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Climate warming, water storage, and Chinook salmon in California's Sacramento Valley

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Abstract The Chinook salmon (*Oncorhynchus tshawytscha*) spawns and rears in the cold, freshwater rivers and tributaries of California's Central Valley, with four separate seasonal runs including fall and late-fall runs, a winter run, and a spring run. Dams and reservoirs have blocked access to most of the Chinook's ancestral spawning areas in the upper reaches and tributaries. Consequently, the fish rely on the mainstem of the Sacramento River for spawning habitat. Future climatic warming could lead to alterations of the river's temperature regime, which could further reduce the already fragmented Chinook habitat. Specifically, increased water temperatures could result in spawning and rearing temperature exceedences, thereby jeopardizing productivity, particularly in drought years. Paradoxically, water management plays a key role in potential adaptation options by maintaining spawning and rearing habitat now and in the future, as reservoirs such as Shasta provide a cold water supply that will be increasingly needed to counter the effects of climate change. Results suggest that the available cold pool behind Shasta could be maintained throughout the summer assuming median projections of mid-21st century warming of 2°C, but the maintenance of the cold pool with warming on the order of 4°C could be very challenging. The winter and spring runs are shown to be most at risk because of the timing of their reproduction.

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1 Introduction

The Chinook salmon (*Oncorhynchus tshawytscha*) is an anadromous fish that spawns in the upper reaches of the mainstem rivers and tributaries of California's Central Valley. After spending a few months in the natal rivers or downriver nursery areas, the juveniles migrate to the Pacific Ocean where, after a stay of 2 or more years, they reach maturity (U.S. DOI 1996). The adult fish then migrate back to their natal rivers and streams to spawn. Shortly after spawning, the adult fish die (Meehan and Bjornn 1991). Historically, there have been four separate seasonal spawning runs of Chinook in the Central Valley (NOAA 2001): fall and late-fall spawning runs, a winter spawning run, and a spring spawning run. The total (i.e., all seasons) peak spawning of Chinook in the Central Valley at the beginning of the 20th century was approximately 800,000 to1 million adult fish (SFEP 1992; NOAA 2001). Spring run fish were the most abundant, followed by the fall and late-fall runs, then the winter run.

Beginning in the late 19th Century, Chinook salmon have come under increasing anthropogenic stress, resulting in major population reductions. The greatest contributor to this has been the construction of dams blocking access to spawning habitat. Suitable spawning habitat has been reduced from historic levels of about 6,000 river-miles in the Central Valley to about 300 river-miles today, concentrated in the Sacramento River's mainstem. Estimated losses of spawning and nursery habitats after the construction of the Shasta and Keswick dams alone were 50 percent (DWR 1988), and subsequent activities such as diversions and bank-protection programs have led to additional habitat losses.

The different runs have not been affected equally. Traditionally, the winter and spring runs spawned at the highest elevations; now, because dams have blocked access to much of their upper elevation spawning habitat, these two runs are most affected. Since the late 1960′s, the winter run has declined from over 100,000 fish to a few thousand today (U.S. DOI 1996). This has resulted in the winter run being listed as endangered under both the federal and California Endangered Species Acts. The spring-run Chinook in the San Joaquin River was eliminated entirely by the construction of the Friant Dam in 1949 (SFEP 1992). The surviving part of this run in the Sacramento River has been listed as Threatened under both the State and federal Endangered Species Acts. The least affected populations have been the fall and late-fall runs. This is because many of these fish spawn below the elevations at which most of the dams were installed. Even so, blocked access to spawning habitat has reduced these runs from a collective 500,000 fish in the 1950s to about 1–200,000 today.

Current populations of Chinook that migrate to and spawn in the Central Valley are, in part, artificially maintained by two activities: releases of hatchery-reared juvenile fish and, paradoxically, water management using dams. On average, 30 million fry and fingerlings per year are released from hatcheries into the rivers of the Central Valley, and approximately 30%–50% of the adults returning to spawn in the watershed are hatchery-reared (SFEP 1992). Meanwhile, releases of cool water from dams are crucial for maintaining suitable thermal conditions for the freshwater stages of the life-cycle, most notably releases from the Shasta Dam in the Sacramento River of the northern Central Valley.

Since they are coldwater fish that avoid areas where water temperatures exceed their physiological requirements (reviewed in DWR 1988; McCullough 1999), Chinook salmon may be vulnerable to climate change. It is possible that rising water temperatures in their natal rivers could adversely affect the ability of salmon to find suitable breeding habitats, especially since that habitat has already been reduced by dam construction. However, dams allow scheduled releases of cold water stored in reservoirs, such that the frequency and timing of these releases may have implications for salmon survival during spawning. In this paper, we assess the potential effects of climate warming and water storage on critical thermal aspects of Chinook freshwater habitat quality in the broader hydrologic and water management context of the entire Sacramento Basin (SB) and specifically with regards to Chinook Salmon, in the Sacramento Valley (SV) portion of California's Central Valley. The impact of climate warming and its implications for salmon population viability are also discussed.

2 Salmon thermal requirements and the effects of current water management practices

While the four Chinook seasonal runs have different migration phenologies, each has evolved to minimize exposure to warmer water temperatures. Prolonged exposures of Chinook salmon to water temperatures above about 20°C can result in a number of adverse effects, depending on the life stage (Moyle et al. 2002). Each life stage has its own optimal temperature range and its own response to temperature exposures outside that range.

Exposure of immigrating adults In laboratory studies, increased mortality and adverse physiological effects (reduced egg and hatchling viability) occurred when adult Chinook were exposed to water temperatures that exceed about 19°C for more than a few hours (Berman 1990; reviewed in McCullough 1999). Hallock et al. (1970) report that water temperatures above 20°C can also constitute a thermal barrier to adult immigration. Immigration stopped in the San Joaquin River when water temperature exceeded 21°C, but resumed when the water temperature fell to 18.3°C (DWR 1988).

