

Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat

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Abstract Water temperature influences the distribution, abundance, and health of aquatic organisms in stream ecosystems, so understanding the impacts of climate warming on stream temperature will help guide management and restoration. This study assesses climate warming impacts on stream temperatures in California's west-slope Sierra Nevada watersheds, and explores stream temperature modeling at the mesoscale. We used natural flow hydrology to isolate climate induced changes from those of water operations and land use changes. A 21 year time series of weekly streamflow estimates from WEAP21, a spatially explicit rainfall-runoff model were passed to RTEMP, an equilibrium temperature model, to estimate stream temperatures. Air temperature was uniformly increased by 2°C, 4°C, and 6°C as a sensitivity analysis to bracket the range of likely outcomes for stream temperatures. Other meteorological conditions, including precipitation, were unchanged from historical values. Raising air temperature affects precipitation partitioning into snowpack, runoff, and snowmelt in WEAP21, which change runoff volume and timing as well as stream temperatures. Overall, stream temperatures increased by an average of 1.6°C for each 2°C rise in air temperature, and increased most during spring and at middle elevations. Viable coldwater habitat shifted to higher elevations and will likely be reduced in California. Thermal heterogeneity existed within and between basins, with the high elevations of the southern Sierra Nevada and the Feather River watershed most resilient to climate warming. The regional equilibrium temperature modeling approach used here is well suited for climate change analysis because it incorporates mechanistic heat exchange, is not overly data or computationally intensive, and can highlight which watersheds are less vulnerable to climate warming. Understanding potential changes to stream temperatures from climate warming will affect how fish and wildlife are managed, and should be incorporated into modeling

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studies, restoration assessments, and licensing operations of hydropower facilities to best estimate future conditions and achieve desired outcomes.

1 Introduction

The thermal regime of rivers and streams is fundamental to the health and function of aquatic ecosystems (Webb et al. 2008; Caissie 2006). Stream temperatures directly influence the biological, physical, and chemical properties of lotic ecosystems, including metabolic rates and life histories of aquatic organisms, dissolved oxygen levels, nutrient cycling, productivity, and rates of chemical reactions (Poole and Berman 2001; Vannote and Sweeney 1980). Stream warming may alter stream habitat conditions, reduce community biodiversity, change the distribution and abundance of organisms, drive local extinctions, and ease the introduction of invasive species (Eaton and Scheller 1996; Hari et al. 2006; Rahel and Olden 2008).

Stream temperatures are strongly correlated with climate (Morrill et al. 2005; Mohseni et al. 1999), and long-term data analysis has shown that stream temperatures have already increased as air temperatures have risen in recent decades (Kaushal et al. 2010; Hari et al. 2006; Webb and Nobilis 2007). For cool and coldwater fish guilds, previous research suggests climate warming may reduce available habitat throughout the U.S. by 36 % (Mohseni et al. 2003) to 47 % (Eaton and Scheller 1996), with the range in estimates depending on the regression modeling approach. Climate warming may also restrict coldwater species to higher elevations or latitudes (Jager et al. 1999; Hari et al. 2006; Sharma et al. 2007), and restoration may only partially offset habitat reductions expected from climate change (Battin et al. 2007). In California, climate models predict air temperature may increase by approximately 4–9°C by the end of the 21st Century, although models disagree as to whether California will become wetter or drier (CDWR 2009; Dettinger et al. 2004).

Stream temperatures are often estimated with deterministic models that simulate net heat flux occurring at the bed- and air-water interfaces and track the fate and transport of heat energy (Deas and Lowney 2000; Caissie 2006). However, this approach is computationally and data intensive, making it difficult to apply over large regions (for example Vogel 2003; FRWT 2008). Isolated reaches or individual rivers are typically modeled, such as reaches below reservoirs to better understand how operational changes affect downstream temperatures (Webb et al. 2008; Caissie 2006). While changes to stream temperatures from climate change are sometime evaluated, it is difficult to compare between studies because models have different modeling assumptions (i.e., governing equations), climate assumptions (i.e., emissions scenarios), and modeled results are often proprietary (Lehner et al. 2006).

Developing empirical relationships between air and stream temperatures is another common approach to assess climate change effects on stream temperature (Eaton and Scheller 1996; Mohseni et al. 1999; Morrill et al. 2005; Mohseni and Stefan 1999). This approach requires only air temperature as input, making it a straightforward method. However, it does not explicitly account for mechanistic heat exchange, so drivers such as solar radiation, evaporative cooling, and source water temperature are represented implicitly as coefficients or constants. Models are thus site-specific and must be re-fitted for new locations (Bogan et al. 2003). Research has shown that the relationship between air and stream temperature is not linear, particularly as stream temperature nears 0°C or exceeds approximately 20°C when evaporative cooling slows heating. Thus, linear models are often not appropriate to measure the effects of climate warming on stream temperatures (Mohseni and Stefan 1999).

Edinger et al. (1968) defined equilibrium temperature as the surface water temperature when net heat flux equals zero, or in other words, the temperature of a water body if exposed

to constant meteorological conditions for infinite time. In real systems, the thermal regime of rivers also reflects source water contributions near headwaters, which in mountain regions are precipitation, snowmelt, and/or groundwater (Caissie 2006; Mohseni and Stefan 1999). Stream temperatures approach equilibrium with atmospheric conditions through time (longitudinally), but are constrained by water volume, channel geometry, stream shading, and travel time, which in turn affect the relative surface area, thermal mass, solar radiation reaching the stream surface, and amount of time streams are exposed to atmospheric conditions (Mohseni and Stefan 1999). Tributary mixing, which may be warmer or cooler than mainstem reaches, further influences thermal dynamics.

Equilibrium temperature modeling is useful because heat flux at the water surface is represented using only meteorological input variables. Equilibrium temperature theory has been used to improve understanding of thermal conditions in rivers, typically by using Edinger's thermal heat coefficient method (Gu et al. 1998; Bogan et al. 2003; Caissie et al. 2005; Wright et al. 2009). Mohseni and Stefan (1999) used equilibrium temperature to examine the effects of climate change on stream temperature, finding stream temperatures vary between equilibrium and source temperatures depending on travel time. Bogan et al. (2003) recommended equilibrium temperature theory as a valid tool for predicting the impacts of climate change on stream temperatures because there is a linear relationship between stream and equilibrium temperatures. These and similar studies have shown that the equilibrium temperature concept is useful for predicting stream temperatures at the reach or watershed scale.

