WATER FORUM ISSUE PAPER

CHINOOK SALMON MORTALITY MODEL: DEVELOPMENT, EVALUATION, AND APPLICATION AS ONE TOOL TO ASSESS THE RELATIVE EFFECTS OF ALTERNATIVE FLOW AND DIVERSION SCENARIOS ON THE LOWER AMERICAN RIVER

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TABLE OF CONTENTS

1. INTRODUCTION

In 1983, the first version of a chinook salmon mortality model (mortality model) was developed by the U.S. Bureau of Reclamation (USBR) for application on the Sacramento River. In 1990, this mortality model was further revised and refined through a collaborative effort by the U.S. Fish and Wildlife Service (USFWS), the California Department of Fish and Game (CDFG), and the USBR for use in the Shasta Reservoir temperature control device studies (USBR 1991). The USFWS and CDFG worked cooperatively to produce a list of biological criteria and assumptions that served as the underlying biological basis for the model's refinement. From these fishery assumptions and biological criteria, the USBR revised the mortality model to assess spawning and hatching success of the various chinook salmon runs using the Sacramento River under different in-river thermal regimes that would result from various alternatives for controlling release temperatures from Shasta Reservoir. The temperature control device that was ultimately selected, based on modeled chinook salmon early life-stage losses and other evaluations, is currently under construction at Shasta Dam.

Since 1990, the mortality model has been further modified by the USBR to facilitate its application to the lower American River. The Sacramento Area Water Plan Forum (Forum) has used this "lower American River version" of the mortality model (LAR mortality model) as one tool for assessing the relative benefits of alternative flow patterns to fall-run chinook salmon production in the lower American River. Because of the importance of these assessments, a quality assurance check on the model to confirm the relevance and accuracy of its inputs, programming code, and output was determined to be warranted at this time.

This report is intended to provide Forum participants with information regarding the original development and intended use of the USBR's mortality model, and its subsequent application to the lower American River. The specific objectives of this report are to:

1) provide a brief overview of how and why the model was developed by the USBR;
2) mechanistically describe how the model calculates chinook salmon mortality;
3) describe the modifications that were made to the original mortality model so that it could be applied to the lower American River;
4) report the results of an independent quality assurance check on the model's inputs and programming code; and
5) present and interpret the mortality model output for two recently revised water-diversion scenarios for the American River [i.e., the Forum's 1995 base condition (base) and the maximum upstream diversion alternative proposed in the Fazio Water Contracts EIS/EIR (alternative)].

2. MODEL DEVELOPMENT

The fishery assumptions developed cooperatively by the USFWS and the CDFG that were used by USBR staff in developing the chinook salmon mortality model for the upper Sacramento River were initially communicated to the USBR by both agencies in memoranda dated January 19, 1990 (see USBR 1991, pp. A-99-A140). These assumptions were tailored to the upper Sacramento River and the model's intended application for evaluating alternative Shasta release temperature control measures. These fishery assumptions stated in the USFWS memorandum dated January 19, 1990 are listed below.

1) Survival of salmon fry and juveniles is density independent at the average spawning population levels existing from the early 1960's through the 1980's. Numerical estimates of mainstream spawner populations are based upon spawning area surveys and counts at Red Bluff Diversion Dam.

2) The temperature-mortality relationship for unfertilized eggs in the female salmon spawner is the same as for fertilized eggs reaching the eyed stage (USBR 1991, p. A109, Figure 2).

3) The percent of the adult salmon population entering the project area is estimated by the records of passage over Red Bluff Diversion Dam (USBR 1991, pp. A106-107, Table 1).

4) Time of spawning for each run of chinook salmon displayed in Table 2 (USBR 1991 pp. A110-111) is estimated for the fall-run, late fall-run and winter-run by aerial redd counts and spawning area surveys. Time of spawning for spring-run is estimated by spawning records recorded in the Baird Hatchery at the turn of the century.

5) Sacramento River salmon spawning distributions displayed in Tables 3 through 7 (USBR 1991, pp. A112, and A115-A118) are from aerial surveys of the spawning grounds. Effort was relatively consistent during the 1980's.

6) Development from fertilized egg to hatching requires 750 (°F) temperature units, and another 750 (°F) temperature units from hatching to emergent fry (32mm), for a total of 1500 (°F) temperature units from egg to emergent fry.

7) Mortality of eggs exposed at various temperatures and exposure durations is displayed in Table 8 (USBR 1991, p. A119).

8) Temperature induced mortality for pre-emergent fry is displayed in Table 9 (USBR 1991, p. A120). There is virtually a total lack of data to base this relationship on other than the apparent increased tolerance of pre-emergent fry as compared to eggs.

9) Project benefits in terms of increased adult stock sizes will be determined by applying the percent increase in survival to emergence to three different stock sizes in each of four water year types as proposed in Table 10 (USBR 1991, p. A122).

It is likely that technical input by USFWS and CDFG staff to the USBR modeler(s) was iterative in nature, involving much more discussion than is implied by the initial comments identified above. In fact, this is shown by the separate mortality rates that now exist for pre-spawned and fertilized eggs. In addition, the life-stage-specific, temperature-dependent average daily mortality rates initially identified by the USFWS and CDFG (as referenced above) were later modified by the USBR based on a memorandum from the USFWS dated March 13, 1992. This USFWS memorandum indicated that the "average daily" rates previously calculated for the egg and fry life stages are what is commonly referred to as "crude mortality rates". Crude mortality rates are the product of simply dividing the percent mortality by the number of days in the reference period to arrive at an average daily rate. It was indicated that calculating daily mortality rates in this manner would not be correct for the mortality model because the rates must operate sequentially throughout the reference period. Use of crude daily mortality rates would result in underestimating mortality for a given period of time.

Rather than using the crude-mortality rate approach, the USFWS recommended calculating "absolute" daily or "instantaneous" daily mortality rates for the reference period. Instantaneous daily mortality rates could be calculated using the following equation:

$$Mi = (1 - Mn) \exp (1/n)$$

Where:
Mi = daily mortality rate
Mn = mortality rate after exposure time
n = exposure time in days

Subsequent to receiving this USFWS recommendation, the USBR's modeler(s) calculated instantaneous daily mortality rates using the above equation for the pre-spawned egg, fertilized egg, and pre-emergent fry life stages for the integer temperatures shown in Tables 1-3. These instantaneous daily mortality rates are the rates currently used by all versions of the mortality model.

Table 1. Estimated temperature and exposure duration-mortality relationships for pre-spawned chinook salmon eggs (in the adult spawner). Instantaneous mortality rates represent the pre-spawned egg criteria (PSC) currently used by the mortality model.

Incubation Temperature (°F)	Mortality Rate at Exposure Time	Instantaneous Daily Mortality Rate[a] (%)
< 52	Natural rate	--
52	Natural rate	--
53	11% @ 30 days	0.034
54	15% @ 30 days	0.171
55	20% @ 30 days	0.351
56	25% @ 30 days	0.540
57	31% @ 30 days	0.783
58	39% @ 30 days	1.135
59	48% @ 30 days	1.581
60	57% @ 30 days	2.094
61	65% @ 30 days	2.627
62	74% @ 30 days	3.348[b]

[a] Using formula derived by Bartholow 1992 (USFWS memorandum to USBR dated March 13, 1992).

[b] Same mortality rate applied for greater temperatures.

Table 2. Estimated temperature and exposure duration-mortality relationships for fertilized chinook salmon eggs (in redds). Instantaneous mortality rates represent the fertilized egg criteria (EC) currently used by the mortality model.

Incubation Temperature (°F)	Mortality Rate at Exposure Time	Instantaneous Daily Mortality Rate[a] (%)
< 56	Natural rate	--
57	8% @ 24 days	0.347
58	15% @ 22 days	0.736
59	25% @ 20 days	1.428
60	50% @ 12 days	5.613
61	80% @ 15 days	10.174
62	100% @ 12 days	31.871
63	100% @ 11 days	34.207
64	100% @ 7 days	48.205
> 64	100% @ 7 days	48.205[b]

[a] Using formula derived by Bartholow 1992 (USFWS memorandum to USBR dated March 13, 1992).

[b] Same mortality rate applied for greater temperatures.

Table 3. Estimated temperature and exposure duration-mortality relationships for pre-emergent chinook salmon fry (in gravel). Instantaneous mortality rates represent the pre-emergent fry criteria (FC) currently used by the mortality model.

Incubation Temperature (°F)	Mortality Rate at Exposure Time	Instantaneous Daily Mortality Rate[a] (%)
< 56	Natural rate	--
57	Natural rate	--
58	Natural rate	--
59	10% @ 14 days	0.750
60	25% @ 14 days	2.034
61	50% @ 14 days	4.830
62	75% @ 14 days	9.428
63	100% @ 14 days	28.031
64	100% @ 10 days[b]	36.904
> 64	100% @ 10 days[b]	36.904[c]

[a] Using formula derived by Bartholow 1992 (USFWS memorandum to USBR dated March 13, 1992).

[b] U.S. Bureau of Reclamation 1992.

[c] Same mortality rate applied for greater temperatures.

3. MODEL CALCULATION OF CHINOOK SALMON LOSSES

The salmon mortality model produces estimates of daily mortality for three early life stages of salmon: 1) pre-spawned eggs; 2) fertilized eggs; and 3) pre-emergent fry. Temperature units (TU), defined as the difference between river temperatures and 32°F, are accounted for on a daily basis by the model, and are used to track life-stage development. For example, incubating eggs exposed to 42°F water for one day would experience 10 TUs. Eggs are assumed to hatch upon exposure to 750 TUs following fertilization. Similarly, the model assumes that fry emerge from the gravel upon being exposed to 750 TUs following hatching into the pre-emergent fry stage.

Mortality incurred by the three early life stages defined above, during a specified period of time, is based on in-river temperatures (i.e., thermal exposures). Hence, the mortality model is sometimes referred to as a chinook salmon "temperature mortality model" or "early life-stage mortality model." Because life-stage-specific mortality rates are dictated by thermal exposure (see Tables 1-3 above for instantaneous mortality rates), the mortality model was designed to be coupled with the USBR's water temperature model. This monthly temperature model consists of a USBR-modified version of a Corps of Engineers' monthly reservoir model and a stream model developed by the USBR. The reservoir model simulates one-dimensional, vertical distribution of reservoir water temperature using monthly input data on initial storage and temperature conditions, inflow, outflow, evaporation, precipitation, radiation, and average air temperature to compute release temperatures from the dams. Using these data, the USBR's stream model calculated resultant monthly mean temperatures at specified locations downstream from the reservoir.

While the USBR's temperature model can be used to determine monthly mean temperatures, it does not define day-to-day temperature variations within a month and, therefore, its' output would not allow quantification of daily fishery impacts. A daily temperature model would be required for such evaluations. Because a daily temperature model that could work effectively with the 70 years of hydrologic record was unavailable at the time the mortality model was being developed, the mortality model was programmed to interpolate daily mean water temperatures from the monthly mean water temperature data output from the USBR water temperature model.

