A MODELING STUDY OF CHANGES IN THE SACRAMENTO RIVER WINTER-RUN CHINOOK SALMON POPULATION DUE TO CLIMATE CHANGE

A Project

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Rosemarie Lingad Dimacali

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Abstract

of

A MODELING STUDY OF CHANGES IN THE SACRAMENTO RIVER WINTER-RUN CHINOOK SALMON POPULATION DUE TO CLIMATE CHANGE

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Rosemarie Lingad Dimacali

Sacramento River Winter-run Chinook Salmon (salmon) populations are declining and have been classified as an endangered species since 1994. Populations are sensitive to water temperatures and flow, both of which have changed due to hydraulic operations, and may continue to change in response to climate change.

The purpose of this study is to estimate changes in salmon populations in response to a hypothetical climate change scenario using computer models. For two hypothetical climate scenarios, flow data for California's water system have been simulated and made publicly available as part of Department of Water Resource’s 2011 State Water Project Delivery Reliability Report. The climate scenarios are: (1) historical climate conditions, and (2) medium-to-high emissions and air temperature changes (a 2050 level of development, A2 greenhouse gas level of emissions). For this study, DWR’s flow data, based on 80 years of historical hydrology, and the associated temperatures projected by the ECHAM-5 climate model were used to simulate water temperatures, salmon mortality rates, and salmon production in the upper Sacramento River between Keswick Dam and

Red Bluff Dam. The models used in this study -- the Sacramento River Water Quality Model (SRWQM) and the Salmonid Population Model (SALMOD) -- are the same models used by the U.S. Department of Interior Bureau of Reclamation (USBR).

SRWQM results show that climate change causes a 3°F increase in maximum water temperatures. SALMOD results show water temperature changes affect the salmon population significantly more than flow. In typical years, calculated salmon mortalities were not changed significantly by climate change (CC). In contrast, when conditions were unfavorable, salmon mortalities were substantially higher under the CC scenario and these unfavorable conditions happened with greater frequency.

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1. INTRODUCTION

The purpose of this study is to estimate, using computer models, changes in salmon populations in response to a hypothetical climate change. The prediction for global and regional climate change is an increase in temperatures (DWR, 2012). The California Department of Water Resources (DWR) Climate Action Team, along with scientists from the California-Nevada Applications Program and California Climate Change Center funded by the National Oceanic Atmospheric Administration and the California Energy Commission, used six global climate models to simulate climate projections for two greenhouse gas emissions scenarios in the Sacramento region. The projections suggest that by the middle of the twenty-first century air temperatures will increase by an average of 1.3 to 4.0 degrees Fahrenheit (°F) in the Sacramento River region (CCCC, 2009). This air temperature increase has the potential to affect the salmon spawning habitat in the upper Sacramento River. Successful salmon production and survival depend on water temperature, and river flows in the appropriate ranges.

As part of its planning of future water transfers by State Water Project facilities, DWR has simulated California's water system under two hypothetical future climate scenarios (DWR, 2012). One climate scenario assumes that the future climate will reflect historical hydrologic observations, which hereafter will be referred to as the “no climate change” (noCC) scenario. The other climate scenario assumes that the future climate will reflect higher air temperatures due to higher greenhouse gas emissions. This will be referred to as the “climate change” (CC) scenario. For this study, the flows created by DWR under the noCC and CC scenarios, as well as the climate data on which these flows are based, were used as inputs to the Sacramento River Water Quality Model (SRWQM), developed by the U.S. Department of Interior, Bureau of Reclamation (USBR) and the U.S Army Corps of Engineers, to estimate future water temperatures. These water temperature results and flows were then used as inputs to SALMOD, the Salmonid Population Model developed by the U.S. Geological Survey, to study potential changes in salmon populations in a particular stretch of the Sacramento River between Keswick Dam and the decommissioned Red Bluff Diversion Dam (Red Bluff Dam). Finally, the resulting salmon mortality rates for the noCC and CC scenarios are compared to the so-called “No Action” and the “baseline” rates published in USBR’s 2011 Shasta Lake Water Resources Investigation and 2008 Biological Assessment on the Continued Long-term Operations of the Central Valley Project and the State Water Project, known as OCAP, respectively (USBR, 2011 and USBR, 2008)[1].

In the present report, the study location, salmon lifecycle stages, and spawning, rearing, and habitat requirements are discussed in the Background chapter. Also in the Background are descriptions of the various models associated with this study. Following that, the Methodology chapter describes the SRWQM and SALMOD in greater detail and describes how the noCC and CC flow and air temperature data were used to simulate water temperatures and salmon populations. Output from the water temperature and salmon population models are presented in the Results chapter. These results are analyzed in the Discussion chapter, followed by conclusions.

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[1] This acronym stems from a previous version of the document entitled “Central Valley Operations Criteria and Plan”, which was updated and renamed, but is still referred to as OCAP.

2. BACKGROUND

This chapter provides information about the location of the study, factors affecting salmon health and survival, and the models used.

2.1 Location of Study

Historically, winter-run Chinook salmon spawned in California's most northern rivers and creeks: Pit River, McCloud River, Battle Creek, and Hat Creek. These rivers and creeks terminate at their confluences with the Sacramento River. When the eggs hatched and the young salmon were ready to migrate they traveled downstream in the Sacramento River past Shasta Lake, through California’s northern Central Valley, Redding, Sacramento, and the San Francisco Bay-Delta, into the San Francisco Bay proper, and from there out to the Pacific Ocean where they become adults. Construction of Shasta Dam, Keswick Dam outside Redding, and Red Bluff Dam on the upper Sacramento River (see Figure 1) has prevented migration of salmon to their historic spawning areas. The completion of the Red Bluff Dam across the Sacramento River provided a location at which the sizes of the annual salmon spawning runs can be estimated from fish counts (Botsford et al., 1998). For this reason, the location of this study is the Sacramento River between Keswick Dam and Red Bluff Dam.

Figure 1. Location of Shasta Dam, Keswick Dam and Red Bluff Dam.

2.2 Sacramento River Winter-run Chinook Salmon

Sacramento River Winter-run Chinook salmon are a portion of the Pacific salmon population. Of the Pacific salmon population, Chinook salmon are smallest in numbers, but are the largest in size. On average, adult Chinook salmon weigh 40 pounds and are 3 feet in length. Chinook salmon are an anadromous species (living in both freshwater and saltwater), that live between 2 to 6 years (NOAA, n.d.). Salmon lifecycle stages, spawning and habitat requirements, and population trends are described below and illustrated in Figure 2.

Adult Chinook salmon migrate upstream from saltwater to freshwater in the winter (hence the name winter-run) or in the early spring to their holding or spawning grounds, where water temperatures are cooler. (“Holding” refers to the time between migration and spawning.) In May or June, salmon spawn in streambeds and deposit their eggs in the gravel. Immediately after spawning, adult Chinook salmon die (Botsford et al., 1998). Rearing occurs when salmon fry emerge from their eggs in the gravel and continue to grow from June or July to October. Young salmon start migrating in July, peaking in September and pass the Red Bluff Dam by October. Fry then become smolt and arrive at the Delta by March. They stay there until they reach 5 to 10 months of age to adjust from freshwater to saltwater. Juveniles emigrate to the ocean from November to May, mature in the ocean, and return after 2 to 6 years, with the majority returning after 3 years (NMFS, 2009).

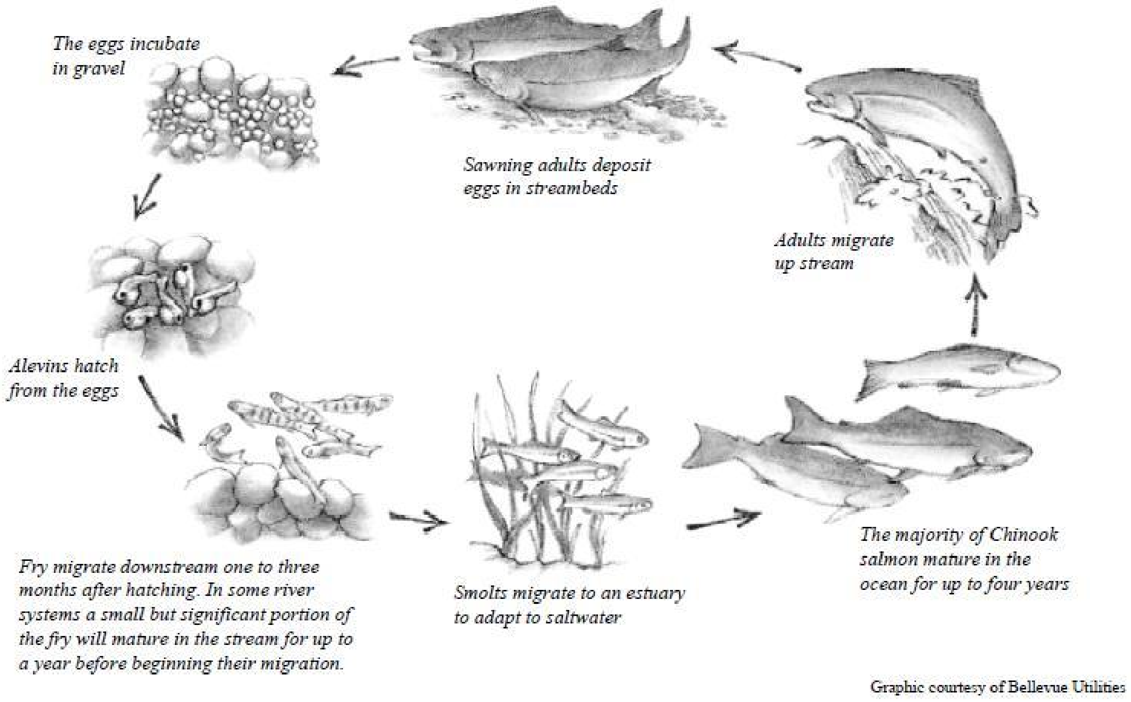

Figure 2. Chinook Salmon Life Cycle (Friends of the Marsh Creek Watershed, n.d.).

At different times of the year, certain water velocities and temperatures are required for successful migration, holding, and spawning. The ideal conditions are summarized in

Table 1. For salmon to migrate, the ideal velocity is 8 feet per second (ft/s) at a depth greater than 8 feet (Thompson, 1972 as cited by NMFS, 2009), and 57 to 67°F (NMFS, 1997). When holding, velocities should be 0.5 to 1.3 ft/s in deep pools (DWR, 2000a) at 59 to 60°F (NMFS, 1997). Successful spawning occurs at velocities ranging from 0.98 ft/s to 2.6 ft/s at depths between a few centimeters and several meters (Moyle, 2002 as cited by NMFS, 2009) or 1.54 to 4.10 ft/s at a depth between 1.4 and 10.1 feet (USFWS, 2003 as cited by NMFS, 2009) at 50°F to 59°F (NMFS, 1997). These velocities and water temperatures affect the success of the migration, holding, and spawning processes, which in turn affects the overall survival of the entire salmon population.

