	NC		NC	1.14	NC
MH20	66.65	98.07	300.30		66.80	98.66	289.38		67.14	97.47	289.36		66.77	98.63	289.35
MH21	32.11	74.93	127.21		32.36	74.19	127.30		31.30	73.23	126.62		31.62	75.10	128.01
MH22	0.10	45.25	56.13		4.58	48.89	56.39		4.06	45.59	55.89		3.50	47.40	55.94
MH23	1.93	17.73	25.99		1.77	17.46	25.63		1.28	16.48	24.48		1.64	17.24	25.35
MH24	1.09	2.40	5.55		1.02	2.35	5.54		1.08	2.34	5.50		1.16	2.35	5.39
MH25	3.05	4.95	9.10		3.47	5.10	9.10		3.20	4.98	9.03		3.30	5.06	9.09
MH26	7.29	8.48	9.15		7.28	8.46	9.13		7.22	8.40	9.06		7.26	8.45	9.11
MH27	1.59	2.59	5.98		1.59	2.56	6.02		1.58	2.55	5.98		1.58	2.55	5.52
FL1	1.00	2.00	4.00		1.00	2.00	3.00		0.70	2.00	4.00		0.00	2.00	3.00
FL2	NC	43.70	NC		NC	43.70	NC		NC	47.50	NC		NC	44.83	NC
FL3	0.00	0.00	0.00		0.00	0.00	0.00		0.00	0.00	0.00		0.00	0.00	0.00
FH1	0.00	2.00	3.30		0.00	2.00	3.30		0.00	2.00	3.30		0.00	2.00	3.30
FH2	NC	48.37	NC		NC	49.21	NC		NC	48.03	NC		NC	48.75	NC
FH3	0.00	0.00	65.30		0.00	0.00	57.50		0.00	0.00	56.50		0.00	0.00	55.60
FH4	0.00	0.00	3.00		0.00	0.00	3.00		0.00	0.00	2.70		0.00	0.00	3.00
FH5	1.00	2.00	3.00		1.00	2.00	3.00		1.00	2.00	3.00		1.00	2.00	3.00
FH6	0.00	0.00	1.00		0.00	0.00	1.00		0.00	0.00	1.30		0.00	0.00	1.00
FH7	0.00	0.00	0.30		0.00	0.00	0.30		0.00	0.00	0.30		0.00	0.00	0.30

Index	Base			6.5-foot raise			12.5-foot raise			18.5-foot raise		
FH8	0.00	2.00	3.30	0.00	2.00	3.30	0.00	2.00	3.30	0.00	2.00	3.30
FH9	1.00	3.00	4.00	1.00	3.00	4.00	1.00	3.00	5.00	1.00	3.00	4.00
FH10	1.00	2.00	3.30	1.00	2.00	4.00	1.00	2.00	4.00	1.00	2.00	4.00
FH11	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
DL1	2350.00	3000.19	4231.06	2500.00	3051.18	4285.34	2500.00	3056.02	4383.01	2500.00	3073.63	4511.21
DL2	2377.10	3025.17	4235.79	2500.00	3053.22	4298.75	2500.00	3067.55	4402.17	2500.00	3074.37	4519.95
DL3	2447.33	3067.18	4366.72	2500.00	3075.93	4404.20	2500.00	3080.47	4422.67	2500.00	3077.96	4545.86
DL4	2940.08	3265.68	4968.83	2964.05	3346.93	5047.56	2940.51	3312.21	5032.29	2933.58	3317.80	4957.29
DL5	3186.67	3993.05	7691.84	3200.44	4137.31	7534.99	3187.12	4137.99	7488.08	3198.42	4136.37	7484.29
DL6	NC	21.12	NC	NC	21.25	NC	NC	21.31	NC	NC	21.32	NC
DL7	NC	21.15	NC	NC	21.16	NC	NC	21.23	NC	NC	21.29	NC
DL8	NC	20.90	NC	NC	21.05	NC	NC	20.76	NC	NC	21.07	NC
DL9	NC	20.04	NC	NC	19.62	NC	NC	19.06	NC	NC	18.75	NC
DL10	NC	32.63	NC	NC	31.81	NC	NC	32.04	NC	NC	31.45	NC
DL11	0.34	0.45	0.71	0.36	0.45	0.72	0.35	0.45	0.71	0.36	0.45	0.71
DL12	0.35	0.46	0.00	0.36	0.46	0.00	0.35	0.46	0.00	0.36	0.46	0.00
DL13	0.42	0.52	0.00	0.42	0.52	0.00	0.42	0.51	0.00	0.42	0.52	0.00
DL14	NC	0.63	NC	NC	0.63	NC	NC	0.63	NC	NC	0.63	NC
DL15	NC	0.49	NC	NC	0.49	NC	NC	0.49	NC	NC	0.49	NC
DL16	11.45	35.50	181.60	9.40	35.50	177.00	9.33	35.50	177.85	11.00	36.33	181.00
DL17	NC	88.17	NC	NC	88.68	NC	NC	88.92	NC	NC	84.20	NC
DL18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DL19	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC
DL20	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC
DH1	10663.95	15691.81	48047.24	10688.66	15785.20	46300.19	10743.03	15595.43	46297.19	10683.04	15780.38	46295.68
DH2	10651.33	15680.01	47935.29	10675.66	15766.90	46221.06	10730.04	15582.99	46218.07	10669.96	15762.88	46216.55
DH3	10624.72	15624.96	47490.00	10645.93	15681.14	45886.09	10700.39	15526.14	45883.22	10635.98	15714.84	45881.54
DH4	10446.54	15049.68	41224.36	10455.20	15048.41	41220.74	10449.99	15047.60	41218.22	10437.99	15095.64	41216.05
DH5	9458.07	12503.29	27902.35	9499.52	12637.23	27970.95	9490.20	12601.69	28018.64	9457.97	12811.64	27955.26
DH6	NC	57.38	NC	NC	56.95	NC	NC	57.25	NC	NC	56.76	NC
DH7	NC	57.32	NC	NC	56.89	NC	NC	57.19	NC	NC	56.70	NC
DH8	NC	57.01	NC	NC	56.56	NC	NC	56.85	NC	NC	56.36	NC
DH9	NC	51.93	NC	NC	51.51	NC	NC	51.58	NC	NC	51.05	NC
DH10	NC	35.79	NC	NC	35.15	NC	NC	35.18	NC	NC	34.62	NC
DH11	1.52	2.90	6.87	1.52	2.87	6.60	1.52	2.84	6.56	1.52	2.85	6.59
DH12	1.52	2.88	6.79	1.52	2.85	6.54	1.52	2.81	6.50	1.51	2.83	6.53

