Water Management Adaptations to Prevent Loss of Spring-Run Chinook Salmon in California under Climate Change

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Abstract: Spring-run Chinook salmon (*Oncorhynchus tshawytscha*) are particularly vulnerable to climate change because adults oversummer in freshwater streams before spawning in autumn. We examined streamflow and water temperature regimes that could lead to long-term reductions in spring-run Chinook salmon (SRCS) in a California stream and evaluated management adaptations to ameliorate these impacts. Bias-corrected and spatially downscaled climate data from six general circulation models and two emission scenarios for the period 2010–2099 were used as input to two linked models: a water evaluation and planning (WEAP) model to simulate weekly mean streamflow and water temperature in Butte Creek, California that were used as input to SALMOD, a spatially explicit and size/stage structured model of salmon population dynamics in freshwater systems. For all climate scenarios and model combinations, WEAP yielded lower summer base flows and higher water temperatures relative to historical conditions, while SALMOD yielded increased adult summer thermal mortality and population declines. Of management adaptations tested, only ceasing water diversion for power production from the summer holding reach resulted in cooler water temperatures, more adults surviving to spawn, and extended population survival time, albeit with a significant loss of power production. The most important conclusion of this work is that long-term survival of SRCS in Butte Creek is unlikely in the face of climate change and that simple changes to water operations are not likely to dramatically change vulnerability to extinction.
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Introduction

The literature on aquatic ecosystem services in freshwater systems has converged on three service categories: provisional, regulatory, and cultural (Millennium Ecosystem Assessment 2005). Within the first set of services, the provision of water for consumptive use (e.g., drinking water), nonconsumptive use (e.g., hydropower), and aquatic organisms (e.g., fish for food) are typically combined. This combination points out the difficult trade-offs inherent in the management of freshwater ecosystem services because these services often conflict. In California, for example, service provision rests on a complex and shifting balance of natural and human forces. Climatic variability and watershed response are critical determinants of flow regime and water quality of streams, but these hydrologic signals are dramatically altered by land management decisions and the operation of hydraulic infrastructure (Graf 1999; Yates et al. 2008; Zalewski 2002; Yates et al. 2009).

After decades of such alteration, provisional services related to aquatic organisms in California have experienced marked decline, most acutely for Pacific salmon (Salmonidae). Historical Chinook salmon (*Oncorhynchus tschawytcha*) runs in the Sacramento-San Joaquin (Central Valley) drainage were 1–3 million fish per year (Yoshiyama et al.1998, 2000), but in recent years runs have usually totaled less than 100,000 fish annually (Lindley et al. 2009). There are myriad reasons why this service may be experiencing such a dramatic decline, but the social importance of salmon runs is revealed by the enormous regulatory and restoration investments being made to arrest their decline (Bernhardt et al. 2005). In 2008 and 2009, prompted by declining runs, the lucrative commercial salmon fishing industry was completely shut down [Pacific Fishery Management Council (PFMC) 2008, 2009].

Wild Pacific salmon populations in California, Oregon, and Washington are in a long-term decline because of factors including

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J. Water Resour. Plann. Manage., 2012, 138(5): 465-478

overfishing, changes in ocean conditions, water quality and habitat degradation, genetic introgression with hatchery stocks, and impassable barriers to migration (Noakes et al. 2000; Lackey et al. 2006; Moyle et al. 2008). The loss of holding, spawning, and rearing habitat in California rivers and streams contributes substantially to the decline in provision of services provided by Chinook salmon (Yoshiyama et al. 2001), largely related to the vast hydraulic manipulation of rivers in the Central Valley. Salmon are currently limited to a small portion of their former range, increasing their vulnerability to climate change. Both young and adult salmon are extremely sensitive to elevated water temperature and associated increases in energy expenditure that can compromise reproductive performance (Torgersen et al. 1999).

Of particular interest are the few remaining populations of the Central Valley spring-run Chinook salmon (SRCS) evolutionarily significant unit (ESU), a species listed as threatened under both the state and federal endangered species acts. SRCS travel from the ocean to spawning sites during the peak snowmelt period of March/April; hold in cold-water pools during the hot, dry summer months; and spawn in autumn. Historically, SRCS were the dominant run in the Central Valley and included 18 independent populations (Lindley et al. 2007). Presently, their distribution is limited to three watersheds with small numbers appearing intermittently in seven other watersheds, where access to cold-water pools remains unobstructed. Annual SRCS runs used to number approximately 1 million fish, but they have declined to approximately 16,000 in the Central Valley.

Recently researchers have used downscaled climate data from one or more general circulation models (GCMs) to drive a habitat model, with the resulting data passed to a biological model (Battin et al. 2007; Crozier et al. 2008; Isaak et al. 2010; Matulla et al. 2007; Tung et al. 2006; Yates et al. 2008). These models fall primarily into two types of frameworks: (1) those that use bioclimatic envelopes and (2) those that simulate life history. Bioclimatic models are used to estimate future habitat availability as a function of future climate predictions without specifically modeling life history. Lindley et al. (2007) modeled the potential spatial distribution of Central Valley SRCS under different expectations of the increase in mean August air temperature; they found that some Central Valley SRCS populations disappear with as little as a 2°C increase in mean August air temperature and most populations are extirpated from historic habitat at an increase of 6°C in mean August air temperature (Lindley et al. 2007). A similar model for Idaho mountain streams predicted that rainbow trout (*Oncorhynchus mykiss*) would have an upstream range shift, but not necessarily a loss of total available habitat, while bull trout (*Salvelinus confluentus*) would have an 11–20% range of available habitat contraction (Isaak et al. 2010). Tung et al. (2006) investigated the change in available habitat for a population of *Oncorhynchus masou formosanus*, a landlocked salmon on Taiwan Island. They report that annual average available habitat was reduced for the climate models and thermal criteria tested; available habitat during summer was reduced or eliminated entirely for most modeled scenarios.

Life history models for salmonid resilience relate life history characteristics to climate variables (water temperature, flow) or climate indices such as the Pacific decadal oscillation (PDO); for example, juvenile survival as a function of water temperature or state of the PDO (Battin et al. 2007; Crozier and Zabel 2006; Rand et al. 2006; Zabel et al. 2006). The relationship between climate and life history is then applied to future climate projections to investigate population response to climate change. Matrix models estimate the probability of quasi-extinction (Ginzburg et al. 1982) in populations of SRCS under climate change projections and identify stage specific parameter relationships that might be of interest with respect to climate change (Crozier et al. 2008; Zabel et al. 2006). In a different model framework, Battin et al. (2007) used the spatial population model Shiraz to characterize changes in the physical characteristics of a watershed as function of climate. They explicitly modeled effects of climate change on water temperature and flow and how changes in them affected population dynamics.

These modeling efforts have been consistent in their predictions of negative impacts of climate change on salmonids, including loss of habitat, decreased abundance, and increased risk of extinction. However, they have also called attention to the shortage of analytical frameworks that test the effectiveness of management actions to mitigate for negative effects of climate change (Bryant 2009; Mote et al. 2003; Wilby et al. 2010). In a rare attempt to consider the effectiveness of management responses to climate change, Battin et al. (2007) found that habitat restoration actions, such as changes in land use, can partly offset the effects of climate change, but may not be adequate to mitigate these effects entirely. A key point is that management responses were limited to modifying the hydrologic response of a watershed to changing climate, but did not consider opportunities offered by alternative adaptive operating regimes associated with building new or managing existing hydraulic infrastructure. For example, cold water could be stored in reservoirs for release to reduce water temperatures downstream; this cold water could be transferred to the salmon habitat via canals, forebays, and powerhouses.

Climate change scenarios for California predict warming atmospheric temperatures, reduced snow pack and snowmelt runoff, and lower dry season flows (Hayhoe et al. 2004). The hydrologic responses of a watershed to climatic forcing are the result of multiple nonlinear physical processes that unfold within a system. These responses can be substantially manipulated by operation of hydraulic infrastructure that is governed by discontinuous conditional rules and agreements. The complex nonlinear nature of these systems makes it extremely difficult to understand the relationship between increasing atmospheric temperature and the future viability of salmon populations. It is even more challenging to determine what management actions might be able to mitigate for climate change effects when human population growth and other factors are having increased impacts on management of water resources (Cifaldi et al. 2004; Field et al. 1999; Hayhoe et al. 2004). To address this issue, an analytical framework was developed that incorporates (1) climate scenarios; (2) a model of watershed response to climate change, including the capacity to model water management adaptations; and (3) a model of salmon population dynamics (Fig. 1). The framework was used to examine the viability of the SRCS population in Butte Creek under current management and under two relatively simple management changes within the system, across a range of climate predictions.