Table 1. Ideal environmental conditions for different salmon life stages

	Migration	Holding	Spawning	Reference
Velocity, ft/s	<8	0.5 – 1.3	0.98 – 2.6 1.54 – 4.10	NMFS, 2009 DWR, 2000a
Depth, ft or meters	>8 ft	deep	cm to meters, or 1.4 – 10.1 ft	NMFS, 2009 DWR, 2000a
Temperature, °F	57 – 67	59 – 60	50 – 59	NMFS, 1997

There was once an abundance of winter-run Chinook salmon in the Sacramento River. Between 1872 and 1896, historical accounts report 180,000 to 300,000 adults (Botsford et al, 1998). When the Red Bluff Dam was constructed in 1967, the California Department of Fish and Game began estimating numbers of salmon adults annually as they migrated upstream to spawn. Between 1967 and the end of the twentieth century estimated populations declined from a high of 118 million in 1969 to a low of 0.191 million in 1991.

From 2000 to 2010, there was a slight increase. The 2010 count was 1,533 adults. Still, these numbers are nowhere near historical values. Population data from 1967 to 2010 are shown in Figure 3.

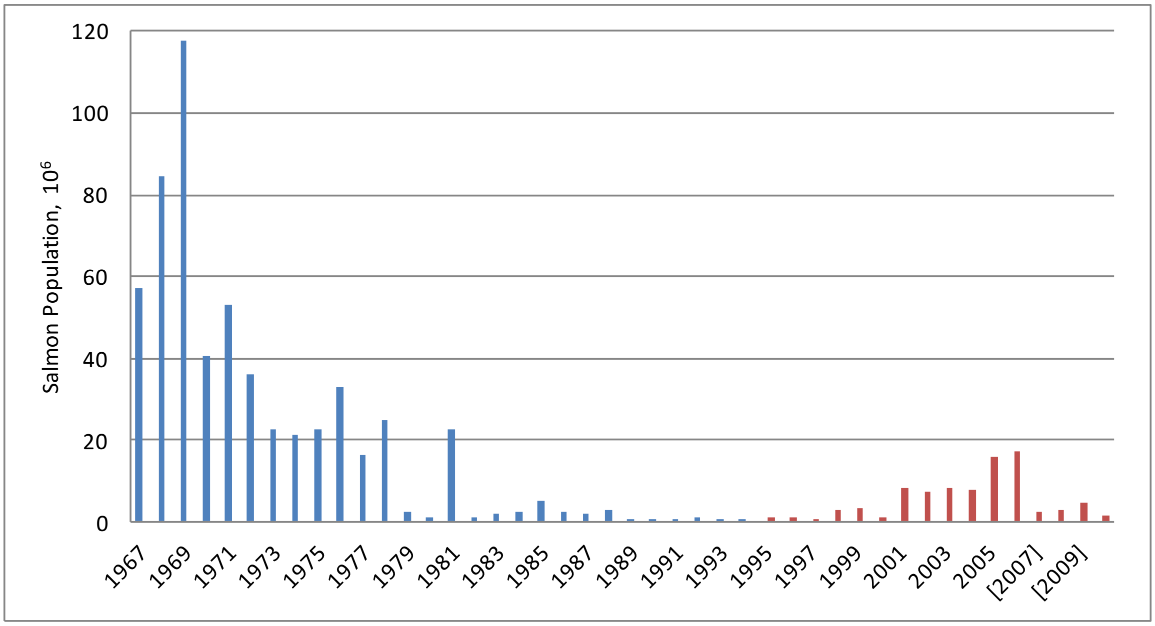

Figure 3. Salmon population estimates at Red Bluff Dam (CDFW, 2009; NMFS, 2011).

In the 1800's, commercial harvesting, hydraulic gold mining, mining flumes and canals, and the use of hydraulic cannons, which disturbed habitat and spawning grounds, were early factors in the decline of salmon numbers (Lufkin, 1996). In the late 1800's and early 1900's, additional disruptive factors included the construction of levees, dams, and other water diversions, which blocked spawning grounds, destroyed habitats, and increased water pollution and water temperatures (Lufkin, 1996). Major water project facilities in the 1900's, such as Shasta Dam, contributed further to the decline of the salmon (USFWS, 2001).

Because of the significant population decline, in 1989 the Sacramento Winter-run Chinook salmon were listed as a threatened species, and then in 1994 were reclassified as an endangered species under the Endangered Species Act (ESA) of 1973 (NMFS, 2011). An endangered species is defined as a species that is in danger of extinction throughout all or a significant portion of its range and a threatened species is a species that is likely to become endangered (Listing of Endangered and Threatened Species and Designating Critical Habitat, 2006). Reviews for species listed under the ESA as threatened or endangered occur every five years to determine if the species needs to be reclassified or removed from the list. In the last 5-year review for the salmon in 2011, NOAA's National Marine Fisheries Service (NMFS), who has jurisdictional authority over anadromous and marine species, concluded that the salmon should remain classified as endangered (NMFS, 2011). Accordingly, NMFS has been required to publish a recovery plan every five years, which specifies recovery goals as well as management actions, and an estimated schedule and cost to meet those goals (NOAA, 2012).

In addition to legal requirements under the ESA, water managers must consider that fish and wildlife mitigation and enhancement were added to the legal purposes of the federal Central Valley Project (CVP) in the Central Valley Project Improvement Act of 1992. The operations of the CVP, the largest water transfer project in California, affects flow and temperature in the Sacramento River between Keswick Dam and Red Bluff Dam, where salmon migrate to spawn and rear. The CVP operates hydraulic facilities for river regulation, navigation, flood control, and delivery to water users throughout California.

Prior to 1992, the list of project purposes did not include mitigating the effects of CVP operations on the migration, holding, and spawning of the salmon.

The construction of Shasta Dam, a CVP facility, blocked the cold water from the higher elevations upstream, which raised the water temperatures in the Sacramento River downstream. To alleviate this problem, the Shasta Temperature Control Device (TCD) was built in 1997 to regulate river temperatures downstream from the late summer to the early fall, which is the critical time and location for salmon to spawn and rear. To meet water objectives the TCD allows coldwater withdrawal from the reservoir at various depths via steel shutters attached to the face of the dam.

Current mitigation and enhancement measures may not, however, be suitable for a warmer future. According to DWR's 2011 State Water Project Delivery Reliability Report, the forecasted future climate includes an increase in average air temperatures (DWR, 2012). As a result, the amount of water stored as snow pack is expected to decrease, since more rain will fall instead of snow and more snow will melt instead of accumulate. Warmer air temperatures will also result in lower storage levels in reservoirs because water releases from reservoirs will need to be more frequent to meet increased demands for municipal, and agricultural demands, and environmental needs such as fish survival. In addition, water temperatures are expected to increase because the coldwater pools will deplete because of lesser snowmelt and reservoirs being drawn down by increased releases. A study on seasonal temperature and flow in the upper Sacramento River was performed by Yates, et al (2008) using a computer model, the Water Evaluation and Planning Decision Support System Version 21. Yates' study concluded that even with technologies such as the Shasta

TCD, air temperature increases higher than four degrees Celsius (39.2°F) make the coldwater pool for the Chinook salmon more difficult to maintain for the salmon spawning habitat below Keswick Dam.

2.3 Water Planning Models

Models are an important tool for projecting the effects of climate change, flow, and water temperature on the salmon population. For this study, results from ECHAM-5, a global climate model, were used in Cal-SIM, a water operation-planning model. Results from both models were input into the Sacramento River Water Quality Model (SRWQM) to determine water temperatures, and SALMOD, the salmon population model to determine salmon mortality rates. USBR used SRWQM and SALMOD in studies for USBR's OCAP and SLWRI (USBR, 2008 and USBR, 2011). The similarities between these USBR studies and the current study will be described in the Methodology chapter. Brief descriptions of the physics and hydraulics of each model are presented below.

2.3.1 ECHAM-5

The global climate model, ECHAM-5, created by the Max Planck Institute of Meteorology, simulates atmospheric climate processes and projects temperatures based on different greenhouse gas emission scenarios. According to the Program for Climate Model Diagnosis and Intercomparison website funded by the U.S Department of Energy, Office of Science (2005), the model consists of adiabatic and diabatic fluid dynamics, and large-scale tracer transport algorithms, which consider cloud cover, convection, boundary layer effects, short wave and long wave radiation, and gravity wave drag processes. These algorithms are based on the atmosphere acting as a fluid (Giorgetta n.d.). The governing equations are the fluid momentum, thermodynamic, and moisture equations (Roeckner et al, 2003). ECHAM-5 was not run specifically for this study, but results from ECHAM-5 projections are available on the Bias Corrected and Downscaled Climate and Hydrology Projections website created through the collaborative work of several agencies (J. Anderson, personal communication, 2012, November 14 and USBR, 2013).

2.3.2 Cal-SIM II

The water operations planning model, Cal-SIM II, created by DWR and USBR, simulates water operations in California and calculates average monthly flows based on historical hydrology, scheduled reservoir releases, and California's water demand. Continuity equations ensure mass balance between reservoirs. Linear equations are used to calculate return flows and evaporation, and to prioritize water transfers. Boundaries and constraints are used to model storage, channel capacities, minimum instream flows, deliveries, reservoir releases, and non-recoverable spills (DWR, 2000b). Flow results from Cal-SIM II for DWR's 2011 Delivery Reliability Report includes reservoir storage volumes and flows for California's waterways for 82 hydrologic years based on noCC and CC conditions (DWR, 2012).

2.3.3 SRWQM –HEC-5Q

The Sacramento River Water Quality Model (SRWQM) originated from another water quality model, HEC-5Q, created by the U.S. Army Corps of Engineers Hydraulic Engineering Center (HEC) (USACE, 1986). In creating SRWQM, the USBR adapted HEC-5Q for the upper Sacramento River. The model includes simplified heat exchange equations, which use meteorological data and flow data from specific stream reaches to calculate water temperatures. Stream reaches are divided into plug flow fluid elements where flows do not pass into or out of each element and diffusion is zero. A differential equation models the heat dynamics within each element based on the principle of energy conservation. Heat sources and sinks for each fluid element that are expressed in the differential equation, include heat transfer due to radiation, conduction, and evaporation. The rate at which heat transfers is calculated using an equilibrium temperature, a coefficient of heat exchange, and the surface water temperature (USACE, 1986).