To understand how the model calculates early life-stage losses, the mortality model input parameters (which are based on fishery assumptions and criteria such as those stated above) must be identified and understood. The principal model input parameters are, therefore, identified and defined below.

JD - Julian day (1-365)

SPAWN - Daily % of run spawning. The SPAWN is reduced by prior pre-spawning losses (PSKIL).

HATCH - Daily % of run hatching from the egg to pre-emergent fry stage. The HATCH occurs 750 temperature units (TU) after the SPAWN and is reduced by prior egg losses (EKIL).

EMERG - Daily % of run developing from a pre-emergent fry into emergent fry. The fry emerge 750 TU after they hatch into a pre-emergent fry and are reduced by prior pre-emergent fry losses (FKIL).

AD - % of pre-spawning adults present on each day. AD is computed from the adults from the previous day plus the daily arrivals (PSD), minus the daily spawn (SD), minus the pre-spawning losses occurring that day (PSKIL). PSD and SD are multiplied by RD to identify reach distribution.

RD - Reach distribution.

ED - % of eggs present on each day. ED is computed from the eggs of the previous day plus the daily SPAWN, minus the daily HATCH, minus the egg losses occurring that day (EKIL).

FD - % of pre-emergent fry present on each day. FD is computed from the pre-emergent fry of the previous day plus the daily HATCH, minus the daily EMERG, minus the pre-emergent fry losses occurring that day (FKIL).

TEMP - The average daily river temperature within the reach (i.e. - reach 2) computed from the river temperature model output (T) in °F.

PSM - The daily pre-spawning mortality in % computed from TEMP and the criteria (PSC) provided in Table 1. The average exposure time for these data was assumed to be 30 days.

EM - The daily egg mortality in % computed from TEMP and the criteria (EC) provided in Table 2.

FM - The daily pre-emergent fry mortality in % computed from TEMP and the criteria (FC) provided in Table 3.

PSKIL - The daily pre-spawning loss in %. This is computed from the AD prior to the pre-spawning loss (previous day AD + daily arrivals - daily spawn) multiplied by the PSM for that day.

ESKIL - the daily egg loss in %. This is computed from the ED prior to the egg loss multiplied by the EM for that day.

FKIL - the daily pre-emergent fry loss in %. This is computed from the FD prior to the fry loss multiplied by the FM for that day.

Based on these critical input parameters, the mortality model calculates the annual percent loss of salmon fry, relative to egg potential (i.e., eggs brought to the river by immigrating female salmon). The model accounts for the daily loss of eggs and/or fry in the calculation of total mortality over the exposure period. To do so, the model independently calculates a daily percent pre-spawning loss (PSKIL), a daily percent egg loss (EKIL), and a daily percent pre-emergent fry loss (FKIL) for distinct river reaches between the regulating reservoir and a specified downstream point on the river (e.g., lower end of the spawning grounds).

The daily PSKIL value is computed using the percent of pre-spawning adults present on each day (AD), daily arrivals, daily spawning, and the daily pre-spawning mortality of adults (PSM), which is based on temperature exposure (i.e., thermal exposure to date). A given day's PSKIL value is equal to: (previous day AD + daily arrivals - daily spawn), multiplied by the PSM for that day. Similarly, daily EKIL values are computed using the percent of spawn present on each day (ED), prior to the egg loss, multiplied by a daily egg mortality factor in percent (EM) for that day, which is based on thermal exposure. Finally, daily FKIL values are computed using the percent of pre-emergent fry present on each day (FD), prior to the fry loss, multiplied by the daily pre-emergent fry mortality factor in percent (FM) for that day, which is based on thermal exposure.

Daily pre-spawning, egg, and fry mortalities for the entire stretch of river being modeled are calculated by summing PSKIL, EKIL, and FKIL, respectively, for all river reaches identified in the model. Monthly and annual salmon mortalities (reported as the % loss from egg potential) for the river are computed by summing the daily losses for all reaches and life stages.

It should be noted that the original intended use of the model was for assessing the relative chinook salmon production benefits that would be achieved by reducing temperature-induced mortality of eggs and pre-emergent fry in the upper Sacramento River by reducing in-river water temperatures. Because the mortality estimates output from the model are based on modeled mean monthly water temperatures, mortality estimates should not be interpreted to be true quantitative predictions, but rather viewed as a "relative index" of chinook salmon early life-stage losses resulting from different thermal exposure scenarios.

4. APPLICATION OF THE MORTALITY MODEL TO THE LOWER AMERICAN RIVER

In early March of 1995, the Forum's Fish Biologist Working Group representative, became aware of the USBR's work to modify the chinook salmon mortality model for use on the lower American River. The LAR mortality model was to be used for evaluating instream flow alternatives for this river as a part of the Programmatic Environmental Impact Statement (PEIS) being prepared by the USBR in support of CVP-wide implementation of instream flows recommended in the USFWS's Anadromous Fish Restoration Plan.

Because the Forum's fishery representative was aware of recently-collected lower American River fishery data that would be beneficial to incorporate into the USBR's mortality model for its application to the lower American River, a meeting was held on March 8, 1995 to discuss model modifications prior to its use for modeling chinook salmon early life-stage mortality in the lower American River.

The new fishery assumptions and criteria that the Forum's representative presented to the USBR for use in refining the LAR mortality model are described below.

1) The temporal spawning distribution for fall-run chinook salmon in the lower American River was defined using CDFG angler creel survey data for the years 1990-1994 and historic (1944-1946) fall-run chinook salmon passage at the fishway at Old Folsom Dam (Table 4).

2) The spatial spawning distribution for fall-run chinook salmon in the lower American River was defined based on aerial redd survey data collected by the CDFG in the fall of 1991, 1992, and 1993 (Table 4).

3) Annual lower American River spawning was to be initiated (by the model) when the daily mean river water temperature became ≤60°F, rather than on a fixed date each year. The threshold temperature of 60°F for initiation of spawning was set for the model after consultation and agreement with CDFG's lower American River fisheries expert, W. Snider. This decision was based on data generated from aerial redd surveys conducted on the lower American River by CDFG from 1991-1993. In order to restrict assessments to American river fall-run chinook salmon only, it was recommended that the model not account for chinook salmon arriving annually prior to September 1.

4) Adult chinook salmon entering the lower American River to spawn prior to the time when daily mean water temperatures decrease to ≤60°F are "held" by the model and are not

"spawned" until after in-river water temperatures became ≤60°F (i.e., until after the "60°F date" was reached).

5) Immigrating adult chinook salmon arriving at the lower American River spawning grounds when daily mean river temperatures are ≤60°F (i.e., after the "60°F date") are "spawned" by the model one week later.

Table 4. Arrival and spawning distribution data for the lower American River provided to the USBR by Beak on April 5, 1995.

Week	Mean[a] Percentage of Run Arriving	River Miles	River Reach	Mean[b] Percentage of Redds Established Annually
Sept (wk 1)	3.0	21.0-23.0	1	31
2	3.0	17.0-20.0	2	57
3	4.2	14.0-16.0	3	9
4	2.2	10.0-13.0	4	1
Oct (wk 1)	5.6	7.5-9.0	5	1
2	5.0	6.5-7.5	6	1
3	5.0	6.0-6.5	7	0
4	8.4	3.0-5.0	8	0
Nov (wk 1)	8.4	0.0-2.0	9	0
2	19.0			
3	16.3			
4	12.4			
Dec (wk 1)	2.0			
2	2.4			
3	1.0			
4	2.2			

[a] Based on lower American River creel survey data collected by the CDFG for the years 1991-1994 (data acquired from L. Wixom).

[b] Based on lower American River aerial redd survey data collected by the CDFG for the years 1991-1993 (data acquired from B. Snider).

The lower American River-specific fishery assumptions and criteria defined above were programmed into the mortality model code by the USBR in April of 1995, which finalized the development of the LAR mortality model. A brief discussion of specific LAR mortality model procedures is provided below to provide additional insight into how this model calculates chinook salmon losses for this river.

As indicated above, the mortality model was programmed to interpolate daily mean in-river water temperatures from monthly mean output from the USBR's water temperature models. This is done using the following approach. First, the mortality model calculates mean monthly reach temperatures based on output from the American River water temperature models. This is accomplished using the following reach-specific formulas:

Reach 1 = ½ * (Nimbus + Sunrise)
Reach 2 = ½ * (Sunrise + Cordova)
Reach 3 = ½ * (Cordova + Arden)
Reach 4 = ½ * (Arden + Watt Ave)
Reach 5 = ½ * (Watt Ave + Filt. Plt.)
Reach 6 = ½ * (Filt. Plt. + H St.)
Reach 7 = H St. + 0.119 * (16th St. - H St.)
Reach 8 = H St. + 0.619 * (16th St. - H St.)
Reach 9 = ½ * (16th St. + Mouth)

Next, the mortality model interpolates daily temperature for each reach so that daily mortalities can be calculated. Daily temperature interpolation is accomplished in the following manner. The mean monthly temperature is assumed to occur at mid-month (T_{15}). Daily temperature is calculated by interpolating between temperatures at mid-month. For example, the temperature for the end of month 1 (T_{30_1}) would be the average of the mid-month temperatures:

$$T_{30_1} = \tfrac{1}{2} * (T_{15_1} + T_{15_2})$$

Temperature for the 20th day of the first month is calculated as follows:

$$T_{20_1} = (10/30) * (T_{15_2} - T_{15_1}) + T_{15_1}$$

Month 1 Month 2

T_{1_1}---------T_{15_1}----------T_{30_1} T_{1_2}---------T_{15_2}----------T_{30_2}

The LAR mortality model triggers the spawning of new arrivals in the lower American River to occur one week after their arrival, when river water temperatures are at or below 60°F. All spawners that arrived more than one week prior to the time when the river temperature decreases to ≤60°F (the "60°F date") spawn in an even distribution over the 7 days immediately following the "60°F date." Fish that arrive one week or less prior to the "60°F date" spawn one week later.

Daily mortalities for each life-stage present are calculated using the instantaneous daily mortality rates shown in Tables 1-3. Because these tables provide rates for integer temperatures only, instantaneous daily mortality rates for all non-integer temperatures are calculated by linear interpolation from the integer rates as shown in Figures 1-3. Using daily data, the LAR mortality model calculates overall chinook salmon losses as described in section III above.