Exposure of spawning adults Spawning Chinook require cooler water temperatures than those that can be tolerated during the adult immigration. In hatchery studies, exposing spawning females to water temperatures that exceeded 14°C resulted in increased egg mortality (Leitritz and Lewis 1976).

Exposure of eggs and hatchlings A number of studies have shown that the optimum upper temperature for egg and hatchling survival is 14°C or less (reviewed in McCullough 1999). In the American River of the SV, hatchling mortality increased in water temperatures exceeding 15.5°C (Hinze et al. 1956).

Exposure of juveniles In laboratory studies, increased mortality of juvenile Chinook generally occurred when water temperatures exceeded 20°C (reviewed in McCullough 1999). However, sub-lethal effects may occur at lower temperatures: reductions in growth rates were found when juvenile fish were held in water temperatures exceeding about 16°C (Bisson and Davis 1976; Marine and Cech 1998). Also, temperatures in excess of about 12–13°C may inhibit the development of migratory response and saltwater adaptation in juvenile fish (DWR 1988).

These requirements and limitations explain the timing of Chinook salmon life history events, which result in the different stages being at particular stream locations during particular times of the year. Based on the above information, in this study it is assumed that suitable adult immigration conditions are limited to areas and seasons where water temperatures are generally lower than 19°C; suitable spawning and rearing conditions require water temperatures of 14°C or less; and juvenile migration to the sea will be disrupted in areas or seasons where water temperatures exceed 18°C (the midpoint between the increased mortality and sub-lethal thresholds identified above).

Figure 1 summarizes the timing of immigration, reproduction, and emigration of the four runs of Chinook salmon in the SV. The result of these reproductive strategies is that adults and juveniles of all runs generally are not present in the lower river reaches during the warmest months of July and August. They migrate in and out of the system and through the lower rivers before or after the warmest months, and spawn and rear their young during colder months in those portions of the cooler, upper reaches that are still accessible.

2.1 Shasta Dam water storage and its effects on water temperature

To assess the implications of future temperature changes for Chinook salmon, it is necessary to examine current water *storage* practices at Shasta Dam and their effects on downriver water temperatures. While dams block migration pathways, they also store and release cool water that can maintain suitable water temperature and flow conditions for salmon spawning and rearing below the dam (SFEP 1992). Releases of water from the cold water pool stored behind a dam may provide cold water that reduces downriver summer water temperatures. Historically, however, this cold water from Shasta was not guaranteed, for as summer progressed, releases from Shasta tended to be warmer due to a deepening of the thermocline and drawdown of the reservoir (Deas et al. 1997).

Following the completion of Shasta Dam, the primary managed spawning habitat has been the reach from Keswick Dam (just above Redding) to Bend Bridge (about 60 km). River water temperature data collected below Shasta Dam following impoundment suggests that the average water temperatures were cooler by about 5°C in the spring (May and June) and cooler by 7–10°C in the summer (July and August) relative to pre-dam temperatures (DWR 1988) and before the reservoir was outfitted with temperature control devices (TCD's). The TCD's are an attempt to counter the seasonal evolution of warm temperatures in Lake Shasta. During the spring, when surface water temperatures are the coolest, operators release water from the highest levels of the reservoir, through the TCD. Then, during the summer and fall, when surface water has warmed, cooler water is taken from the mid- and low-level intakes, with an average targeted release temperature of around 11°C to 12°C from May to October, keeping the temperatures near Red Bluff near 13.3°C.

Measurements of Sacramento River water temperatures before the TDCs suggest that during normal hydrologic years, temperatures in the late summer were around 14°C downriver at Keswick, warming to around 17°C near Hamilton City (see Fig. 2 for locations). In the lower reaches of the Sacramento River, where the flow slows as the river transitions into the heavily-levied Delta area, the water warms considerably in the summer, with water temperatures climbing to nearly 25°C below the City of Sacramento. Sacramento River water temperature data for severe drought years, such as 1976–1977, show that during the late summer/early fall of 1977, water temperatures ranged from around 18°C to nearly 20°C between Redding and Red Bluff (DWR 1988). More moderate differences between historic and current river water temperatures occur in the early fall, while winter water temperatures are slightly warmer than pre-dam temperatures due to the warmer waters held and released during this period.

Having examined some of the factors affecting water temperatures in the SV and Chinook salmon survival, we can now design an approach for reaching the objectives of this paper: to identify which salmon runs are most at risk under changing climatic conditions and at what life stages, and to determine whether reservoir management may mitigate or exacerbate Chinook salmon vulnerability.