Index	Base				6.5-foot raise				12.5-foot raise				18.5-foot raise		
DH13	1.49	2.63	5.89		1.49	2.61	5.88		1.48	2.59	5.84		1.49	2.60	5.87
DH14	NC	0.39	NC		NC	0.39	NC		NC	0.39	NC		NC	0.39	NC
DH15	28.80	51.17	100.30		29.40	53.00	94.40		31.00	55.00	99.50		28.45	57.00	99.30
DH16	NC	40.11	NC		NC	38.43	NC		NC	38.40	NC		NC	39.74	NC
DH17	63.48	101.00	160.50		61.75	101.00	156.55		63.70	100.00	186.30		62.35	100.00	161.90
DH18	3.20	29.00	68.70		16.00	31.33	66.00		15.00	29.00	66.00		15.00	29.50	66.00
DH19	10.00	20.00	20.00		10.00	20.00	20.00		9.00	19.00	20.00		10.00	20.00	20.00
DH20	28.80	51.17	100.30		29.40	53.00	94.40		31.00	55.00	99.50		28.45	57.00	99.30
DH21	61.10	97.50	180.80		59.14	97.50	180.65		57.48	97.67	235.50		64.59	99.00	365.00
DH22	NC	NC	NC		NC	NC	NC		NC	NC	NC		NC	NC	NC
DH23	NC	NC	NC		NC	NC	NC		NC	NC	NC		NC	NC	NC
DH24	NC	NC	NC		NC	NC	NC		NC	NC	NC		NC	NC	NC
TA1	NC	0.72	NC		NC	0.72	NC		NC	0.72	NC		NC	0.72	NC
TA2	NC	82.57	NC		NC	82.80	NC		NC	82.83	NC		NC	83.03	NC
TA3	NC	NC	NC		NC	NC	NC		NC	NC	NC		NC	NC	NC
TL1	NC	29.42	NC		NC	28.14	NC		NC	30.37	NC		NC	31.20	NC
TL2	NC	45.35	NC		NC	45.49	NC		NC	44.43	NC		NC	45.46	NC
TL3	NC	NC	NC		NC	NC	NC		NC	NC	NC		NC	NC	NC
TL4	NC	NC	NC		NC	NC	NC		NC	NC	NC		NC	NC	NC
TH1	NC	159.25	NC		NC	159.49	NC		NC	161.99	NC		NC	168.43	NC
TH2	NC	65.92	NC		NC	66.65	NC		NC	65.01	NC		NC	63.97	NC
TH3	NC	NC	NC		NC	NC	NC		NC	NC	NC		NC	NC	NC
RA1	2.45	61.78	603.18		1.97	60.26	589.60		2.32	59.88	593.71		2.61	59.56	590.46
RA2	NC	263.15	NC		NC	258.87	NC		NC	258.96	NC		NC	262.77	NC
RA3	-509.97	-53.02	-2.08		-496.44	-49.42	-2.78		-491.86	-47.70	-2.66		-494.91	-48.74	-2.50
RA4	NC	-325.08	NC		NC	-326.80	NC		NC	-331.02	NC		NC	-328.81	NC
RA5	NC	0.47	NC		NC	0.47	NC		NC	0.47	NC		NC	0.47	NC
RA6	0.00	0.01	0.06		0.00	0.01	0.05		0.00	0.01	0.05		0.00	0.01	0.05
RA7	-0.05	-0.01	0.00		-0.05	-0.01	0.00		-0.05	-0.01	0.00		-0.05	-0.01	0.00
RA8	10.00	15.00	24.60		10.00	15.00	22.00		9.40	14.00	22.00		9.40	15.00	22.00
RA9	NC	26.67	NC		NC	27.03	NC		NC	28.92	NC		NC	25.30	NC

Table A-2. Indices computed from daily water temperature (℃) for water years 1922 to 1994. Refer to the definitions below to interpret the values. NC means not computed.

Index	Base			6.5-foot raise			12.5-foot raise			18.5-foot raise		
	Lower Limit	Value	Upper Limit	Lower Limit	Value	Upper Limit	Lower Limit	Value	Upper Limit	Lower Limit	Value	Upper Limit
MA1	7.18	10.14	13.64	7.20	10.08	13.59	7.24	10.04	13.43	7.25	10.00	13.36
MA2	7.18	10.01	13.64	7.20	9.97	13.59	7.24	9.98	13.43	7.25	9.94	13.36
MA3	13.73	17.09	33.38	12.83	16.48	32.71	12.01	15.24	32.68	11.48	15.22	32.79
MA4	NC	7.79	NC	NC	7.60	NC	NC	7.28	NC	NC	7.17	NC
MA5	NC	1.01	NC	NC	1.01	NC	NC	1.01	NC	NC	1.01	NC
MA6	NC	1.67	NC	NC	1.64	NC	NC	1.61	NC	NC	1.59	NC
MA7	NC	1.43	NC	NC	1.41	NC	NC	1.38	NC	NC	1.37	NC
MA8	NC	1.33	NC	NC	1.31	NC	NC	1.29	NC	NC	1.28	NC
MA9	NC	0.22	NC	NC	0.22	NC	NC	0.21	NC	NC	0.20	NC
MA10	NC	0.16	NC	NC	0.15	NC	NC	0.14	NC	NC	0.14	NC
MA11	NC	0.13	NC	NC	0.12	NC	NC	0.11	NC	NC	0.11	NC
MA12	6.59	7.98	8.87	6.60	7.95	8.81	6.66	8.02	8.88	6.69	8.05	8.91
MA13	6.32	7.58	8.48	6.39	7.59	8.48	6.43	7.62	8.48	6.46	7.62	8.49
MA14	6.96	8.18	9.10	7.01	8.20	9.09	7.03	8.25	9.22	7.04	8.27	9.22
MA15	7.67	8.82	10.16	7.68	8.83	10.32	7.70	8.85	10.60	7.69	8.85	10.67
MA16	8.49	9.41	10.64	8.37	9.43	10.67	8.33	9.45	10.66	8.28	9.46	10.70
MA17	9.23	9.97	10.45	9.22	9.91	10.47	9.19	9.89	10.45	9.12	9.86	10.41
MA18	9.83	10.42	12.76	9.86	10.42	12.78	9.90	10.41	12.45	9.87	10.35	12.49
MA19	10.40	11.29	17.20	10.40	11.23	16.88	10.35	11.01	16.70	10.32	11.02	16.99
MA20	10.69	12.47	17.77	10.44	12.28	17.71	10.32	11.93	17.74	10.30	11.97	17.70
MA21	11.07	12.66	16.06	10.65	12.30	16.06	10.30	11.91	16.05	10.01	11.80	15.98
MA22	10.44	11.60	12.75	10.36	11.50	12.75	10.21	11.30	12.66	10.09	11.19	12.74
MA23	8.45	9.89	11.14	8.48	9.72	10.81	8.51	9.83	11.10	8.43	9.72	11.18
MA24	2.83	5.53	9.95	2.62	5.28	10.21	2.73	5.23	9.88	2.67	5.14	9.88
MA25	1.31	2.13	5.59	1.32	2.10	5.40	1.22	2.06	5.45	1.14	2.06	5.34
MA26	1.96	3.91	7.40	1.97	3.96	7.49	1.99	3.93	7.72	1.81	3.94	7.60
MA27	2.00	3.92	6.81	1.85	3.86	7.06	1.80	3.79	7.13	1.89	3.67	7.01
MA28	1.59	3.15	6.36	1.79	3.16	7.46	1.76	3.16	7.10	1.67	3.08	6.96
MA29	1.52	2.47	4.85	1.65	2.62	4.65	1.58	2.77	4.57	1.50	2.77	4.48
MA30	1.65	2.84	9.32	1.47	2.86	9.20	1.48	2.45	9.08	1.47	2.53	9.47
MA31	1.51	3.04	5.78	1.33	2.89	5.55	1.41	2.75	6.47	1.30	2.66	6.15