Geographic and Management Settings

Butte Creek (Fig. 2) is characterized by hydrologic and geomorphic conditions that provide one of the last remaining favorable habitats for SRCS, supplemented by cold-water transfers from the adjacent Feather River. The aquatic ecosystem of Butte Creek is vulnerable to climatic change because the watershed resides at a climatological margin for cold-water species. Its headwaters emanate from lower elevations within the Sierra Nevada where snow accumulation is limited. During the spring, summer, and early fall months, adult SRCS occupy approximately 17 km of holding and spawning habitat (Ward et al. 2004); their habitat in this reach is influenced by

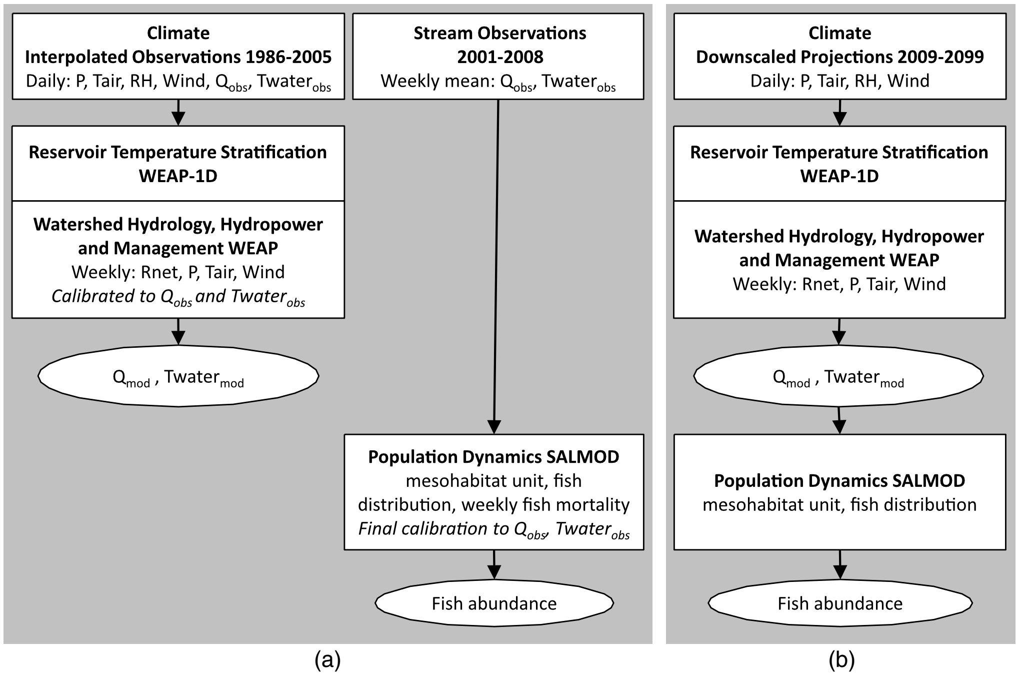

Fig. 1. (a) Assemblage of analytical framework, model coupling, and data transfer used to model historical conditions; P = precipitation, Tair = air temperature, RH = relative humidity, Q_{obs} = observed streamflow, $T\text{water}_{\text{obs}}$ = observed water temperature, Rnet = net radiation, Q_{mod} = modeled streamflow, $T\text{water}_{\text{mod}}$ = modeled water temperature; (b) analytical framework used to model future conditions

operation of the DeSabla-Centerville hydroelectric project operated by Pacific Gas and Electric (PG&E).

Recently, the National Marine Fisheries Service issued a "Biological Opinion on the Central Valley Water Project" that gives numerous directives aimed at salmon recovery (NMFS 2009). While some of the restoration actions recommended may be beneficial for SRCS, there is currently no formal management plan for Butte Creek. Most future management changes for Butte Creek are likely to come from the ongoing Federal Energy Regulatory Commission (FERC) relicensing process for the DeSabla-Centerville hydroelectric project (PG&E 2007). At this point in time, proposals include cooling the water in the DeSabla Forebay above the DeSabla Powerhouse and experimenting with different flow regimes through the holding habitat by reducing water diversion at the Centerville diversion dam. Other management options include intentionally managing cold water in upstream reservoirs to counteract water temperature increases in critical SRCS holding reaches. These are examples of the type of water management adaptation that can be explored through the application of the proposed analytical framework.

Description of Approach

Climate change does not act on biophysical processes in isolation from infrastructure that redistributes water spatially and temporally. Furthermore, infrastructure may provide management adaptation options. As a consequence, the analysis of management adaptations to climate change impacts on SRCS in Butte Creek required linking physical, ecological, and water management processes into a single framework (Fig. 1).

WEAP Model

Our framework begins with the water evaluation and planning (WEAP) system to simulate potential changes in streamflow and water temperature in response to climate inputs under a given water management scenario (Null et al. 2010; Purkey et al. 2007; Yates et al. 2005a, 2009; Young et al. 2009). The WEAP hydrologic model uses an empirical, one-dimensional (1D), 2-store soil moisture accounting scheme to estimate evapotranspiration, surface runoff, and subsurface flow within a hydrologic unit or catchment. WEAP also models snow accumulation and melt based on a temperature index formulation. For a full description of the model, the reader is referred to Yates et al. (2005a) and Young et al. (2009) where the algorithms for each hydrologic component are described. WEAP models physical hydrologic processes within a water management context, as opposed to the variable infiltration capacity (VIC) model (Liang 1994), for example, that simulates only hydrology (Maurer and Duffy 2005), and from CALSIM (Water Resources Simulation Model 2000, Sacramento, California) that describes complex operational criteria, but requires hydrologic inputs as boundary conditions.

Butte Creek (512 km^2 down to the USGS Chico gauge) was divided into catchments with an average spatial resolution of 15 $\text{km}^2 \pm 15$ km^2 (Fig. 2) and a water balance calculated on a weekly time step. An interpolated weather product with a spatial resolution of 12 km between 1986 and 2005 as climatic boundary conditions was used (Maurer et al. 2002). Water management was modeled by assigning operating rules to system reservoirs and instream flows in accordance with the existing FERC license (PG&E 2007). Hydropower operations logic was based on the 1986–2005 weekly average operations composite developed for the FERC license application (PG&E 2007). WEAP allocation routines were adjusted to capture the observed operation of the DeSabla-Centerville project.

PEST (Doherty 2002) was used to guide calibration of snow, streamflow, and water temperature parameters, minimizing the weighted sum of squared differences between simulated values and field observations. To assess model fit, the study used root mean square error (RMSE) and BIAS previously used to assess WEAP model fit in Sierra watersheds (Young et al. 2009) and added the Nash-Sutcliffe efficiency criteria (E).