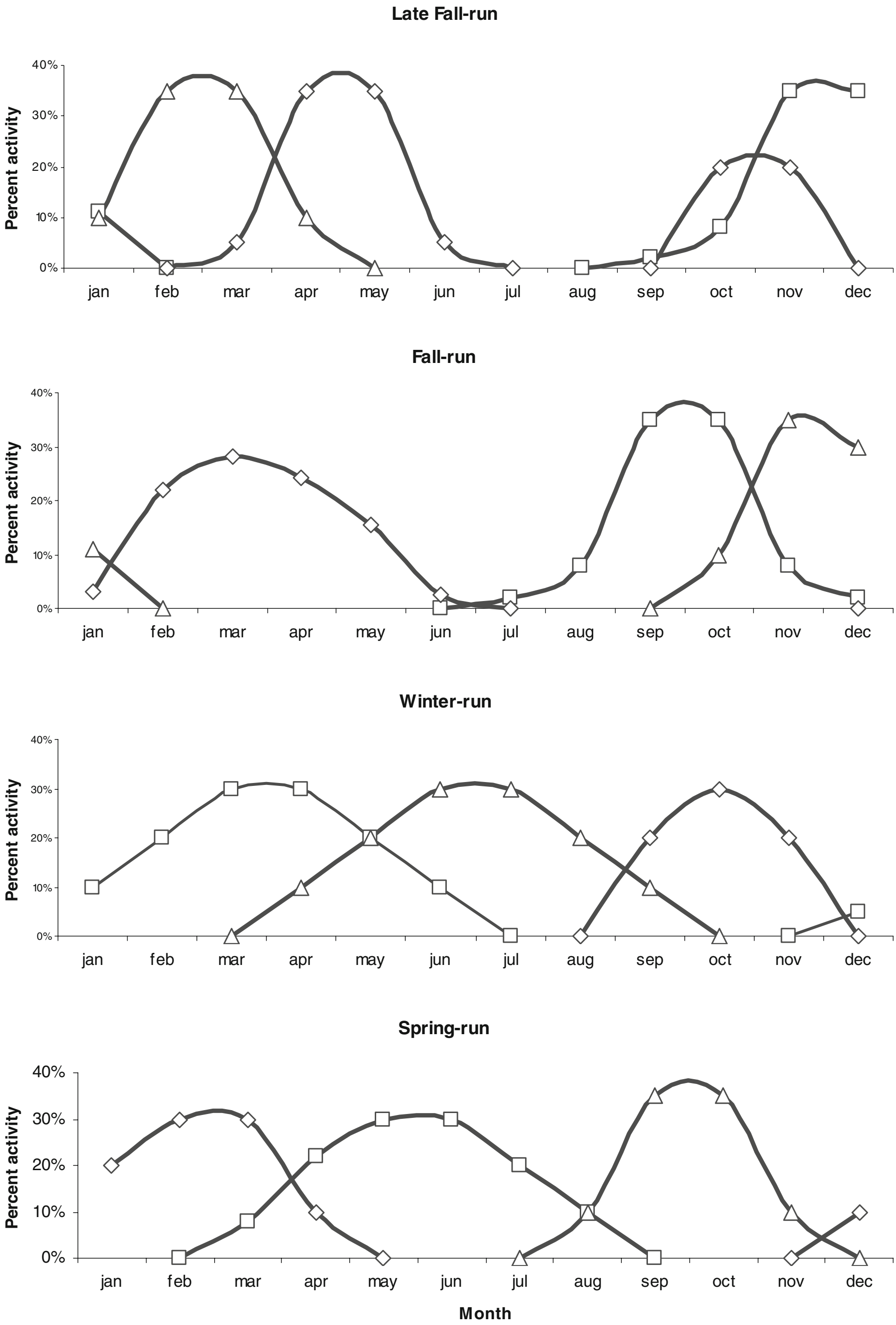

Fig. 1 Phenologies of reproductive events in freshwater phase of Chinook salmon life-cycle in the SV watershed. *open square* adult immigration; *open upright triangle* spawning and hatching; *open diamond* juvenile emigration. Compiled from data in NOAA (2001), DWR (1988), and U.S. DOI (1996)

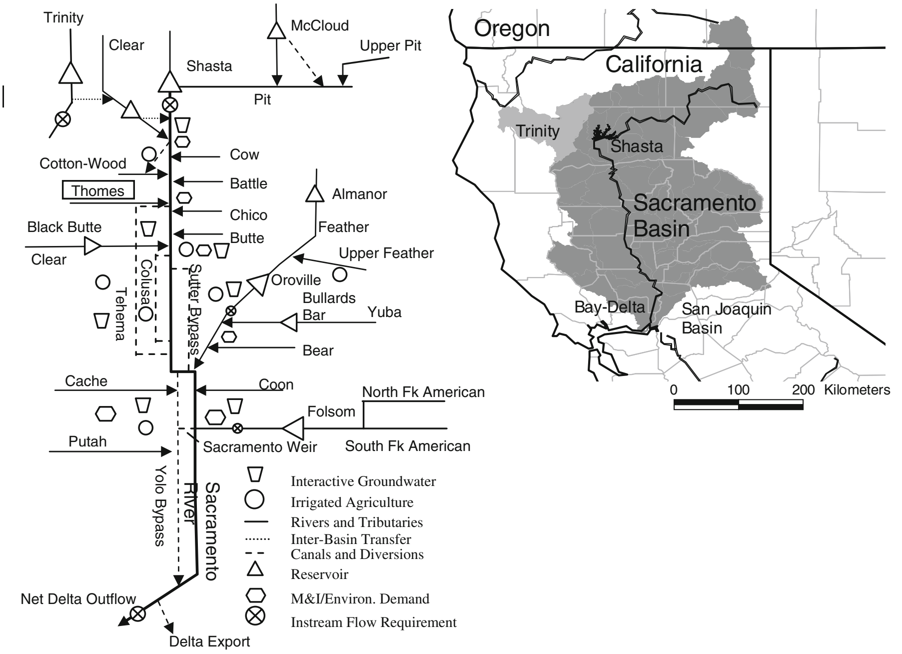

Fig. 2 Simplified schematic of the water resource elements implemented in the WEAP21 model of the SB (*left*), and the position of the Sacramento Basin in California (*right*). Map of the Sacramento watershed and important geographic locations, including counties (*light gray*) and state boundaries (*dark line*). The *hatch symbols* show the general locations where water temperatures are reported in the paper. Thomes Creek outflow (*outlined*) is approximately 100 km below Shasta reservoir and roughly the position of Red Bluff and Bend Bridge

3 A WEAP21 model of the Sacramento River

We investigated the potential impacts of climate warming and water storage on Chinook salmon in the Sacramento portion of the SV using a quantitative model of seasonal river flow and temperature regime for the river, from the Shasta Reservoir down to about Hamilton City (Fig. 2). This region includes the main spawning and rearing habitats and the portion of the river through which adults and juveniles must pass to reach their spawning areas and the sea. Downriver of Sacramento, the river bifurcates into the Delta, is tidally influenced, and is increasingly brackish. Our current hydrological model cannot adequately capture the complex flow paths below Sacramento that alter the river's temperature regime in this region, so we have focused on the spawning, rearing, and migration habitats that comprise the freshwater portion of the watershed.

The model was the Water Evaluation and Planning Decision Support System Version 21 (WEAP21, Yates et al. 2005a, b), which included coupled water management, physical hydrology, and river temperature models that can address both natural and managed water components (Hsu and Cheng 2002; Westphal et al. 2003).