Index	Base			6.5-foot raise			12.5-foot raise			18.5-foot raise		
MA32	1.19	2.03	4.04	1.20	1.94	3.77	1.17	1.91	3.76	1.11	1.85	3.60
MA33	0.98	1.88	6.69	0.95	1.81	6.55	0.89	1.91	6.69	0.87	1.86	6.40
MA34	2.92	5.79	10.97	2.28	5.28	10.93	1.75	4.60	10.78	1.65	4.35	10.34
MA35	4.71	6.94	13.55	3.21	5.64	12.01	4.09	6.69	12.49	3.84	6.79	12.48
MA36	NC	1.23	NC	NC	1.23	NC	NC	1.22	NC	NC	1.21	NC
MA37	NC	0.28	NC	NC	0.27	NC	NC	0.25	NC	NC	0.24	NC
MA38	NC	0.50	NC	NC	0.49	NC	NC	0.46	NC	NC	0.46	NC
MA39	NC	20.50	NC	NC	20.23	NC	NC	19.67	NC	NC	19.44	NC
MA40	NC	0.01	NC	NC	0.01	NC	NC	0.01	NC	NC	0.01	NC
MA41	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.07
MA42	NC	0.32	NC	NC	0.33	NC	NC	0.34	NC	NC	0.34	NC
MA43	NC	0.08	NC	NC	0.08	NC	NC	0.08	NC	NC	0.09	NC
MA44	NC	0.20	NC	NC	0.20	NC	NC	0.21	NC	NC	0.21	NC
MA45	NC	0.01	NC	NC	0.01	NC	NC	0.01	NC	NC	0.01	NC
ML1	6.01	7.34	8.28	6.04	7.33	8.25	6.15	7.43	8.28	6.19	7.49	8.25
ML2	6.08	7.21	8.12	6.10	7.25	8.08	6.17	7.27	8.14	6.20	7.29	8.13
ML3	6.36	7.59	8.53	6.35	7.61	8.53	6.41	7.63	8.55	6.46	7.64	8.54
ML4	6.92	8.22	9.26	6.91	8.30	9.35	6.94	8.31	9.46	6.99	8.30	9.47
ML5	7.77	8.85	9.85	7.75	8.80	9.80	7.76	8.81	9.84	7.69	8.82	9.82
ML6	8.53	9.44	10.01	8.48	9.43	10.04	8.60	9.36	10.03	8.49	9.36	10.03
ML7	9.28	9.95	10.97	9.32	9.92	10.87	9.37	9.92	10.73	9.29	9.90	10.73
ML8	9.88	10.60	15.55	9.89	10.63	15.17	9.94	10.57	14.61	9.83	10.54	14.75
ML9	10.29	11.89	16.83	9.99	11.83	16.69	9.77	11.59	16.89	9.80	11.53	16.72
ML10	10.53	12.22	14.50	10.18	11.82	14.50	9.84	11.58	14.53	9.57	11.51	14.38
ML11	9.15	10.39	11.26	9.23	10.35	11.27	9.35	10.21	11.25	9.32	10.17	11.30
ML12	7.11	8.74	10.13	7.23	8.77	10.11	7.26	8.86	10.14	7.18	8.82	10.15
ML13	NC	20.96	NC	NC	20.69	NC	NC	20.00	NC	NC	19.74	NC
ML14	0.62	0.72	0.78	0.61	0.73	0.78	0.63	0.73	0.78	0.64	0.74	0.79
ML15	0.59	0.71	0.77	0.59	0.72	0.77	0.59	0.73	0.78	0.60	0.73	0.78
ML16	0.62	0.72	0.78	0.61	0.73	0.78	0.63	0.73	0.78	0.64	0.74	0.79
ML17	0.65	0.74	0.79	0.65	0.74	0.80	0.65	0.75	0.81	0.66	0.76	0.81
ML18	NC	6.26	NC	NC	6.46	NC	NC	6.61	NC	NC	6.58	NC
ML19	58.94	71.16	76.55	58.71	71.94	77.17	59.15	72.42	78.03	60.01	73.00	78.32
ML20	NC	0.98	NC	NC	0.98	NC	NC	0.98	NC	NC	0.98	NC
ML21	NC	8.84	NC	NC	8.76	NC	NC	8.64	NC	NC	8.46	NC
ML22	0.04	0.05	0.05	0.04	0.05	0.05	0.04	0.05	0.05	0.04	0.05	0.05

Index	Base			6.5-foot raise			12.5-foot raise			18.5-foot raise		
MH1	7.19	8.79	10.11	7.20	8.79	10.11	7.25	8.87	10.09	7.20	8.95	10.08
MH2	6.63	7.97	9.02	6.66	7.98	8.96	6.70	8.04	8.96	6.73	8.03	8.96
MH3	7.46	8.74	9.59	7.51	8.77	9.73	7.53	8.78	9.72	7.53	8.80	9.72
MH4	8.31	9.36	10.85	8.26	9.35	11.59	8.22	9.40	11.59	8.21	9.38	11.62
MH5	9.07	9.93	11.46	9.03	9.93	11.98	8.98	9.96	12.23	8.91	9.90	12.16
MH6	9.64	10.41	11.17	9.75	10.39	11.14	9.70	10.39	11.10	9.64	10.35	11.06
MH7	10.30	10.91	15.41	10.35	10.87	15.15	10.34	10.83	14.44	10.33	10.80	14.53
MH8	10.75	12.00	18.12	10.73	11.82	18.07	10.65	11.67	18.17	10.60	11.66	18.18
MH9	11.07	12.89	18.29	11.01	12.59	18.18	10.78	12.28	18.32	10.68	12.30	18.27
MH10	11.51	12.98	17.20	11.00	12.63	17.17	10.65	12.27	17.20	10.34	12.17	17.14
MH11	11.36	12.63	14.37	11.10	12.42	14.39	10.80	12.14	14.39	10.59	12.06	14.27
MH12	9.49	11.14	12.50	9.36	10.78	11.57	9.34	11.03	12.50	9.29	10.87	12.50
MH13	NC	20.22	NC	NC	19.95	NC	NC	19.53	NC	NC	19.33	NC
MH14	1.24	1.35	1.80	1.22	1.33	1.79	1.20	1.31	1.80	1.18	1.30	1.79
MH15	NC	1.72	NC	NC	1.72	NC	NC	1.72	NC	NC	1.72	NC
MH16	NC	1.27	NC	NC	1.26	NC	NC	1.24	NC	NC	1.23	NC
MH17	NC	1.14	NC	NC	1.12	NC	NC	1.11	NC	NC	1.10	NC
MH18	NC	4.84	NC	NC	5.14	NC	NC	5.53	NC	NC	5.64	NC
MH19	NC	1.21	NC	NC	1.07	NC	NC	1.08	NC	NC	1.08	NC
MH20	0.08	0.08	0.12	0.07	0.08	0.12	0.07	0.08	0.12	0.07	0.08	0.12
MH21	3.83	5.26	7.32	3.52	5.20	8.09	2.43	4.78	8.90	2.24	4.61	7.48
MH22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MH23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MH24	1.00	1.13	1.51	1.00	1.13	1.53	1.00	1.12	1.53	1.00	1.12	1.47
MH25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MH26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MH27	1.14	1.27	1.71	1.12	1.24	1.72	1.11	1.23	1.71	1.10	1.21	1.68
FL1	1.00	3.00	6.00	1.00	3.00	6.00	1.00	3.00	6.30	1.00	3.00	7.00
FL2	NC	51.65	NC	NC	53.00	NC	NC	53.14	NC	NC	54.62	NC
FL3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FH1	1.00	3.00	6.00	1.00	3.00	7.30	1.00	3.00	7.30	1.00	4.00	9.00
FH2	NC	42.03	NC	NC	64.22	NC	NC	59.32	NC	NC	51.90	NC
FH3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FH4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FH5	3.00	6.00	10.90	3.00	6.00	10.00	3.00	6.00	9.00	3.00	6.00	10.60
FH6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Index	Base			6.5-foot raise			12.5-foot raise			18.5-foot raise		
FH7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FH8	1.00	3.00	6.00	1.00	3.00	7.30	1.00	3.00	7.30	1.00	4.00	9.00
FH9	2.00	4.00	7.30	2.00	4.00	7.00	2.00	4.00	7.30	2.00	4.00	8.00
FH10	1.00	2.00	6.00	1.00	2.00	5.30	1.00	2.00	5.00	1.00	2.00	6.30
FH11	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
DL1	5.91	7.16	7.94	5.86	7.20	7.98	6.05	7.23	8.03	6.06	7.26	8.06
DL2	5.96	7.20	7.98	5.92	7.24	8.02	6.10	7.26	8.08	6.12	7.28	8.09
DL3	6.05	7.27	8.09	6.06	7.28	8.11	6.28	7.30	8.22	6.29	7.34	8.21
DL4	6.24	7.49	8.26	6.28	7.52	8.27	6.38	7.55	8.36	6.39	7.57	8.37
DL5	6.71	7.86	8.75	6.72	7.91	8.76	6.80	7.95	8.82	6.82	7.95	8.83
DL6	NC	8.84	NC	NC	8.76	NC	NC	8.64	NC	NC	8.46	NC
DL7	NC	8.75	NC	NC	8.70	NC	NC	8.55	NC	NC	8.41	NC
DL8	NC	8.63	NC	NC	8.56	NC	NC	8.42	NC	NC	8.31	NC
DL9	NC	8.33	NC	NC	8.18	NC	NC	8.08	NC	NC	7.98	NC
DL10	NC	7.74	NC	NC	7.67	NC	NC	7.67	NC	NC	7.57	NC
DL11	0.59	0.71	0.83	0.59	0.71	0.83	0.61	0.72	0.84	0.61	0.72	0.84
DL12	0.60	0.72	0.00	0.61	0.72	0.00	0.63	0.73	0.00	0.63	0.73	0.00
DL13	0.62	0.74	0.00	0.63	0.74	0.00	0.64	0.75	0.00	0.64	0.75	0.00
DL14	NC	0.85	NC	NC	0.86	NC	NC	0.86	NC	NC	0.86	NC
DL15	NC	0.76	NC	NC	0.77	NC	NC	0.77	NC	NC	0.77	NC
DL16	11.17	31.00	87.70	10.45	27.50	119.40	11.80	29.67	119.70	10.95	28.75	101.00
DL17	NC	67.10	NC	NC	80.95	NC	NC	77.77	NC	NC	74.41	NC
DL18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DL19	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC
DL20	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC	NC	0.00	NC
DH1	12.20	13.24	18.40	11.83	13.03	18.32	11.56	12.77	18.52	11.44	12.78	18.40
DH2	12.10	13.19	18.36	11.71	13.00	18.30	11.45	12.72	18.46	11.40	12.76	18.36
DH3	11.95	13.08	18.32	11.67	12.93	18.27	11.38	12.68	18.39	11.31	12.63	18.26
DH4	11.74	12.77	17.99	11.35	12.68	17.96	11.12	12.44	18.07	11.02	12.35	17.98
DH5	10.63	11.67	15.98	10.57	11.51	15.89	10.49	11.45	15.80	10.48	11.40	15.68
DH6	NC	13.71	NC	NC	14.41	NC	NC	15.51	NC	NC	15.78	NC
DH7	NC	13.81	NC	NC	14.49	NC	NC	15.57	NC	NC	15.82	NC
DH8	NC	13.91	NC	NC	14.57	NC	NC	15.68	NC	NC	15.88	NC
DH9	NC	13.80	NC	NC	14.33	NC	NC	15.31	NC	NC	15.47	NC
DH10	NC	12.11	NC	NC	12.31	NC	NC	12.53	NC	NC	12.58	NC
DH11	1.22	1.40	1.84	1.19	1.39	1.84	1.16	1.37	1.86	1.15	1.36	1.85