Figure 1 Estimated Temperature Exposure-Mortality Relationship for Pre-Spawned Chinook Salmon Eggs

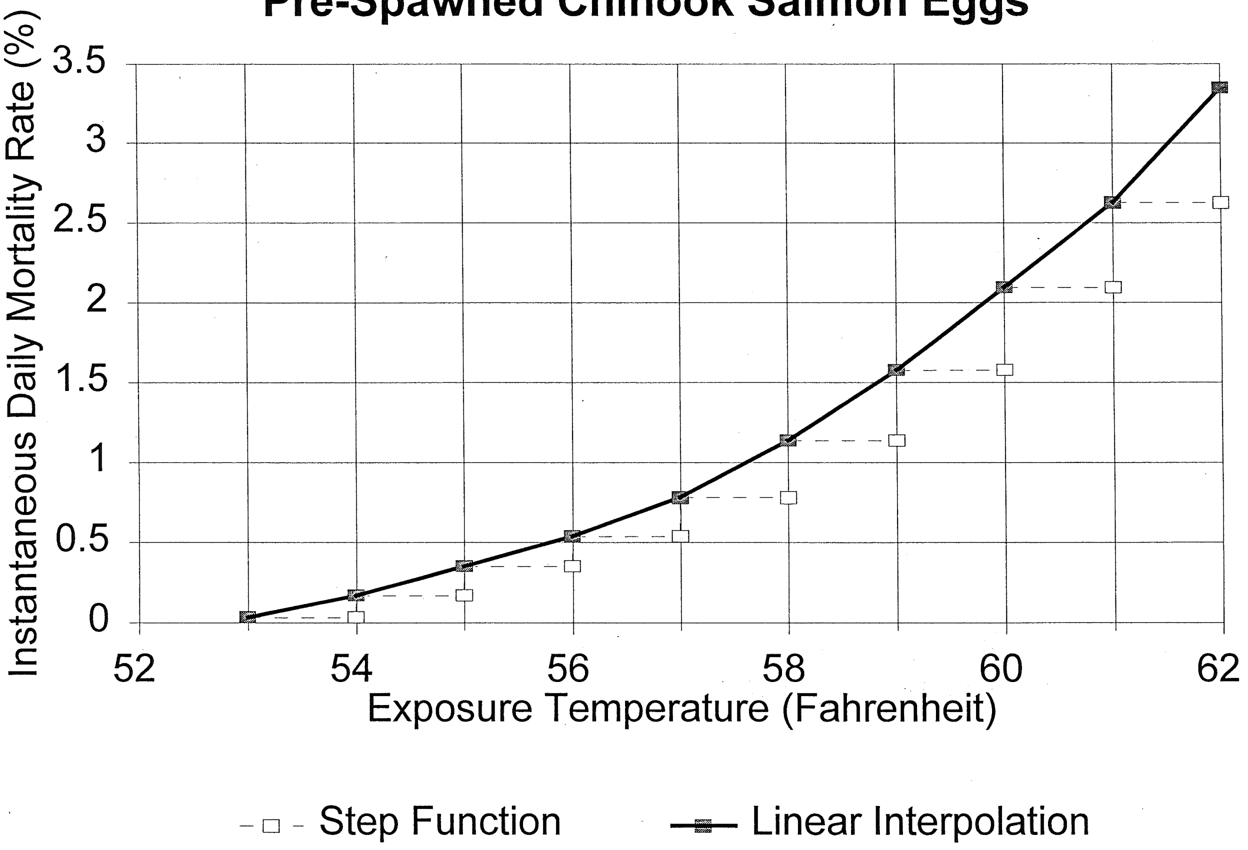


Figure 2 Estimated Temperature Exposure-Mortality Relationship for Fertilized Chinook Salmon Eggs

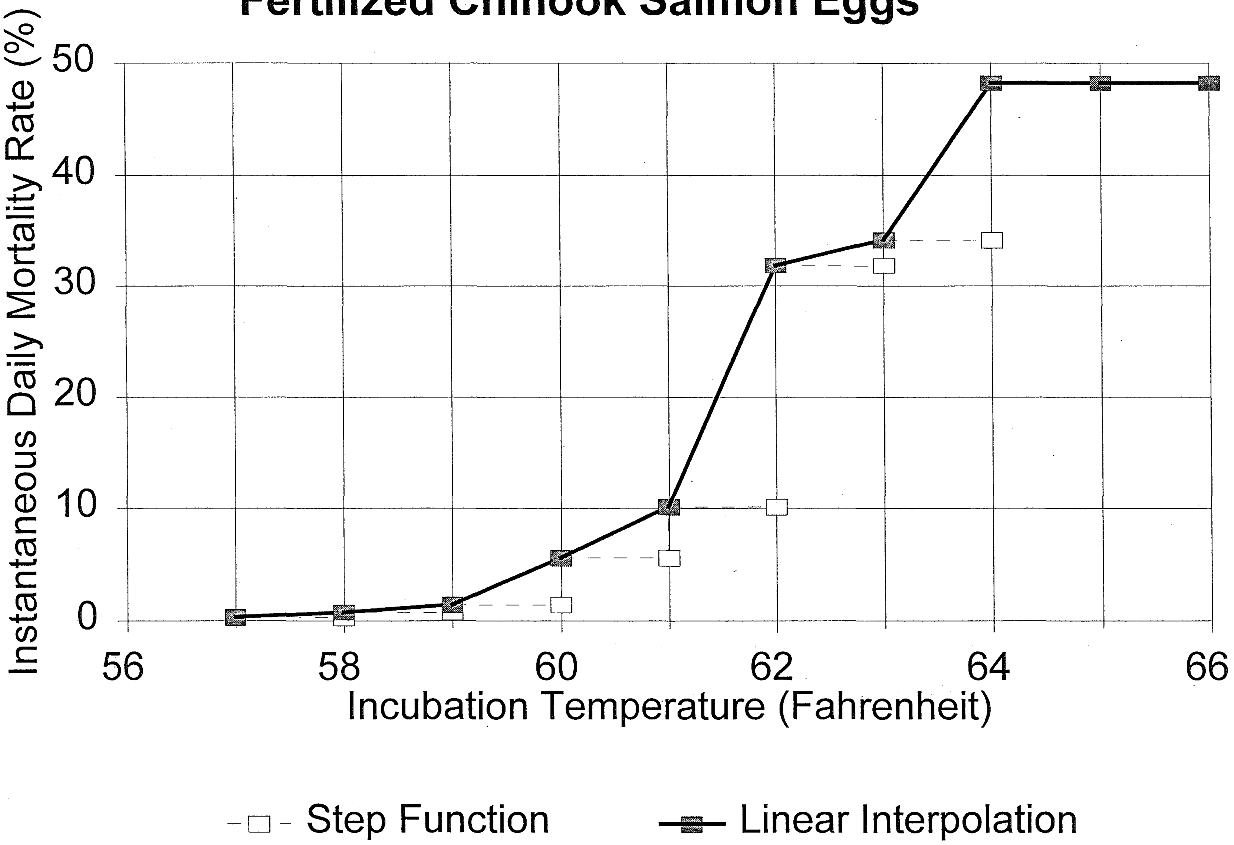
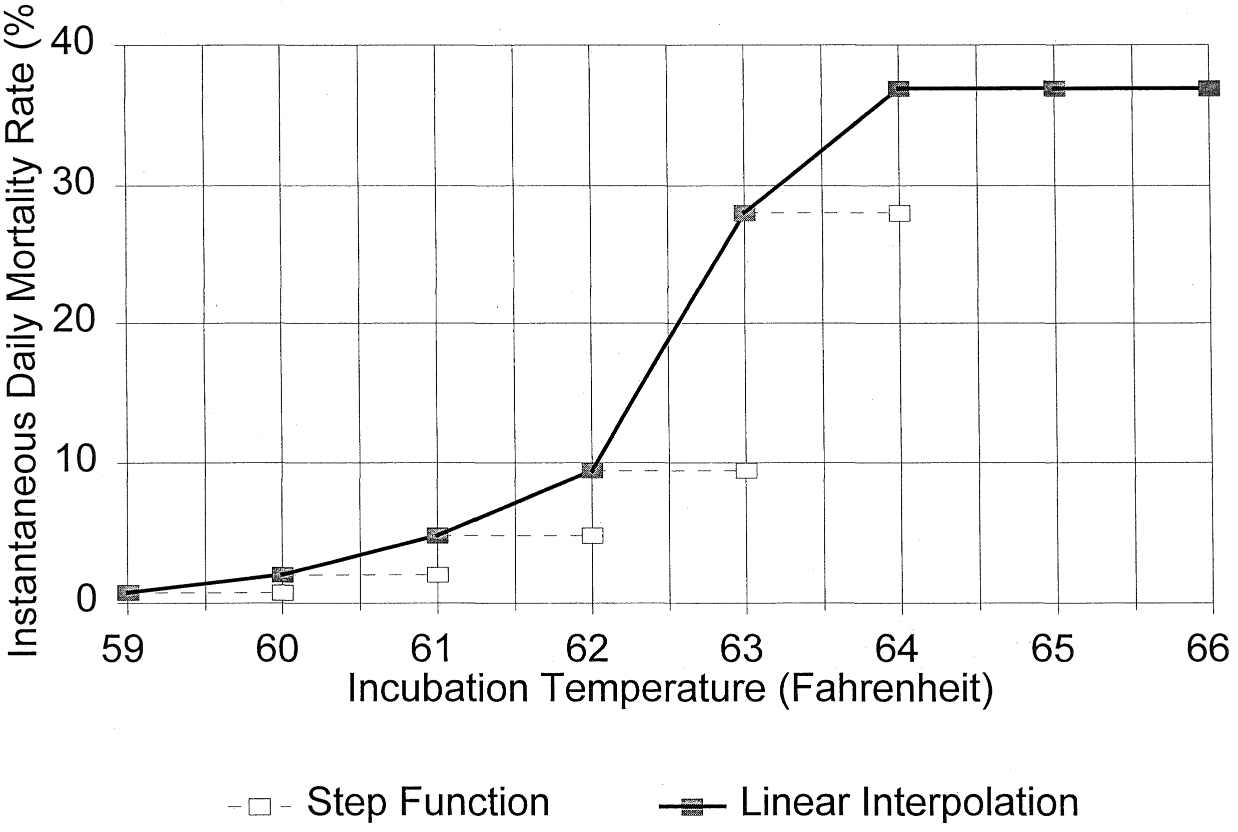


Figure 3 Estimated Temperature Exposure-Mortality Relationship for Chinook Salmon Alevins



5. LOWER AMERICAN RIVER SALMON MORTALITY MODEL EVALUATION

The evaluation of the LAR salmon mortality model involved two phases. Phase I involved an evaluation of the model source code to ensure that: 1) the model accurately reflects all fishery assumptions and criteria for fall-run chinook salmon using the lower American River; and 2) there are no errors in the model logic or calculations performed. In Phase II the model inputs that are produced by PROSIM and the Folsom Reservoir and American River temperature models were reviewed.