3.1 The WEAP21 model of the Sacramento River flow and temperature

The WEAP21 model of the Sacramento Basin includes coupled water management, physical hydrology, and river temperature models that simultaneously simulate both natural

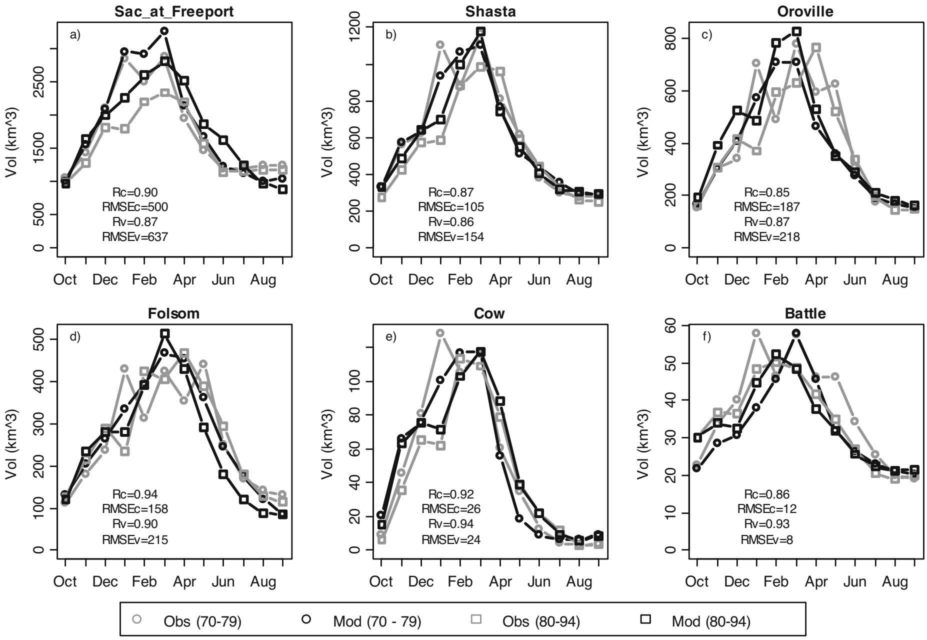

Fig. 3 Average monthly streamflow for select points throughout the Sacramento Basin for the calibration period (1970 through 1980) and the validation period (1980–1990)

and water management processes. The SB was disaggregated into representative catchments using a Geographical Information System (GIS) analysis of the United States Geological Survey's (USGS) Hydrologic Unit Classification (HUC) eight-digit cataloging unit and stream gage data. This resulted in 54 representative catchments. For each catchment, the USGS 30-meter National Land Cover Data set (NLCD92, Vogelmann et al. 2001) was used to identify the unique fractional-areas based on land use and cover (LULC) types including deciduous and evergreen trees, shrubs, grassland, wetlands, barren land and open water as natural types; cereals, oilcrops, orchards, pasture, rice, and rowcrops as irrigated agriculture; and finally urban pervious and impervious areas. The perimeter catchments were often dominated by only a few LULC's (evergreen and deciduous trees) while some of the valley floor catchments often contained nearly all the LULC types. For each of the 54 catchments, a monthly climate time series was derived from the individual 1/8 deg gridded daily time series as an average of all grid cell values contained within the catchment (Maurer et al. 2002). Monthly precipitation was given as the sum of the daily values. Other climate variables include temperature, wind speed and humidity each given as average monthly values for each catchment.

Each of the 54 catchments provides the hydrologic flux back to rivers, canals, and drains. There are 32 smaller tributaries, such as Cache, Battle, Cow, and Cottonwood Creeks and larger rivers such as the Feather, American, Yuba, and Pit Rivers. In the case of small tributaries, their contributing areas often included two to three catchments whose runoff incrementally contributes to streamflow generation. The larger rivers, most notably the Pit, Feather, and American, included catchments and their own individual tributary streams. The model includes the major trans-basin diversion from the Trinity River and its diversion into the Sacramento Basin via Clear Creek and the Whiskeytown facilities. Irrigation diversions include the Anderson–Cottonwood in the northern SB valley and the

Tehema Colusa and Glenn Colusa canals in the central SB valley, with the Colusa drain picking up irrigation return flows from this expansive irrigated region. Three flood conveyance systems are represented, including the Yolo, the Sacramento Weir, and the Sutter bypasses (Fig. 2).

3.2 Streamflow and reservoir storage

Relevant model outputs included predictions of reservoir operations and flow and temperature at specific locations throughout the Sacramento basin. The model was calibrated for the period 1971 to 1998 and consisted of historical reproduction of observed river flow and temperature regimes, water demands, irrigation requirements, reservoir storages and operations. Our model evaluation compared observational data against projections of Shasta storage volumes, Sacramento mainstream streamflows, and projections of river temperatures at points on the Sacramento mainstem (Figs. 3 and 4)

The model independent, non-linear parameter estimation software PEST© (Doherty 2002) was used to calibrate the hydrologic component of the WEAP21 Sacramento model based on normalized inflows into the three major reservoirs—Shasta, Oroville, and Folsom (CALSIM-II 2000). The 28 year period from 1971 through 1998 was used in the calibration and validation procedure based on a split sample (1971 to 1980 for calibration and 1981 to 1998 for validation) and is referred to as the *CALVAL* scenario. These include 17 above normal years, with thirteen classified as 'wet' and 12 below normal years, including the dry years of 1981, 1985, 1987, and 1989 and the critically dry years of 1976, 1977, 1988, 1990, 1991, 1992, and 1994. Figure 3a–f are the observed and modeled monthly streamflows for both the (c)alibration and (v)alidation series. These includes inflows to the major reservoirs, Shasta (b), Oroville (c) and Folsom (d); inflows to two smaller tributaries, (e) Cow Creek and (f) Battle Creek; and the overall flow of the SB at Freeport (a). The inset of each graph includes the correlation coefficient and the Root Mean Square Error (RMSE) for both the calibration and validation series. In some cases, the correlations tended to be higher for the validation, primarily because the calibrations years (1970 to 1980) include the 1976 and 1977 low-flow period, with the model tending to overestimate discharge in these extreme years. Overall, the model adequately reproduced the inflows to these major reservoirs.