Index	Base			6.5-foot raise			12.5-foot raise			18.5-foot raise		
DH12	1.19	1.38	1.83	1.17	1.37	1.83	1.14	1.35	1.84	1.14	1.35	1.84
DH13	1.17	1.35	1.80	1.14	1.34	1.80	1.11	1.32	1.81	1.11	1.32	1.81
DH14	NC	0.72	NC	NC	0.72	NC	NC	0.73	NC	NC	0.73	NC
DH15	9.14	30.00	52.00	6.32	29.00	69.50	5.96	26.00	51.83	5.53	25.00	50.60
DH16	NC	44.33	NC	NC	58.03	NC	NC	52.99	NC	NC	58.97	NC
DH17	17.85	31.40	60.23	17.56	29.00	72.53	17.50	29.67	62.53	13.39	28.86	70.60
DH18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DH19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DH20	9.14	30.00	52.00	6.32	29.00	69.50	5.96	26.00	51.83	5.53	25.00	50.60
DH21	35.47	76.00	145.15	35.63	69.50	142.75	35.21	73.75	147.20	32.25	75.75	145.30
DH22	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
DH23	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
DH24	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
TA1	NC	0.70	NC	NC	0.70	NC	NC	0.70	NC	NC	0.70	NC
TA2	NC	90.09	NC	NC	90.02	NC	NC	89.32	NC	NC	88.74	NC
TA3	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
TL1	NC	34.43	NC	NC	35.95	NC	NC	35.92	NC	NC	38.10	NC
TL2	NC	11.94	NC	NC	13.02	NC	NC	11.75	NC	NC	13.42	NC
TL3	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
TL4	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
TH1	NC	274.18	NC	NC	273.12	NC	NC	272.62	NC	NC	272.58	NC
TH2	NC	21.11	NC	NC	23.84	NC	NC	24.11	NC	NC	24.32	NC
TH3	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
RA1	0.01	0.08	0.28	0.01	0.08	0.27	0.01	0.08	0.27	0.01	0.08	0.27
RA2	NC	82.80	NC	NC	81.74	NC	NC	83.41	NC	NC	82.71	NC
RA3	-0.27	-0.08	-0.01	-0.27	-0.08	-0.01	-0.27	-0.08	-0.01	-0.27	-0.08	-0.01
RA4	NC	-82.06	NC	NC	-83.13	NC	NC	-83.03	NC	NC	-83.58	NC
RA5	NC	0.48	NC	NC	0.48	NC	NC	0.48	NC	NC	0.48	NC
RA6	0.00	0.01	0.03	0.00	0.01	0.03	0.00	0.01	0.03	0.00	0.01	0.03
RA7	-0.03	-0.01	0.00	-0.03	-0.01	0.00	-0.03	-0.01	0.00	-0.03	-0.01	0.00
RA8	93.50	126.00	154.00	97.70	128.00	153.90	94.40	130.00	158.30	95.70	129.00	156.20
RA9	NC	13.21	NC	NC	13.29	NC	NC	14.06	NC	NC	14.50	NC

Hydrologic Index Definitions

Explanation – The following information for the 171 hydrologic indices is from Olden and Poff (2003). USGS revised a limited number of the formula and/or definitions when deemed appropriate. A USGS Scientific Investigation Report in preparation will document these changes. The Olden and Poff (2003) article contains 12 additional references from which the indices were derived. Two of these articles are referenced here because they provide examples and additional explanation for complex indices.

The alphanumeric code preceding each definition refers to the category of the flow regime (magnitude, frequency, duration, timing, and rate of change) the hydrologic index was developed to describe, and indices are numbered successively within each category. For example, **MA1** is the first index describing magnitude of the average flow condition.

MA# – Magnitude, average flow event
ML# – Magnitude, low flow event
MH# – Magnitude, high flow event

FL# – Frequency, low flow event
FH# – Frequency, high flow event

DL# – Duration, low flow event
DH# – Duration, high flow event

TA# – Timing, average flow event
TL# – Timing, low flow event
TH# – Timing, high flow event

RA# – Rate of change, average event

Exceedance and percentile are used in the calculation for a number of indices. Note the difference–a 90 percent exceedance means that 90 percent of the values are equal to or greater than the 90 percent exceedance value, while a 90th percentile means that 10 percent of the values are equal to or greater than the 90th percentile value.

Code	Definition (units in parentheses)
MA1	Mean for the entire flow record (cubic feet per second).
MA2	Median for the entire flow record (cubic feet per second).
MA3	Mean (or median–Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows. Compute the mean of the annual coefficients of variation (percent).
MA4	Standard deviation of the percentiles of the logs of the entire flow record divided by the mean of percentiles of the logs. Compute the $\log_{10}$ of the daily flows for the entire record. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the logs of the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) logs of the flow values. Compute the standard deviation and mean for the percentile values. Divide the standard deviation by the mean (percent).