We apply the concept as a regional assessment of climate warming impacts on stream temperatures in California's west-slope Sierra Nevada watersheds under natural flow conditions to improve understanding of likely habitat changes for salmonids (trout and salmon in the Salmonidae Family). While stream temperatures have been monitored and modeled for isolated river reaches, there have been no mesoscale studies that simulate how thermal conditions may change within and between watersheds with climate warming. The regional scale is important to study because large areas such as mountain ranges are isolated from other similar habitat, making it difficult for species to shift their distributions if climate warming alters or reduces current habitat suitability. Our model is based on equilibrium temperature theory and uses a simple form of the advection-dispersion equation. Increasing air temperature by 2°C increments is illustrative of how change may progress through time and can help inform decision-making for prioritizing restoration (and restoration dollars) in different watersheds or sub-watersheds within the Sierra Nevada to enhance or maintain thermal habitat for coldwater fish species. Specific research questions include:

- How does climate warming impact stream temperatures on a regional scale (for a mountain range)?
- How does climate warming alter thermal conditions within and between basins?
- How will the distribution of coldwater habitat change with climate warming?

2 Study area

The study area includes fifteen west-slope watersheds of California's Sierra Nevada, extending from the Feather River in the north to the Kern River in the south, and encompassing an area of approximately 47,657 km² (Fig. 1). West-slope rivers travel generally westward to their confluence with the Sacramento or San Joaquin Rivers in the Central Valley, and through the Sacramento-San Joaquin Delta into the San Francisco Estuary. Watersheds (and sub-watersheds) differ in terms of area, elevation, latitude, precipitation, and mean annual flow (Table 1).

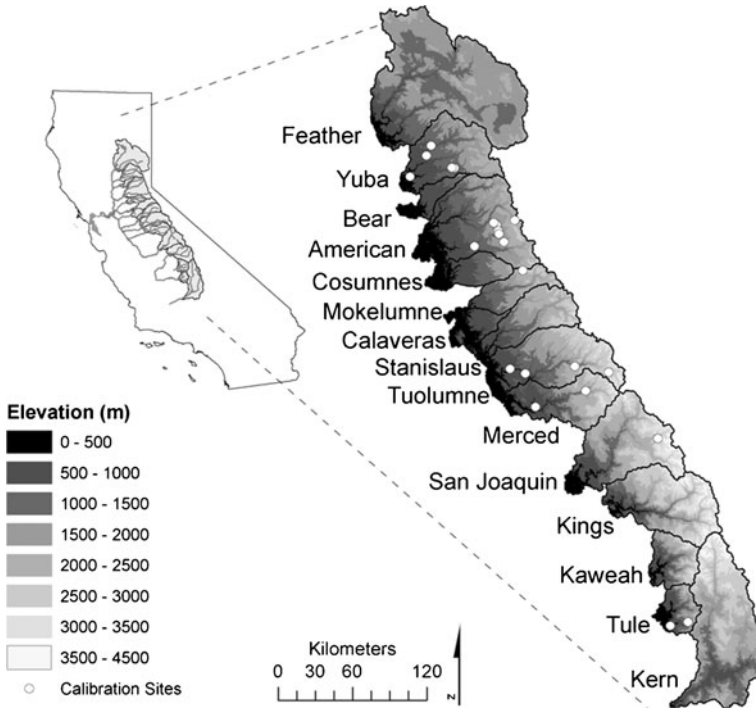


Fig. 1 Study watersheds, topography, and model calibration sites

Table 1 Physical characteristics at watershed outlets (north to south) (Null et al. 2010)

Watershed	Area (km ²)	Mean Annual Runoff (1*10 ⁶ m ³)	Mean Precip. (mm/yr)	Precip. Range (Min–Max) (mm/yr)	Elevation Range (m)	Northing Centroid (km)	Max Strahler Stream Order
Feather	9,412	5,776	1,215	366–3,014	275–2,853	4,425	7
Yuba	3,114	3,020	1,675	832–2,236	76–2,772	4,370	6
Bear	730	492	1,221	632–1,870	90–1,772	4,334	5
American	4,822	3,556	1,358	630–2,036	39–3,163	4,313	7
Cosumnes	1,385	603	1,073	589–1,434	55–2,359	4,275	6
Mokelumne	1,498	979	1,233	578–1,643	72–3,162	4,261	6
Calaveras	937	330	865	553–1,428	212–1,851	4,231	5
Stanislaus	2,341	1,561	1,159	648–1,681	211–3,520	4,238	6
Tuolumne	3,971	2,445	1,101	435–1,728	245–3,989	4,206	6
Merced	2,685	1,348	1,045	501–1,593	245–3,990	4,174	6
San Joaquin	4,315	2,294	1,014	355–1,591	97–4,224	4,139	6
Kings	3,998	2,117	964	501–1,545	177–4,349	4,094	6
Kaweah	1,451	586	940	368–1,511	154–3,846	4,047	6
Tule	1,015	199	764	286–1,192	174–3,119	4,008	6
Kern	5,983	926	560	244–1,473	171–4,418	3,992	7

The Sierra Nevada crest is highest at its southern end, with elevations greater than 4,000 m. Northern watersheds are generally less than 3,000 m (Fig. 1). Most Sierra Nevada watersheds are steep at their headwaters, with slope generally decreasing toward the alluvial Central Valley. The Bear, Cosumnes, Calaveras, Kaweah, and Tule watersheds are lower elevation basins that do not reach the crest of the Sierra Nevada.