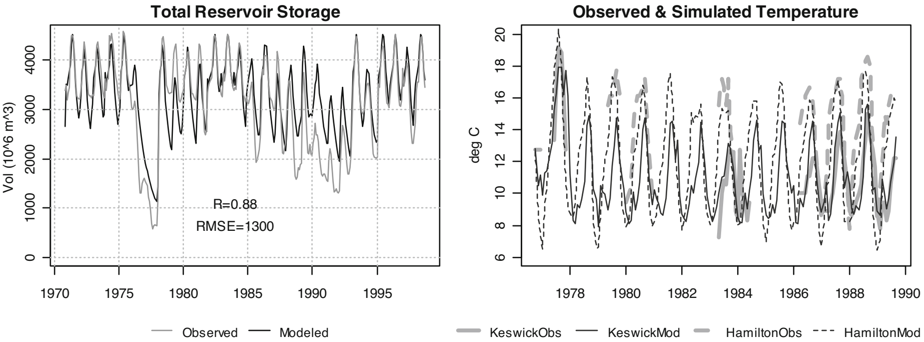

Fig. 4 Time series of observed and simulated total reservoir storage of the major reservoirs of the Sacramento River (*left*) and observed and simulated river temperatures along the Sacramento mainstem near Keswick and Hamilton City (*right*)

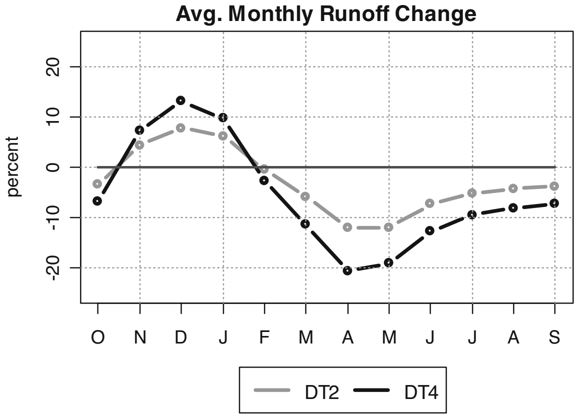

Fig. 5 Average percent change in monthly catchment runoff to rivers for the *DT2* and *DT4* warming scenarios relative to the *CALVAL* scenario

3.3 Water temperatures

River water temperature estimates are made in WEAP21 based on climate forcing (solar radiation and temperature) and the monthly flow characteristics generated by the embedded WEAP21 hydrology module (see Yates et al. 2005a, b). The California Department of Water Resources (DWR) has compiled a record of observed temperatures along the Sacramento mainstem, which were used to calibrate the water temperature estimates made by WEAP21.

Water temperatures in Shasta Reservoir were not explicitly modeled; rather, a monthly temperature release profile was prescribed based on the reservoir's storage state, estimates of water temperatures near Keswick, and extrapolation of inflow temperatures into Shasta on discharge temperatures (DWR 1988). The observational record used to calibrate and validate the water temperature model include only years before the TCD's were installed, thus reservoir release temperatures were based on the assumption that no TCD's were in place to control water temperatures: if the storage volume in the reservoir fell below 1,480 million m^3 (MM3) or 1.2 million acre-feet (MAF) in the summer, then the release temperature was prescribed at 15°C in July, August and September. Subsequent Shasta release water temperatures were prescribed according to storage volumes as: 13°C for volumes between 1,480 and 2,470 MM3 (1.2 to 2.0 MAF); 12°C between 2,470 and 2,700 MM3 (2.0 to 2.2 MAF); and 11°C for volumes greater than 2,700 MM3 (2.2 MAF).

The main tributaries of the SB included in the WEAP model were, among others, Cottonwood, Cow, Battle, Butte, and Thomes. Water temperatures of the Trinity Diversion, which spill into the Sacramento River near Keswick were not explicitly modeled since they are influenced by the Clair Engle and Whiskeytown reservoirs. Here, an average temperature profile was assumed based on tributary flow temperatures, with a January minimum of 8.7°C and a July maximum of 17.1°C.

Figure 4 (right) shows estimates of average monthly observed and modeled temperatures at Keswick and Hamilton City with the above assumptions. The observed water temperature data is relatively sparse, so a strong statistical analysis was not possible. However, the correlations between observed and modeled water temperatures were strong for the data that were available, with Keswick yielding a value of 0.7 and Hamilton 0.9. A qualitative assessment showed the model fit to be quite good, with a slight low bias at Keswick during the severe drought of 1976 and 1977. Unfortunately, no water temperatures were reported at Hamilton during this drought, and the model seems to produce cooler mid winter water temperatures. Figure 4 (left) is the simulated vs. the observed total water storage in Shasta Reservoir, showing good agreement. With the hydrology and water temperature models adequately calibrated and validated for a historic period, we turn out attention to a simple climate warming experiment described in the next section.

4 Potential effects of climate warming on Chinook salmon in the Sacramento River

The utility of WEAP21 to simulate the potential impact of future warming on SB hydrology and its attending consequences on water management and salmon habitat is demonstrated through two simple climate warming experiments referred, to as *DT2* and *DT4* (Field et al. 1999; Hayhoe et al. 2004; Tebaldi et al. 2005). These scenarios assume a uniform warming of Δ+2°C (DT2) and Δ+4°C (DT4) imposed on the historic temperature sequence of all 54 catchments throughout of the SB for the period 1971 through 1998. While these scenarios are simplistic, they illustrate how WEAP21 can directly translate a climate signal into changes in supply and demand, and how they can facilitate an analysis of the watershed's overall water balance (supply, demand, environmental flows, groundwater-surface water interactions, reservoir storage, surface water temperatures, etc.).