MA5	The skewness of the entire flow record is computed as the mean for the entire flow record (MA1) divided by the median (MA2) for the entire flow record (dimensionless).
MA6	Range in daily flows is the ratio of the 10 percent to 90 percent exceedance values for the entire flow record. Compute the 5 percent to 95 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 10 percent exceedance value by the 90 percent value (dimensionless).
MA7	Range in daily flows is computed like MA6 except using the 20 percent and 80 percent exceedance values. Divide the 20 percent exceedance value by the 80 percent value (dimensionless).
MA8	Range in daily flows is computed like MA6 except using the 25 percent and 75 percent exceedance values. Divide the 25 percent exceedance value by the 75 percent value (dimensionless).
MA9	Spread in daily flows is the ratio of the difference between the 90th and 10th percentile of the logs of the flow data to the log of the median of the entire flow record. Compute the $\log_{10}$ of the daily flows for the entire record. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the logs of the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) logs of the flow values. Compute MA9 as (90th–10th) /$\log_{10}$(MA2) (dimensionless).
MA10	Spread in daily flows is computed like MA9 except using the 20th and 80th percentiles (dimensionless).
MA11	Spread in daily flows is computed like MA9 except using the 25th and 75th percentiles (dimensionless).
MA12 – MA23	Means (or medians–Use Preference option) of monthly flow values. Compute the means for each month over the entire flow record. For example, MA12 is the mean of all January flow values over the entire record (cubic feet per second–temporal).
MA24 – MA35	Variability (coefficient of variation) of monthly flow values. Compute the standard deviation for each month in each year over the entire flow record. Divide the standard deviation by the mean for each month. Average (or median–Use Preference option) these values for each month across all years (percent).
MA36	Variability across monthly flows. Compute the minimum, maximum, and mean flows for each month in the entire flow record. MA36 is the maximum monthly flow minus the minimum monthly flow divided by the median monthly flow (dimensionless).
MA37	Variability across monthly flows. Compute the first (25th percentile) and the third (75th percentile) quartiles (every month in the flow record). MA37 is the third quartile minus the first quartile divided by the median of the monthly means (dimensionless).
MA38	Variability across monthly flows. Compute the 10th and 90th percentiles for the monthly means (every month in the flow record). MA38 is the 90th percentile minus the 10th percentile divided by the median of the monthly means (dimensionless).

MA39	Variability across monthly flows. Compute the standard deviation for the monthly means. MA39 is the standard deviation times 100 divided by the mean of the monthly means (percent).
MA40	Skewness in the monthly flows. MA40 is the mean of the monthly flow means minus the median of the monthly means divided by the median of the monthly means (dimensionless).
MA41	Annual runoff. Compute the annual mean daily flows. MA41 is the mean of the annual means divided by the drainage area (cubic feet per second/square mile).
MA42	Variability across annual flows. MA42 is the maximum annual flow minus the minimum annual flow divided by the median annual flow (dimensionless).
MA43	Variability across annual flows. Compute the first (25th percentile) and third (75th percentile) quartiles and the 10th and 90th percentiles for the annual means (every year in the flow record). MA43 is the third quartile minus the first quartile divided by the median of the annual means (dimensionless).
MA44	Variability across annual flows. Compute the first (25th percentile) and third (75th percentile) quartiles and the 10th and 90th percentiles for the annual means (every year in the flow record). MA44 is the 90th percentile minus the 10th percentile divided by the median of the annual means (dimensionless).
MA45	Skewness in the annual flows. MA45 is the mean of the annual flow means minus the median of the annual means divided by the median of the annual means (dimensionless).
ML1 – ML12	Mean (or median–Use Preference option) minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. For example, ML1 is the mean of the minimums of all January flow values over the entire record (cubic feet per second–temporal).
ML13	Variability (coefficient of variation) across minimum monthly flow values. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years (percent).
ML14	Compute the minimum annual flow for each year. ML14 is the mean (or median–Use Preference option) of the ratios of minimum annual flows to the median flow for each year (dimensionless).
ML15	Low flow index. ML15 is the mean (or median–Use Preference option) of the ratios of minimum annual flows to the mean flow for each year (dimensionless).
ML16	Median of annual minimum flows. ML16 is the median of the ratios of minimum annual flows to the median flow for each year (dimensionless).
ML17	Base flow. Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median–Use Preference option) of those ratios (dimensionless).
ML18	Variability in base flow. Compute the standard deviation for the ratios of 7-day moving average flows to mean annual flows for each year. ML18 is the standard deviation times 100 divided by the mean of the ratios (percent).

ML19	Base flow. Compute the ratios of the minimum annual flow to mean annual flow for each year. ML19 is the mean (or median–Use Preference option) of these ratios times 100 (dimensionless).
ML20	Base flow. Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow (dimensionless).
ML21	Variability across annual minimum flows. Compute the mean and standard deviation for the annual minimum flows. ML21 is the standard deviation times 100 divided by the mean (percent).
ML22	Specific mean annual minimum flow. ML22 is the mean (or median–Use Preference option) of the annual minimum flows divided by the drainage area (cubic feet per second/square mile).
MH1 – MH12	Mean (or median–Use Preference option) maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. For example, MH1 is the mean of the maximums of all January flow values over the entire record (cubic feet per second–temporal).
MH13	Variability (coefficient of variation) across maximum monthly flow values. Compute the mean and standard deviation for the maximum monthly flows over the entire flow record. MH13 is the standard deviation times 100 divided by the mean maximum monthly flow for all years (percent).
MH14	Median of annual maximum flows. Compute the annual maximum flows from monthly maximum flows. Compute the ratio of annual maximum flow to median annual flow for each year. MH14 is the median of these ratios (dimensionless).
MH15	High flow discharge index. Compute the 1 percent exceedance value for the entire data record. MH15 is the 1 percent exceedance value divided by the median flow for the entire record (dimensionless).
MH16	High flow discharge index. Compute the 10 percent exceedance value for the entire data record. MH16 is the 10 percent exceedance value divided by the median flow for the entire record (dimensionless).
MH17	High flow discharge index. Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record (dimensionless).
MH18	Variability across annual maximum flows. Compute the logs ($\log_{10}$) of the maximum annual flows. Find the standard deviation and mean for these values. MH18 is the standard deviation times 100 divided by the mean (percent).
MH19	Skewness in annual maximum flows. Use the equation: $\text{MH19} = \frac{N^2 \text{ x sum}(qm^3) - 3N \text{ x sum}(qm) \text{ x sum}(qm^2) + 2 \text{ x } (\text{sum}(qm))^3}{N \text{ x } (N-1) \text{ x } (N-2) \text{ x stddev}^3}$

where: N = Number of years
qm = Log_{10}(annual maximum flows)
stddev = Standard deviation of the annual maximum flows

(dimensionless).

MH20	Specific mean annual maximum flow. MH20 is the mean (or median–Use Preference option) of the annual maximum flows divided by the drainage area (cubic feet per second/square mile).
MH21	High flow volume index. Compute the average volume for flow events above a threshold equal to the median flow for the entire record. MH21 is the average volume divided by the median flow for the entire record (days).
MH22	High flow volume. Compute the average volume for flow events above a threshold equal to three times the median flow for the entire record. MH22 is the average volume divided by the median flow for the entire record (days).
MH23	High flow volume. Compute the average volume for flow events above a threshold equal to seven times the median flow for the entire record. MH23 is the average volume divided by the median flow for the entire record (days).
MH24	High peak flow. Compute the average peak flow value for flow events above a threshold equal to the median flow for the entire record. MH24 is the average peak flow divided by the median flow for the entire record (dimensionless).
MH25	High peak flow. Compute the average peak flow value for flow events above a threshold equal to three times the median flow for the entire record. MH25 is the average peak flow divided by the median flow for the entire record (dimensionless).
MH26	High peak flow. Compute the average peak flow value for flow events above a threshold equal to seven times the median flow for the entire record. MH26 is the average peak flow divided by the median flow for the entire record (dimensionless).
MH27	High peak flow. Compute the average peak flow value for flow events above a threshold equal to 75th percentile value for the entire flow record. MH27 is the average peak flow divided by the median flow for the entire record (dimensionless).
FL1	Low flood pulse count. Compute the average number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the average (or median–Use Preference option) number of events (number of events/year).
FL2	Variability in low pulse count. Compute the standard deviation in the annual pulse counts for FL1. FL2 is 100 times the standard deviation divided by the mean pulse count (percent).
FL3	Frequency of low pulse spells. Compute the average number of flow events with flows below a threshold equal to 5 percent of the mean flow value for the entire flow record. FL3 is the average (or median–Use Preference option) number of events (number of events/year).