The Sierra Nevada has a Mediterranean-montane climate with a cool, wet season from November to April and a warm, dry season from May to October. Precipitation averages approximately 1,080 mm/yr for the region, although it is highly variable due to elevation, latitude, and local weather patterns (Table 1). Precipitation falls as both snow and rainfall, and snowline is approximately 1,000 m. At elevations above 2,000 m, the Sierra Nevada receives considerable snowfall. The snowpack not only contributes to spring runoff, it also maintains cold stream temperatures at upper elevations for much of the year. Water regulation and land use changes have altered the thermal regime of most rivers in this region, and warm stream temperatures often inhibit distribution and survival of coldwater species (Moyle et al. 2002). Climate warming threatens to exacerbate these problems.

3 Salmonid thermal thresholds

We used maximum temperature threshold estimates for coldwater fish species to improve understanding of how stream temperature warming could affect fish populations and distributions (other coldwater species including amphibians and some macro-invertebrates will likely face similar changes). This approach provides a first-cut assessment of climate warming effects. Uncertainty remains regarding maximum temperature thresholds for coldwater guild species, and thresholds are variable by life stage, previous acclimation, duration of thermal maxima and minima, food abundance, competition, predation, body size and condition (McCullough 1999).

The focus here is on thermal habitat conditions for coldwater fishes from the Family Salmonidae. For modeling simplicity, and to help gauge restoration potential above large dams, we use thermal habitat requirements of Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*O. mykiss*), though other salmonid species have similar thresholds. Chinook salmon runs in the western Sierra Nevada were historically some of the most productive on the Pacific coast. Following the construction of large dams, most runs have now been extirpated from Sierra Nevada rivers (Yoshiyama et al. 1998). Above approximately 2,000 m, the western slope of the high Sierra Nevada was mostly fishless prior to stocking, although today rivers are managed to sustain native rainbow (*O. mykiss*) and a small population of golden trout (*O. mykiss aguabonita*) as well as non-native but naturalized brown (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*).

Eaton and Scheller (1996) report 24°C as the maximum thermal tolerance for Chinook salmon and steelhead trout, although both species can tolerate warmer temperatures for shorter periods of time (Myrick and Cech 2001). We assume 24°C as a maximum weekly average temperature tolerance for both species as a target threshold. Some age classes or life stages (i.e., eggs and alevin) require lower temperatures for optimal growth and survival (Myrick and Cech 2001).

Salmonid species begin experiencing detrimental, but sub-lethal, effects to health and fitness at temperatures below chronic lethal limits (Myrick and Cech 2001; McCullough 1999), thus we also use a weekly average threshold of 21°C as an indicator for when Chinook salmon and steelhead trout become inhibited by stream temperature. This thermal threshold is above the upper optimal temperature envelope of 19°C for juvenile Chinook and

steelhead, but below the maximum lethal temperature tolerance, and is cited as a thermal block for Chinook salmon migration (US EPA 2001). We assume no minimum temperature threshold for coldwater fishes.

4 Methods

Modeled natural flow hydrology from the Stockholm Environment Institute's Water Evaluation and Planning System (WEAP21), a spatially explicit rainfall-runoff model, was input to RTEMP, an equilibrium temperature model. This application used a weekly timestep and spatial resolution of 250 m (vertical) elevation bands for all streams within the modeled domain. Simulations were completed for the 1981–2001 historical hydrology, which captures the range of variability in the hydrologic record with an extended drought, the largest flood in the 90-yr record, and the wettest year on record.

Climate warming was modeled with spatially and temporally uniform air temperature increases of 2°C, 4°C, and 6°C as a sensitivity analysis of climate induced alterations to stream temperatures in Sierra Nevada watersheds (results are labeled as T0, T2, T4, and T6, respectively). We assume a uniform rise in air temperature, although previous modeling research has demonstrated seasonal variations in predicted air temperatures (Hayhoe et al. 2004). Hydrology and climatic variables except air temperature were unchanged from observed values. The three climate warming alternatives modeled here represent progressively severe warming (or warming over a progressively longer timeframe). These alternatives are within the range forecast by climate models (Dettinger et al. 2004; Hayhoe et al. 2004) (Table 2). Sensitivity analysis using uniform deviations from historical climate conditions is a common approach for assessing the impacts of climate change and to improve understanding of the range of expected hydrologic and thermal responses (Miller et al. 2003; Fu et al. 2007).

4.1 WEAP21—hydrologic modeling

WEAP21 models the terrestrial water cycle to represent physical hydrology using a one-dimensional, two-storage soil compartment water balance (Yates et al. 2005; Young et al. 2009; Null et al. 2010). Sub-watersheds from the Feather River to the Kern River were intersected with 250 m elevation bands to delineate 1,268 spatial units, with an average area of 37.6 km² (Young et al. 2009). WEAP21 uses a mass water balance approach to partition precipitation as snow, runoff, or infiltration depending on air temperature, land cover, soil

Table 2 Approximate average annual air temperature increase by model, emissions scenario, and time horizon (HadCM3 is the medium-sensitivity U.K. Met Office Hadley Centre Climate Model, and PCM is the low-sensitivity National Center for Atmospheric Research/Department of Energy Parallel Climate Model) (Dettinger et al. 2004; Hayhoe et al. 2004)

Average Annual Air Temperature Increase	Model	Emissions Scenario	Time Horizon
+ 2°C	HadCM3	A1fi (higher emissions)	2020–2049
	PCM	B1 (lower emissions)	2070–2099
+ 4°C	PCM	A1fi (higher emissions)	2070–2099
+ 6°C	HadCM3	A1fi (higher emissions)	2070–2099

depth, and previous soil moisture conditions. Meteorology data (air temperature, precipitation, and water vapor pressure deficits), land cover, soil depth, and topography data are the inputs for WEAP21.

The 15 modeled west-slope Sierra Nevada watersheds were individually represented and calibrated for natural flow hydrologic conditions using monthly natural flow estimates at watershed outlets, and snow water equivalent measurements at upstream sites within each watershed (Young et al. 2009). Overall, WEAP21 represents flow hydrographs well at the watershed scale, and mean bias between simulated and measured natural flow at watershed outlets was -1% , with a range of -6 to 2% . Snow water equivalent was also compared for each watershed. Pearson's correlation coefficients ranged from 0.71 – 0.94 , with a mean of 0.87 , indicating the magnitude and timing of simulated snow accumulation and melt generally matched that of measured data (Young et al. 2009).