Warming experiments like DT2 and DT4 are consistent with current projections of future warming, noting that projections of precipitation change are much more uncertain (Maurer 2007; Tebaldi et al. 2005). Additionally, placing climate warming scenarios in a historical context allows one to imagine the relative impact of warming on a period of record in recent memory, particularly in a complicated setting like the SV, where both the natural hydrology and managed systems are so intertwined.

Because of the existence of the TCD to selectively tap cold water behind the Shasta reservoir, release temperatures are now strongly influenced by the availability of this cold pool. The current Shasta water management strategy is to maintain 13.5°C water for approximately 60 km below Shasta (e.g. a point above Red Bluff). A relationship has been developed between total Shasta storage (ST_t) and cold water availability (CW_t) at or below an 11.1°C threshold, where t is time (USDOI 1996). This relationship, given as $\mathrm{CW}_{\mathrm{apr}} = 0.65 \times \mathrm{ST}_t - 206$ (acre–feet), was used to determine the release temperature from May through October by tracking the coldwater storage through the summer as, $\mathrm{CW}_t = \mathrm{CW}_{t-1} - \mathrm{SR}_{t-1}$, where SR_{t-1} is the Shasta release (in acre–feet). Coldwater availability is established for each April ($\mathrm{CW}_{\mathrm{apr}}$) and if $\mathrm{CW}_t<0$ from April through October, the release temperature is increased incrementally per month as, $\mathrm{TR}_t = \mathrm{TR}_{t-1} + 1.0°\mathrm{C}$. The targeted total storage by May is 3,900 MM3 (3.2 MAF) which is roughly 2,500 MM3 (2 MAF) of stored water at or below 11.1°C).

4.1 Water temperatures estimates of an unmanaged Sacramento River

Before we examine the warming scenarios relative to the historic climate represented by the CALVAL scenario, it is informative to consider what the water temperature regime would be for these two scenarios under the assumption that dams and diversions did not exist and there were no irrigation demands (e.g. "Unmanaged Watershed"). This is done in WEAP by simply removing the dams/reservoirs objects and turning off irrigation demand throughout the SB. In essence, this returns the watershed to its quasi natural state, making it possible to evaluate the relative impact of dams and irrigation on the river's hydrologic and temperature regimes. Similar to the CALVAL scenario, the DT2 and DT4 scenarios assumed an average water temperature from the Trinity Diversion based on the average monthly temperature profiles from the modeled tributary water temperatures, with a January minimum of 9.3°C and 10.6°C; and a July maximum of 17.8°C and 19.1°C for the DT2 and DT4 scenarios, respectively.

Before examining water temperatures, it is interesting to note that the warming scenarios did not lead to substantial reductions in total runoff. In fact, both the DT2 and DT4 scenarios implied greater runoff production in early and mid-winter, as a larger fraction of precipitation falls as rain rather than snow at lower elevations, meanwhile potential evapotranspiration is smaller in the winter months leading to smaller evaporative losses and greater runoff coefficients (ratios of runoff to precipitation). The DT2 and DT4 scenarios generally showed increased runoff from November through February, decreased runoff from March through September, with a total runoff reduction of only two and five percent, respectively; but with considerable month-to-month variability (Fig. 5).

Figure 6 (bottom, "Unmanaged Watershed") are monthly box-and-whisker plots that show the mean and standard-deviation of water temperatures near Keswick and Hamilton City, respectively (see Fig. 2 for locations) for the CALVAL, DT2, and DT4 scenarios. The water temperatures at Keswick are similar to those at Hamilton City, being well above the salmon thresholds from May through September, since the northern portion of the Sacramento Valley experiences some of the highest summer temperatures in the entire SV. This suggests that prior to human interventions throughout the Sacramento Basin, the mean monthly water temperatures near Redding would have been substantially elevated during the summer months, well above the egg and fry threshold of 14°C, and near or above the juvenile and adult physiological thresholds of 18°C and 19°C, respectively. These simulations help to illustrate why the Chinook migration strategies evolved to enable fish to avoid the mainstem during these months.

The DT2 and DT4 scenarios pushed the mean monthly water temperatures upward, with more water warming in the summer and winter months and less warming in the spring and fall "shoulder" seasons. The simulations encompassed in Fig. 6 (bottom) suggest that without the existence of Shasta, the May through September water temperatures would exceed the spawning and rearing thresholds, from about 6°C to 8°C for the DT2 and DT4 scenarios, respectively. Notwithstanding the blockage of critical upstream habitat due to the existence of Shasta dam, this result highlights the utility of the dam to provide suitable spawning temperatures below the reservoir.

4.2 Implications of climate warming and Shasta management for Salmon in the Sacramento Valley

Figure 6 (top, "Managed Watershed") shows monthly mean, standard deviation, and monthly maximum water temperatures at Keswick and Hamilton City for the CALVAL, DT2, and DT4 scenarios, which represent the upper and lower portion of the Sacramento River where Chinook salmon now spawn and their young are reared before emigrating to the sea. The model results show that in the recent past, with the TCD in place, seasonal fluctuations of water temperatures in the reach of the Sacramento River below the reservoir have ranged between 11°C to 12°C (CALVAL).