Given monthly flows and 6-hour meteorological data for the upper Sacramento River, SRWQM simulates average daily water temperatures from Keswick Dam to just upstream of the Red Bluff Dam, an approximately 85-mile reach. These temperatures are influenced by the water released through the temperature control device at Shasta Dam. These water releases are based on water storage available in Shasta Lake at the end of May, and provides an indication of how to manage the available coldwater pool. Depending on the storage volume at the end of May, the temperature control device will allow seasonal releases of cold water to the Sacramento River to reach seasonal target temperatures. For the current study, SRWQM was run using the water release schedule documented by USBR in the OCAP study (USBR, 2008). Since the same version of the SRWQM that was used in the OCAP study is used in the current study, the assumptions used to run the SRWQM are the same, as presented in the Discussion Chapter.

2.3.4 SALMOD

The U.S. Geological Survey developed the salmon population model, SALMOD, which was then adapted for the upper Sacramento River by USBR. SALMOD simulates anadromous or resident salmon populations on a weekly time step. In SALMOD, egg and fish mortality calculations are dependent on a variety of variables (e.g. entrainment, predation, disease, etc.) but the two of interest in this study are the available space and temperature of the habitat, both of which depend on flow and meteorological data (Bartholow et al., 2002). The model's methodical structure is based on an Instream Flow Incremental Methodology, in which problems are identified and then variables are specified, gathered, utilized, and analyzed (Anderson, 2000). The input variables and parameters required for SALMOD include water temperature, stream flow, and mesohabitat and microhabitat characteristics, as well as salmon biological characteristics, such as length and weight for development and the potential for reproduction.

In SALMOD, salmon populations are calculated over time along a specified reach by modeling salmon lifecycle processes, such as spawning, egg development and juvenile growth, movement, and associated mortality. Spawning numbers are dependent on spawner characteristic inputs, such a male-to-female ratio, egg-to-spawning-female ratios, redd area (where the salmon lay their eggs), superimposition constraints (different salmon cannot use the same redd area in the same week), and the spatial and temporal distribution of spawners. The number of eggs developed is based on a rate function, where rapid egg maturation occurs at 50°F. Alevin, or hatchlings, are specified to emerge at a minimum temperature of 42.8°F, at a weight of 0.275 grams, and at a length of 34 ± 4 mm. Juveniles, such as fry, grow at a rate dependent on mean weekly water temperatures. They move downstream as habitats become more impacted, signified by a habitat density constraint, or die because there is not enough usable area for all of the fish to inhabit at the same time.

Flow is a factor influencing mortality in this case because flow determines the volume of water in the river, which in turn establishes the usable or habitable area. In the model, fish also move through the stream based on time periods inputted into the model. Salmon production and mortality are tracked by life stage, such as egg, in vivo eggs (eggs inside of the female), juvenile, and adult according to the equations shown in Table 2. These mortality rate equations are described in more detail in Chapter 5 of USBR's SLWRI Modeling Appendix (USBR 2011).

As noted above, USBR adapted SALMOD for Chinook salmon in the upper Sacramento River. This version of the model was obtained from USBR to be used for this study. Sacramento River channel characteristics were obtained from USBR, as well as a male-to-female ratio, egg-to-spawning-female ratios, redd areas, and flow-to-habitat ratios (USBR, 2011). More information regarding the version of SALMOD used in this study can be found in Chapter 5 of USBR's SLWRI Modeling Appendix (USBR 2011). Flow and temperature values, calculated by SRWQM, were automatically converted to 7-day average values because SALMOD requires weekly flow and temperature data. SALMOD uses weekly data because the 7-day mortality rates used in SALMOD reflect both acute and long-term exposure effects.

Table 2. Mortality Rate Equations

Life Stage	Mortality Rate Equation
Egg Thermal	$M = 1 - (1 - M_n)^{1/n}$ where, n = number of days in the reference period M_n = mean weekly mortality rates as a function of mean daily water temperatures (calculated values are available in Table 5-10 of USBR, 2011).
In Vivo Egg	Same as the Egg Thermal Mortality rate equation (above)
Juvenile and Adult	$Survival\ rate = \frac{1}{1 + e^{-a-bT}}$ Where, a = 15.56 b = -0.6765 T = mean daily water temperature for the sampling period, °F

Source: USBR, 2011

3. METHODOLOGY

In this chapter, how previously simulated flow data and associated climate data were used to model water temperatures and salmon populations is presented. Climate data and flow data for both noCC and CC scenarios are also presented. Water temperature and salmon population results are presented in the next chapter.

The procedure used in USBR's OCAP study to estimate salmon populations was emulated in the current study in how the SRWQM and SALMOD were used (USBR, 2008). The current study is based on air temperature from ECHAM-5, which was not used in the OCAP study, and flow outputs from Cal-SIM II, also based on ECHAM-5 results, to calculate water temperatures in SRWQM (USBR, 2008). The flows and water temperatures were then used as inputs in SALMOD to estimate salmon populations. The difference between USBR's OCAP study and the current study are the flow outputs from Cal-SIM II and the meteorological data used as CC inputs into the SRWQM, which include equilibrium temperatures and heat exchange rates.

The interaction between the models can best be described with Figure 4. The boxes in bold indicate the results generated in this study. The boxes enclosed by the dashed lines indicate results that were generated by others. A location and an emissions scenario were required to retrieve average monthly air temperatures simulated by the ECHAM-5 model. The climate data, including air temperatures, were applied to DWR's CalSIM II model to determine average monthly flows, which were already simulated as part of DWR's 2011 Delivery Reliability Report (2012). For the current study, the noCC meteorological data set and the SRWQM were obtained from USBR. The ECHAM-5 air temperatures were used to adjust the noCC 6-hour meteorological data to create the CC 6-hour meteorological data. Both the meteorological data and flow data were used in the SRWQM, which calculated average daily water temperatures. SRWQM produced weekly average flows and water temperatures, which is the time series required by SALMOD. More detailed descriptions of the assumptions and the applications of each model are presented below.

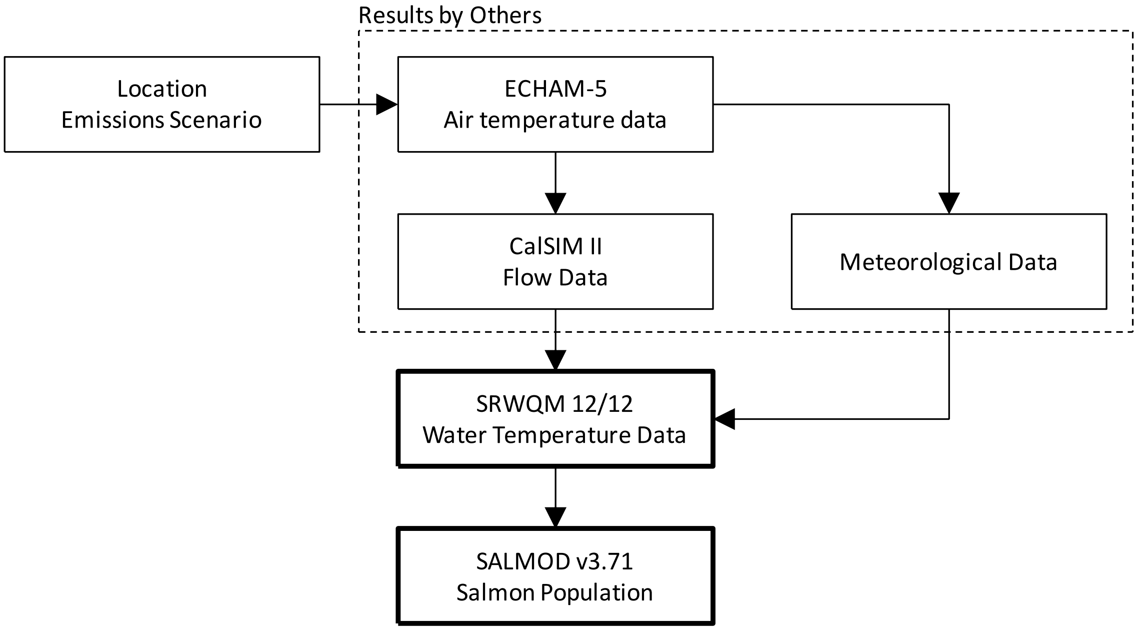

Figure 4. Model interactions.

3.1 Climate Information

The climate information was generated by others. To project, or generate hypothetical flows in California's water system over time, two hypothetical climate scenarios were chosen by DWR as part of its 2011 State Water Project Delivery Reliability Report projecting to a 2050 level of development (DWR, 2012). The simulated climate information was generated using ECHAM-5 but the actual values used by DWR were obtained from the multi-agency website described earlier. On the website are options for retrieving observed climate data and projected climate data under different emissions scenarios. The scenario chosen by DWR was the A2 greenhouse gas level of emission, which is a scenario that represents a future, with high population growth, and slow economic and technologic development. Compared to other climate scenarios A2 is considered a medium-to-high emissions scenario with medium-to-high air temperature changes relative to California's current annual average temperatures (CCCC, 2006).

The climate data sets obtained from the website described earlier for the noCC and CC scenarios were monthly air temperatures at the Gerber station, near Red Bluff[2]. Air temperature data for the noCC scenario were available for 50 years from 1950 to 1999, and CC air temperatures were projected for 150 years from 1950 to 2099 by the ECHAM-5 climate model. To calculate a set of monthly average air temperature changes that can be used later in SRQWM, the recommendations contained in the Guide to Climatological Practices (Guide) by the World Meteorological Organization (2010), were followed with some modifications.. In the current study, for the noCC scenario, or observed scenario, the period in which the average observed air temperatures are determined, differ from that specified in the Guide, which suggests a 30-year averaging period beginning in January in a year ending in "1" (e.g. 1971, 2001, 2031, etc.). (The reference period of 30 years was chosen because at the time this method was created, there were only 30 years of data available.) For the current study, however, 30 years from the most recent current

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[2] The multi-agency website from which the climate data set was obtained refers to the noCC or historical data as "observed" and the CC data as "projected".

observed data is 1970. Therefore, the period of reference chosen for the noCC scenario was 1970 to 1999. The period of reference for the CC, or projected, air temperatures was chosen so that the 2050 level of development was at the center of a 30-year distribution, 15 years prior to 2050 and 15 year after 2050, or 2035 to 2064. To determine the change in air temperature from the noCC scenario to the CC scenario, monthly air temperature data from the noCC scenario, from 1970 to 1999, were subtracted from monthly air temperatures from the CC scenario, from 2035 to 2064. For example, the 1970 and 1999 average January air temperature was subtracted from the 2035-2064 average air temperature for January. Figure 5 depicts the periods of reference used to determine the air temperature change.