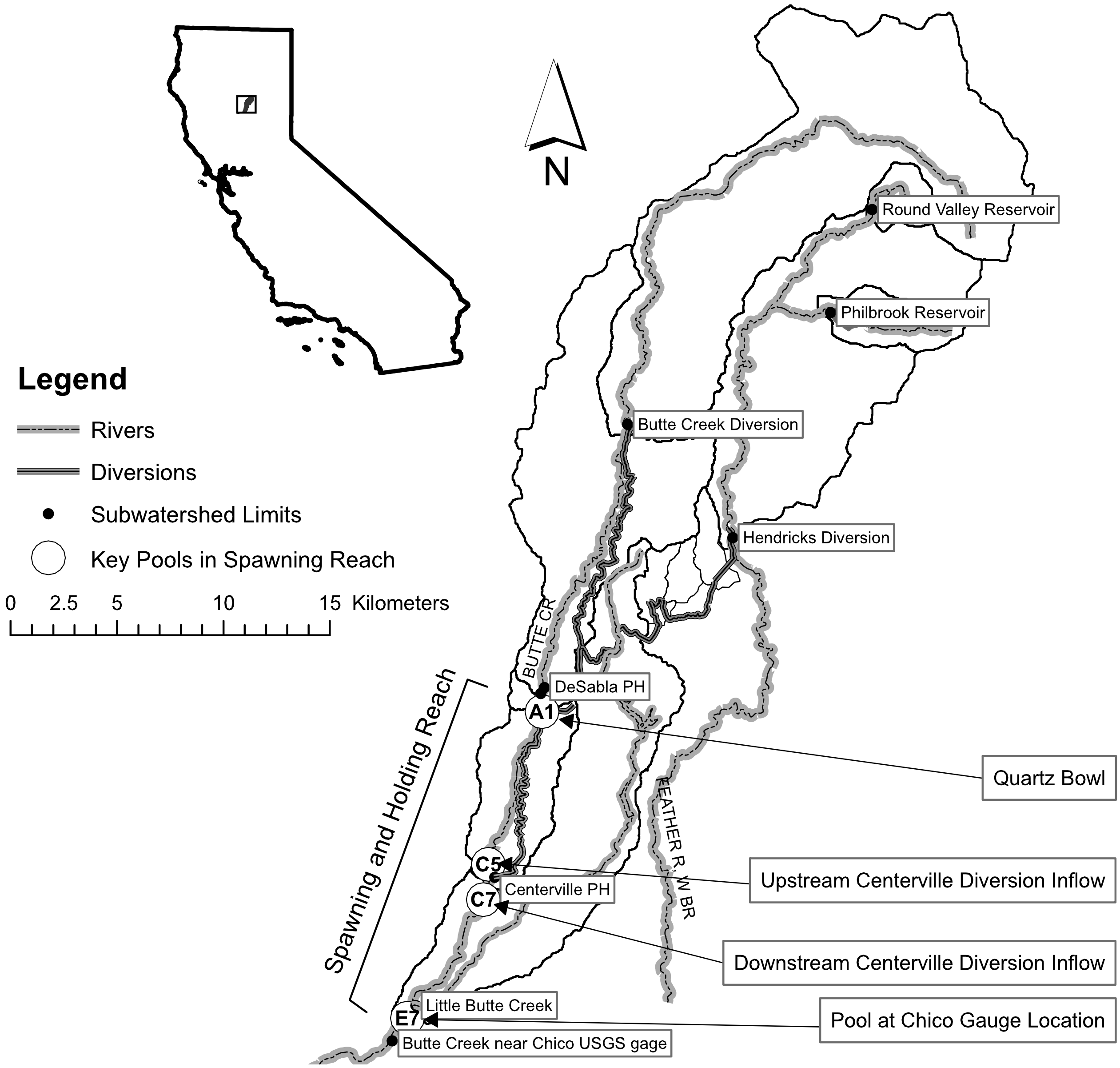

Fig. 2. Location of Butte Creek watershed in California and watershed model domain with rivers, diversions, and management points used for subwatershed and catchments delineation; in the lower Butte Creek are CDFG spring-run Chinook salmon holding and spawning reach pools numbered as A1 (Quartz Bowl), C5 (above the inflow from Centerville Diversion), C7 (below inflow from Centerville Diversion), and E7 (location of USGS Chico gauge); total length of spawning and holding reach is 17 km, starting at Quartz Bowl and ending at USGS Chico gauge

For snow accumulation, two snow gauges, Commission California Data Exchange Center (CDEC) FOR (Four Trees) and HMB (Humbug), located in the Feather River watershed at 1,570 m and at 1,981 m elevation were compared to model results at the corresponding elevation bands (i.e., 1,500–1,750 m and 1,750–2,000 m). RMSE of 0.78 and 0.84 m water equivalent, BIAS of −10% and −33%, and E of 0.76 and 0.25, respectively, were obtained. Modeled snowmelt contributes 15% to total annual streamflow. Consequently, the negative BIAS in snowmelt, when considered in the context of total streamflow volume, represents an error of only −1.5 to −4.4%, which was considered acceptable.

To calibrate streamflow, a split time series approach in which the calibration period was 1996–2005 and the validation period was 1986–1995 was used, focusing calibration statistics on data from June to September—the critical period for species survival. We compared the USGS Butte Creek gauge (USGS 11390000), located at the watershed outlet (a composite of natural and managed hydrology), to simulated streamflow [Fig. 3(a)]. We obtained RMSE of 0.46 and 0.73 m^3/s, BIAS of −2% and 12%, and E of 0.74 and 0.66 for the calibration and validation periods, respectively.

To assess stream water temperature, the WEAP internal heat balance equation was used (Yates et al. 2005b) for stream segments defined by a length and a stage-discharge relationship. The water temperature in each segment is assumed to reach steady state within a time step. In all areas outside the spawning reach, all stream segments were assumed to have a single, representative cross section and flow-stage-width relationship. Within the spawning reach (A1 to E7 in Fig. 2), 40 subreaches were defined by the California Department of Fish and Game (CDFG). Each subreach was divided into a pool, riffle, and run for a total of 120 habitat units.

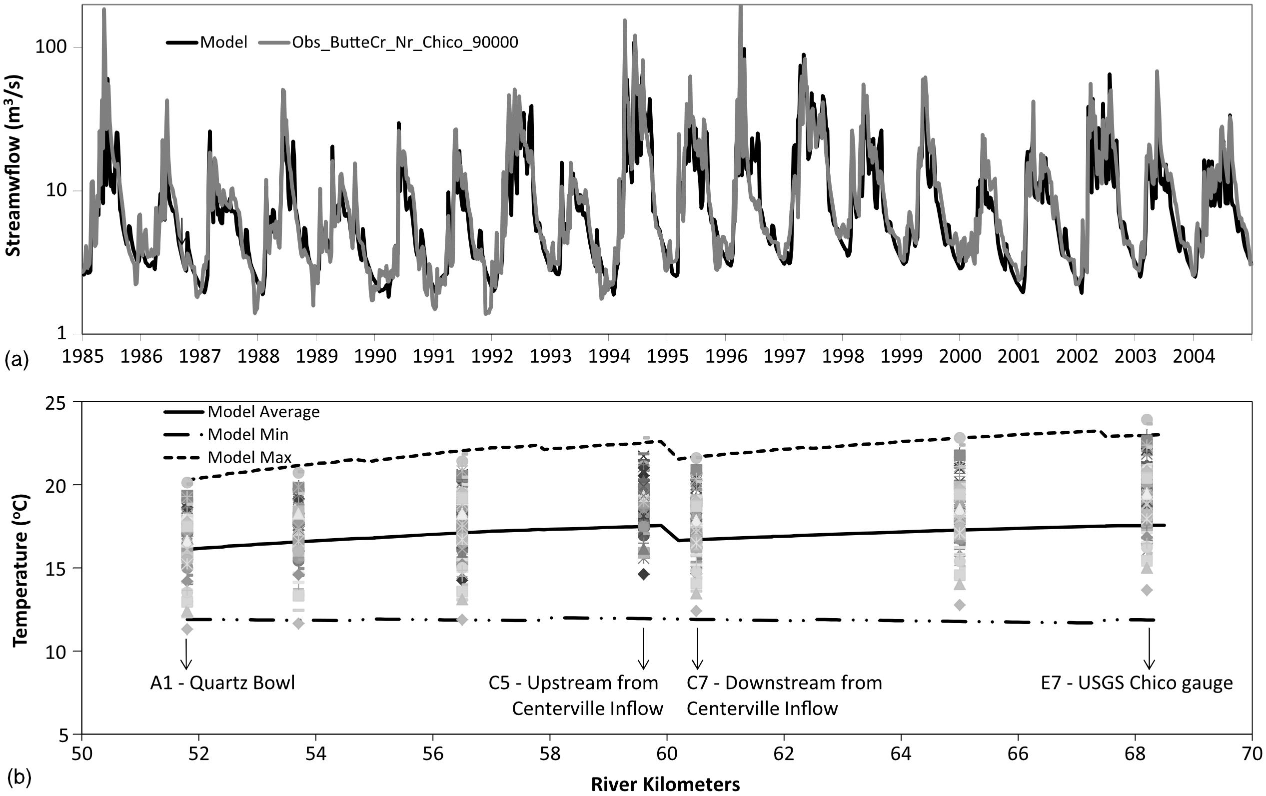

Fig. 3. Streamflow and water temperature calibration: (a) observed (gray line) and simulated (black line) streamflow for 1986–2005; calibration was focused on summer low flow periods; (b) observed (gray symbols) and simulated water temperatures (black solid and dashed lines) for spawning reach from Quartz Bowl to USGS Chico gauge; calibration focused on hot summer weeks, observations are weekly average water temperatures available at seven different pools in spawning reach, and simulated are average, minimum, and maximum weekly average water temperatures from July to September for 2000–2005; river kilometers in the *x*-axis refers to the distance from Butte Creek headwaters

Habitat unit stage-discharge relationships were derived from 14 cross sections and flow-stage-width relationships available from Gard (2003).

To account for water temperature stratification in upstream Philbrook Reservoir on the West Branch Feather River, we integrated a 1D temperature model within WEAP to solve the one-dimensional heat flux equation (Chapra 1997). The solutions were based on reservoir volume-area-elevation curves, meteorological information, flows in and out of the reservoir, and the vertical location of reservoir outflow. The routine estimates surface layer temperature of the reservoir and the energy available to warm subsurface layers; it updates the previous temperature profile once the input energy has been diffused. The routine checks for profile stability and, if dense water is overlaying less dense water, convective mixing occurs. Model parameters include surface radiation absorption, extinction depth, and effective diffusivity. The parameters were adjusted to obtain the best fit to seven available temperature profiles measured in 2004 and 2005.