5.1 Phase I: Model code evaluation

The code evaluation performed involved a line-by-line evaluation of the LAR salmon mortality model's FORTRAN code. The objectives of this exercise were to: 1) gain an understanding of the model logic, thereby assuring that all appropriate biological assumptions and criteria have been incorporated into the model; and 2) assure that no mathematical or logic errors exist in the model that would prevent it from calculating accurate and appropriate early life-stage losses for fall-run chinook salmon in the lower American River. The biological processes being simulated by the model were compared to actual field-collected and literature data as well as our current understanding of chinook salmon biology. Once it was established that the model properly reflected all appropriate and necessary biologic assumptions, the FORTRAN code was reviewed for errors (i.e., programming "bugs"). During this effort the model code was evaluated using hand calculations and all model input parameters were reviewed for accuracy.

The Phase I evaluation determined that, for the most part, the model currently reflects all appropriate fishery assumptions and criteria for fall-run chinook salmon spawning and rearing in the lower American River. The manner in which the model simulates early life-stage salmon losses is consistent with our current understanding of fall-run chinook salmon biology in the lower American River. However, one error in the model code was identified. A single model parameter describing the period when pre-spawning egg mortality was occurring was set incorrectly, resulting in the pre-spawning egg losses being underestimated. Upon correcting this error in the code, the model now estimates higher pre-spawning and total mortality than it did previously.

A second model parameter defining subsequent losses was recently found to be suspect, and is currently being investigated by the USBR. Consequently, the Phase I code evaluation remains ongoing at this time.

5.2 Phase II: Model input evaluation

Phase II of the LAR salmon mortality model evaluation involved reviewing all inputs to this model. Because the only information that constitutes "direct" input to the LAR salmon mortality model is temperature at nine locations along the lower American River, the focus of this work was to evaluate factors that influence the simulated temperatures for the lower American River which the LAR salmon mortality model uses to calculate annual early life-stage losses from egg potential. Several models are used to ultimately establish temperatures in the lower American River for use by the LAR salmon mortality model. These models include: 1) the USBR's PROSIM model; 2) the USBR's Folsom Reservoir temperature model; and 3) the USBR's American River temperature model.

The USBR's PROSIM model is a complex reservoir simulation model that simulates operation of the entire Central Valley Project and the State Water Project on a monthly basis. There are numerous assumptions and inputs that drive PROSIM, and a tremendous amount of reservoir storage and release data that can be output from PROSIM. When using the LAR salmon mortality model to assess the relative impacts to fall-run chinook salmon of two proposed flow regimes and/or diversion patterns for the lower American River, the PROSIM model is run first to characterize monthly Folsom Reservoir storage and release rates under each alternative. PROSIM output (e.g., monthly reservoir storage and release rates, diversions) are then input into the Folsom Reservoir temperature model. The Folsom Reservoir temperature model uses Folsom Reservoir inflows, releases, and diversions from PROSIM along with various other model inputs to simulate mean monthly reservoir release temperatures. Folsom Reservoir release temperatures and flow rates are then extracted from the Folsom Reservoir temperature model and input into the USBR's American River temperature model. This model simulates lower American River water temperatures at the nine locations between Nimbus Dam and the mouth that are used in the LAR salmon mortality model.

As indicated by the discussion above, the USBR's PROSIM, Folsom Reservoir temperature, and American River temperature models are all required to produce the necessary input to the LAR salmon mortality model. Consequently, numerous computer files and output data sets are produced, and must be verified prior to their use in the LAR salmon mortality model. Due to the multi-model, iterative approach required to run the LAR salmon mortality model, errors can be made at numerous stages of the overall process that may affect the output from the LAR salmon mortality model. Nevertheless, if all appropriate quality assurance checks are made throughout the process, the LAR salmon mortality model will appropriately estimate annual alternative-specific early life-stage losses of fall-run chinook salmon from egg potential.

The inputs to PROSIM dictate PROSIM's simulation of Central Valley Project operations, which can indirectly (i.e., through altered seasonal Folsom Reservoir storage and release rates and temperature) influence calculations of lower American River salmon losses by the LAR salmon mortality model. Two major potential sources of error in this iterative modeling process are: 1) in extracting data from PROSIM for use in the reservoir and river temperature models; and 2) in defining appropriate input parameters for the Folsom Reservoir temperature model. Therefore, we focused our review of inputs to the LAR salmon mortality model on these two areas.

Extracting data from PROSIM for use in the reservoir and river temperature models is rather straight forward, but must be checked each time to assure that errors are not made. For example, demands for the American River are aggregated in PROSIM but require de-aggregation for input and use in the temperature models. This is required because it is important for the temperature models to acknowledge the specific volumes and locations of water diverted in order to accurately estimate water temperatures at the nine locations in the lower American River, which the LAR salmon mortality model uses to calculate losses.

The USBR's Folsom Reservoir temperature model uses numerous input parameters that can directly impact its estimates of reservoir release temperatures, which can ultimately affect the LAR salmon mortality model's estimates of salmon losses. Therefore, it must be assured that all input parameters to this model are appropriate. Examples of such inputs parameters include:

- ambient air temperature for the 1922-1990 hydrologic period of record modeled;
- monthly Folsom Reservoir inflow rates and temperatures;
- reservoir stratification criteria;
- Folsom Dam shutter configuration;
- monthly target release temperatures for Folsom Reservoir; and
- solar radiation coefficients.

The USBR's Folsom Reservoir temperature model uses measured ambient air temperature for the hydrologic period of record. Unlike inputs for ambient air temperature, the inputs defining reservoir inflow rates and temperatures are static. Consequently, a sensitivity analysis on these input parameters may be appropriate to determine whether refinement of the reservoir inflow rate and temperature input parameters would affect estimates of salmon losses sufficiently to warrant the effort to refine them. Examination of the reservoir stratification, solar radiation, and shutter configuration parameters of the reservoir temperature model indicate that these parameters are defined appropriately at this time. Finally, a critically important input parameter that largely affects the model's estimates of Folsom Reservoir release temperatures is the monthly target release temperatures for Folsom Reservoir or "boundary conditions".

If the monthly target release parameters for the Folsom Reservoir temperature model were set differently for two modeling runs, it would not be appropriate to make a direct comparison of the resulting estimates of salmon losses from the LAR salmon mortality model. Furthermore, the monthly target release temperatures that provide maximum benefits for fall-run chinook salmon only are not the same target release temperatures that would maximize benefits for both chinook salmon and steelhead in the lower American River. Therefore, it may be appropriate to provide additional consideration of the target release temperature parameters currently being used in the Folsom Reservoir temperature model. At a minimum, it must be assured that losses for any two runs of the LAR salmon mortality model that are to be compared were generated from runs of the

Folsom Reservoir temperature model that had the same monthly target release temperature inputs.

6. DEVELOPMENT OF ADDITIONAL MODEL OUTPUT CAPABILITIES

As a part of this comprehensive evaluation of the LAR salmon mortality model, additional output capabilities were programmed into the LAR salmon mortality model's code. This was done to provide the flexibility to request tabular and graphical output from a model run for a single year (e.g., the year of greatest difference in losses between two alternatives modeled) or any combination of years (e.g., those of a given water year type) for determining *why* one alternative results in greater salmon losses that another for the identified year or period of years. Examples of the new graphical output capabilities of the LAR salmon mortality model and their use for diagnosing why losses are greater under one alternative than another for the 1922-1990 hydrologic period of record, and for a specific year when the difference in calculated loss is great relative to other years, are provided in Section 7, below.

7. ASSESSMENT OF LOWER AMERICAN RIVER FLOW ALTERNATIVES USING THE CHINOOK SALMON MORTALITY MODEL

7.1 Alternatives comparison

Following this evaluation of the LAR salmon mortality model, the model was used to assess the differences in fall-run chinook salmon early life-stage losses under two American River diversion-demand scenarios: 1) the Sacramento Area Water Plan Forum's 1995 base condition (base); and 2) the maximum upstream diversion alternative proposed in the P.L. 101-514 (206) Water Contracts EIS/EIR (alternative). The differences under the alternative relative to the base are: 1) an additional 20,000 acre-feet (af) diversion out of Folsom Reservoir at Folsom Dam; and 2) an additional 15,000 af diversion out of the lower American River at the existing Fairbairn water treatment plant.

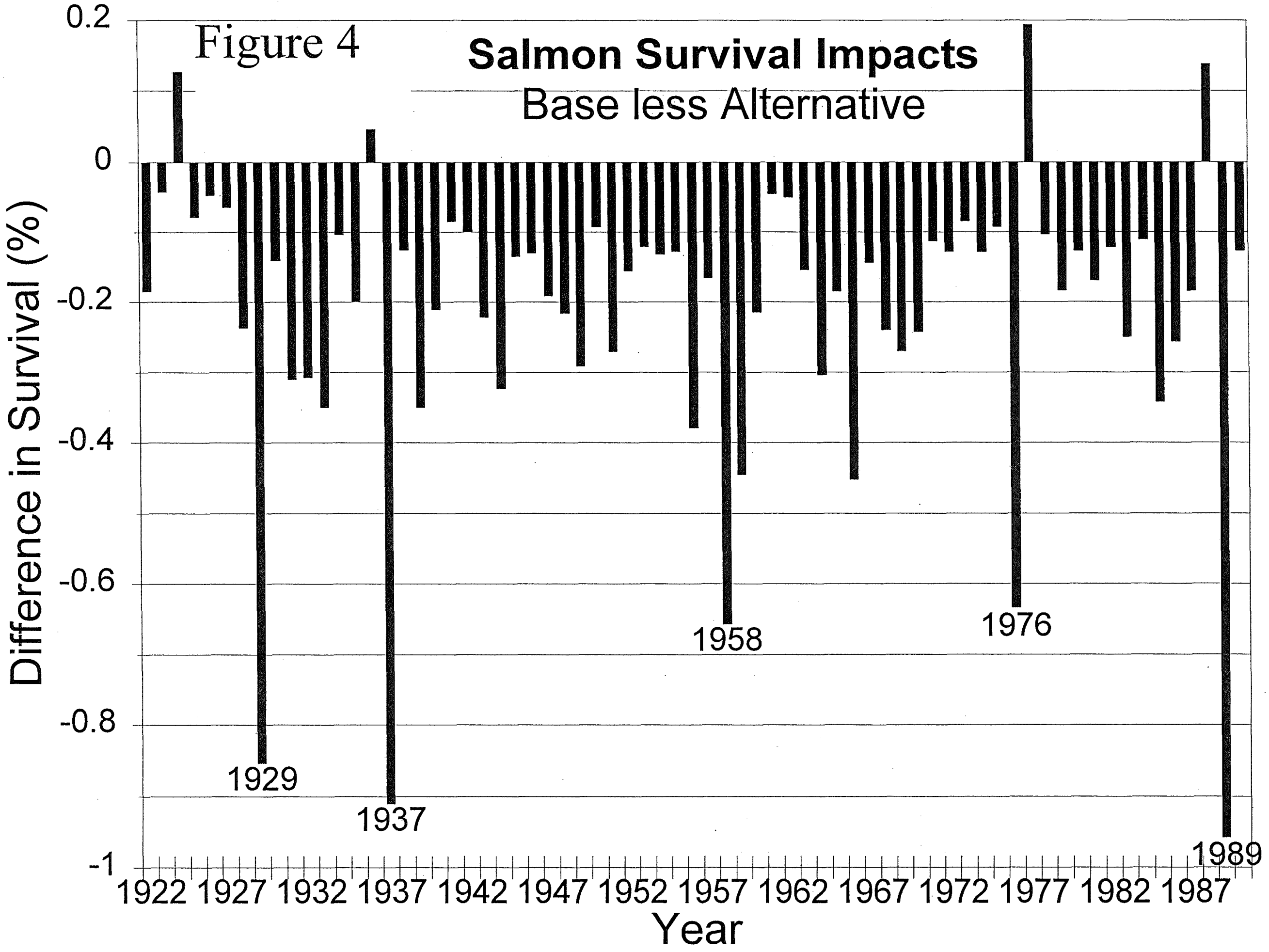
7.2 Evaluation of results

The preliminary results obtained from modeling the base condition and the alternative defined above indicate that the average annual chinook salmon losses under these two water-diversion scenarios differ by a maximum of 0.96 % for any given year, and by only 0.19% when averaged over the 1922-1990 period of record modeled (Table 5; Figure 4). Further assessment of the mortality model output indicates that the alternative diversion scenario would result in the same number of years as the base condition having total annual salmon loss exceeding 5, 10, and 15% (Table 5).