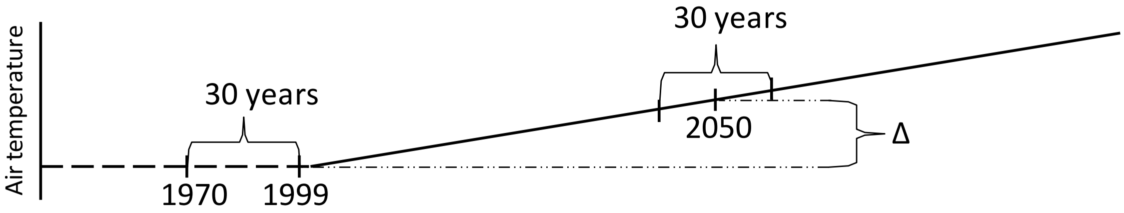

Figure 5. Periods of reference for air temperature change.

Box plots illustrating statistical values for the noCC (1970 to 1999) and CC (2035 to 2064) air temperature data are shown in Figure 6 and Figure 7. The minimum (bottom whisker) and maximum (top whisker) monthly air temperatures are 40.5° and 86.3°F, respectively, for the noCC scenario and 41.5° and 89.2°F, respectively, for the CC scenario. The box encompasses the 25th to 75th percentile range, with the lines showing the medians. Averages, minimums, maximums, and percentiles of the 30-year periods for the noCC and CC scenarios and their differences are shown in Table 3. These differences closely resemble the air temperature changes described in DWR's 2011 Delivery Reliability Report, which are 1.3 to 4 degrees Fahrenheit.

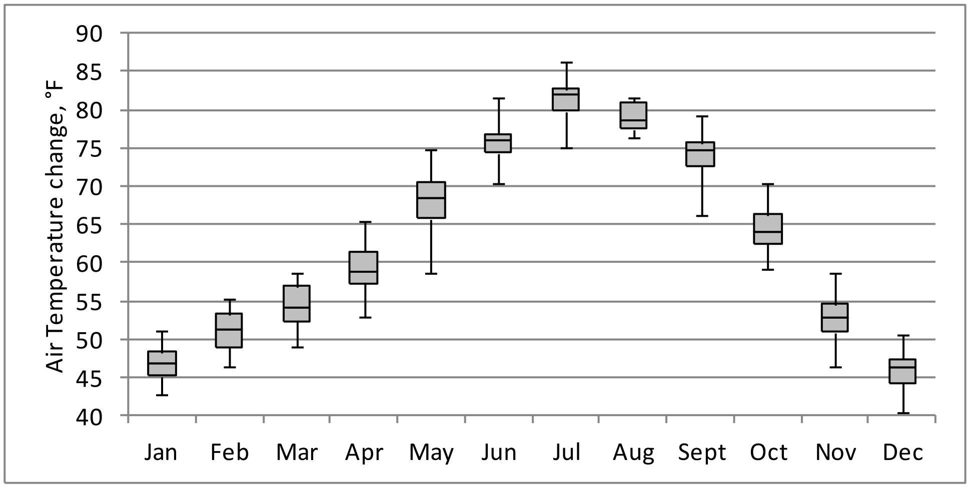

Figure 6. Box and whisker plot of monthly noCC air temperatures, 1950-1999.

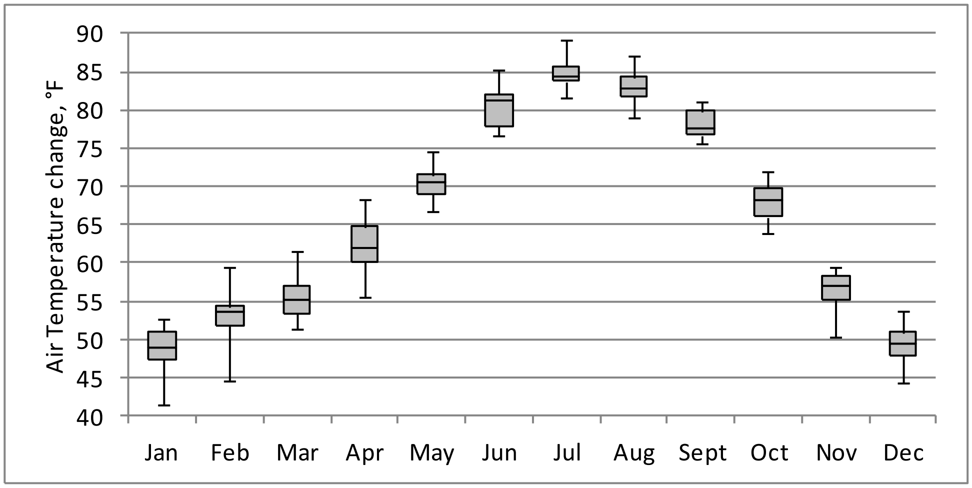

Figure 7. Box and whisker plot of monthly CC air temperatures, 2035-2064.

Table 3. Air temperature data for the noCC and CC scenarios, °F

	Average	Minimum	25th Percentile	Median	75th Percentile	Maximum
noCC (1970-1999)	62.8	40.5	51.4	62.0	75.1	86.3
CC (2035-2064)	65.9	41.5	53.9	66.0	79.0	89.2
Difference	3.1	1.1	2.5	4.0	3.9	2.9

Monthly averages and percent differences between the noCC and CC are shown in Table 4. The smallest difference between the noCC and CC air temperatures is 0.96°F in March. The largest difference between the noCC and CC air temperatures is 4.78°F in June. The difference between these monthly values and the ones shown in Table 3 is that Table 3 shows data over each of the 30-year periods. The percent differences shown in Table 4 are monthly and were used to create the CC equilibrium temperatures data for inputs into the SRWQM, as discussed later in this chapter.

Table 4. Average air temperatures for the noCC (1970-1999) and CC (2035-2064) scenarios, °F

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
noCC	46.8	51.1	54.5	59.5	68.1	75.8	81.3	79.1	74.2	64.5	52.6	46.1
CC	48.8	53.1	55.5	62.4	70.4	80.6	84.9	83.1	78.1	68.1	56.5	49.4
Δ	1.97	2.02	0.96	2.86	2.35	4.78	3.56	3.97	3.85	3.59	3.88	3.34
% Δ	4.21	3.96	1.77	4.81	3.45	6.30	4.38	5.01	5.19	5.55	7.36	7.25

3.2 Flow Data

The flow data were generated by others. Monthly flows outputted from CalSIM for the two alternatives were generated by DWR for the 2011 Delivery Reliability Report. DWR applied hydraulic operations rules, which meet water demand and biological requirements set by the NMFS biological opinions, and 82 years of hydrologic data to project river flow rates for the noCC and CC scenarios. The 82 years of hydrology used for the noCC scenario are reflective of hydrologic conditions from water years 1921 to 2003, chosen to reflect infrequent, but extreme droughts that California has been known to experience. For the CC scenario, the historic rainfall, runoff, and snowmelt record were used and Cal-SIM used demand calculations and ECHAM-5 average monthly temperatures to allocate flows. For both scenarios, flow rates reflect the assumption that all waterway infrastructure projects currently in progress are completed and operational.

Sacramento River monthly flows changed only slightly as a result of the hypothetical projected climate change scenario. Box plots showing statistical data for the noCC and CC monthly average flows, calculated from daily average flows from SRWQM, as previously described in the Background Chapter, from 1921 to 2003 are shown in Figure 8 and Figure 9. The box indicates the 25th to 75th percentile range, with the line showing the median for each month. Notice the large range in flows. The minimum (bottom whisker) and maximum (top whisker) for the noCC scenario are 2,349 and 84,132 cfs, respectively. The minimum and maximum daily average river flows for the CC scenario are 3,631, and 96,991 cfs, respectively. Averages, minimums, maximums, and percentiles of the 82-year period for the noCC and CC scenarios and their differences are shown in Table 5. Notice that while the maximum flows of the two scenarios change significantly, especially in the winter, median flows do not.

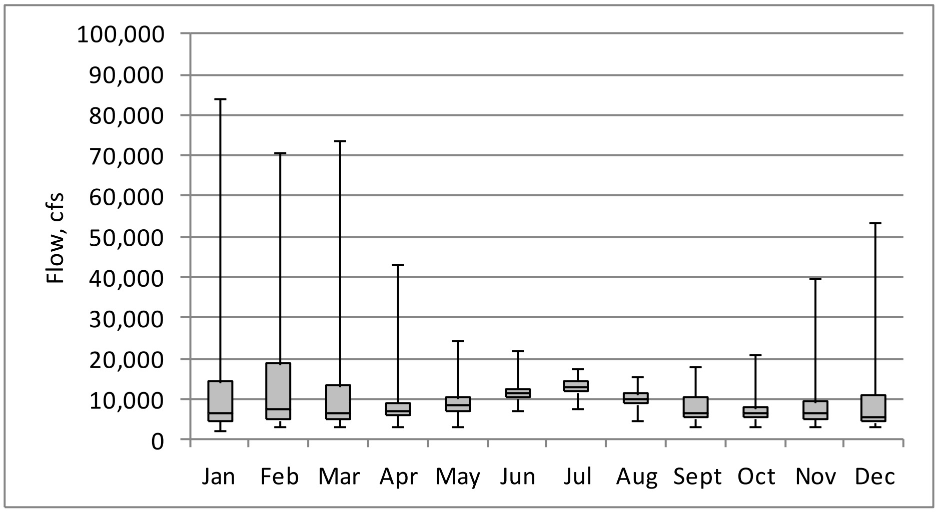

Figure 8. Box and whisker plot of monthly noCC flows based on historical hydrology from 1921 to 2003.

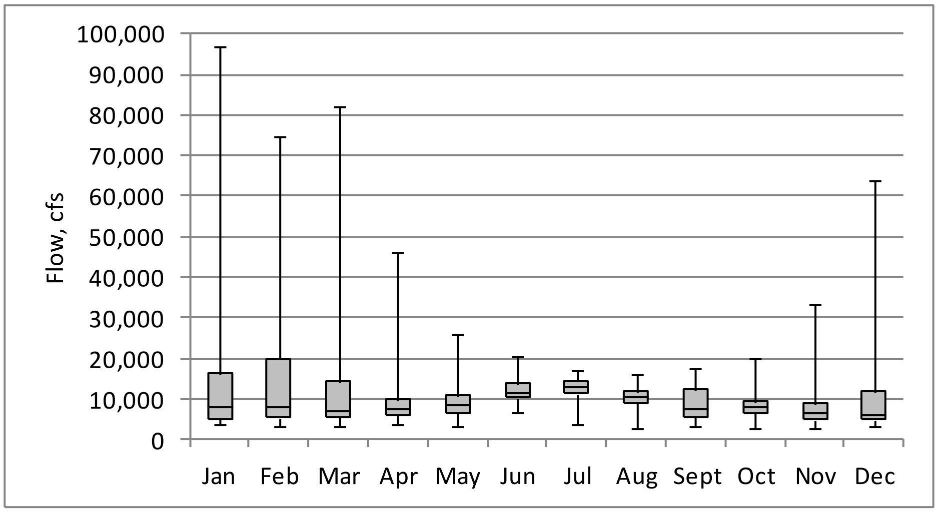

Figure 9. Box and whisker plot of monthly CC flows based on historical hydrology from 1921 to 2003.