Although air temperature was the only climatic variable changed in model runs, hydrology and streamflow output varied between climate alternatives because more rainfall and less snowfall altered runoff magnitude and timing, and higher evapotranspiration rates resulted in overall drier conditions (Null et al. 2010). WEAP21 output data were passed to RTEMP, and the two models were run sequentially. See Yates et al. (2005) for WEAP21 governing equations and additional model detail, Young et al. (2009) for a description of Sierra Nevada flow modeling, and Null et al. (2010) for hydrologic sensitivity to climate warming in California's Sierra Nevada.

4.2 RTEMP—water temperature modeling

The Regional Equilibrium Temperature Model (RTEMP) was developed by Watercourse Engineering, Inc. to estimate stream temperatures based on meteorology, hydrology, and channel geometry input data (Deas et al., unpublished data). This application uses average weekly input data from WEAP21. A weekly timestep has previously been shown to be appropriate for equilibrium temperature modeling (Bogan et al. 2003), while still providing useful indicators for fish habitat conditions (Eaton and Scheller 1996; USFWS 1996). This section provides governing equations and an overview of the modeling approach.

4.2.1 Thermal equilibrium conditions

The advection-dispersion equation governing one-dimensional flow and heat transfer in a river is:

$$\frac{\partial T_w}{\partial t} = -v \frac{\partial T_w}{\partial x} + D \frac{\partial^2 T_w}{\partial x^2} + \frac{wH_{air} + pH_{bed}}{C_p \rho A} \quad (1)$$

where T_w is water temperature ($^{\circ}\text{C}$), t is time (week), v is mean channel velocity (m/s), x is longitudinal distance (m), D is the dispersion coefficient in the downstream direction (m^2/s), w is channel width (m), H_{air} is net heat flux across the water surface (W/m^2), p is the wetted perimeter of the bed (m), H_{bed} is heat flux at the bed surface (W/m^2), C_p is the specific heat of water ($4185 \text{ J}/\text{kg}/^{\circ}\text{C}$), ρ is water density ($1000 \text{ kg}/\text{m}^3$), and A is the cross-sectional area (m^2) (Caissie et al. 2005).

For rivers that are advection dominated, the dispersion term in Eq. 1 can be ignored ($\frac{\partial^2 T_w}{\partial x^2} \approx 0$) (Gu et al. 1998). Additionally, for streams with relatively uniform water temperatures, changes in temperature longitudinally along the stream are typically correlated

with time and are driven by meteorological conditions ($\frac{\partial T_w}{\partial x} \ll \frac{\partial T_w}{\partial t}$) (Deas et al., unpublished data). In such instances, the advection term can also be ignored for conserving heat energy in a river in an unsteady state (Caissie and Satish 2005). This reduces Eq. 1 to:

$$\frac{\partial T_w}{\partial t} = \frac{wH_{air} + pH_{bed}}{C_p \rho A} \tag{2}$$

We further simplified Eq. 2 by assuming the wetted perimeter is the same width as the channel ($w \approx p$) so heat exchange at the water surface occurs over the same width as the streambed. We assumed a rectangular channel ($\frac{w}{A} = \frac{1}{d}$), where d is depth (m) for our final version of the equilibrium temperature equation:

$$\frac{\partial T_w}{\partial t} = \frac{H_{net}}{C_p \rho d} \tag{3}$$

where H_{net} is net heat exchange at both the bed- and air-water interfaces (W/m^2) (Deas et al., unpublished data).

Just as a mass balance can be used to calculate water volumes, a heat balance can be written for heat fluxes in and out of rivers:

$$H_{net} = H_{sn} + H_{at} - (H_{ws} + H_h + H_{evap}) + H_{bed} \tag{4}$$

where H_{sn} is solar short-wave radiation (W/m^2), H_{at} is atmospheric long-wave radiation (W/m^2), H_{ws} is water surface back radiation (W/m^2), H_h is conduction and convection (W/m^2), and H_{evap} is evaporative heat loss (W/m^2). Supporting equations for surface heat exchange terms are consistent with other water temperature studies (Edinger et al. 1968; Bogan et al. 2003). Average weekly meteorological data to estimate the heat budget are from WEAP21 (originally derived from daily interpolated DayMet data). Cloud cover and wind speed were estimated from nearby weather stations.

We included bed conduction because it influences stream temperatures in shallow, bedrock streams (Brown 1969), which occur in Sierra Nevada watersheds.

$$H_{bed} = c(T_w - T_{bed}) \tag{5}$$

where c is a bed heat exchange coefficient ($W/m^2\text{ }^\circ C$) and T_{bed} is bed temperature ($^\circ C$). Bed temperature estimates vary by elevation, and were identical for all watersheds because bed temperature data for all watersheds were unavailable. Bed temperatures were estimated using measurements from the Middle Fork American and Tuolumne Rivers between 500 and 1,500 m (Deas et al., unpublished data). Bed temperatures for 1,500 m were assigned to all higher elevations.

The travel time of water through each reach at each timestep limited exposure to atmospheric conditions (travel time was typically a fraction of a week). The resulting change in water temperature was added to the source temperature (source temperatures are discussed below in the section 4.2.3) or temperature from the previous timestep. This modified the equilibrium temperature equation to estimate stream temperature for each reach and timestep.

$$T_{w_{i,j}} = T_{w_{i-1,j}} + \left(\frac{H_{net_{i,j}} h_{i,j}}{C_p \rho d_{i,j}} \right) \tag{6}$$

where $T_{w_{i,j}}$ is water temperature at time i and reach j, $T_{w_{i-1,j}}$ is water temperature at the previous timestep i-1 and reach j, and $h_{i,j}$ is travel time at time i and reach j (s/wk).

This is the final form of the stream temperature equation used in RTEMP, producing a time series of dynamic stream temperatures where water seeks equilibrium temperature but is constrained by travel time and river geometry. Streamflow conditions change through time and stream temperatures respond to discharge-driven depth between timesteps. A fourth-order Runge–Kutta method was used to integrate Eq. 6 for net change in the system with respect to time, where each timestep is broken into four discrete time periods, with a weighted average that is typically more accurate than without the Runge–Kutta.