Table 5. Comparison of annual fall-run chinook salmon losses in the lower American River under the base and the alternative for the years 1922-1990.

Year	Base	Alternative	Difference
1922	5.494	5.68	-0.186
1923	10.391	10.433	-0.042
1924	13.488	13.362	0.126
1925	6.053	6.131	-0.078
1926	11.041	11.09	-0.049
1927	5.977	6.041	-0.064
1928	7.438	7.674	-0.236
1929	10.607	11.459	-0.852
1930	7.755	7.897	-0.142
1931	15.674	15.985	-0.311
1932	6.884	7.19	-0.306
1933	11.586	11.935	-0.349
1934	14.247	14.352	-0.105
1935	7.304	7.504	-0.2
1936	9.546	9.499	0.047
1937	6.054	6.963	-0.909
1938	6.589	6.714	-0.125
1939	14.022	14.371	-0.349
1940	6.268	6.478	-0.21
1941	6.073	6.159	-0.086
1942	5.703	5.804	-0.101
1943	5.977	6.198	-0.221
1944	7.91	8.233	-0.323
1945	6.151	6.285	-0.134
1946	6.038	6.169	-0.131
1947	7.441	7.631	-0.19
1948	5.933	6.15	-0.217
1949	5.887	6.177	-0.29
1950	6.391	6.483	-0.092
1951	7.092	7.364	-0.272
1952	6.505	6.661	-0.156
1953	6.351	6.471	-0.12
1954	6.659	6.792	-0.133
1955	7.405	7.534	-0.129
1956	8.209	8.589	-0.38
1957	6.969	7.134	-0.165
1958	10.956	11.612	-0.656
1959	16.141	16.586	-0.445
1960	11.815	12.031	-0.216
1961	17.592	17.639	-0.047
1962	7.935	7.985	-0.05
1963	6.021	6.174	-0.153
1964	7.513	7.816	-0.303
1965	6.615	6.801	-0.186
1966	8.451	8.905	-0.454
1967	6.527	6.672	-0.145
1968	7.533	7.774	-0.241
1969	6.171	6.442	-0.271
1970	7.374	7.618	-0.244
1971	5.542	5.654	-0.112
1972	6.333	6.463	-0.13
1973	6.027	6.111	-0.084
1974	6.182	6.312	-0.13
1975	5.976	6.068	-0.092
1976	15.364	16	-0.636
1977	19.227	19.033	0.194
1978	6.37	6.475	-0.105
1979	7.36	7.544	-0.184
1980	6.419	6.546	-0.127
1981	10.364	10.533	-0.169
1982	7.056	7.177	-0.121
1983	6.67	6.919	-0.249
1984	7.554	7.664	-0.11
1985	9.355	9.698	-0.343
1986	6.697	6.955	-0.258
1987	16.471	16.656	-0.185
1988	19.408	19.271	0.137
1989	10.726	11.685	-0.959
1990	17.952	18.079	-0.127
Mean:	8.79	9.01	-0.21
Maximum:	19.41	19.27	0.19
Minimum:	5.49	5.65	-0.96
No. > 5%:	69	69	
No. > 10%:	19	19	
No. > 15%:	8	8	

Figure 4


Salmon Survival Impacts
Base less Alternative
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Difference in Survival (%)
1929
1937
1958
1976
1989
1922
1927
1932
1937
1942
1947
1952
1957
1962
1967
1972
1977
1982
1987
Year

The new graphical output programmed into the LAR salmon mortality model was used to demonstrate that the alternative water-diversion scenario modeled would cause only small changes in lower American River water temperatures and, therefore, only small differences in salmon losses (Figures 5-8). One of the modeled years with the most dramatic difference in mortality estimates, 1937, was selected for comparing losses under the base and the alternative. The year 1937 was selected for the comparison because it exhibited the second largest difference among all years for this comparison, and the largest single difference for a previously constructed version of the Forum's "Trial Balloon". The comparison was made to determine the month(s) during which elevated temperatures occur under the alternative (relative to the base) and, consequently, which early life-stage(s) of salmon (i.e., pre-spawning, egg incubation, and/or pre-emergent fry) incur the additional losses (Figures 9-12). For 1937, the additional 0.91% loss that was estimated under the alternative was incurred during the pre-spawning (Figure 10) and egg incubation (Figure 11) life stages, with the pre-emergent fry life-stage being unaffected (Figure 12). These findings make intuitive sense because in-river water temperatures were only slightly higher under the alternative throughout the primary pre-spawning and egg incubation periods of the year (i.e., September through November), and river temperatures for both alternatives during the primary pre-emergent fry life-stage (i.e., late November through February) were below levels that would result in temperature-induced mortality (Figure 12; Table 3).

Because there is inherent variation in the biological processes being modeled, and because there is variation ("error") associated with each of the iterative modeling steps required to produce estimates of fall-run chinook salmon losses in the lower American River, the difference in total early life-stage loss estimated for the two water-diversion scenarios defined for a given period should not be interpreted to be absolute, but rather as a relative difference for comparative purposes. Although not quantified, the "error" associated with average annual loss estimates from the LAR salmon mortality model may be on the order of 10-20% of the estimated loss (J. Rowell, USBR, pers. comm., May 8, 1996).

8. CONCLUSIONS

Based on this evaluation of the LAR salmon mortality model, it was concluded that the model's code appropriately reflects our current understanding of how water temperatures in the lower American River contribute to chinook salmon early life-stage mortality. This evaluation found two programming errors in the LAR salmon mortality model's code, both of which have been corrected. However, because two programming errors were found, the USBR is currently conducting its own evaluation of the model's code to assure that no additional programming errors remain. The USBR anticipates completing its evaluation by the end of May, 1996.

It was further concluded that inputs to the LAR salmon mortality model from the USBR's PROSIM, Folsom Reservoir temperature, and American River temperature models are technically appropriate. Nevertheless, several input parameters to the Folsom Reservoir temperature model (e.g., reservoir inflow temperatures and rates and Folsom Reservoir monthly target release temperatures) may warrant further evaluation to determine: 1) the degree to which

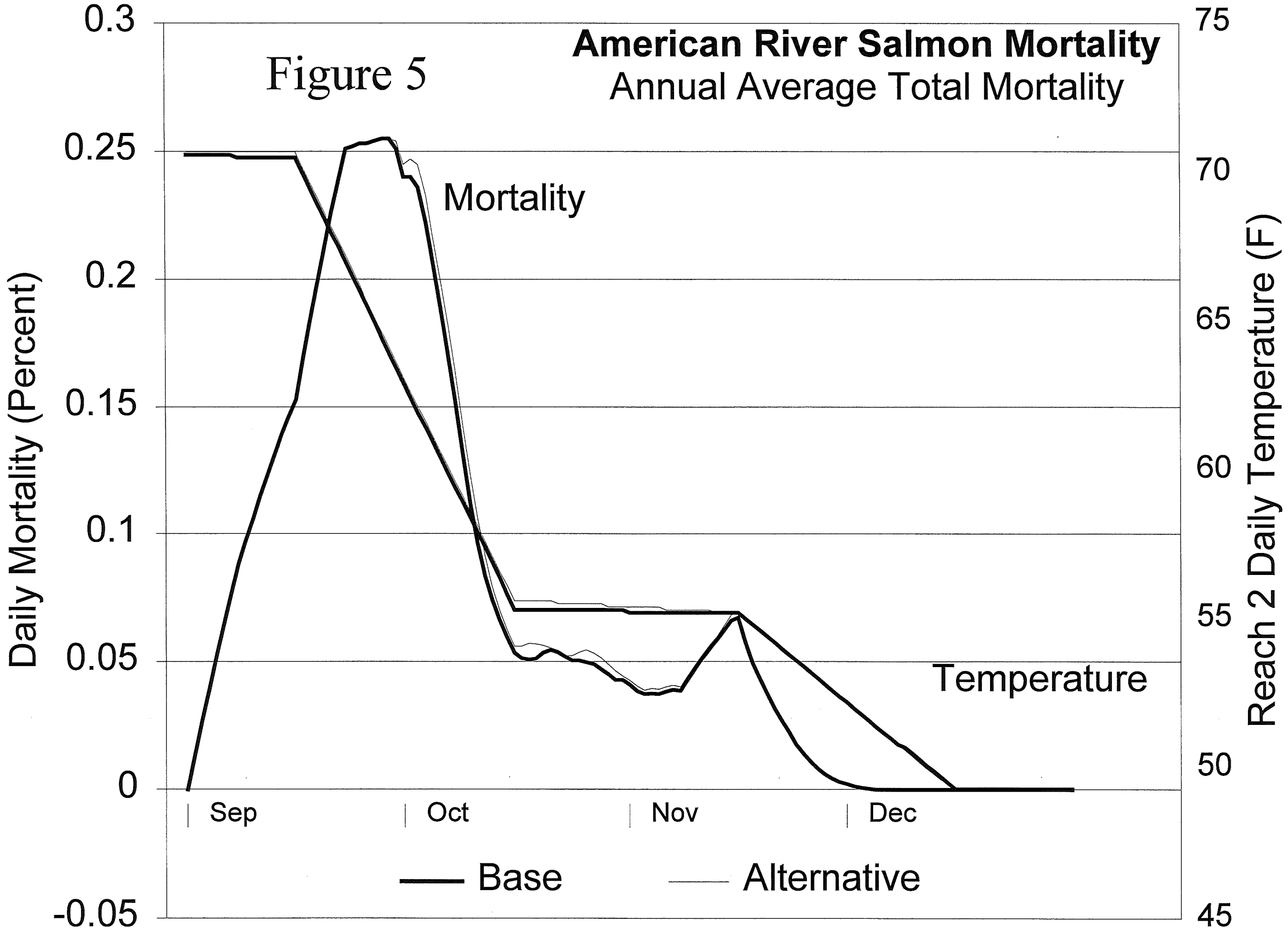


Figure 5
American River Salmon Mortality
Annual Average Total Mortality
Mortality
Temperature
Daily Mortality (Percent)
Reach 2 Daily Temperature (F)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
75
70
65
60
55
50
45
Sep
Oct
Nov
Dec
Base
Alternative