Table 5. Daily flows based on 82-year model results, cfs

	Average	Minimum	25th Percentile	Median	75th Percentile	Maximum
noCC	10,048	2,349	4,590	6,681	14,210	84,132
CC	10,634	2,847	6,117	8,869	12,395	96,991
Difference	586	498	1,526	2,188	-1,815	12,860

3.3 Water Temperature Calculations

In the current study, Sacramento River water temperatures under the two climate scenarios were determined using SRWQM. A version of the model with meteorological data, which is specified in the SRWQM as equilibrium temperatures, heat exchange rates, short wave radiation, and wind speed, and stream geometry for the noCC scenario was obtained from USBR. For the current study, the stream geometry was assumed to be the same for both scenarios. The input flow values, provided with the model from USBR, were replaced for both the noCC and CC scenarios with the flows from Cal-SIM II for DWR's 2011 report based on the ECHAM-5 runs. For the noCC scenario, the USBR-supplied meteorological data were used under the assumption that these were the same conditions used for DWR's 2011 study. In HEC-5Q, the model underlying the SRWQM, a separate module is used to calculate meteorological data. This module was not accessible in the version of the model used in this study, so the following approach was taken to estimate the heat transfer rate in order to calculate water temperatures in SRWQM.

There are four meteorological variables in the SRWQM: short wave solar radiation, wind speed, equilibrium temperature, and heat exchange rate. Short wave radiation and wind speed were assumed to remain the same for both the noCC and CC scenarios. Short wave radiation is dependent on the atmospheric ozone, suspended particulate matter, and water vapor. Although water vapor will be affected by air temperature and will be different under the CC scenario, the effect of this change on the heat balance was assumed to be negligible. Wind speed is dependent on air pressure and air pressure is dependent on air temperature. While wind speeds under the CC scenario may be different than those under the noCC scenario due to the interactions of high and low pressure zones in the atmosphere, wind speed is used in the SRWQM only to calculate effective diffusion, or a combination of molecular and turbulent diffusion, in analyzing water quality and water temperature in reservoirs. In streams, SRWQM assumes that diffusion is zero, so changes in wind speed will not affect the calculation of river temperatures (USACE, 1998).

In the current study, it is assumed that equilibrium temperatures would increase as air temperatures increase. This assumption is based on the net rate heat transfer equation, which is the product of the coefficient of surface heat exchange and the difference between the equilibrium temperature and the surface water temperature, as shown in Equation 1 (USACE, 1986):

$$H_n = K_e (T_e - T_s) \tag{1}$$

where H_n = net rate of heat transfer in BTU/day-ft^2

K_e = coefficient of surface heat exchange in BTU/day-ft^2 /°F

T_e = equilibrium temperature in degrees Fahrenheit

T_s = surface temperature in degrees Fahrenheit

At equilibrium, the net rate of heat transfer is zero and the equilibrium temperature is equal to the surface water temperature. If surface water temperature is directly proportional to air temperature, then equilibrium temperature is directly proportional to air temperature and can be adjusted by a factor proportional to the air temperature change. The monthly average fractional differences between the noCC and CC air temperatures were calculated and then multiplied by the noCC monthly equilibrium temperatures to create the CC equilibrium temperatures. The increases in equilibrium temperatures ranged from 1.77 to 7.36 percent, as shown previously in Table 4.

To create CC scenario values for the heat exchange rate, also called the net rate of heat transfer, the assumption was made that there is a linear relationship between the heat exchange rate and equilibrium temperature. Heat exchange rate components include radiation, heat conduction, and evaporation, as shown in Equation 2 (USACE, 1986):

$$H_n = H_s - H_{sr} + H_a - H_{ar} \pm H_c - H_{br} - H_e \qquad (2)$$

where H_n = the net heat transfer (BTU/day-ft^2)

H_s = the short wave solar radiation arriving at the water surface

H_{sr} = the reflected short wave radiation

H_a = the long wave atmospheric radiation

H_{ar} = the reflected long wave atmospheric radiation

H_c = the heat transfer due to conduction

H_{br} = the back radiation from the water surface

H_e = the heat loss due to evaporation

All of the terms above are in units of BTU/day-ft^2. Because many of the variables in Equation 2 are unknown, several functions relating the noCC equilibrium temperatures and heat exchange rates, obtained from the USBR-supplied model, were examined. The 6-hour meteorological data were converted to daily averages. Then, the noCC daily equilibrium temperature data were plotted against the daily average noCC heat exchange rates as shown in Figure 10. Exponential, logarithmic, polynomial, and power functions were applied, but the linear function was the best fit to model the data. The linear function, Equation 3:

$$H_{n,CC} = 54.496 + 1.0772\,(T_{e,CC}) \tag{3}$$

where $H_{n,CC}$ = the net heat transfer for the CC scenario (BTU/day-ft^2)

$T_{e,CC}$ = the equilibrium temperature change for the CC scenario, °F

was then used to calculate new heat exchange rates for the CC scenario using the new equilibrium temperatures that were adjusted according to the CC air temperatures. The new heat exchange rates and equilibrium temperatures were then inputted into the SRWQM for the CC scenario.

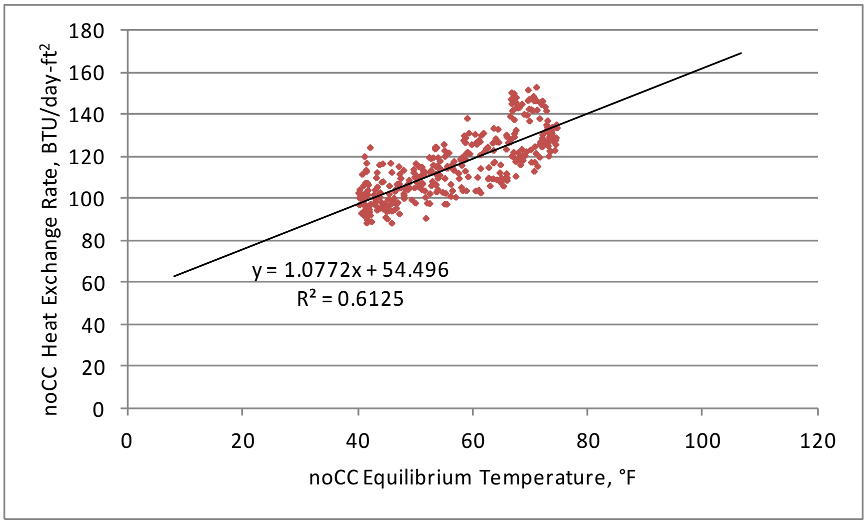

Figure 10. Linear trend line applied to heat exchange rate vs. equilibrium temperature in the noCC scenario.

3.4 Salmon Population Data

In the current study, salmon mortality rates were calculated using SALMOD. The version of SALMOD that is specific to the upper Sacramento River was obtained from the USBR. It included inputs for stream geometry, the number of potential salmon and salmon biological requirements such as those described in the Background chapter. This model uses 82 years of 7-day average flow data and water temperature data provided by SRWQM. The model then outputs 80 years of weekly or annual salmon mortality rates. The duration shifts from 82 years to 80 years of data because SALMOD begins to analyze Sacramento River Winter-run Chinook salmon beginning February 4 as opposed to the typical water year, which begins in October. In other words, the input data for SALMOD ranges from October 1922 to September 2003, the output data ranges from February 1923 to February 2003. Hence the 80 year output.

Study assumptions specified in the U.S. Bureau of Reclamation's SLWRI regarding SALMOD are that egg and fish mortality are directly affected by the habitat, which in turn is affected by space and temperature. Also, salmon do not use or compete to use the same habitat (USBR, 2011). Changes in flow are assumed to not change channel geometry, gravel quantity or quality, or cover availability. Flows, however, do change the size of the habitat available due to changing water depths.

4. RESULTS

Water temperatures from SRWQM and salmon populations for the noCC and CC scenarios are presented in this chapter. Tabular results can be found in the Appendix.

4.1 SRWQM output

As described in the previous chapter, water temperatures were calculated for 82 years. Monthly water temperatures, calculated from daily water temperatures, in the upper Sacramento River just upstream of the Red Bluff Dam, are presented as box and whisker plots in Figure 11 and Figure 12. The minimum (bottom whisker) and maximum (top whisker) daily water temperatures for the noCC scenario are 39° and 68°F, respectively. The minimum and maximum daily water temperatures for the CC scenario are 40° and 71°F, respectively, as shown in Table 6. The plots show that upper Sacramento River water temperatures are the greatest in the mid-summer to early fall months (July-September). The plots also show that the largest water temperature increases are in the spring (March – May) and summer (July-August) months. The monthly water temperatures are a conservative representation of the data.

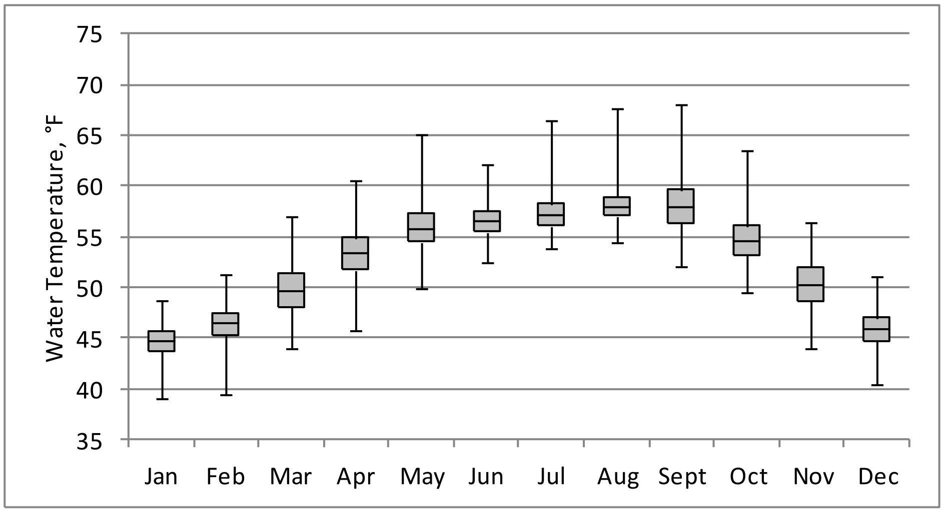

Figure 11. Box and whisker plot of monthly noCC water temperatures.