Since the DT2 and DT4 warming scenarios assumed a uniform temperature increase for all 28 years of simulation, it was assumed that this warming led to new cold pool equilibrium temperatures. Thus, for the DT2 and DT4 scenarios, the cold pool temperatures were increased by 0.7°C and 1.4°C for the full 28 years of simulation, computed as the difference between the average inflow temperature to Shasta for the CALVAL and DT2 and DT4 scenarios, respectively. This is a crude estimate of how snow pack volume and the

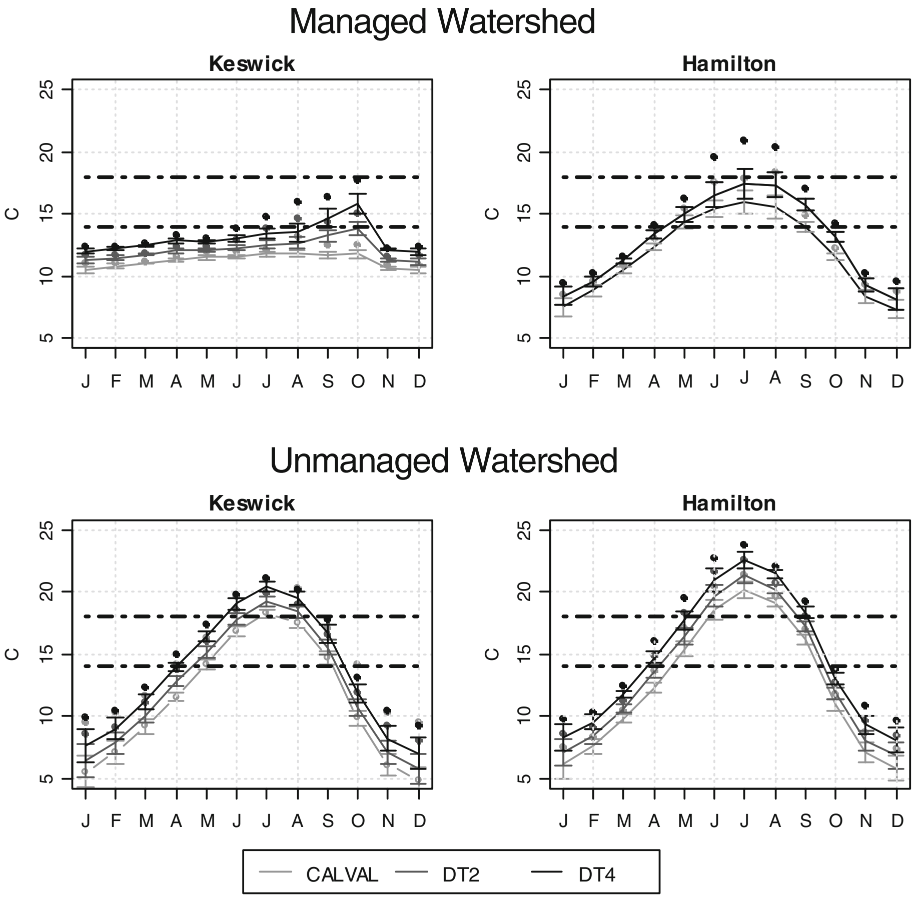

Fig. 6 Simulated monthly mean and standard deviation of Sacramento River temperatures near Keswick and Hamilton City for the *CALVAL*, *DT2* and *DT4* scenarios. The *top, horizontal dashed line* represent the 18°C threshold for juvenile emigration and the *bottom dashed line* is the 14°C spawning and rearing temperature threshold. The *solid symbols* are the period monthly maximum values that happen to correspond to the drought years of 1976 and 1977

rain/snow mix contribute to changes in Shasta storage temperatures. Shasta release temperatures were based on estimates of cold pool availability for the three scenarios from May through October, with November release temperatures "reset" to 11.1°C, 11.8°C, 12.5°C, leading to the observed inflection point in November. The focus of the analysis is, therefore, the May through October period.

Except in the driest years, cool water releases from Shasta did help to maintain water temperatures below the spawning and rearing threshold to Keswick for the DT2 climate warming scenario, as the cold pool remained into the late summer. Warming on the order of Δ4°C, as is implied in the DT4 scenario, suggested that even in wet years, spawning and rearing threshold temperatures (14°C) would be exceeded to Keswick in September and October, while this temperature would only be exceeded in the driest years under the more modest Δ2°C (DT2) warming scenario. At Hamilton City, water temperatures pushed beyond the 14°C threshold from May through September for both the CALVAL and DT2 scenarios, although for both the DT2 and DT4 scenarios, these thresholds were exceeded for all years. For the extreme dry years corresponding to 1976 and 1977, the DT2 scenario neared the 18°C threshold in July and August, while for the DT4 scenario, this threshold was substantially exceeded in June, July and August (Fig. 6, right).

Comparing the DT2 scenario with the CALVAL scenario, 1) there was a disproportionate amount of warmer water in July; 2) July and August temperatures reached the 18°C juvenile emigration threshold in dry years, 3) September temperatures stayed largely above the 14°C spawning and rearing threshold during both wet and dry years. Comparing the results from DT4 scenarios with those of the CALVAL scenario suggests that, 1) the 14°C threshold would be perpetually difficult to maintain immediately below Shasta during the late summer/early fall; and 2) in the driest years, 18°C juvenile emigration thresholds would likely be exceeded in important spawning areas below Shasta.

Figure 7 (left) show the monthly average, standard deviation, and period monthly minimums of Shasta releases. Interestingly, summer releases are slightly greater in the DT2 and DT4 scenarios, as the planning component of the WEAP model makes additional reservoir releases to meet increased downstream irrigation demands. These releases help maintain downstream temperatures, but lead to reduced overall and cold pool storage in Shasta (Fig. 7, right). This could challenge the ability of the reservoirs to supply cold water for salmon under future climatic change, especially when accompanied by prolonged drought.

These results suggest that a warmer climate, accompanied by drought, will challenge water managers ability to maintain suitable water temperatures in the Sacramento River even with the TCD. Together, Figs. 1 and 6 suggest that the young winter-run and spring-run Chinook, now confined to the Sacramento mainstem below Shasta are the most threatened from climate warming. Through their earlier spawning and rearing seasons, fall and late-fall fish are able to take advantage of the naturally cooler water temperatures during the winter months and are less dependent on dam releases, as they have already completed their rearing by May and most of the yearlings have moved downriver and would not be so affected.