FH1	High flood pulse count. Compute the average number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the average (or median–Use Preference option) number of events (number of events/year).
FH2	Variability in high pulse count. Compute the standard deviation in the annual pulse counts for FH1. FH2 is 100 times the standard deviation divided by the mean pulse count (number of events/year).
FH3	High flood pulse count. Compute the average number of days per year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median–Use Preference option) of the annual number of days for all years (number of days/year).
FH4	High flood pulse count. Compute the average number of days per year that the flow is above a threshold equal to seven times the median flow for the entire record. FH4 is the mean (or median–Use Preference option) of the annual number of days for all years (number of days/year).
FH5	Flood frequency. Compute the average number of flow events with flows above a threshold equal to the median flow value for the entire flow record. FH5 is the average (or median–Use Preference option) number of events (number of events/year).
FH6	Flood frequency. Compute the average number of flow events with flows above a threshold equal to three times the median flow value for the entire flow record. FH6 is the average (or median–Use Preference option) number of events (number of events/year).
FH7	Flood frequency. Compute the average number of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. FH6 is the average (or median–Use Preference option) number of events (number of events/year).
FH8	Flood frequency. Compute the average number of flow events with flows above a threshold equal to 25 percent exceedance value for the entire flow record. FH8 is the average (or median–Use Preference option) number of events (number of events/year).
FH9	Flood frequency. Compute the average number of flow events with flows above a threshold equal to 75 percent exceedance value for the entire flow record. FH9 is the average (or median–Use Preference option) number of events (number of events/year).
FH10	Flood frequency. Compute the average number of flow events with flows above a threshold equal to median of the annual minima for the entire flow record. FH10 is the average (or median–Use Preference option) number of events (number of events/year).
Note –	1.67 year flood threshold (Poff, 1996)–For indices FH11, DH22, DH23, DH24, TA3, and TH3 compute the $\log_{10}$ of the peak annual flows. Compute the $\log_{10}$ of the daily flows for the peak annual flow days. Calculate the coefficients for a linear regression equation for logs of peak annual flow versus logs of average daily flow for peak days. Using the log peak flow for the 1.67 year recurrence interval (60th percentile) as input to the regression equation, predict the $\log_{10}$ of the average daily flow. The threshold is 10 to the $\log_{10}$ (average daily flow) power (cubic feet/second).
FH11	Flood frequency. Compute the average number of flow events with flows above a threshold equal to flow corresponding to a 1.67 year recurrence interval. FH11 is the average (or median–Use Preference option) number of events (number of events/year).

DL1	Annual minimum daily flow. Compute the minimum 1-day average flow for each year. DL1 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DL2	Annual minimum of 3-day moving average flow. Compute the minimum of a 3-day moving average flow for each year. DL2 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DL3	Annual minimum of 7-day moving average flow. Compute the minimum of a 7-day moving average flow for each year. DL3 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DL4	Annual minimum of 30-day moving average flow. Compute the minimum of a 30-day moving average flow for each year. DL4 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DL5	Annual minimum of 90-day moving average flow. Compute the minimum of a 90-day moving average flow for each year. DL5 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DL6	Variability of annual minimum daily average flow. Compute the standard deviation for the minimum daily average flow. DL6 is 100 times the standard deviation divided by the mean (percent).
DL7	Variability of annual minimum of 3-day moving average flow. Compute the standard deviation for the minimum 3-day moving averages. DL7 is 100 times the standard deviation divided by the mean (percent).
DL8	Variability of annual minimum of 7-day moving average flow. Compute the standard deviation for the minimum 7-day moving averages. DL8 is 100 times the standard deviation divided by the mean (percent).
DL9	Variability of annual minimum of 30-day moving average flow. Compute the standard deviation for the minimum 30-day moving averages. DL9 is 100 times the standard deviation divided by the mean (percent).
DL10	Variability of annual minimum of 90-day moving average flow. Compute the standard deviation for the minimum 90-day moving averages. DL10 is 100 times the standard deviation divided by the mean (percent).
DL11	Annual minimum daily flow divided by the median for the entire record. Compute the minimum daily flow for each year. DL11 is the mean of these values divided by the median for the entire record (dimensionless).
DL12	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record. (dimensionless).
DL13	Annual minimum of 30-day moving average flow divided by the median for the entire record. Compute the minimum of a 30-day moving average flow for each year. DL13 is the mean of these values divided by the median for the entire record. (dimensionless).

DL14	Low exceedance flows. Compute the 75 percent exceedance value for the entire flow record. DL14 is the exceedance value divided by the median for the entire record. (dimensionless).
DL15	Low exceedance flows. Compute the 90 percent exceedance value for the entire flow record. DL14 is the exceedance value divided by the median for the entire record (dimensionless).
DL16	Low flow pulse duration. Compute the average pulse duration for each year for flow events below a threshold equal to the 25th percentile value for the entire flow record. DL16 is the median of the yearly average durations (number of days).
DL17	Variability in low pulse duration. Compute the standard deviation for the yearly average low pulse durations. DL17 is 100 times the standard deviation divided by the mean of the yearly average low pulse durations (percent).
DL18	Number of zero-flow days. Count the number of zero-flow days for the entire flow record. DL18 is the mean (or median–Use Preference option) annual number of zero flow days (number of days/year).
DL19	Variability in the number of zero-flow days. Compute the standard deviation for the annual number of zero-flow days. DL19 is 100 times the standard deviation divided by the mean annual number of zero-flow days (percent).
DL20	Number of zero-flow months. While computing the mean monthly flow values, count the number of months in which there was no flow over the entire flow record (percent).
DH1	Annual maximum daily flow. Compute the maximum of a 1-day moving average flow for each year. DH1 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DH2	Annual maximum of 3-day moving average flows. Compute the maximum of a 3-day moving average flow for each year. DH2 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DH3	Annual maximum of 7-day moving average flows. Compute the maximum of a 7-day moving average flow for each year. DH3 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DH4	Annual maximum of 30-day moving average flows. Compute the maximum of a 30-day moving average flow for each year. DH4 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DH5	Annual maximum of 90-day moving average flows. Compute the maximum of a 90-day moving average flow for each year. DH5 is the mean (or median–Use Preference option) of these values (cubic feet per second).
DH6	Variability of annual maximum daily flows. Compute the standard deviation for the maximum 1-day moving averages. DH6 is 100 times the standard deviation divided by the mean (percent).