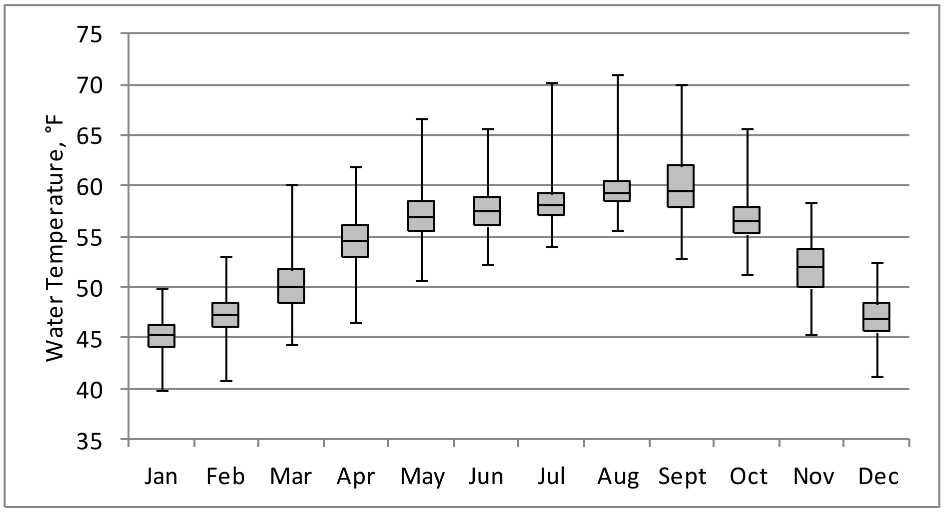

Figure 12. Box and whisker plot of monthly CC water temperatures.

Table 6. Daily water temperatures based on 82-year model results, °F

	Average	Minimum	25th percentile	Median	75th percentile	Maximum
noCC	51.28	39.12	47.67	51.56	54.43	68.10
CC	52.46	39.94	48.42	52.74	55.94	70.99
Difference	1.18	0.82	0.75	1.18	1.52	2.89

The changes in weekly water temperatures are actually more significant to the salmon because the thermal mortality rates calculated in SALMOD are based on 7-day averages to account for acute (96 hours) and long-term exposure (Ligon et al., 1999). The weekly average statistics calculated in the SRWQM are presented in Table 7. Although the differences between the noCC and CC water temperatures are small, the effects are large, which is shown in the salmon population results.

Table 7. Weekly water temperatures based on 82-year model results, °F

	Average	Minimum	25th Percentile	Median	75th Percentile	Maximum
noCC	51.28	41.59	47.90	51.98	54.11	66.44
CC	52.46	41.94	48.63	53.05	55.60	68.71
Difference	1.18	0.35	0.73	1.06	1.49	2.27

4.2 SALMOD Output

Salmon populations were projected for the upper Sacramento River for 80 years, the period of analysis described in the Methodology chapter. The resulting monthly salmon mortality rates, calculated from weekly rates, for the noCC and CC scenarios are presented in Figure 13 and Figure 14. The figures show that the median salmon mortality rates in the upper Sacramento River change only slightly between the noCC and CC scenarios. The maximum mortalities for the CC scenario are, however, significantly higher than those in the noCC scenario. The figures also show a shift in the worst-case month, from August in the noCC scenario to July in the CC scenario. Averages, minimums, maximums, and percentiles of the weekly data for the 80-year period for the noCC and CC scenarios and their differences are shown in Table 8. The maximum (top whisker) salmon mortality rate for the noCC scenario is 5.1 in August and for the CC scenario, it is 9.6 million fish for the month of July. The winter months are much lower in both scenarios because the winter-run salmon begin to migrate from the ocean at that time and have not yet reached the upper Sacramento River.

Annual mortality rates for 80 years based on historical hydrology as well as current water and land use demands and increased air temperatures for both the noCC and CC scenario are shown in Figure 15. The figure shows that the typical annual mortality rates for both climate scenarios are approximately 8.5 million fish per year, a little over two thirds of the approximately 12 million potential salmon predicted in U.S. Bureau of Reclamation’s SLRWI (2011). In other words, during most years, climate change has little effect on salmon mortality. When climate conditions are unfavorable, however, an excess annual mortality of one to three million fish may occur due to climate change. The maximum mortality rate that may occur as a result of the CC scenario conditions is 12.3 million compared to the 10.6 million for the noCC scenario.

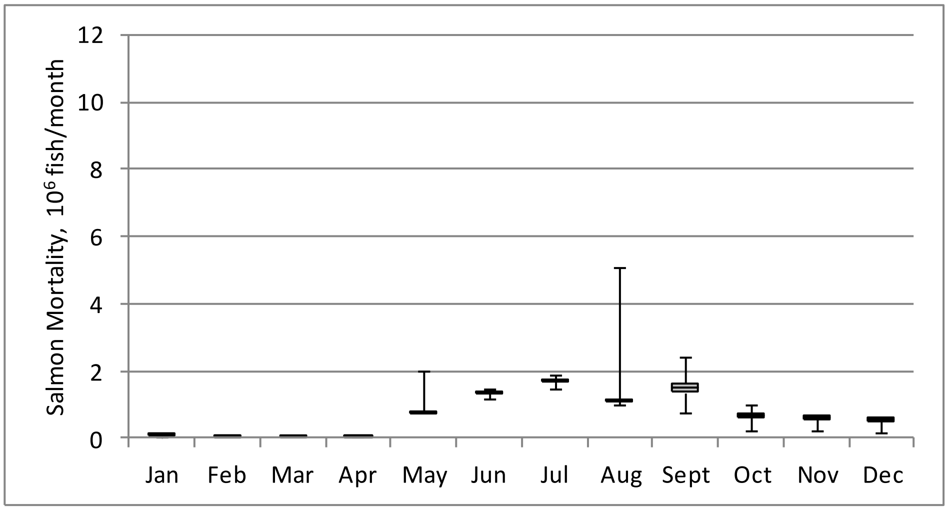

Figure 13. Box and whisker plot of monthly noCC salmon mortalities.

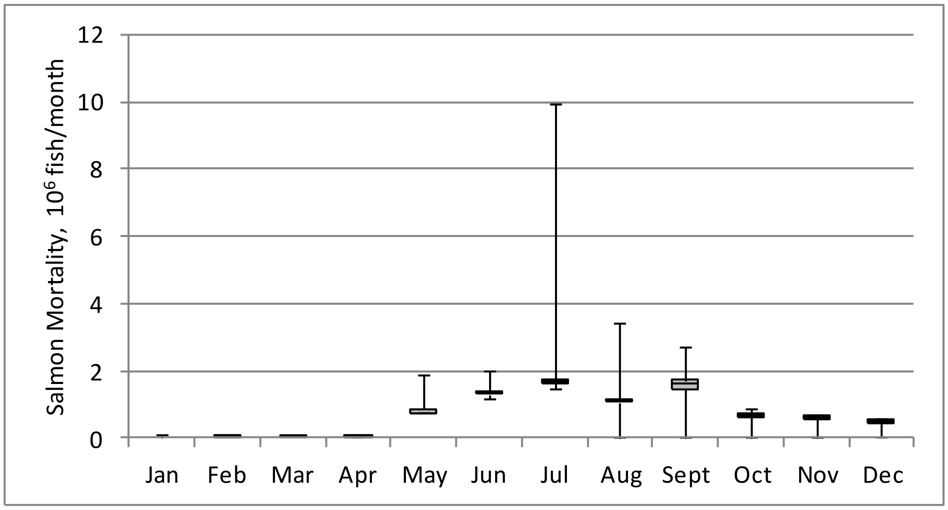

Figure 14. Box and whisker plot of monthly CC salmon mortalities.

Table 8. Weekly mortality rates statistics based on 80-year model results, 10^6fish/week

	Average	Minimum	25th Percentile	Median	75th	Maximum
noCC	0.16	0.00	0.01	0.15	0.29	1.65
CC	0.17	0.00	0.00	0.14	0.29	6.82
Difference	0.01	0.00	-0.01	-0.01	0.01	5.17

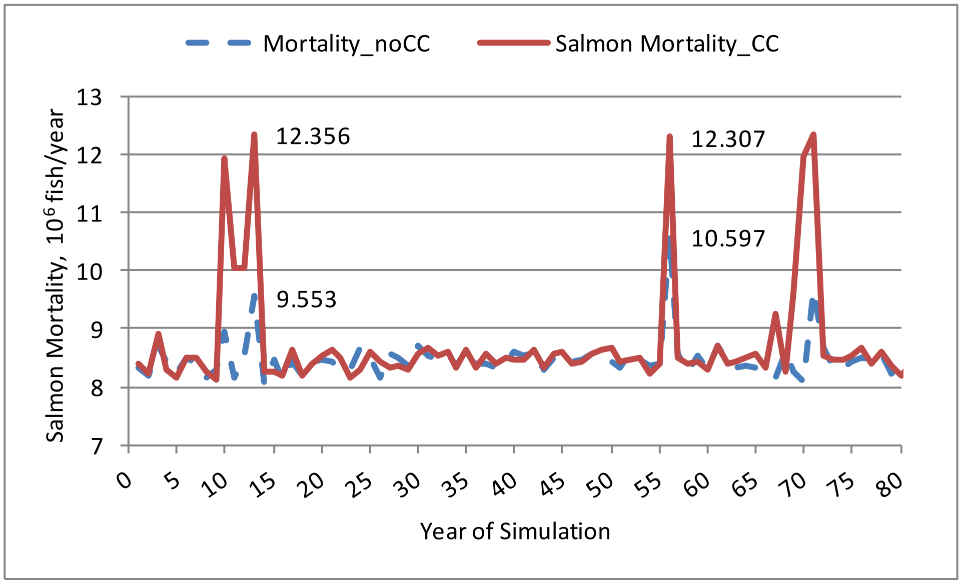

Figure 15. Salmon mortality rates for 80 years based on historical hydrology from 1923-2003, 10^6 fish per year.

Figure 15 is a bit misleading because the methodology used in this study is not specific enough to predict mortality in any particular year. Instead, the 80 years of mortality results should be used as a pseudo-data set on which to base estimates of the potential frequency or risk of different mortality levels. These can be illustrated in exceedance curves. Exceedance curves show the frequencies (expressed as probabilities) that mortalities will exceed given values. Such curves for noCC and CC scenarios, are presented in Figure 16. Under noCC conditions, there is a 5 percent probability, based on the 80 years analyzed, that the mortality rate is more than 8.7 million fish per year out of about 12 million potential salmon. Mortalities exceeding 8.7 million fish occur more often in the CC scenario, with a probability of 14 percent. The mortality rate with a 5 percent probability of exceedence in the CC scenario is about 11.9 million fish per year.