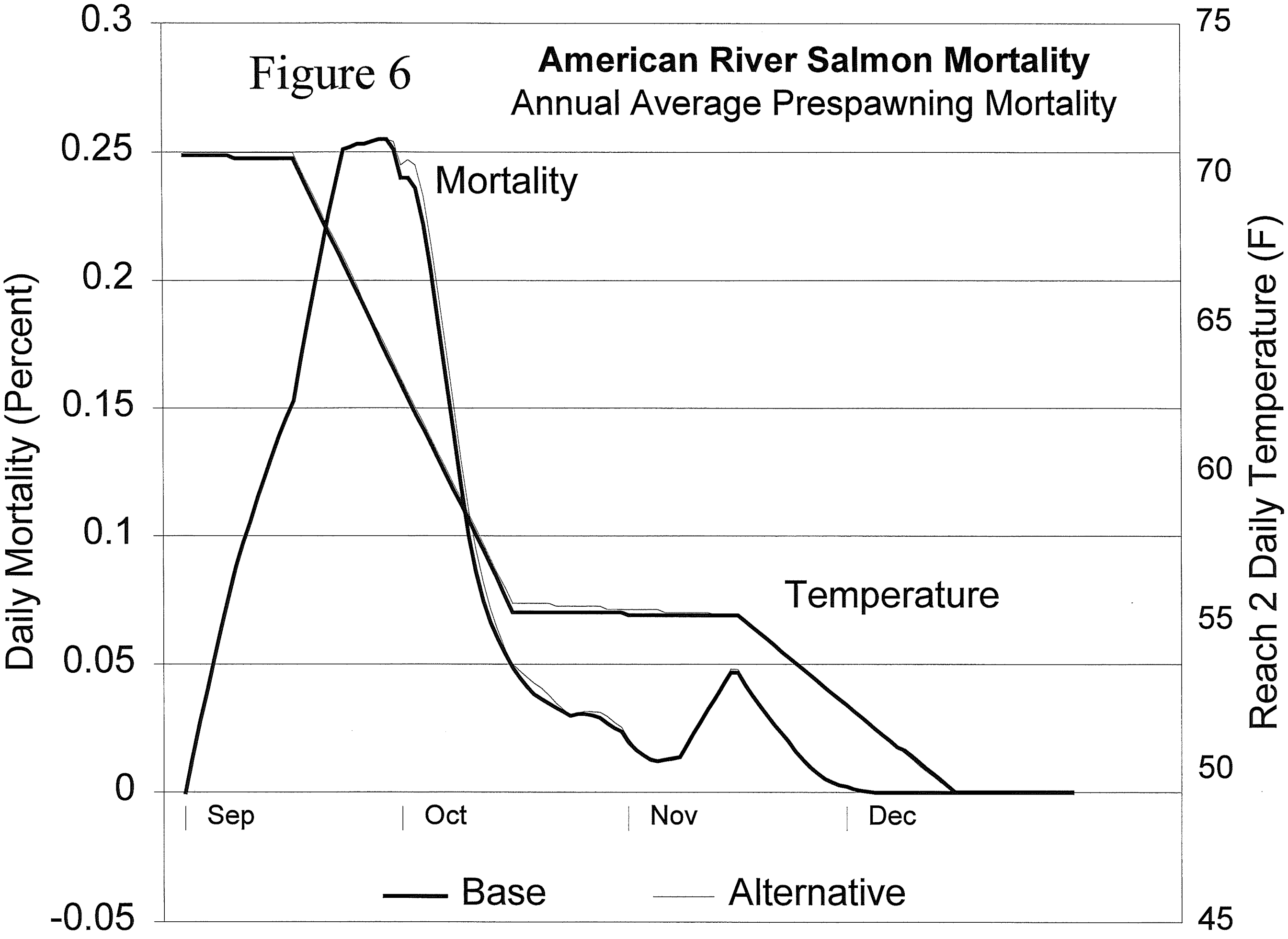


Figure 6
American River Salmon Mortality
Annual Average Prespawning Mortality
Mortality
Temperature
Daily Mortality (Percent)
Reach 2 Daily Temperature (F)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
75
70
65
60
55
50
45
Sep
Oct
Nov
Dec
Base
Alternative

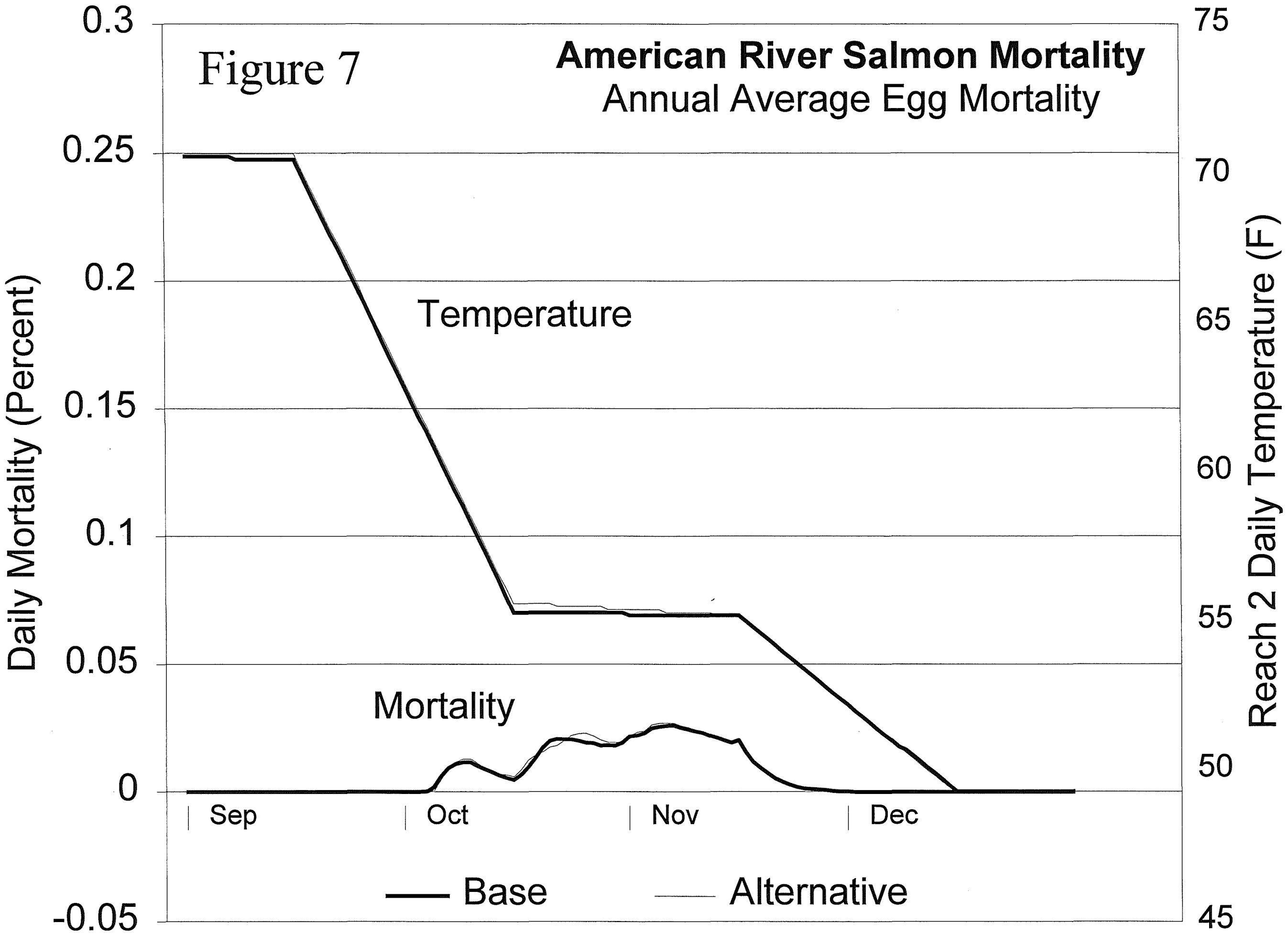


Figure 7

American River Salmon Mortality
Annual Average Egg Mortality
Daily Mortality (Percent)
Reach 2 Daily Temperature (F)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
75
70
65
60
55
50
45
Temperature
Mortality
Sep
Oct
Nov
Dec
Base
Alternative