4.2.2 Supporting equations

The length of time that water was exposed to equilibrium conditions depends on travel time in each reach and is a function of stream length and velocity.

$$h_{i,j} = \frac{SL_j}{v_{i,j}} \tag{7}$$

where SL_j is stream length at reach j (m), and $v_{i,j}$ is velocity at time i and reach j (m/s).

Depth (m) in Eq. 8 and velocity (m/s) in Eq. 9 were estimated with power functions using the hydraulic geometry method (Leopold et al. 1995). This accounts for thermal mass in the system by approximating the ratio of surface heat exchange to the volume of water. As new weekly averaged flows were input into RTEMP, new depths and velocities were calculated. This approach has been used in previous equilibrium temperature modeling studies (Caissie and Satish 2005).

$$d_{i,j} = aQ_{i,j}^b \tag{8}$$

$$v_{i,j} = kQ_{i,j}^m \tag{9}$$

where a , b , k , and m are empirically derived coefficients from rating data representative of gaging stations in the US, with values of 1, 0.43, 1 and 0.45, respectively (Leopold et al. 1995), and $Q_{i,j}$ is river discharge at time i and reach j (m³/s).

4.2.3 Physical representation

Like WEAP21, RTEMP reaches were delineated by 250 m elevation bands, where stream temperatures were calculated for mainstem rivers and separately for tributaries, which have lumped inflow and temperatures. Mainstem and tributary channels mix at the downstream end of each reach on a volumetric basis using a mass balance approach:

$$Tw_{i,j} = \frac{\sum_{k=1}^{n=4} Tw_{i,j,k} Q_{i,j,k}}{\sum_{k=1}^{n=4} Q_{i,j,k}} \tag{10}$$

where $Tw_{i,j}$ is blended stream temperature at time i at reach j (°C), $Tw_{i,j,k}$ is water temperature at time i , reach j , and source k (sources are mainstem or tributary) (°C), and $Q_{i,j,k}$ is discharge at time i , reach j , and source k (m³/s). Snowmelt was assumed to be 1°C to account for slight overland flow heating from snowpatch to stream, and precipitation temperature was set equal to air temperature. We estimated groundwater to be 7.5°C as a first-cut estimate, the mean annual air temperature at approximately 2,500 m.

Separating tributaries from mainstream rivers enables them to heat at different rates depending on water volume (thermal mass), channel geometry (relative surface area), and velocity (travel time) in each channel. Tributary temperatures influence mainstem temperatures when mixing occurs. In tributary reaches, precipitation, groundwater, and snowmelt contributions are distributed linearly over the length of the channel. Channel lengths for tributary and mainstem channels were estimated using USGS 10 m DEMs, with mainstem channel length a function of the highest order streams, and tributary length a function of the lengths of lower order streams.

4.2.4 Topographic and riparian shading

Topographic and riparian shading reduce solar radiation reaching a stream surface. RTEMP reduces solar radiation by the larger of topographic or riparian shading, which vary through time and catchment, but are identical for mainstem and tributary channels. When stream channels were covered by snow, atmospheric heating does not occur.

Topographic shading was estimated with the solar radiation tool in ArcGIS (v.9.3, ESRI), using 30 m DEMs to calculate mean solar radiation for each 250 m elevation banded catchment. Solar radiation was calculated for each catchment on equinox, summer solstice, and winter solstice, then linearly interpolated between those days. This method adjusted solar radiation by aspect, latitude (which varied between different watersheds, but was constant within single watersheds), day length, and distance from ridges or other topographic features, all of which influence incoming solar radiation (Lundquist and Flint 2006).

LeBlanc and Brown (2000) describe riparian vegetation species, height, density, location, and stream orientation as important factors that affect stream temperatures. However, riparian vegetation shading estimates for Sierra Nevada streams under historical conditions were unavailable. We assumed that above 2,750 m elevation, shading was negligible due to short growing season and poor soils. From 1,750–2,500 m, we assumed riparian shading ranged from 0 to 40 %, with less shading at upper elevations and during fall and winter seasons. From 500 to 1,500 m, we assumed 5–70 % shading, with more shading during spring and summer, and a longer summer season at lower elevations.

4.2.5 Model testing

Estimated stream temperatures from RTEMP were compared with measured water temperatures at 22 sites in 7 watersheds from the Yuba watershed in the north to the Tule watershed in the south where water regulation was absent or negligible (Fig. 1). Elevations of measured stream temperatures ranged from 3,060 m in the San Joaquin watershed to less than 500 m (at numerous sites) (Table 3). This variability enabled RTEMP to be tested under diverse conditions.

Stream temperature in west-slope Sierra Nevada watersheds was modeled for 1981–2001 because modeled natural flow hydrologic data were available for that period (Young et al. 2009). However, observed stream temperature data for unregulated rivers in the same time period were largely unavailable. Simulated stream temperatures were thus compared with more recent measured stream temperature data collected at 15 min (South Yuba River Citizen's League, unpublished data; CDEC 2010), or hourly intervals (U.C. Davis, unpublished data; CDEC 2010), or that had been averaged to daily data by the collector

Table 3 Observed versus simulated stream temperature statistics (Data sources: ¹South Yuba River Citizen’s League, unpublished data; ²Sacramento Municipal Utilities District, unpublished data; ³CDEC, 2010; ⁴U.C. Davis, unpublished data; ⁵USGS, 2010)