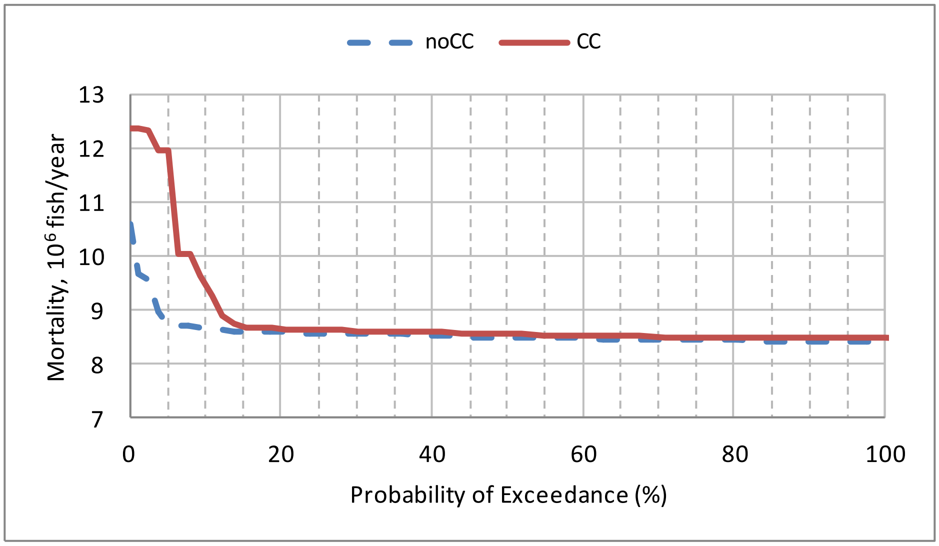

Figure 16. Exceedence curves for annual salmon mortality rates due to all causes.

As noted earlier, mortalities in SALMOD include a variety of factors, many of which are constant in the ranges of flows and temperatures occurring in most of the 80-year simulation. This is why the mortality rates in Figures 15 and 16 are relatively constant over the bulk of the simulation period. In about 20 percent of the simulated years, though, habitat and temperature play important roles. Habitat-based mortality, which is based on a habitat constraint on a maximum fish density, is affected mainly by flows. Between the two, temperature mortality is the primary cause of deaths in extreme cases. Figure 17 shows that the 5 percent habitat-caused mortality rates are about 1.2 million fish per year for the noCC scenario and about 1.4 million fish per year for the CC scenario. In contrast, the 5 percent temperature-caused mortality rates are about 1 million fish per year for the noCC scenario and about 8 million fish per year for the CC scenario, as shown in Figure 18. This comparison indicates that increased mortality under the CC scenario is due primarily to increases in temperature rather than changes in flow.

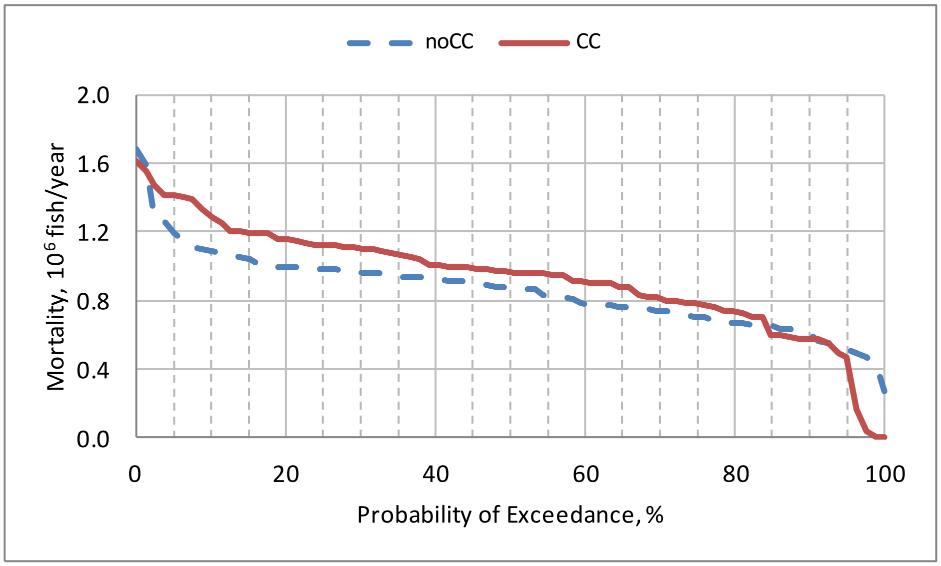

Figure 17. Exceedence curves for annual salmon mortality rates caused by changes in habitat (flow) only.

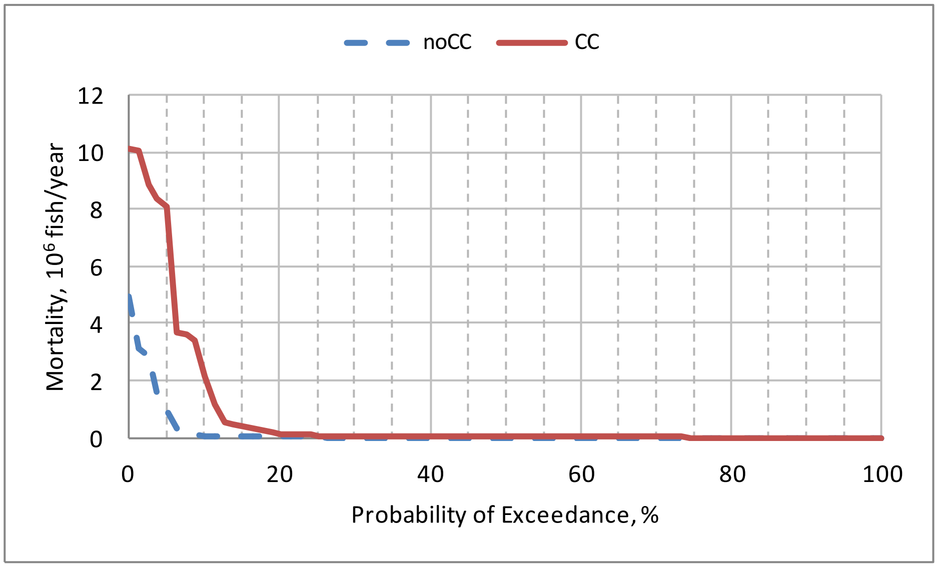

Figure 18. Exceedence curves for annual salmon mortality rates caused by changes in water temperature only.

5. DISCUSSION

In this chapter, the reliability and significance of the results from the SRWQM and SALMOD model runs are presented.

5.1 Potential Sources of Error

The reliability of the results is examined through consideration of the assumptions, the functionality of the models, and the quality of the input data.

A fundamental source of uncertainty in the current study is the use of a climate model to provide the meteorological input data for the SRWQM. First, this study assumes that the A2 climate scenario, which assumes medium-to-high emission rates, is a good estimate of California's future. Second, there are many potential sources of error in ECHAM-5, which could produce incorrect air temperatures. Calculated air temperatures that are too high would lead to underestimated stream inflows, overestimated water temperatures, and overestimated salmon mortality rates. It is beyond the scope of this project to provide a critique of ECHAM-5 or the idea of using climate models, and it must be admitted from the beginning that the project gives salmon estimated mortalities for this particular climate scenario and assumes the climate calculations are right.

Uncertainty in Cal-SIM II results may be attributed to the use of 82 years of historic hydrologic records. The results are only good for years with similar rainfall, runoff, snowmelt, and air temperatures. Air temperatures are expected to increase, and as a result, hydrology, land use and water demands may not be accurately reflected in] the 82-year hydrology on which this study is based. So, the use of one future temperature data set generates uncertainty in the outcome. Another source of uncertainty is that the 82 years of hydrology are connected to each other in Cal-SIM II. Flows in one year depend on water storage held over from the previous year. So, the resulting exceedance curves cannot be thought of as probabilities of risk because not all the possibilities are being considered.

The assumptions made in SRWQM may overestimate water temperatures and salmon mortalities. SRWQM models the Sacramento River as a plug flow system with no heat diffusion. The model divides the river into segments, where temperatures and flows remain the same in each segment. In reality, however, heat diffusion in the stream is not zero because temperatures and flows downstream are affected by those upstream. SRWQM assumes that the End-of-May storage in the Shasta reservoir, simulated in CalSIM II, indicates the available coldwater in the reservoir for the TCD to release, to meet target coldwater temperatures downstream. However, SRWQM does not account for leakages, overflow, and performance of the side intakes of Shasta's TCD, which make water temperatures modeled in the SRWQM cooler than actual temperatures (USBR, 2008).

In addition, the meteorological input data set for the SRWQM in the current study uses historical short wave solar radiation values and assumes that they will remain constant in the future because there was not a good basis for estimating future values. Short wave solar radiation is dependent on ozone, the latitude of the earth, the time of day, and the season of the year. Although, these variables may remain the same, other factors such as suspended particulate matter and water vapor are more likely to differ under the CC scenario. Although water vapor will be affected by air temperature and will be different under the CC scenario, the effect of this change on the heat balance was also assumed to be negligible. Uncertainty is also present with the use of simplified linear regressions when calculating equilibrium temperatures and heat exchange rates for the CC scenario instead of using standard equations such as Equations 1 and 2. Another source of uncertainty is the use of different input data with differing durations and time series for all models. Monthly air temperatures for two 30-year periods were retrieved to calculate monthly percent increases from the noCC to CC scenario. Monthly percent increases between the noCC and the CC air temperatures were multiplied by the noCC 6-hour equilibrium temperatures as the basis for creating the CC meteorological data, specifically the equilibrium temperature and heat exchange rates. The 82-years of 6-hour meteorological data, and monthly river flows were used to calculate weekly average water temperatures for the CC scenario. These weekly average water temperatures were used to simulate 80-years of weekly salmon population data. Uncertainty in the model results used as inputs to SRWQM will ripple through to the salmon mortality estimates from SALMOD. Averaging data with different time series may underestimate salmon mortality rates.

SRWQM was calibrated in 2003 as described in OCAP. Water temperature results from SRWQM were calibrated using water temperatures, recorded by agencies such as DWR, USBR, and USACE at several locations within the upper Sacramento River from January 1998 to November 2002 (USBR, 2008). From 1990 to 1997, Shasta Lake's vertical reservoir temperature profiles were validated with observed values for the summer and fall season (USBR, 2008). This calibration analysis could be further improved by increasing the calibration record by an additional 10 years. The model, previously calibrated from 1998 to 2002, now could be calibrated from 1998 to 2012. For more details regarding assumptions, uncertainty, validation, and limitation for the SRWQM refer to USBR's OCAP (2008).