In catchments higher than 1,750 meters above sea level, a snowmelt water temperature of 0°C was assigned. Surface runoff temperature was estimated by assuming a linear relationship between runoff temperature and a lagged air temperature, with the slope, intercept, and time lag serving as calibration parameters. A constant temperature was assigned to subsurface flows, which was used as a calibration parameter. To stabilize the numerical routines for the short length scales relative to the time scales, a length scale multiplier factor, which was also used as a calibration parameter, was introduced. Linear regression coefficients of 4.5 and 4.4, slopes of 0.3 and 0.6 and time lags of 2.4 and 3.4 weeks were obtained for the runoff/air temperature relationship in Butte Creek and the West Branch Feather River, respectively. A subsurface temperature of 17°C was obtained. A reach length factor of 3.7 with 95% confidence interval of 3.05–4.42 was obtained. With this calibration, a reasonable upstream-downstream water temperature profile in the habitat reach [Fig. 3(b)] was obtained as compared to observations with a RMSE range of 0.09 to 0.14°C, BIAS range of −0.02 to −0.10, and an E range of 0.36 to 0.49.

WEAP outputs weekly mean water flow and weekly mean water temperature to a csv file, which is modified manually in Excel into the format required by the salmon population dynamics model, then used as an input data file for that model.

SALMOD Fish Population Dynamics Model

Our framework continues with SALMOD—a population dynamics model that simulates the freshwater life stages of the salmonid life cycle, including threshold effects on survival in response to environmental conditions (Bartholow 1996). It is deterministic and spatially explicit, operates on a weekly time step, and relates stage-based demographic parameters (e.g., growth and mortality) and biological processes (e.g., migration and spawning) to habitat units and climatic variables (e.g., water temperature and flow) (Bartholow et al. 1993). For a full description of the model, see Bartholow et al. (2002). We chose SALMOD because it has been used in other California watersheds (Bartholow 2004; Bartholow and Heasley 2006; Campbell et al. 2010), making it familiar to local water managers. In addition, SALMOD's basic features include the ability to

J. Water Resour. Plann. Manage., 2012, 138(5): 465-478

model SRCS distribution across the 120 habitat units, which was important because in most years SRCS were concentrated in the upstream habitat units. SALMOD's ability to model multiple life stages was also important because the study objective was to investigate adult over-summering mortality, egg mortality (in vivo and in situ), and juvenile mortality, and there was not an a priori way to determine the life stage that would be most affected by climate change. Additionally, starting off with a framework designed for the complete freshwater life history allows for future research to include other life history stages in a relatively seamless manner.

SALMOD requires an input file with parameters for each age class of salmon (Table S1). For example, for adult salmon this includes a water temperature-mortality relationship, base mortality, density-related mortality and movement, length:weight regression, weight:fecundity regression, sex ratio, spawning habitat capacity, and water temperature-based timing of spawning. Parameter estimates were obtained from agency reports, primary literature, books, and previous SALMOD implementations. Parameters for all age classes in SALMOD were included in model calibration, but because of the strong influence of adult summer mortality on population persistence, model results were largely insensitive to parameters for other age classes.

Preliminary model runs indicated that in many instances few adult SRCS survived the over-summering period to spawn, making conditions for in situ egg survival and juvenile survival less relevant and indicating that the temperature-mortality relationship for over-summering adults was critical to the SALMOD calibration. A relationship based on field data specific to Butte Creek SRCS was estimated. Eight years (2001–2008) of overlapping data from prespawn carcass surveys, summer snorkel surveys, spawner abundance estimates, and water temperature data from 6 of the 40 CDFG reaches were used (Garman and McReynolds 2009; Ward et al. 2004; California Dept. of Fish and Game, unpublished data, 2008). Rather than applying a constant temperature across all intermediate habitat units (stream segments) as has been done in some previous SALMOD implementations, a linear interpolation was performed so that temperature would gradually change between points of known temperature. Fish were spatially distributed in SALMOD each calibration year according to the estimated spatial distribution from the annual snorkel survey. The total number of fish in the system each year was based on estimated number of spawners and prespawn mortality for that particular year. The water temperature-mortality relationship for summer holding adults was described by a logistic function, similar in its final form to that used by Baker et al. (1995). The logistic function was chosen because it is a natural model for dose-response relationships, such as temperature and mortality rate, where weekly mortality rate is bounded by 0 and 1. The relationship was calculated within SALMOD using the PEST PAR2PAR routine (Doherty 2002) and was achieved by minimizing the sum of squared error between annual modeled mortality versus annual observed mortality. The resulting temperature-mortality relationship [Fig. 4(a)] had parameter estimates (95% confidence intervals) $\alpha = 115.08$ (100.178, 129.982) and $\beta = -5.421$ (-5.99, -4.86), respectively. The most sensitive range of weekly mean temperature lies between 20°C and 22°C, which is consistent with values found in the literature (see review in McCullough 1999). However, it should be noted that this temperature-mortality relationship may be specific to Butte Creek SRCS because it implicitly incorporates the effects of Butte Creek-specific water flow, including the instream flow requirement above the Centerville Powerhouse; the weighted usable area of each habitat unit; the spatial distribution of the SRCS in the years for which historical data were available; and any disease-related mortality that may have occurred.

SALMOD could be calibrated using either mean or maximum weekly water temperature. The mean was chosen because of the concern that prolonged warm periods would stress fish and increase their metabolic rates (and, in the case of juveniles, food requirements). A few hot days followed by cool nights may have been less likely to cause mortality than a sustained period with days almost as hot, but followed by warm nights. It was also not clear whether the weekly mean, weekly mean of daily maximums, or the weekly maximum would be the most appropriate metric to use because each potentially could play a role.

SALMOD was calibrated to annual estimates of adult prespawn mortality from prespawn carcass surveys. SALMOD was calibrated using two different habitat data sources: (1) observed water flow and observed water temperature and (2) modeled water flow and observed water temperature generated by WEAP for the five years when historical climate forcing data overlapped the eight years of ecosystem observation data (2001–2005). During the summer months water flow varied little in the upstream half of the SRCS

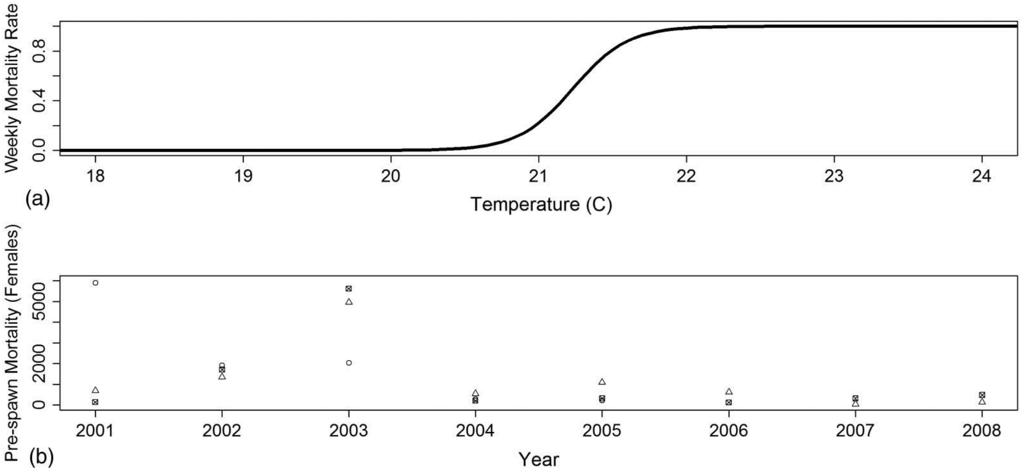

Fig. 4. SALMOD calibration: (a) water temperature-mortality relationship based on Butte Creek spring-run Chinook salmon data (2001–2008), using weekly mean temperature and weekly mortality; (b) comparison of observed summer prespawn mortality (2001–2008) (squares), simulated mortality using observed weekly mean flow and water temperature data (2001–2008) (triangles), and simulated mortality using WEAP-simulated weekly mean flow and water temperature data (2001–2005) (circles)

holding area because of the minimum flow requirement of 1.13 m^3/s that applies during this period between DeSabla Powerhouse and Centerville Powerhouse, where the majority of SRCS hold. As a result, water temperature dominated the SRCS prespawn mortality calibration. The modeled water temperature captured the overall structure of the historical temperature data, and the modeled data displayed reasonable accuracy and bias across the summer season, as well as across years. However, modeled water temperature differed from observed by ±2°C in a few key weeks (week 27 of 2001 and week 29 of 2003), reducing the SALMOD performance in simulating adult prespawn mortality. For comparison, the observed salmon mortality and the simulated salmon mortality are presented: (1) using observed flow and water temperature data and (2) using modeled flow and water temperature data [Fig. 4(b)].