Watershed and Site Description (data sources in caption)	Elev m	n (weeks) count	\overline{T}_o °C	$T_{min_s} < T_o < T_{max_s}$ %	MAE °C	RMSE °C	$J_{T_{max_s}}$ week	$J_{T_{max_o}}$ Range weeks
Yuba								
Scotchman Crk ¹	1000	32	14.2	63	0.5	0.9	32	28–31
Poorman Crk ¹	1000	18	17.2	100	0.0	0.0	32	28
N Yuba blw Hwy 49 ¹	750	18	18.4	100	0.0	0.0	33	33
Oregon Crk ¹	750	39	17.3	38	1.1	1.7	32	28–30
Bridgeport ¹	500	19	22.0	68	0.4	0.8	32	28
American								
Rubicon R abv Rubicon Res ²	2250	121	7.2	81	0.1	0.2	32	30–34
SF Rubicon R abv Robbs Forebay ²	1750	170	7.2	64	0.4	0.7	31	28–32
SF Rubicon R 2 mi blw Gerle Crk ²	1750	17	12.1	76	0.3	0.8	31	30
SF Silver Crk abv Ice House ²	1750	169	6.7	76	0.2	0.5	32	28–32
Tells Crk abv Union Valley ²	1750	208	6.9	65	0.5	1.1	31	27–30
Big Silver Crk abv Union Valley ²	1500	170	7.9	82	0.1	0.5	32	28–32
SF Amer. R abv Silver Crk ²	750	170	10.8	94	0.1	0.3	33	28–32
Mokelumne								
Nr Mud Lake ³	2500	124	6.4	51	1.1	2.0	32	27–28
Tuolumne								
Tuolumne Meadows ³	2750	136	5.6	76	0.1	0.2	32	32–34
Tuolumne R at Grand Cyn of Tuolumne ³	1500	97	9.0	95	0.0	0.2	32	30–32
Clavey R abv Tuolumne R ⁴	500	19	19.2	53	0.5	0.8	32	35
NF Tuolumne abv Tuolumne R ⁴	500	19	20.3	32	1.2	1.9	32	35
Merced								
Merced R at Happy Isles Br ⁵	1250	175	7.3	90	0.1	0.4	35	33–36
Merced R. at Briceburg ³	500	99	13.3	92	0.2	0.8	35	32–36
San Joaquin								
Volcanic Knob ³	3250	364	5.6	58	0.8	1.6	32	28 – 33
Tule								
SF Tule R nr Cholollo Cmpgd ⁵	1250	17	9.4	94	0.0	0.1	n/a	n/a
SF Tule R nr Reservation ⁵	500	17	14.3	88	0.0	0.1	n/a	n/a

(Sacramento Municipal Utilities District, unpublished data; CDEC 2010; USGS 2010) (Table 3). Additionally, observed daily minimum and maximum data were available for the sites in the Tule watershed (USGS, USGS 2010). All measured data were aggregated to weekly temperatures here.

To test RTEMP, we assumed that maximum and minimum simulated stream temperatures from years 1981–2001 should span the range of thermal variability and that measured data should fall within the envelope of simulated data, $T_{min_s} < T_o < T_{max_s}$ (%) using Eq. 11. We computed mean absolute error (MAE) (°C) using Eq. 12 and root mean square error (RMSE) (°C) using Eq. 13 (Table 3). Table 3 includes observed data site description, data source, elevation, number of weeks of measured data (n), mean observed stream temperature (\overline{T}_o),

julian week of maximum simulated stream temperature ($J_{T_{max_s}}$), and the range of julian weeks of maximum observed stream temperatures ($J_{T_{max_o}}$ range).

$$(T_{min_s} < T_o < T_{max_s}) = \left(\frac{\sum W_{T_{min_{s_i} < T_{o_i} < T_{max_{s_i}}}}}{n} \right) * 100 \tag{11}$$

$$MAE = \frac{\sum_{i=1}^n |T_{s'} - T_o|}{n} \tag{12}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (T_{s'} - T_o)^2}{n}} \tag{13}$$

where $W_{T_{min_{s_i} < T_{o_i} < T_{max_{s_i}}}}$ is weeks that observed water temperature is within simulated minimum and maximum temperatures for julian week i (count), T_{o_i} is observed water temperature for julian week i (°C), $T_{max_{s_i}}$ is maximum simulated water temperature for julian week i (°C), $T_{min_{s_i}}$ is minimum simulated water temperature for julian week i (°C), and $T_{s'}$ is $T_{max_{s_i}} - T_{o_i}$ (if $T_{o_i} > T_{max_{s_i}}$) or $T_{min_{s_i}} - T_{o_i}$ (if $T_{o_i} < T_{min_{s_i}}$).

5 Results and discussion

Simulated stream temperatures fit measured data well and the timing of seasonal maximum temperatures was consistent between modeled and observed data (Table 3). MAE was within 1.2°C of measured maximum or minimum temperatures for all sites, with a mean of 0.4°C. At approximately half of the sites, modeled mean annual maximum temperature occurred within the week that measured stream temperature reached its annual maximum, and was offset by only 1 week for 4 additional sites.

5.1 Stream temperatures with climate warming

Average annual stream temperatures warmed by approximately 1.6°C for each 2°C rise in average annual air temperatures, and varied from approximately 1.2–1.9°C over different elevations (Fig. 2). Climate warming caused the greatest rise in stream temperatures at middle elevations (1,500–2,500 m) where climate warming shifted precipitation from

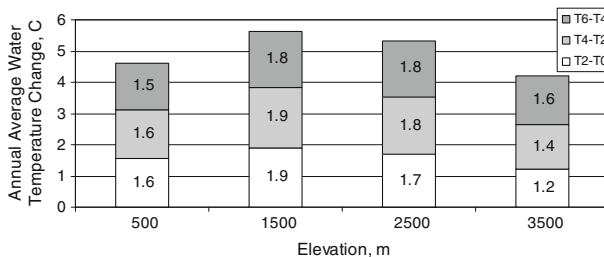


Fig. 2 Average annual stream temperature change by elevation and climate alternative (e.g., T2-T0 is the temperature difference between baseline and 2°C warming, T4-T2 is between 2°C and 4°C warming, and T6-T4 is between 4°C and 6°C warming). Values in columns are average stream temperature changes for each 2°C increase in air temperature

snowmelt to rainfall. At the highest elevations (>3,000 m), stream temperatures rose by progressively larger amounts as climate warming became more severe. Again, these temperature increases are an effect of reduced snowpack in a drastically warmer climate.