SALMOD has not been calibrated (USBR, 2011). USBR's 2011 Shasta report states that performing a statistical analysis on SALMOD results including quantifying the confidence interval, may not be applicable because the model results have not been calibrated (USBR, 2011). As a result, there are several potential sources of error. Uncertainty in SALMOD results may also come from SALMOD not being a full cycle model. In other words, SALMOD tracks when salmon migrate from their spawning grounds from Keswick Dam to just upstream of Red Bluff down, but not when salmon migrate back upstream. So, although in reality when some salmon return to the study area, SALMOD does not account for that and starts the analysis for a new year with the user-specified eggs. SALMOD assumes a set number of females that produce a certain number of eggs at the beginning of each year studied. This assumption that the initial potential salmon are the same every year may overestimate habitat-based mortality rates in a case where less eggs are actually produced. As presented in Table 2, SALMOD assumes that the mortality rate for eggs before and after being deposited into the gravel is the same, and the mortality rate for juveniles and adults is the same (USBR, 2011). However, adults may have a stronger barrier shielding them from exposure to ambient water temperatures (USBR, 2011). So, these assumptions may overestimate the mortality rate results in adults and are a cause for uncertainty.

5.2 Comparison of Results by Others

To check that the salmon mortality rates from SALMOD are reasonable in the current study, noCC SALMOD results were compared to SLWRI's No Action results and OCAP's baseline results. CC results data were not compared because SLWRI and OCAP do not include climate change.

The methodology used in the current study is similar to SWLRI and OCAP. To elaborate, scenarios, the noCC, SLWRI's No Action, and OCAP's baseline scenarios all use the same set of models to simulate water operations, river flows, temperatures, and salmon populations. The water operations are governed by the assumed regulatory standards and objectives to meet municipal, industrial, and agricultural demands, as well as other operation requirements such as those prescribed under the biological opinions of the NMFS and USFWS.

Salmon productions, salmon that have survived the conditions within the study area, as a percentage of potential eggs for the noCC scenario, the SLWRI No Action, and the OCAP baseline are compared, in Figure 19. The figure shows that salmon production is higher for the noCC scenario in the current study, compared to SLWRI's No Action for extreme hydrologic events, but similar for other years because both sets of calculations are based on the same historical hydrologic period, 1923 to 2003. The noCC production rates are higher in these cases than SLWRI's No Action possibly because of differing Cal-Sim II modeling assumptions. The 2004 and 2005 biological opinions was used in

USBR's SLRWI as opposed to DWR's use of the 2009 biological opinions in the 2011 Delivery Reliability Report (2012) which is the basis of the noCC scenario. USBR used the 2004 and 2005 biological opinions in the SLWRI because of litigation issues with the 2008 and 2009 biological opinions (USBR, 2011). One of the intentions of the 2009 biological opinions is to increase the population of the endangered Sacramento River Winter-run Chinook salmon, which appears to be reflected in the noCC results.

Salmon production rates for the noCC scenario and the USBR's OCAP baseline also show similar patterns but different numbers. The assumptions regarding the initial spawners appear to be different between noCC and OCAP, which may be leading to the difference between the noCC scenario and the OCAP baseline results. In the text of USBR's OCAP report, the number of potential eggs is the same as that used in the current study, but the supporting files suggest that the potential eggs are much less.

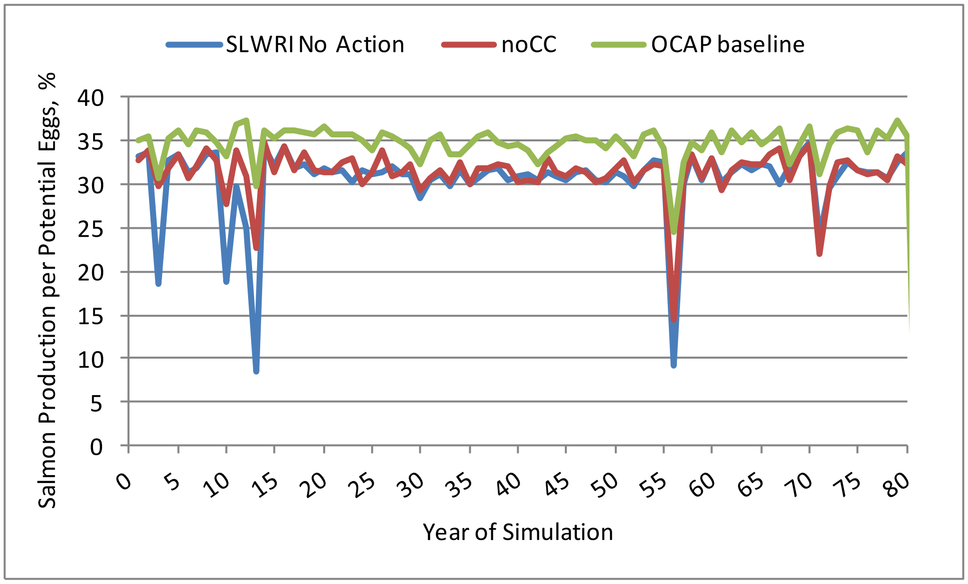

Figure 19. Salmon production results for SLWRI' No Action and the noCC scenario.

5.3 Analysis of results

At first glance, climate change effects on calculated salmon mortality rates seem reasonable. Mortality rates are generally consistent with temperatures. As shown in Figure 20, salmon mortality rates significantly increase as result of water temperatures exceeding the critical threshold of 54°F. These occurrences correspond to drought periods that limit the availability of coldwater in Shasta Lake for managing temperatures in the river. Figure 21 shows that the frequency of temperatures higher than 54 °F increases from 49 percent for the noCC scenario to 56 percent for the CC scenario, which explains the increased mortality under the CC scenario. As water temperatures goes above 54°F mortality rates increase significantly, causing higher mortality in about 20 percent of the years under the CC scenario as shown in Figure 18. If significant increases in mortality were to occur, the critical months for the salmon survival may be in July or August since temperatures are typically higher already. The maximum mortality rate that may occur as a result of the CC scenario conditions is 12.3 million compared to the 10.6 million for the noCC scenario (Figure 16).

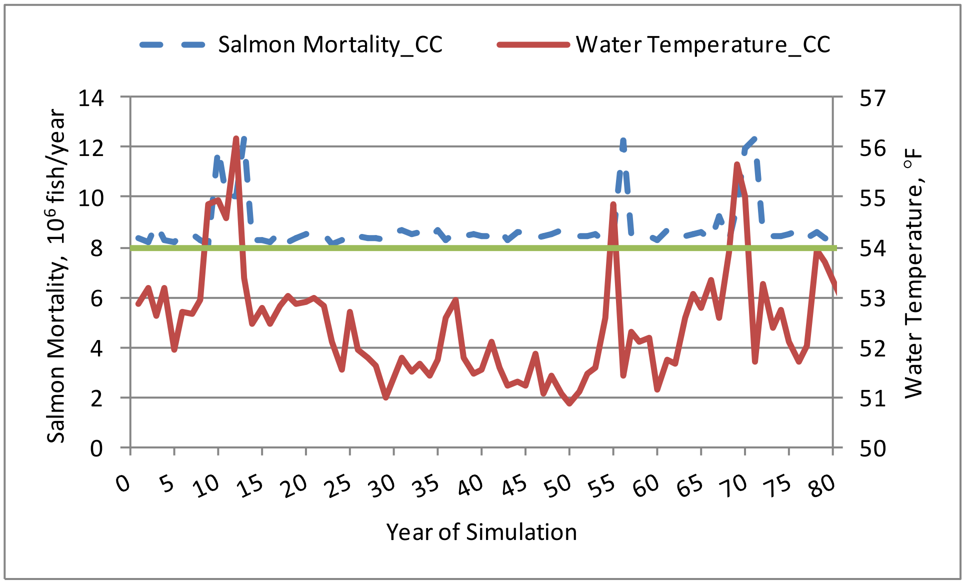

Figure 20. Mortality Rates vs. Water Temperature data for the CC scenario.

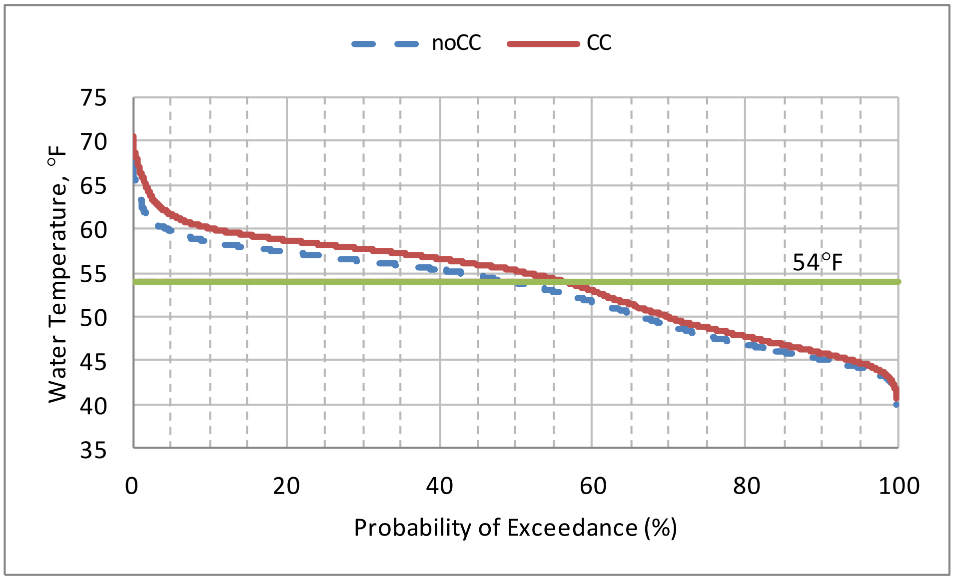

Figure 21. Exceedence curves for weekly water temperatures based on historical hydrology from 1921 to 2003.

6. CONCLUSION

Within an 80-year simulation, based on historical hydrology, current land use and water demand, and increased air temperatures in the upper Sacramento River valley, calculated mortalities for the two scenarios are generally similar, with elevated mortalities during drought periods when water temperatures exceed the critical threshold of 54°F. In these extreme conditions, mortality rates significantly exceed the typical mortality rates of approximately 8.5 million fish per year over the 80-year period.

Based on SALMOD results, water temperature changes affect the salmon population significantly more than flow. Model results show that peak weekly water temperatures increase from 66°F in the noCC scenario to almost 69°F in the CC scenario. In 5 percent of the simulated years under the noCC scenario, the mortality exceeds 8.7 million fish per year, but under the CC scenario, this mortality is exceeded in 14 percent of the simulated years. In the CC scenario, the mortality that is exceeded in 5 percent of the simulated years is 11.9 million fish per year. It would be prudent to continue to incorporate climate change into plans to increase winter-run Chinook salmon populations so that this fish can be removed from the endangered species list.

7. APPENDIX A. Tabular Results

See CD

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