SALMOD clearly performs better when observed environmental data, rather than when data modeled using WEAP, are used to guide the calibration. To evaluate model fit, a linear regression of model output (X) on observation data (Y) of the form $Y = A + BX$ was created. The coefficient of determination, R^2, had a value of 0.9252 for the observed historical climate data, but $R^2 = 0.0017$ for the WEAP-generated historical data. The regression estimates for A and B would equal 0 and 1, respectively, if model predictions perfectly matched observations. When this is not the case, differences between model output and observed data are from unexplained variance rather than a systematic bias or inconsistency (Pineiro et al. 2008). Use of observed environmental data yielded P-values for the tests for intercept and coefficient of 0.338 and 0.21, respectively, suggesting that SALMOD provides an adequate prediction of adult salmon summer mortality based on observed spawner abundance and spatial distribution, water temperature, and flow. SALMOD was calibrated based on observed water flow and water temperature data, and, by necessity, model output was used as the unknown environmental conditions under future climate scenarios. This gave a salmon model that is calibrated to have the best possible fit to historical conditions.

Given the errors inherent in the WEAP calibration, a number of factors may reduce the accuracy of the predictions: (1) in any particular year of the future scenarios, modeled water temperatures may not be perfectly accurate, so the salmon survival may be under or overestimated; (2) climate scenarios currently available may not accurately reflect future climate, particularly if emissions continue to exceed those in any of the available scenarios; and (3) over the 90-year time frame of the predictions, other factors not included in this modeling exercise, such as ocean conditions, may have large climate-related impacts on adult salmon survival before their return to freshwater to spawn. Nevertheless, modeled long-term trends in salmon survival should be representative, as should the effects of management actions undertaken to decrease temperatures given the abilkity of WEAP to accurately capture broader trends in water temperature. This is because the key aim of this research was to identify environmental tipping points beyond which salmon could go extinct, not the exact year in which this would occur.

To model effects of future climate and management actions on the summer survival of adult SRCS the parameter set from the SALMOD calibration based on observed environmental data was used. Because SALMOD does not include an ocean habitat component to calculate the number of returning adults for a given cohort, the system was seeded each year with 15,000 holding adults, the approximate annual spawner abundance in the last decade. It should be stressed that this accommodation likely causes the results to overpredict the time that salmon will persist. Also in the historical data set, the initial spatial distribution of adult salmon along the creek is quite variable from year to year. There is no way to know what initial distribution would occur in the future. Therefore, the mean initial spatial distribution from the eight years of historical data (2001–2008) was used as the initial distribution in all future scenarios.

Implementation of Analytical Framework for Future Climate Scenarios and Management Adaptations

The experimental design relied upon identification of a set of GCMs run under a pair of emission scenarios that would allow for estimation of the uncertain fate of SRCS in the system. While this approach is not sufficient to characterize the probability of any potential future state of the system, it provides a first estimation of system vulnerability to progressive climate change while considering possible changes in the hydrologic regime (e.g., change time and duration of dry periods) over the course of the entire 21st century. Multiple GCMs and emissions scenarios were used because we had no a priori method to know how variable the predictions would be for the Butte Creek watershed or which would be most accurate. The intention is to show that the group of models and scenarios used provide a reasonable "predictive envelope" of the future climate.

Six GCMs (cnrmcm3, gfdlcm21, microc32med, mpiecham5, ncarccsm3, and ncarpcm1) were used for the analysis, which have been selected for California's "2008 Climate Change Impact Assessment" (http://meteora.ucsd.edu/cap/scen08.html) and two emission scenarios, A2 and B1 (IPCC 2007). Downscaling to the Butte Creek system was accomplished using the bias correction and spatially downscaling method (Maurer and Hidalgo 2008), which generated continuous daily fields of key climate variables on a 12 km × 12 km grid scale over the system. This method uses statistical transformations to match observed climate data to outputs from GCMs during the historical period that are then applied to future climate projections. These daily values were converted to weekly averages for use in WEAP. There is a general consensus among models that conditions in Butte Creek will become drier and hotter over the course of the 21st century with obvious negative implications for SRSC in the system (Cayan et al. 2008).

To assess the vulnerability of the system under these potential climate futures, the Butte Creek WEAP application was first run assuming that current management arrangements remain in place. Having established baseline vulnerability, three simple management adaptations were considered: (1) eliminate the diversion of water from Butte Creek at the Centerville diversion dam during the critical July-September holding period, with all flow in the creek released into the SRCS summer holding reaches; (2) release water from Philbrook Reservoir from the warm top layer prior to week 30 (July 23–29) and after week 40 (October 1–7) while releasing from the cooler bottom of the reservoir between these dates (in actuality releases are currently possible only from the bottom of the reservoir); and (3) combine adaptations 1 and 2. Options 1 and 3 result in loss of power generation from Centerville Powerhouse. Neither current nor upcoming climatic conditions nor the actual water temperature conditions in critical reaches of Butte Creek were used to condition these management actions.

These changes in operations (adaptations) are being considered as part of ongoing FERC relicensing of the DeSabla-Centerville project, based on recognition that even under historical climatic and hydrologic conditions, SRCS in Butte Creek are vulnerable to water temperature conditions in excess of critical thresholds during the summer holding period. One potential advantage of the current analysis is the focus on understanding how these adaptations may perform under future climatic and hydrologic regimes that depart from conditions observed in the recent historical past.

Climate Scenario Analysis

Weekly mean precipitation, air temperature, and wind speed for the 12 GCM-emission scenario combinations for the 2009–2099 period were used in the WEAP model. Streamflow predictions were made for June, July, and August (JJA) and December, January, and February (DJF) for three periods (2009–2034, 2035–2069, and 2070–2099). These predictions indicate that, although some scenarios may have greater streamflow in the winter, all scenarios have a 20–50% reduction in summer streamflow [black bar in Fig. 5(a)] for the 2070–2099 period relative to historical averages. Summer water temperatures are predicted to increase 2–5°C for the 2070–2099 period, relative to historical averages [Fig. 5(b)]. This range of variability in the results highlights the inherent uncertainty of this sort of analysis and the need to evaluate a range of plausible future conditions.

To observe the spatial effect of these climate scenarios throughout the spawning reach, the aggregated water temperature distribution of all six A2 scenarios and all six B1 scenarios for pools A1, C5, C7, and E7 was plotted and compared to the historic modeled temperature distribution (Fig. 6). These box plots represent the range of uncertainty. The results indicate a consistent increase in temperature in all pools for the analyzed climate scenarios. The increase in the median rises linearly from 1.42 to 2.33°C from pools A1 to C7 for A2 scenarios and from 1.04 to 1.65°C for B2 scenarios.

SRCS extinction was defined as four consecutive years of zero prespawn survival of adult salmon. Because most Butte Creek SRCS spawn at three and four years of age (McReynolds et al. 2007), after four years in which no adults survive to spawn there would be no fish alive to return from the ocean to reproduce. This survival rate is based on an initial seeding of 15,000 adult salmon each year because of the inability of SALMOD to estimate the number of returning adults for a given cohort. This did not allow population declines to accumulate over years, suggesting the population extinction is likely to occur before there are four