DH7	Variability of annual maximum of 3-day moving average flows. Compute the standard deviation for the maximum 3-day moving averages. DH7 is 100 times the standard deviation divided by the mean (percent).
DH8	Variability of annual maximum of 7-day moving average flows. Compute the standard deviation for the maximum 7-day moving averages. DH8 is 100 times the standard deviation divided by the mean (percent).
DH9	Variability of annual maximum of 30-day moving average flows. Compute the standard deviation for the maximum 30-day moving averages. DH9 is 100 times the standard deviation divided by the mean (percent).
DH10	Variability of annual maximum of 90-day moving average flows. Compute the standard deviation for the maximum 90-day moving averages. DH10 is 100 times the standard deviation divided by the mean (percent).
DH11	Annual maximum of 1-day moving average flows divided by the median for the entire record. Compute the maximum of a 1-day moving average flow for each year. DL11 is the mean of these values divided by the median for the entire record (dimensionless).
DH12	Annual maximum of 7-day moving average flows divided by the median for the entire record. Compute the maximum daily average flow for each year. DL12 is the mean of these values divided by the median for the entire record (dimensionless).
DH13	Annual maximum of 30-day moving average flows divided by the median for the entire record. Compute the maximum of a 30-day moving average flow for each year. DL13 is the mean of these values divided by the median for the entire record. (dimensionless).
DH14	Flood duration. Compute the mean of the mean monthly flow values. Find the 95th percentile for the mean monthly flows. DH14 is the 95th percentile value divided by the mean of the monthly means (dimensionless).
DH15	High flow pulse duration. Compute the average duration for flow events with flows above a threshold equal to the 75th percentile value for each year in the flow record. DH15 is the median of the yearly average durations (days/year).
DH16	Variability in high flow pulse duration. Compute the standard deviation for the yearly average high pulse durations. DH16 is 100 times the standard deviation divided by the mean of the yearly average high pulse durations (percent).
DH17	High flow duration. Compute the average duration of flow events with flows above a threshold equal to the median flow value for the entire flow record. DH17 is the average (or median–Use Preference option) duration of the events (days).
DH18	High flow duration. Compute the average duration of flow events with flows above a threshold equal to three times the median flow value for the entire flow record. DH18 is the average (or median–Use Preference option) duration of the events (days).
DH19	High flow duration. Compute the average duration of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. DH19 is the average (or median–Use Preference option) duration of the events (days).

DH20 High flow duration. Compute the 75th percentile value for the entire flow record. Compute the average duration of flow events with flows above a threshold equal to the 75th percentile value for the median annual flows. DH20 is the average (or median–Use Preference option) duration of the events (days).

DH21 High flow duration. Compute the 25th percentile value for the entire flow record. Compute the average duration of flow events with flows above a threshold equal to the 25th percentile value for the entire set of flows. DH21 is the average (or median–Use Preference option) duration of the events (days).

DH22 Flood interval. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Determine the median number of days between flood events for each year. DH22 is the mean (or median–Use Preference option) of the yearly median number of days between flood events (days).

DH23 Flood duration. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Determine the number of days each year that the flow remains above the flood threshold. DH23 is the mean (or median–Use Preference option) of the number of flood days for years in which floods occur (days).

DH24 Flood free days. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Compute the maximum number of days that the flow is below the threshold for each year. DH24 is the mean (or median–Use Preference option) of the maximum yearly no flood days (days).

TA1 Constancy. Constancy is computed via the formulation of Colwell (see example in Colwell, 1974). A matrix of values is compiled where the rows are 11 flow categories and the columns are 365 (no Feb 29th) days of the year. The cell values are the number of times that a flow falls into a category on each day. The categories are:

log(flow) < .1 x log(mean flow),
.1 x log(mean flow) <= log(flow) < .25 x log(mean flow)
.25 x log(mean flow) <= log(flow) < .5 x log(mean flow)
.5 x log(mean flow) <= log(flow) < .75 x log(mean flow)
.75 x log(mean flow) <= log(flow) < 1.0 x log(mean flow)
1.0 x log(mean flow) <= log(flow) < 1.25 x log(mean flow)
1.25 x log(mean flow) <= log(flow) < 1.5 x log(mean flow)
1.5 x log(mean flow) <= log(flow) < 1.75 x log(mean flow)
1.75 x log(mean flow) <= log(flow) < 2.0 x log(mean flow)
2.0 x log(mean flow) <= log(flow) < 2.25 x log(mean flow)
log(flow) >= 2.25 x log(mean flow)

The row totals, column totals, and grand total are computed. Using the equations for Shannon information theory parameters, constancy is computed as:

$$1-\frac{\text{(uncertainty with respect to state)}}{\text{log (number of states)}}$$

(dimensionless).

TA2	Predictability. Predictability is computed from the same matrix as constancy (see example in Colwell, 1974). Dimensionless. It is computed as: $1-\frac{\text{(uncertainty with respect to interaction of time and state–uncertainty with respect to time)}}{\text{log (number of states)}}$
TA3	Seasonal predictability of flooding. Divide years up into 2-month periods (that is Oct-Nov, Dec-Jan, and so forth). Count the number of flood days (flow events with flows > 1.67 year flood) in each period over the entire flow record. TA3 is the maximum number of flood days in any one period divided by the total number of flood days (dimensionless).
TL1	Julian date of annual minimum. Determine the Julian date that the minimum flow occurs for each water year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date (Julian day).
TL2	Variability in Julian date of annual minima. Compute the coefficient of variation for the mean x and y components and convert to a date (Julian day).
Note –	5 year flood threshold (Poff, 1996)–For TL3 and TH3 compute the $\log_{10}$ of the peak annual flows. Compute the $\log_{10}$ of the daily flows for the peak annual flow days. Calculate the coefficients for a linear regression equation for logs of peak annual flow versus logs of average daily flow for peak days. Using the log peak flow for the 5 year recurrence interval (20th percentile) as input to the regression equation, predict the $\log_{10}$ of the average daily flow. The threshold is 10 to the $\log_{10}$ (average daily flow) power (cubic feet per second).
TL3	Seasonal predictability of low flow. Divide years up into 2-month periods (that is Oct-Nov, Dec-Jan, and so forth). Count the number of low events (flow events with flows <= 5 year flood threshold) in each period over the entire flow record. TL3 is the maximum number of low flow events in any one period divided by the total number of low flow events (dimensionless).
TL4	Seasonal predictability of non-low flow. Compute the number of days that flow is above the 5-year flood threshold as the ratio of number of days to 365 or 366 (leap year) for each year. TL4 is the maximum of the yearly ratios (dimensionless).
TH1	Julian date of annual maximum. Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date (Julian day).
TH2	Variability in Julian date of annual maxima. Compute the coefficient of variation for the mean x and y components and convert to a date (Julian days).
TH3	Seasonal predictability of non-flooding. Computed as the maximum proportion of a 365-day year that the flow is less than the 1.67 year flood threshold and also occurs in all years.

	Accumulate non-flood days that span all years. TH3 is maximum length of those flood free periods divided by 365 (dimensionless).
RA1	Rise rate. Compute the change in flow for days in which the change is positive for the entire flow record. RA1 is the mean (or median–Use Preference option) of these values (cubic feet per second/day).
RA2	Variability in rise rate. Compute the standard deviation for the positive flow changes. RA2 is 100 times the standard deviation divided by the mean (percent).
RA3	Fall rate. Compute the change in flow for days in which the change is negative for the entire flow record. RA3 is the mean (or median–Use Preference option) of these values (cubic feet per second/day).
RA4	Variability in fall rate. Compute the standard deviation for the negative flow changes. RA4 is 100 times the standard deviation divided by the mean (percent).
RA5	Number of day rises. Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record (dimensionless).
RA6	Change of flow. Compute the $\log_{10}$ of the flows for the entire flow record. Compute the change in log of flow for days in which the change is positive for the entire flow record. RA6 is the median of these values (cubic feet per second).
RA7	Change of flow. Compute the $\log_{10}$ of the flows for the entire flow record. Compute the change in log of flow for days in which the change is negative for the entire flow record. RA7 is the median of these log values (cubic feet per second/day).
RA8	Number of reversals. Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median–Use Preference option) of the yearly values (days).
RA9	Variability in reversals. Compute the standard deviation for the yearly reversal values.RA9 is 100 times the standard deviation divided by the mean (percent).

Appendix References

Colwell R.K., 1974, Predictability, constancy, and contingency of periodic phenomena: Ecology. V. 55, p. 1148–1153.