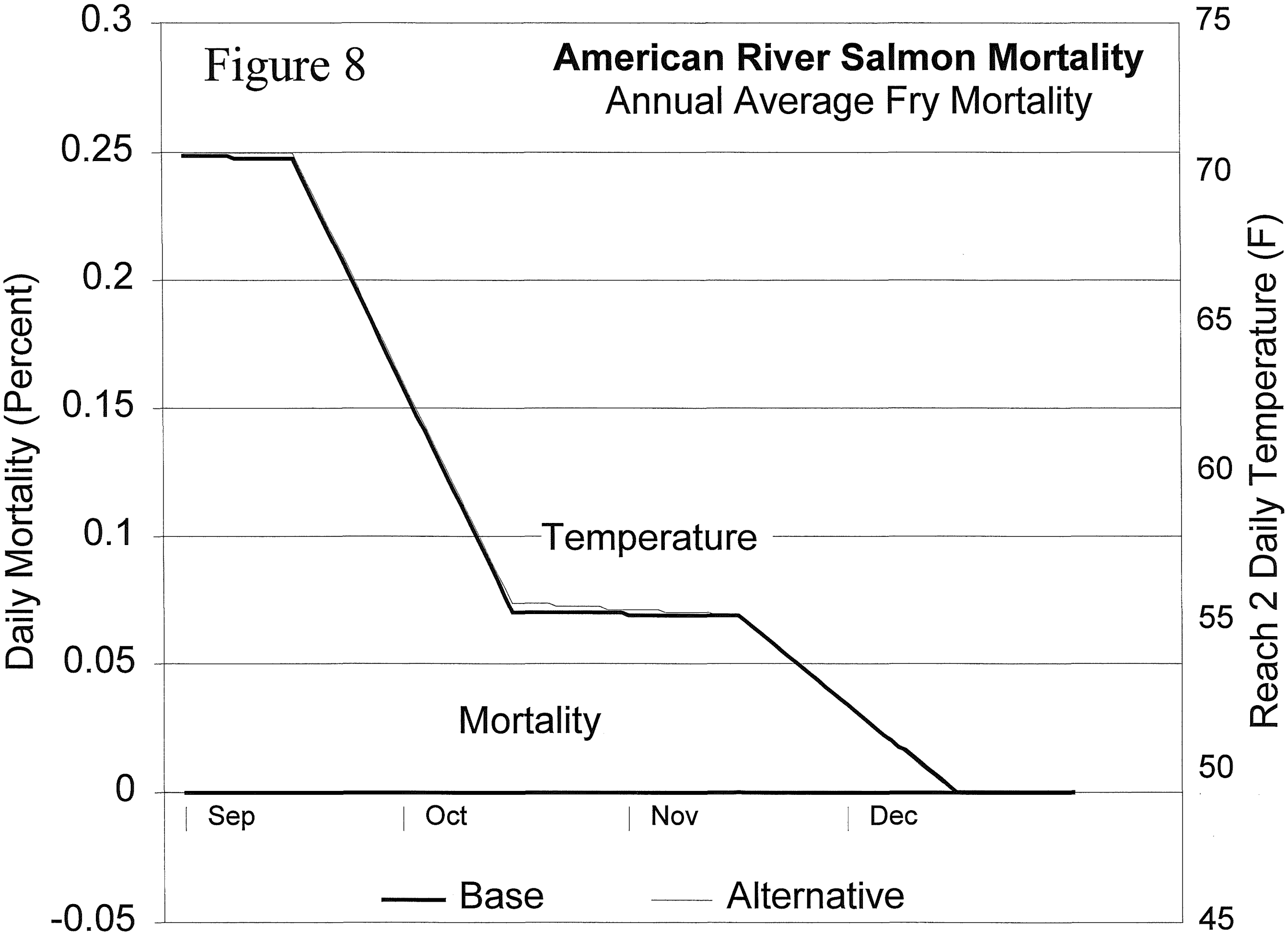
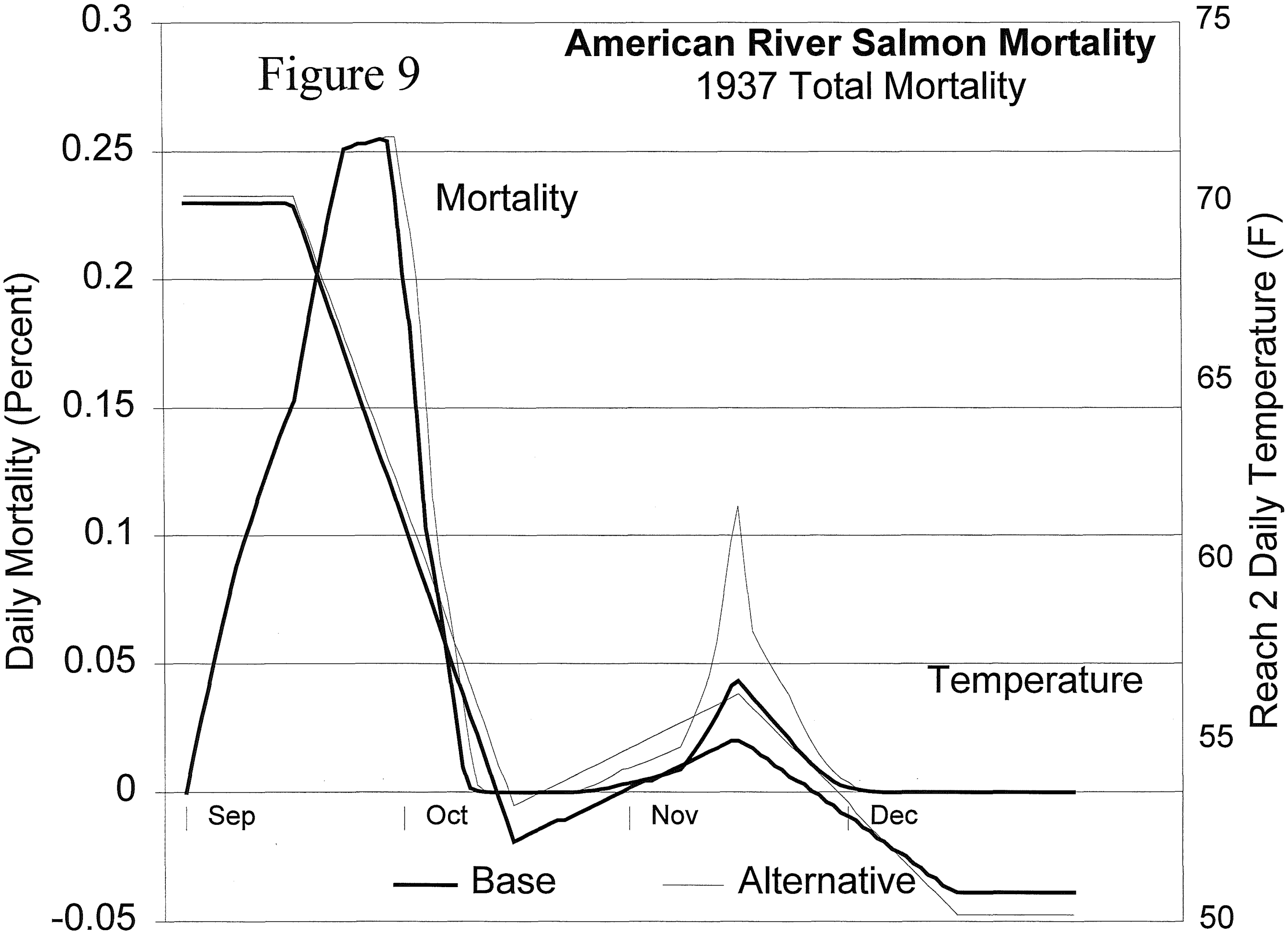


Figure 8
American River Salmon Mortality
Annual Average Fry Mortality
Daily Mortality (Percent)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Reach 2 Daily Temperature (F)
75
70
65
60
55
50
45
Temperature
Mortality
Sep
Oct
Nov
Dec
Base
Alternative

Figure 9


American River Salmon Mortality
1937 Total Mortality
Mortality
Temperature
Daily Mortality (Percent)
Reach 2 Daily Temperature (F)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
75
70
65
60
55
50
Sep
Oct
Nov
Dec
Base
Alternative

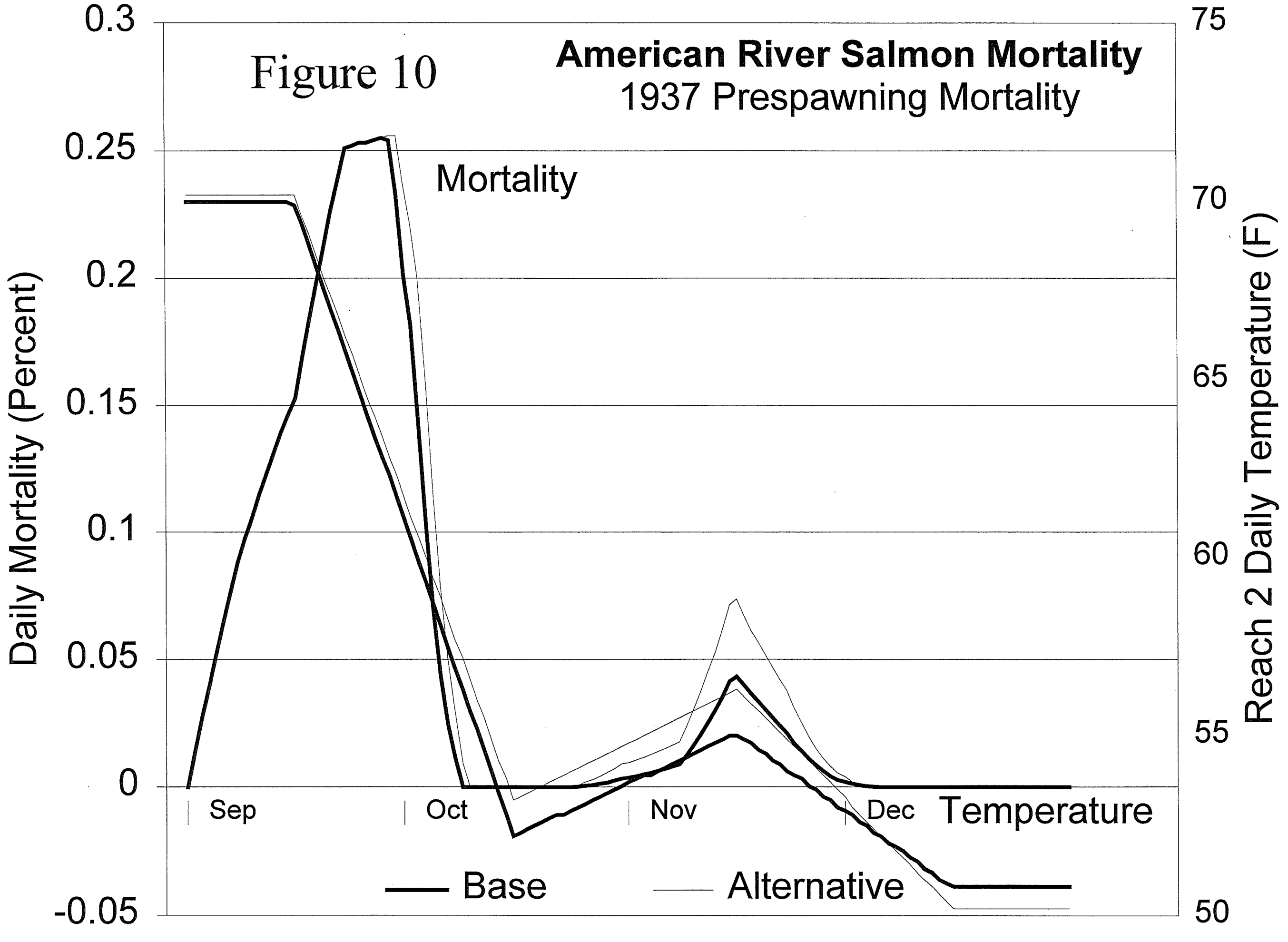


Figure 10
American River Salmon Mortality
1937 Prespawning Mortality
Mortality
Temperature
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Daily Mortality (Percent)
75
70
65
60
55
50
Reach 2 Daily Temperature (F)
Sep
Oct
Nov
Dec
Base
Alternative