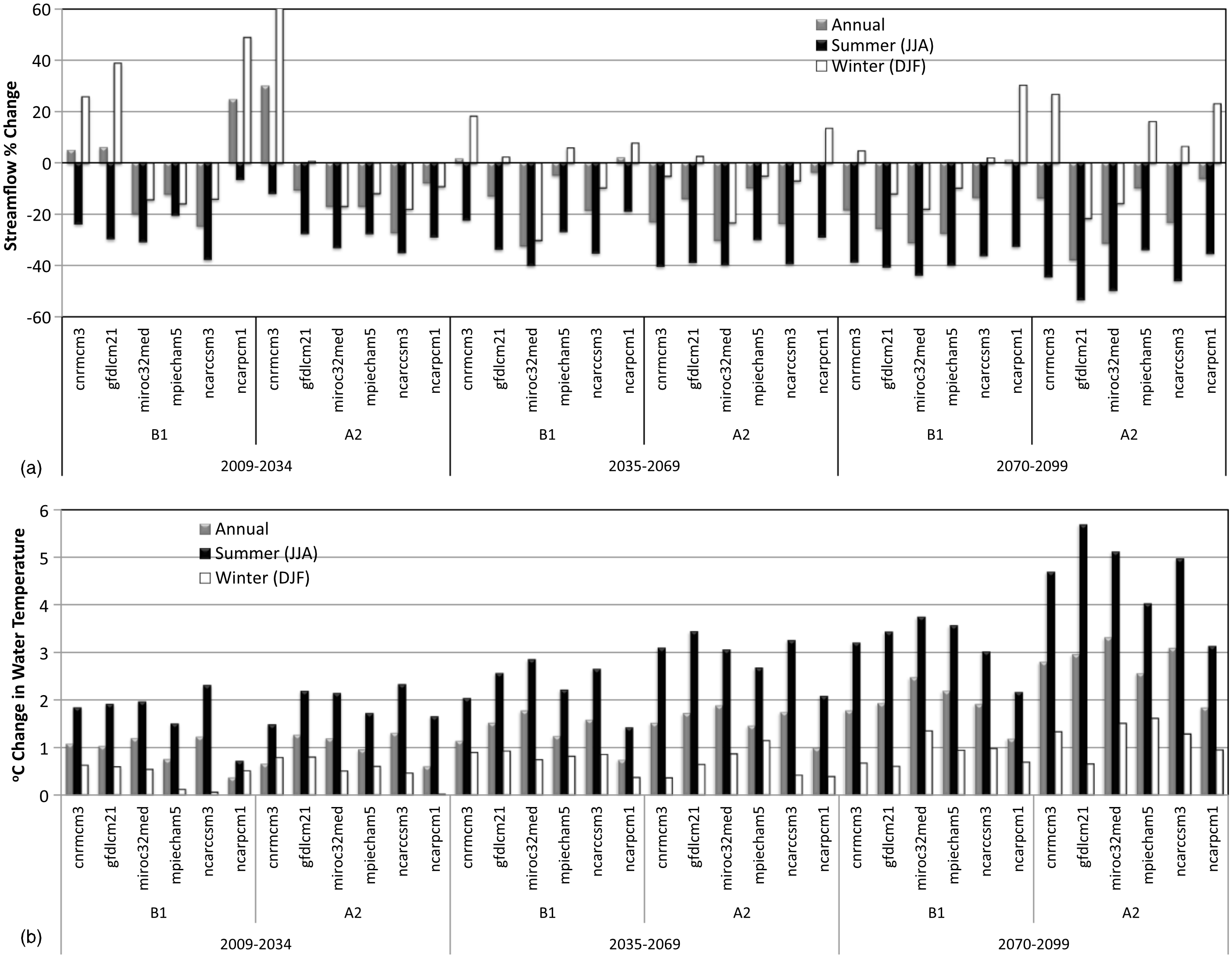

Fig. 5. Simulated: (a) streamflow and (b) water temperature change for periods 2009–2034, 2035–2069, and 2070–2099 for six GCMs under A2 and B1 greenhouse gas emission scenarios, relative to 1986–2005 historical averages for annual (10 m^3/s, 11°C), summer (6 m^3/s, 18°C), and winter (15 m^3/s, 5°C) simulated streamflow and water temperature, respectively; 30-year mean changes are shown for visualization; weekly mean streamflow and water temperature were actually generated by WEAP and passed to SALMOD; for detailed explanations of the greenhouse gas emissions scenarios, see IPCC [2007, Fig. 3(a)] and for information regarding GCMs, see California Applications Program/California Climate Change Center website on California's 2008 Climate Change Impact Assessment (http://meteora.ucsd.edu/cap/scen08.html)

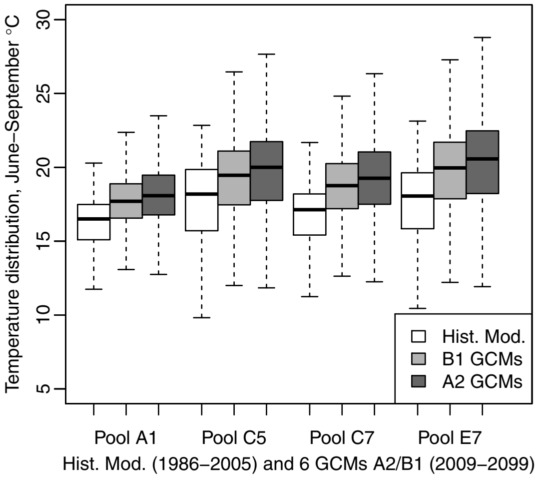

Fig. 6. Water temperatures predicted for six GCMs under A2 and B1 greenhouse gas emission scenarios (distribution of all GCMs for 2009–2099 are graphed together for each scenario and pool) and historical modeled (1986–2005) weekly average water temperature distribution for weeks 24–39 for pools A1, C5, C7, and E7

consecutive years of simulated zero prespawn survival. For three of the six B1 scenarios, salmon were able to survive the full 90-year simulation without meeting the extinction criterion, whereas none of the A2 scenarios saw salmon survive for the full 90-year simulation. The shortest time to extinction was 49 years and occurred for the A2 cnrmcm3 model-scenario combination. There is a distinct difference between the extinction times predicted by the A2 and B1 emission scenarios, averaging 63.5 and 84 years, respectively (Fig. 7).

There is considerable variation and uncertainty among predictions for the 12 GCM-emission scenario combinations in terms of the proportion of adult salmon that survived the freshwater summer holding period and spawned each year, ranging from years where most fish survived the summer to years where no fish survived (Fig. 7). Over the full 90-year simulation the average proportion of fish that survived to spawn each year was similar for the A2 and B1 emission scenarios, 0.29 and 0.39, respectively. When counting only years in which there were surviving fish, these values increase to 0.43 and 0.46, respectively.

Management Adaptation Analysis

To observe the spatial effect of the management adaptations throughout the spawning reach, the aggregated water temperature distribution of all 12 GCM-climate scenario combinations for each management adaptation for pools A1, C5, C7, and E7 was plotted and compared to the aggregated temperature distribution of all climate scenarios for business-as-usual (baseline) management (Fig. 8). The temperature distribution is a range that represents the uncertainty of all 12 GCM-emission scenario combinations. The results indicate slight decreases of <0.01°C in water temperature for all quartiles of all management adaptations in pools C7 and E7. Management adaptation 1 and management adaptation 3 indicate a reduction in the median temperature in pool A1 of 0.2–0.3°C and a reduction in the median temperature in pool C5 of 0.8–1°C.

Across the 12 GCM-emission scenario combinations, management adaptation 1 increased the estimated time to extinction of salmon by zero to 17 years over the respective baseline values (Fig. 9). The mean increase in time was 4.75 years (for all comparisons all 12 model climate scenario combinations were considered,

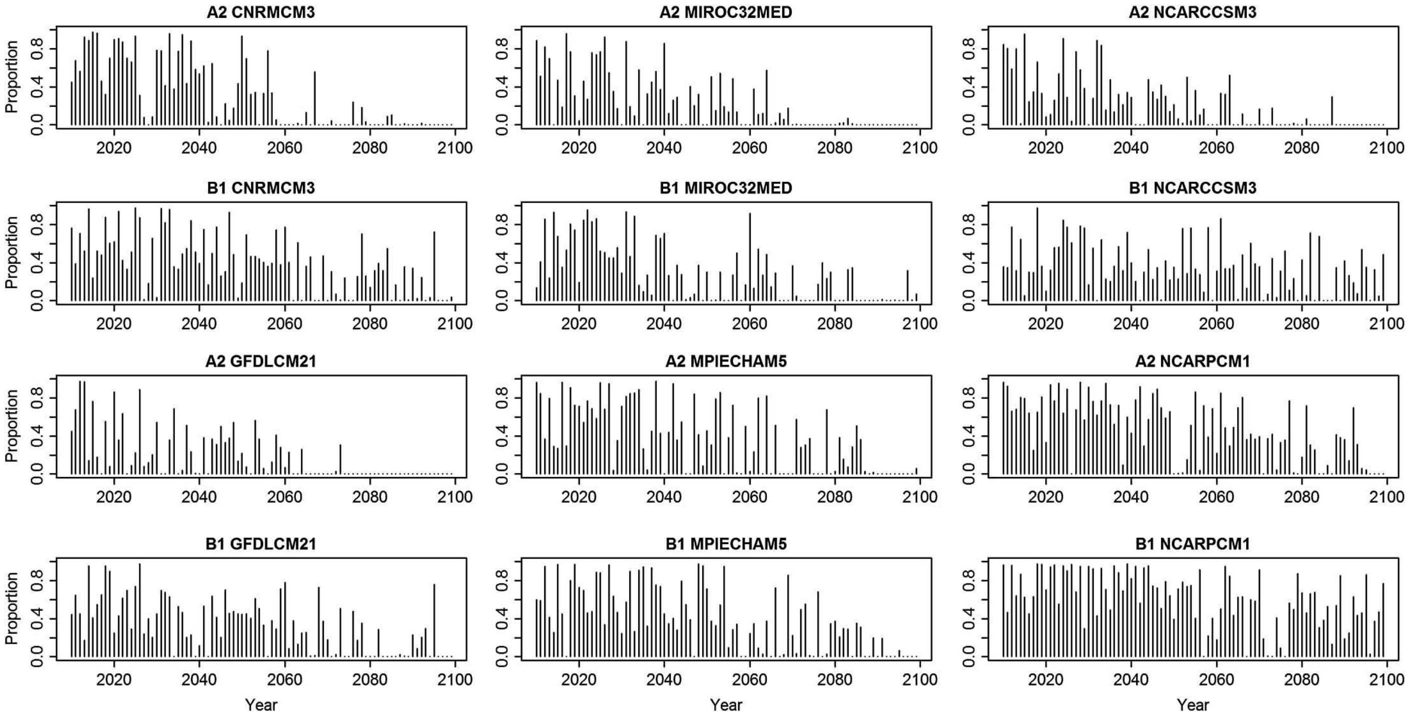
A2 CNRMCM3
A2 MIROC32MED
A2 NCARCCSM3
B1 CNRMCM3
B1 MIROC32MED
B1 NCARCCSM3
A2 GFDLCM21
A2 MPIECHAM5
A2 NCARPCM1
B1 GFDLCM21
B1 MPIECHAM5
B1 NCARPCM1