We compared the driest year in the modeled period (1987) with the wettest (1983), to understand how seasonal runoff volume and water year type affect stream temperatures. Large stream temperature changes were coincident with the spring runoff recession for both wet and dry years, although the timing of the spring recession changed between year types (for reference, spring recession discharge for 4°C climate warming was plotted for wet and dry years) (Fig. 3a). Stream temperature increases were driven by the start of the low flow period, which reduced the thermal mass of the river so it heated toward equilibrium temperature conditions more rapidly.

The spring runoff recession occurred later and thus stream temperatures warmed later during wet years. Wet years also had a larger overall temperature increase (Fig. 3a) from relatively cooler temperatures throughout winter than occurred in drier years (Fig. 3b). In both wet and dry year types, stream temperatures warmed most during spring, with increases of approximately 5°C for each 2°C rise in air temperature (labeled as ‘spring heating’ in Fig. 3b). Interestingly, stream temperatures between dry and wet years had similar maximum temperatures, but warm water conditions (greater than about 18°C) were brief for wet years (1–2 months), and were more prolonged for dry years (3–4 months) (Fig. 3b). This general pattern persisted with climate warming, when heating occurred sooner for both wet and dry years. Model results suggest that the start of low flow conditions is a good predictor for

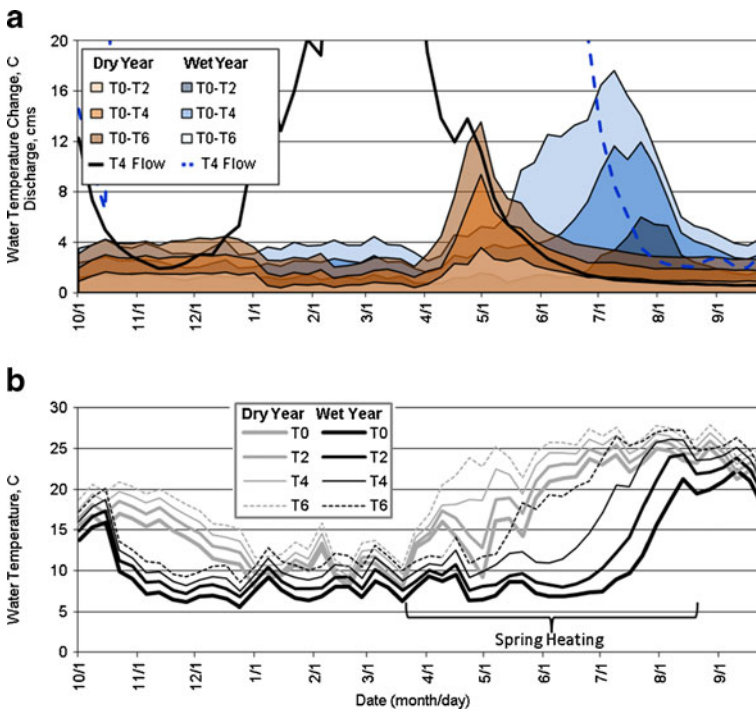


Fig. 3 Stream temperature change with climate warming in the wettest and driest modeled years at 500 m in the American River (a), and stream temperature with climate warming alternatives at 500 m in the American River (b). (T0-T2 is the temperature increase between baseline and 2°C warming, T2-T4 is between 2°C and 4°C warming, and T4-T6 is between 4°C and 6°C warming)

stream temperature warming (Fig. 3a) and wet years in a much warmer California will mirror current dry years in terms of stream temperature (Fig. 3b). Previous research indicates that climate warming is expected to shift the timing and magnitude of the snowmelt recession, altering stream and riparian species compositions in California’s Sierra Nevada (Yarnell et al. 2010), although it is beyond the scope of this study to incorporate these types of feedback mechanisms. The rapid change in stream temperatures during this period supports that finding, and suggests that coldwater fish species will encounter warm stream temperatures earlier in a warmer climate.

5.2 Impacts for coldwater habitat

We superimposed the 21°C stress threshold on modeled temperatures in the South Fork American River to illustrate the effect of climate warming on coldwater habitat during July and January (Fig. 4). With natural flow hydrology and historical climate conditions, model results indicate the downstream 30 km, or 20 % of the river length, exceeded 21°C in July, leaving approximately 80 % of the river for coldwater species. Air temperature increases of 2°C, 4°C, and 6°C resulted in coldwater habitat reductions of 57 %, 91 %, and 99.3 % for coldwater species, respectively (Fig. 4). Longitudinal thermal heterogeneity typically remained about the same or declined slightly with climate warming. Stream headwaters are typically steep and potentially impassable for fish because upper elevations are restricted by natural barriers such as waterfalls or steep rapids. Thus headwater reaches are unlikely to provide suitable habitat for anadromous salmonids, but may provide some habitat to introduced species such as rainbow, brown, and brook trout. With climate warming, habitat in geomorphic units such as lower elevation meandering reaches was largely eliminated. Our results support similar findings from Jager et al. (1999) and Eaton and Scheller (1996) that coldwater fish species will be restricted to higher elevations with climate warming.

To show likely temporal changes in habitat distributions of coldwater fish guilds, we plotted the number of weeks that weekly average stream temperature exceeded 21°C, the stress threshold (Fig. 5), and 24°C, the lethal threshold (Fig. 6), for all watersheds in the modeled domain (note scale change between Figs. 5 and 6). In general, the high-elevation

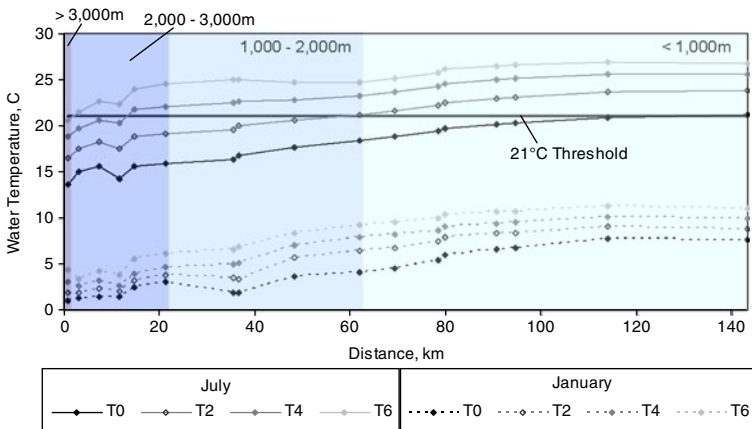


Fig. 4 Average July and January stream temperature with climate warming alternatives for the South Fork American River. Shading represents longitudinal distance in each 1,000 m elevation band. (T0, T2, T4, and T6 represent climate warming of 0°C, 2°C, 4°C, and 6°C, respectively)