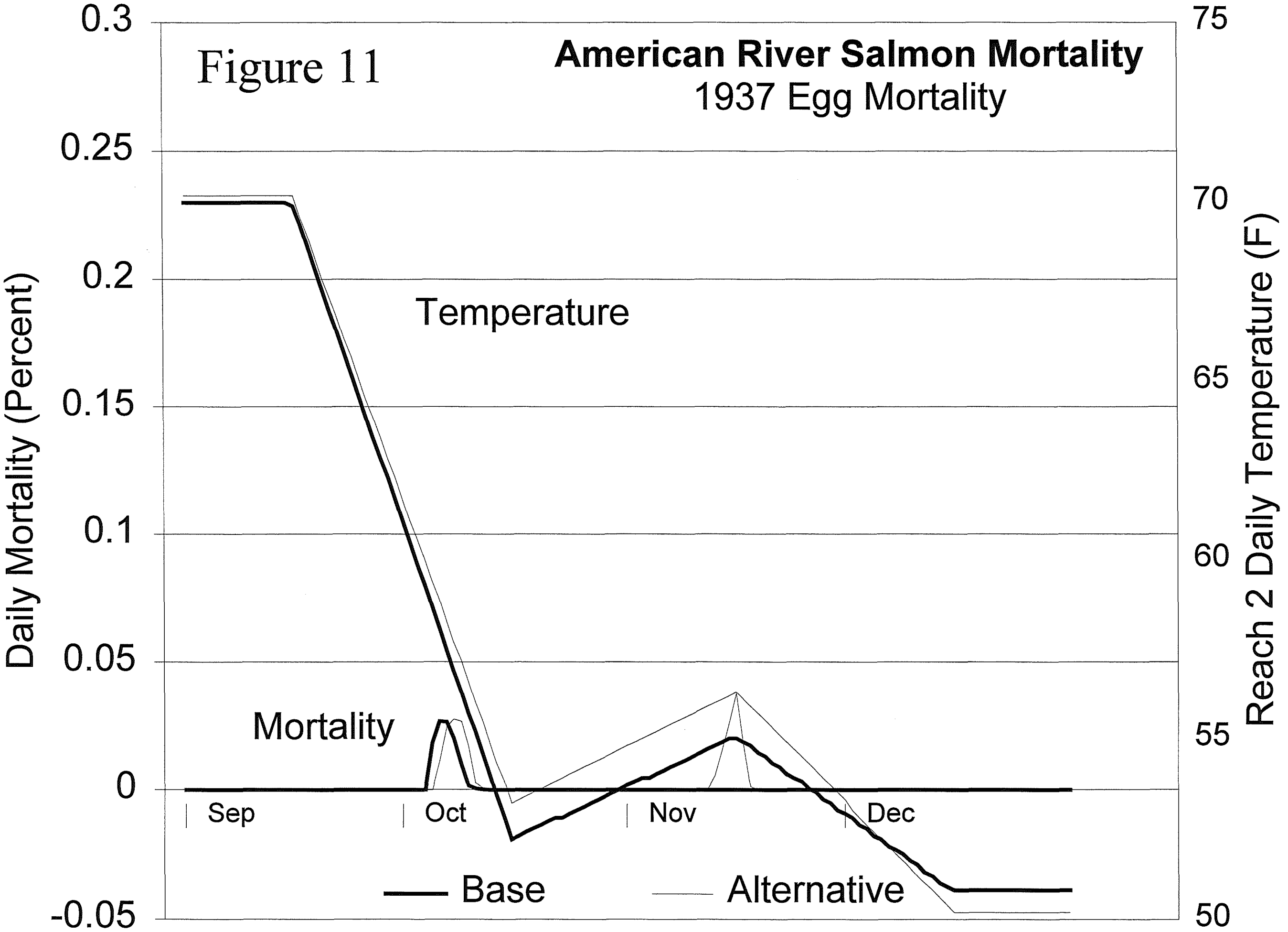


Figure 11
American River Salmon Mortality
1937 Egg Mortality
Daily Mortality (Percent)
Reach 2 Daily Temperature (F)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
75
70
65
60
55
50
Temperature
Mortality
Sep
Oct
Nov
Dec
Base
Alternative

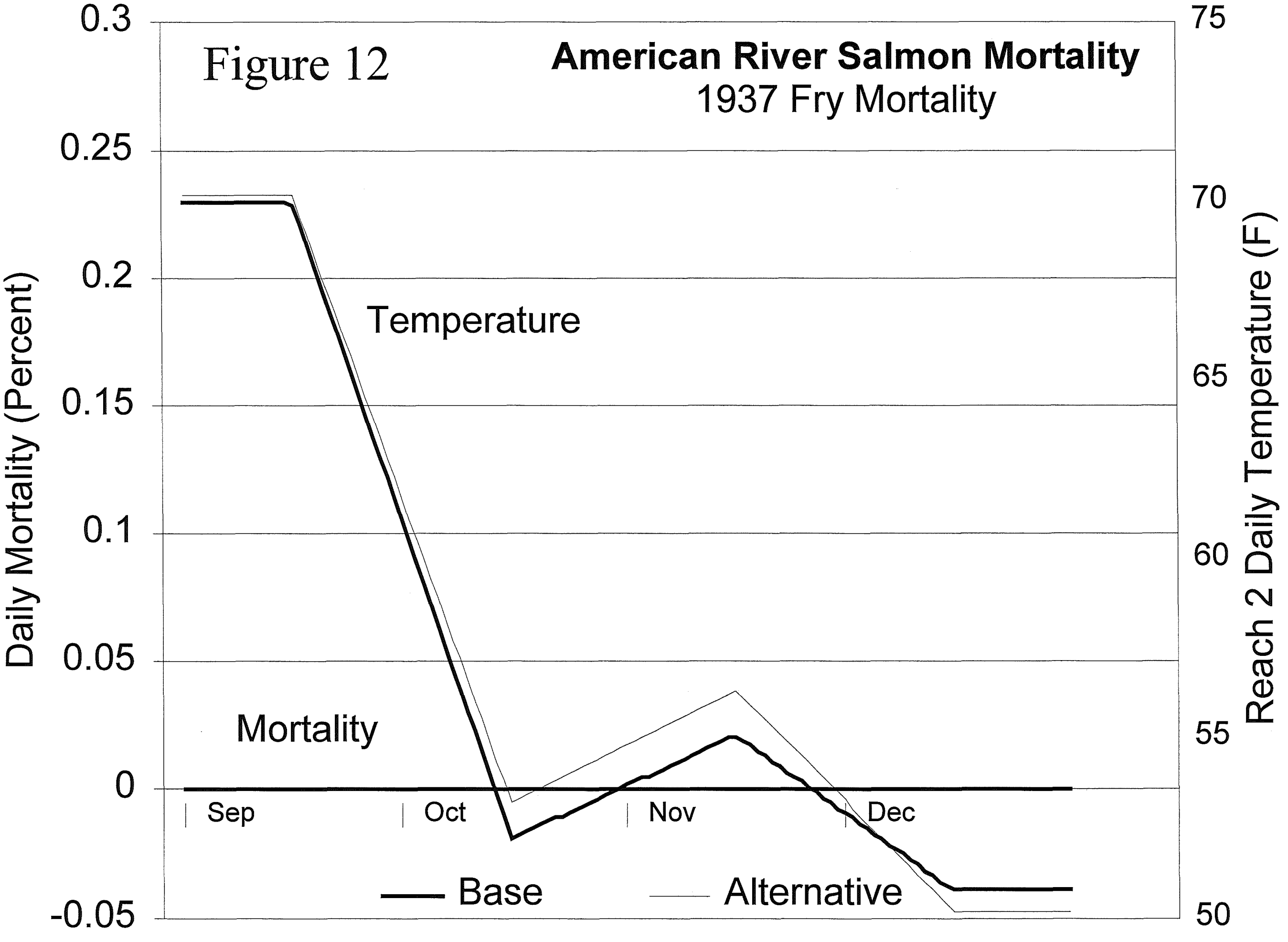


Figure 12
American River Salmon Mortality
1937 Fry Mortality
Daily Mortality (Percent)
Reach 2 Daily Temperature (F)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
75
70
65
60
55
50
Temperature
Mortality
Sep
Oct
Nov
Dec
Base
Alternative

they affect LAR salmon mortality model output; and 2) whether the current values being used are optimal for the modeling being performed.

The LAR salmon mortality model is a valuable tool for assessing the relative effects of alternative flow and water-diversion scenarios on the lower American River. However, as with any tool, its true utility is dependent upon its proper use. In order to assure that this tool is used appropriately, individuals using of LAR salmon mortality model output need to understand the following two important concepts.

First, there is inherent variation in the biological processes being modeled as well as variation (i.e., error of estimation) associated with each of the iterative modeling steps required to produce estimates of fall-run chinook salmon losses in the lower American River. Therefore, the early life-state losses that are output from this model have variation or "error" associated with them and, consequently, are most appropriately used for relative comparisons only. Chinook salmon early life-stage loss estimates should not be interpreted as actual, absolute values that would occur under the alternatives and conditions modeled.

Second, the LAR salmon mortality model estimates temperature-induced early life-stage losses only. Rates of overall cohort mortality (i.e., mortality from all factors between spawning and subsequent adult escapement three years later) would be much higher than those estimated by the LAR salmon mortality model. For example, based on the ocean return of chinook salmon from the same brood year - marked and released as both fry and smolts in the Sacramento River at Red Bluff - mortality from the fry to smolt life-stage ranged from 66-97% for the 1980-82 cohort (Healey 1991). From his review of the literature, Healey (1991) reported 80-100% mortality of chinook salmon occurs in North American rivers between the spawning and fry/smolt life stages. Add to this mortality the additional losses from numerous factors during emigration, estuarine residence, ocean residence, and immigration back to the natal river, and overall cohort mortality from egg potential to adult escapement three years later is likely to approach 100%. In other words, a small fraction of the egg potential for any given cohort actually survives to return to natal rivers as adults.

Because the LAR mortality model accounts for only temperature-induced losses from egg potential, and because the model calculates those losses only through the fry emergence life-stage, the model's loss estimates reflect only a component of the overall freshwater mortality that occurs between spawning and fry emergence, and only a fraction of the overall cohort mortality as well. Within this context, losses from about 5-20% output by the model for this exercise seem intuitively appropriate.

9. REFERENCES

Healey, M.C. 1991. Chinook Salmon (*Oncorhynchus tshawytscha*). Pages 311-393 *In* Groot, C. and L. Margolis (eds.). Pacific Salmon Life Histories. UBC Press, Vancouver, British Columbia. 564 p.

USBR (United States Bureau of Reclamation). 1991. Appendixes to Shasta outflow temperature control planning report/environmental statement. (Appendix A: modeling; Appendix B: part I - fisheries, Part II - recreation, Part III - cultural resources; Appendix C: design and cost estimates). United States Department of the Interior, Bureau of Reclamation, Mid-Pacific Region. November 1990, revised May 1991.