Fig. 7. Proportion of adult salmon that survived freshwater summer holding period, predicted for six GCMs under A2 and B1 greenhouse gas emission scenarios for 2009–2099; salmon were assumed to be extirpated when there were four consecutive years with no adult summer survival

J. Water Resour. Plann. Manage., 2012, 138(5): 465-478

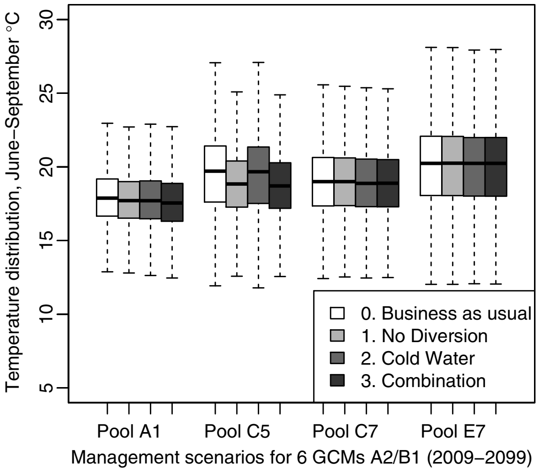

Fig. 8. Water temperatures predicted for six GCMs under A2 and B1 greenhouse gas emission scenarios and three management adaptations: 1-no diversion, 2-cold water savings, and 3-combination of both; data for 12 model and climate scenario combinations for 2009–2099 are graphed together for each pool A1, C5, C7, and E7; *Y*-axis shows weekly average temperature distribution for weeks 24–39

including those where salmon survived to 2099). Management adaptation 2 was not effective for any of the 12 model climate scenario combinations, and in some cases made extinction occur sooner. The range of changes in extinction time was zero to 6 years sooner. The average change in extinction time was 0.58 years sooner. For management adaption 3, the range of changes to extinction time are from 1 year sooner to 17 years later. The mean change in extinction time was 3.4 years later. The effects of management adaptations 1 and 2 appear to be cumulative in management adaptation 3, with any net benefit being caused by management adaptation 1. Management adaptation 2 appears to be counterproductive.

The management adaptations changed the proportion of adult salmon that survived to spawn each year over the duration of the simulation (Fig. 10). For management adaptation 1, there was a mean increase of 0.52 (range from 0.32 to 0.64), with emission scenarios A2 and B1 having similar mean values of 0.51 and 0.52, respectively. As was the case for extinction time, management adaptation 2 was ineffective in improving fish survival. It had a mean proportional decrease of 0.08 (range from −0.04 to −0.12), with emission scenarios A2 and B1 having similar values of 0.08 each. Management adaptation 3 had a mean proportional increase of 0.42 surviving fish (range from 0.30 to 0.53). The A2 and B1 scenarios had similar mean values of 0.41 and 0.43, respectively.

Analyses Uncertainty

Each of the components in the analytical framework contributes unique errors and uncertainties that have implications for this study's results. This raises the issue of how best to represent uncertain future climate conditions in the framework. Key sources of uncertainty at this stage of the analysis are model inputs and parameter choices (Van Asselt and Rotman 2002). This study worked from the premise that a method is useful if it produces a plausible set of expectations about what is an inherently uncertain future and is also appropriate to the question at hand. This was the standard used to select a set of climate projections used to derive insights on the possible trajectory of SRCS in Butte Creek.

Uncertainty in precipitation and air temperature input data obtained from GCMs and emission scenarios translates into greater uncertainty in the climate and management predictions generated. Given the wide variability of possible future scenarios, the approach to incorporating this uncertainty into the analysis was to run multiple GCMs and two emission scenarios to generate a comprehensive ensemble of potential future climates. By selecting this approach, the future projections provide a range of possible responses of the system to climate and to potential management adaptations.

The set of parameters used to calibrate models for historic conditions have ranges of uncertainty provided by the confidence intervals found during calibration. These parameters may change in the future; however, it is not possible to know how they will change

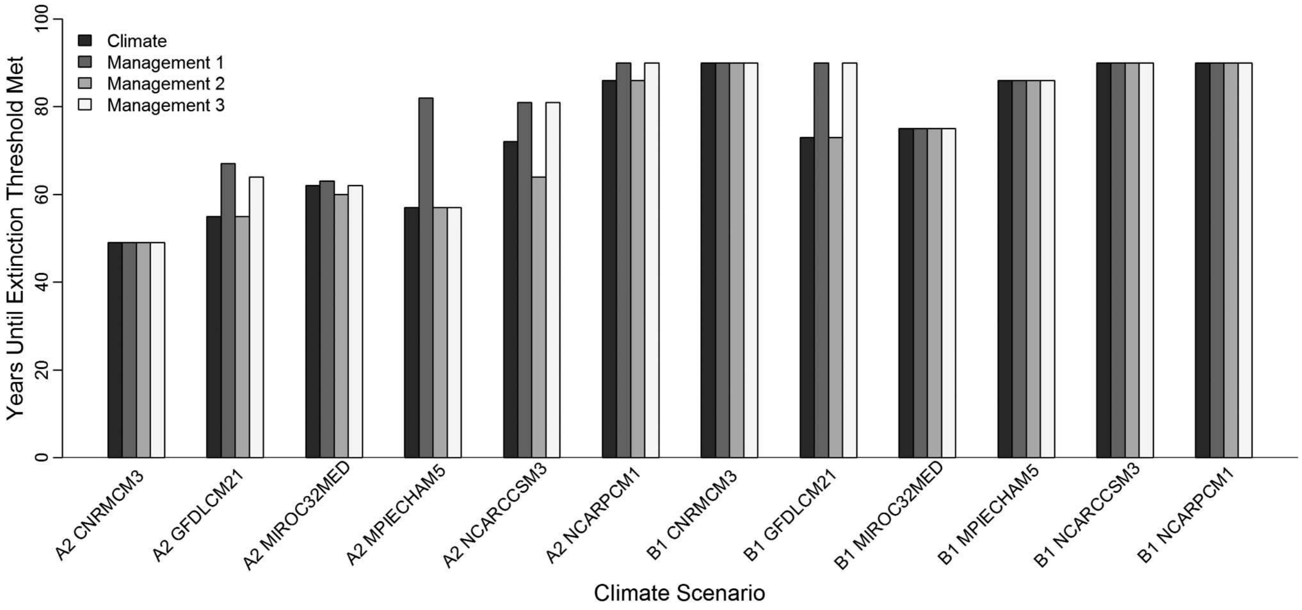

Fig. 9. Survival time of spring-run Chinook salmon in Butte Creek predicted by SALMOD for six GCMs and A2 and B1 emission scenarios, baseline climate change case, and three management adaptations; model was run for 90 years (October 2009–September 2099)