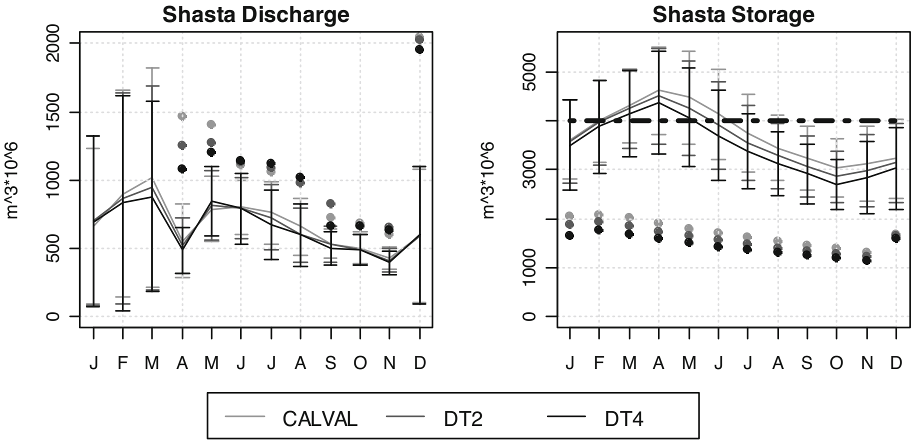

Fig. 7 Monthly average and standard deviation of Shasta reservoir storage (*right*) and discharge (*left*) for the *CALVAL*, *DT2*, and *DT4* scenarios for the full 28 year record. The *marks* are the monthly period minimum values. The May targeted storage of 4 MM3 (3.3 maf) is also show (*right*), which corresponds to necessary May storage to maintain downstream temperatures

Figure 6 illustrates several major points. First, releases from dams play a role in maintaining suitable thermal habitat for Chinook spawning and rearing and migration as far downriver as Hamilton City. Second, climate change could be a major determinant of the future viability of adult and juvenile reproductive and migration strategies, especially during drought years when cold water availability is less certain. Third, in the upriver spawning areas and the downriver areas through which adults and juveniles migrate, adverse effects of climate change might be mitigated by continued releases of cool water, but this cool water might not be available through the late summer. Finally, the two most vulnerable runs are likely to be the winter and spring runs (which are affected on both the spawning areas and during migrations). These results emphasize that releases of cool water are critical to maintaining suitable thermal habitat in the future. However, the availability of cool water from reservoirs could become problematic as warming also increases downstream demands and evaporative losses from the reservoir.

Model results suggest that cold pool availability will not be substantially reduced under a 2°C warming except in drought years, while a 4°C warming implies much greater challenges to maintaining suitable salmon habitat. For example, the average cold pool was reduced by 25% in September for the dry 1990, 1991, 1992, and 1994 water years, while only reduced by 6% for the corresponding wet years of 1993, 1995, 1996, and 1997. Table 1 shows the distances down river from Shasta Reservoir, where Sacramento river water temperatures exceed the 14°C threshold in September. The management strategy to maintain 13.5°C water temperatures for the 60 km reach between Shasta and Red Bluff was challenged for dry years for the DT2 scenario, with a reduction of nearly 50% of available water below 14°C threshold.

5 Discussion

In highly managed river systems, such as the Sacramento River, past human interventions have often been disastrous for fish populations and communities. Paradoxically, this study has shown that the very management structures and practices that adversely affected the fish, may provide an opportunity to alleviate some of the future impacts of climate change, while "natural" or unmanaged systems may provide fewer opportunities. However, projections of greater mid-winter and earlier spring flows suggest little opportunity for changes in operating rules, as reservoirs like Shasta will need to continue to serve their flood control mission, perhaps with a need for deeper winter drafting. This coupled with

Table 1 Approximate river distances from Shasta Reservoir to the downstream location where Sacramento water temperatures exceeded the 14°C threshold (km)

	Aug	Sep
CALVAL (wet)	140	250+
DT2 (wet)	55	88
DT4 (wet)	–[a]	–[a]
CALVAL (dry)	70	150
DT2 (dry)	*25*	88
DT4 (dry)	–[a]	–[a]

Dry years included 1990, 1991, 1992, and 1994; while wet years were 1993, 1995, 1996, and 1997. October temperatures never exceeded 14°C beyond Hamilton City.

[a] For the DT4 scenario, water temperatures always exceeded the threshold

increased downstream demands from growth and warming, makes re-operation for cold-pool maintenance seem unlikely.

Between May and September, the existence of suitable spawning and rearing habitat for Chinook in the upper Sacramento River is currently dependent on releases of cool water from the reservoir hypolimnia (particularly from the Shasta Dam). Without these releases, the water temperatures would exceed the physiological tolerances of the eggs and juveniles of the winter and spring runs by three or more degrees centigrade. It is unlikely that these populations could persist without these releases. By spawning later and earlier in the year, the fall and late-fall runs are able to reduce their vulnerability to this potentially critical period and are, therefore, less dependent on changes in water management practices.

Future climate change will increase the importance of controlled releases of cool water. We estimate that under 2°C and 4°C warming projections and without releases of cool water, the water temperatures in the spawning and rearing areas immediately downriver of Shasta Dam would be substantially warmer during the May–September period, with monthly means as high as 21°C to 24°C, respectively. Such conditions would be lethal for Chinook eggs or hatchlings, jeopardizing the viability of the winter and spring runs which spawn and hatch during this period. Our model projections show that releases from Shasta Dam could counteract this by maintaining water temperatures in spawning areas below salmon physiological thresholds, but that warming upwards of 4°C could lead to a loss of this cold pool advantage, which serves to maintain downstream temperatures.

The availability of suitable thermal habitat for migrating adult and juvenile Chinook in the lower Sacramento River is also affected by releases from dams. The main determinants of the midsummer high water temperatures in the lower river are high ambient air temperatures and slow and low flows. Releases from dams, however, currently keep the river water temperatures below the physiological thresholds for migrating fish. Continuing releases would keep the river temperatures below the salmon thresholds, except in August and September drought years when the juvenile threshold would be exceeded. Also, the period over which Chinook thermal tolerances would be exceeded would be extended from the current three months to five months. The runs most affected by this would be adults and juveniles of the winter, and spring runs.

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