Henriksen, J.A., Heasley, J., Kennen, J.G., and Nieswand, S., 2006, Users' Manual for the Hydroecological Integrity Assessment Process Software (including the New Jersey Assessment Tools): USGS Open File Report 2006–1093, 72p.

Olden, J.D. and Poff, N.L., 2003, Redundancy and the choice of hydrologic indices for characterizing streamflow regimes: River Research and Applications, V. 19, p. 101–121.

Poff, N.L., 1996, A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors: Freshwater Biology, V. 36, p. 71–91.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P., 1996, A method for assessing hydrologic alteration within a river network: Conservation Biology, V. 10, p. 1163–1174.

Appendix B. Fahrenheit to Celsius, and Celsius to Fahrenheit Conversion Chart.

°F	°C	°F	°C	°F	°C	°F	°C		°C	°F	°C	°F
32.0	0.0	52.5	11.4	73.0	22.8	93.5	34.2		0.0	32.0	20.5	68.9
32.5	0.3	53.0	11.7	73.5	23.1	94.0	34.4		0.5	32.9	21.0	69.8
33.0	0.6	53.5	11.9	74.0	23.3	94.5	34.7		1.0	33.8	21.5	70.7
33.5	0.8	54.0	12.2	74.5	23.6	95.0	35.0		1.5	34.7	22.0	71.6
34.0	1.1	54.5	12.5	75.0	23.9	95.5	35.3		2.0	35.6	22.5	72.5
34.5	1.4	55.0	12.8	75.5	24.2	96.0	35.6		2.5	36.5	23.0	73.4
35.0	1.7	55.5	13.1	76.0	24.4	96.5	35.8		3.0	37.4	23.5	74.3
35.5	1.9	56.0	13.3	76.5	24.7	97.0	36.1		3.5	38.3	24.0	75.2
36.0	2.2	56.5	13.6	77.0	25.0	97.5	36.4		4.0	39.2	24.5	76.1
36.5	2.5	57.0	13.9	77.5	25.3	98.0	36.7		4.5	40.1	25.0	77.0
37.0	2.8	57.5	14.2	78.0	25.6	98.5	36.9		5.0	41.0	25.5	77.9
37.5	3.1	58.0	14.4	78.5	25.8	99.0	37.2		5.5	41.9	26.0	78.8
38.0	3.3	58.5	14.7	79.0	26.1	99.5	37.5		6.0	42.8	26.5	79.7
38.5	3.6	59.0	15.0	79.5	26.4	100.0	37.8		6.5	43.7	27.0	80.6
39.0	3.9	59.5	15.3	80.0	26.7	100.5	38.1		7.0	44.6	27.5	81.5
39.5	4.2	60.0	15.6	80.5	26.9	101.0	38.3		7.5	45.5	28.0	82.4
40.0	4.4	60.5	15.8	81.0	27.2	101.5	38.6		8.0	46.4	28.5	83.3
40.5	4.7	61.0	16.1	81.5	27.5	102.0	38.9		8.5	47.3	29.0	84.2
41.0	5.0	61.5	16.4	82.0	27.8	102.5	39.2		9.0	48.2	29.5	85.1
41.5	5.3	62.0	16.7	82.5	28.1	103.0	39.4		9.5	49.1	30.0	86.0
42.0	5.6	62.5	16.9	83.0	28.3	103.5	39.7		10.0	50.0	30.5	86.9
42.5	5.8	63.0	17.2	83.5	28.6	104.0	40.0		10.5	50.9	31.0	87.8
43.0	6.1	63.5	17.5	84.0	28.9				11.0	51.8	31.5	88.7
43.5	6.4	64.0	17.8	84.5	29.2				11.5	52.7	32.0	89.6
44.0	6.7	64.5	18.1	85.0	29.4				12.0	53.6	32.5	90.5
44.5	6.9	65.0	18.3	85.5	29.7				12.5	54.5	33.0	91.4
45.0	7.2	65.5	18.6	86.0	30.0				13.0	55.4	33.5	92.3
45.5	7.5	66.0	18.9	86.5	30.3				13.5	56.3	34.0	93.2
46.0	7.8	66.5	19.2	87.0	30.6				14.0	57.2	34.5	94.1
46.5	8.1	67.0	19.4	87.5	30.8				14.5	58.1	35.0	95.0
47.0	8.3	67.5	19.7	88.0	31.1				15.0	59.0	35.5	95.9
47.5	8.6	68.0	20.0	88.5	31.4				15.5	59.9	36.0	96.8
48.0	8.9	68.5	20.3	89.0	31.7				16.0	60.8	36.5	97.7
48.5	9.2	69.0	20.6	89.5	31.9				16.5	61.7	37.0	98.6
49.0	9.4	69.5	20.8	90.0	32.2				17.0	62.6	37.5	99.5
49.5	9.7	70.0	21.1	90.5	32.5				17.5	63.5	38.0	100.4
50.0	10.0	70.5	21.4	91.0	32.8				18.0	64.4	38.5	101.3
50.5	10.3	71.0	21.7	91.5	33.1				18.5	65.3	39.0	102.2
51.0	10.6	71.5	21.9	92.0	33.3				19.0	66.2	39.5	103.1
51.5	10.8	72.0	22.2	92.5	33.6				19.5	67.1	40.0	104.0
52.0	11.1	72.5	22.5	93.0	33.9				20.0	68.0		

Appendix C. Programs and Data Files Used in Analysis

Salmod programs and file nomenclature used for this analysis are listed in the following table. Dates given are approximate simply because they may have changed and may differ slightly among the races or alternatives simulated. See the Salmod user's manual for more information about exact formatting of specific input files.

Program Name	Approximate Date	Purpose
Rdmbal.exe	2/22/2006	Windows "read mass balance" program that reads standard Salmod output file to create annual summary of sources and sinks for eggs and juveniles
Salftin.exe	11/9/2005	Salmod flow and temperature input program. Reads water year record of "daily" average flows and temperatures from Reclamation's HEC-5Q program and formats them into space-delimited, race-specific flow and temperature files
Salmodinst.exe	2/8/2006	Salmod installation program that "unpacks" Windows and Fortran programs necessary to run individual Salmod race-by-race alternatives
Model Input Data File Nomenclature	**Approximate Date**	**Contents**
Files_Race_Alt.Dat	2/22/2006	File containing list of all input and output files necessary to run a single race/alternative. Example: Files_Fall_BaseAltA.Dat
Flow_Race_Alt.csv	1/11/2006	File containing race and alternative-specific flows by week and river segment. Example: Flow_Fall_BaseAltA.csv. Note that this is not a true comma-separated values file, but can be read directly into Excel.
Relation_Race_2.Dat	2/9/2006	File containing most race-specific "relationship" parameters for Salmod. Example: Relation_Fall_2.Dat
Spawn_Race.Dat	1/23/2006	File containing race-specific spawning parameters. Example: Spawn_Fall.Dat
Species_Race.Dat	11/14/2001	File containing race-specific life stage and size class descriptors. Example: Species_Fall.Dat
Stream_Race.dat	1/23/2006	File containing race-specific stream mesohabitat/computation unit sequence and flow/temperature segment lengths. Example: Stream_Fall.dat
Suplment_Race_100[CC].Dat	1/24/2006	File containing race-specific adult escapement numbers, locations, and attributes. Example: Suplment_Fall_100[CC].Dat. Note that the CC suffix refers to the addition of Clear Creek and Battle Creek juveniles and only applies to fall Chinook.
Temp_Race_Alt.csv	1/11/2006	File containing race and alternative-specific water temperatures by week and river segment. Example: Temp_Fall_BaseAltA.csv. Note that this is not a true comma-separated values file, but can be read directly into Excel.
WUA_Race.Dat	1/24/2006	File containing race-specific weighted usable area as a function of flow and life stage. Example: WUA_Fall.Dat