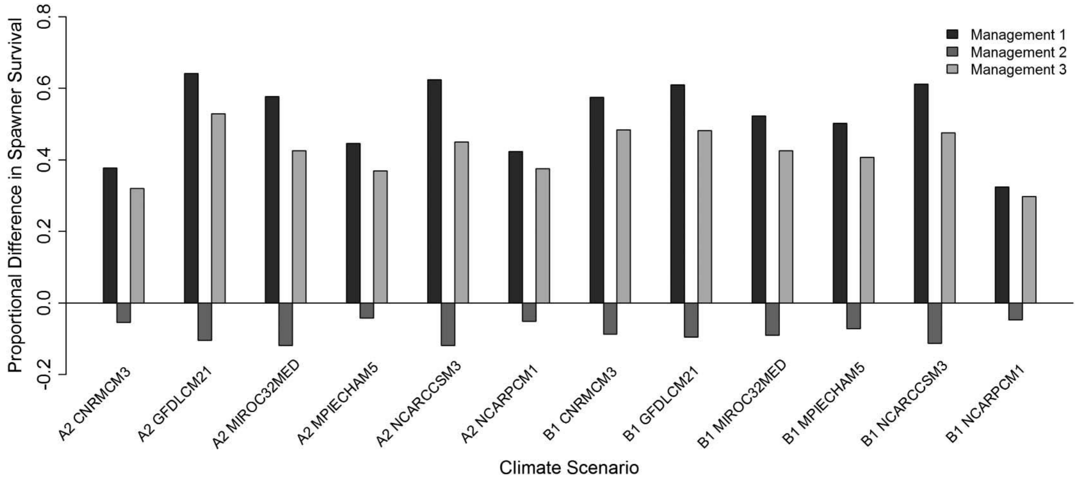

Fig. 10. Proportional difference in annual survival of spring-run Chinook salmon in Butte Creek predicted by SALMOD for six GCMs and A2 and B1 emission scenarios for three management adaptations, relative to baseline climate change case

and consequently, using them for estimates of future fish abundance adds additional uncertainty to the predictions.

In the future, the spatial distribution of adult SRCS along Butte Creek may differ from past observations. We explored how sensitive the model results are to uncertainty in this distribution. Using the most extreme GCM-climate scenario combination (A2 cnrmcm3), the study bootstrapped from its known spatial distributions to create 20 different fish distributions. After inspection of the output, it appeared that only three of the 20 scenarios resulted in extinction at the same time as the initial simulation, while in the rest the salmon made it to the end of the 90-year simulation. However, if the threshold criterion for determining extinction is increased from four consecutive years of zero surviving fish to four consecutive years of 20 or fewer fish, all 20 bootstrapped scenarios are consistent in that extinction occurs at the same time as in the initial simulation. A reinspection of the initial scenario showed that the same extinction time is predicted by a minimum threshold population size of 20 fish as when the threshold is at zero fish for all 12 GCM-climate scenario combinations. This result indicates that model performance is relatively robust with respect to the spatial distribution used. Furthermore, the most upstream habitat unit will always be the coldest, so, assuming that some SRCS will always hold in this habitat unit, the year of extinction for a given model run will ultimately depend on water temperature in this unit. The spatial distribution of fish in other habitat units and the temperature gradient along the creek will affect the abundance trend over years of the simulation, but when no SRCS adults can survive the summer in the upstream habitat unit, all SRCS adults in all other units would also not survive.

Ecosystem modeling must make simplifications relative to the complexity of the real world. The models in this study were simplified by the exclusion of processes such as hyporheic flow, potential pool stratification, changes in channel morphology or land use, ocean conditions, fish disease dynamics, and metapopulation dynamics between Butte Creek and other SRCS watersheds. However, because these factors would have both positive and negative effects on abundance, the assumption was made that any resulting errors would cancel each other out. Excluding some relevant processes from the analytical framework increases uncertainty in model predictions, although it was anticipated that changes would be small. The analytical framework may be improved by adding one or more of these influences, but at the cost of increased complexity and reduced comprehension of results.

Discussion

An analytical framework linking climate data, a watershed hydrology model, water management, and salmon population dynamics was assembled and applied to SRCS in Butte Creek. Given the availability of historical data, the WEAP and SALMOD models were calibrated to fit historical records of flow, water temperature, and over-summer adult salmon mortality for the watershed. This framework was used to predict outcomes of current water management on SRCS populations, as well as management under future climate change and management adaptation. The analytical framework offers a clear advantage over previous work, in that it allows explicit modeling of specific water management options as a response to flow and water temperature requirements of salmon.

The management options investigated all come to the basic conclusion that a dramatic change in the system will take place in the second half of the 21st century. Only halting all diversions from the creek during the critical July to September holding period has potential for delaying the year when the system tips past a critical threshold for SRCS, but at the expense of a great deal of hydropower generation. Particularly vexing is the implication that changing management of the upstream reservoir has little positive impact. This raises another set of questions about whether it is prudent, from a policy perspective, to continue efforts to define management regimes to maintain SRCS in Butte Creek. A closer look suggests that while there would certainly be ample justification for refining SRCS restoration plans that consider the large metapopulation in the Central Valley, there is also reason to consider more aggressive and refined management regimes within Butte Creek itself.

Consider, for example, the potential management of the cold water pool in Philbrook Reservoir. Analysis of the simulated water temperature profiles suggest that rather than producing a system with an enhanced cold water pool, the release of water from near the top of the reservoir outside the critical summer period actually degraded thermal stratification of the reservoir. This was likely associated with a general thinning of the upper warm layer, allowing for deeper penetration of incoming solar energy. While Philbrook Reservoir is likely not large enough to support this sort of operation while maintaining stratification, it is worth noting that the management strategy modeled was relatively rigid in that the change in operations was set at a specific week and not based on downstream water temperature estimates. Rules designed to make more judicious use of the cold water resource when conditions in the over-summer holding reach were actually approaching critical water temperatures could potentially be adjusted relative to the thermal characteristics of Philbrook Reservoir to improve system viability. Evaluating more aggressive and refined adaptation strategies will be the focus of future modeling work conducted using this study's analytical framework. They represent the kinds of water management adaptation strategies that will be required to protect vulnerable aquatic ecosystems throughout California.

Climate change may affect metapopulation processes in ways that will be important to salmon dynamics (Schindler et al. 2008). Given the vulnerable nature of SRCS in Butte Creek, this may be particularly important for the sustainability of SRCS in the Central Valley. Historically, the Central Valley SRCS ESU comprised 18 independent populations, but it has only three independent populations remaining (Lindley et al. 2007). While the project focused on Butte Creek SRCS, it is likely that management adaptations that sustain Butte Creek SRCS will not be adequate to ensure the survival of the ESU. Reintroduction of salmon above impassable dams (potentially through trap and truck operations) has been recommended (NMFS 2009) to allow salmon to reach cooler water at higher elevations and to increase the number of watersheds occupied by SRCS. Watersheds in the southern half of the Sierra Nevada are predicted to retain more snow pack (and thus more summer base flow) than those in the northern half (Maurer et al. 2007), so reintroducing SRCS to southern watersheds may be a particularly effective method to distribute the risk of extinction. Indeed, SRCS reintroductions have been recommended above the lowest dam on the Stanislaus River and in the San Joaquin River below Friant dam (NMFS 2009). However, it is not known whether future climate scenarios will provide adequate conditions for SRCS in other watersheds or whether water management adaptations exist in these watersheds to mitigate climate change impacts. The framework developed in this paper could be applied to other SRCS watersheds and could form the basis for metapopulation-scale salmon management to balance human water needs with habitat requirements of salmon.

Conclusions

The most important conclusion of this work is that the long-term survival of SRCS in Butte Creek is questionable in the face of climate change and that simple changes to water operations are not likely to dramatically change vulnerability to extinction. Specifically, the analysis reveals that it is plausible to expect that the system will tip past critical thresholds some time during the second half of the 21st century. For the managers of SRCS in Butte Creek, and in the wider Central Valley, this conclusion poses significant challenges that require an ecosystem protection strategy that moves well beyond incremental changes in management of SRCS. It is likely that Butte Creek SRCS are not the only resource facing such a challenge.

This highlights the second important conclusion—water management adaptations may extend the survival of threatened salmon populations on the time scale of decades. Linked analytical frameworks such as the one presented in this study can guide adaptation of water management regimes to protect important ecosystem services. Furthermore, the results imply that management options available with current infrastructure need to be fine tuned to obtain the maximum benefit from power production while significantly reducing SRCS vulnerability to extinction. Without such changes in water management, SRCS are likely to go extinct in Butte Creek and elsewhere in California.

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Supplemental Data

Table S1 (SALMOD input files Relation.dat, Suplement.dat, and Control.dat) is available online in the ASCE Library (www.ascelibrary.org).

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