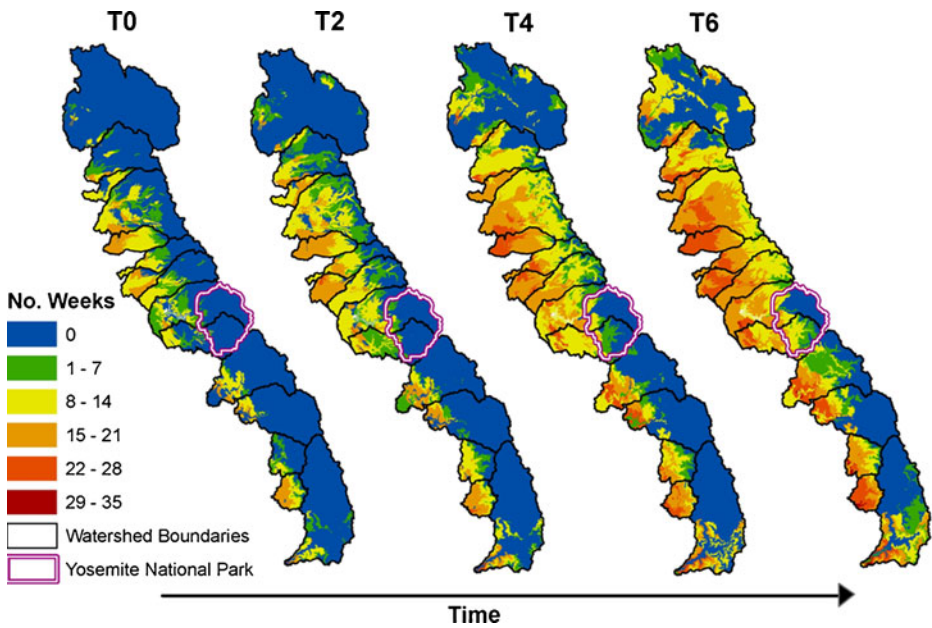


Fig. 5 Average annual number of weeks stream temperature exceeds 21°C with incremental uniform 2°C air temperature increases (T0, T2, T4, and T6 represent climate warming of 0°C, 2°C, 4°C, and 6°C, respectively)

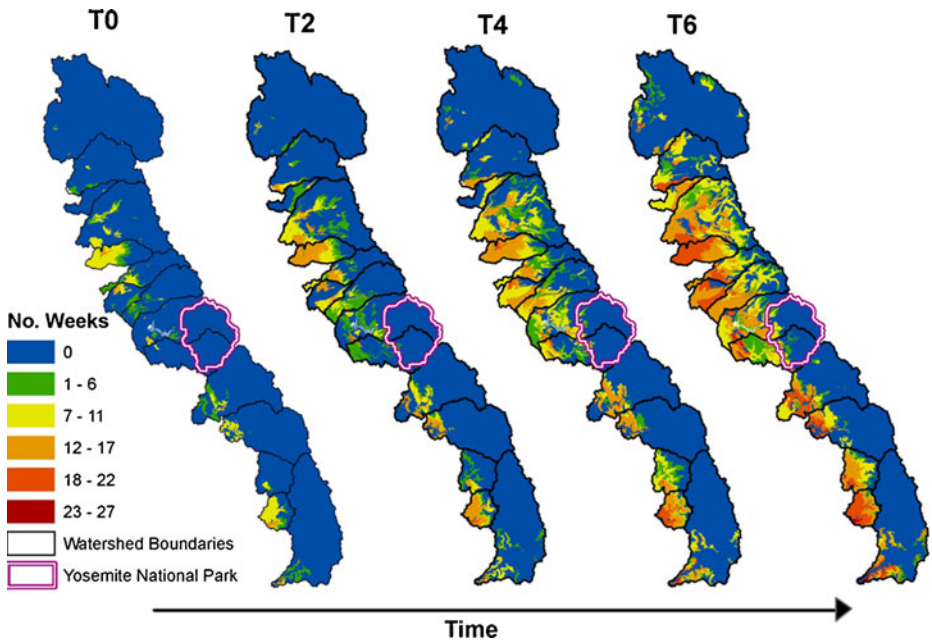


Fig. 6 Average annual number of weeks stream temperature exceeds 24°C with incremental uniform 2°C air temperature increases (T0, T2, T4, and T6 represent climate warming of 0°C, 2°C, 4°C, and 6°C, respectively)

watersheds in the southern extent of the range were less vulnerable to climate warming. The Feather watershed was also less vulnerable to elevated river temperatures because of the larger flow volumes that raise thermal mass and moderate the response of the river to atmospheric conditions. The Feather watershed is anomalous to other study watersheds because it has mostly middle elevation terrain, approximately 80 % lies within 1,500–2,500 m. Also, it straddles a geologic transition between the granitic bedrock representative of the Sierra Nevada and the volcanic bedrock of the Cascade Range, allowing more percolation and larger groundwater contributions (Koczo et al. 2005).

The thermal regime of streams within single watersheds can be heterogeneous (Brown and Hannah 2008), which was further supported by our results. However, it is clear that despite pockets of resiliency to climate warming, stream temperatures will generally become warmer for more weeks of the year with climate warming. From left to right, the climate alternatives in Figs. 5 and 6 illustrate time passing and California becoming progressively warmer. This provides a baseline of stream temperatures without water regulation but with climate warming, and can be used to compare the effects of water regulation and to prioritize basins for restoration in a warmer climate.

Yosemite National Park was highlighted in both maps as an area managed to conserve wildlife and natural resources for future generations, and where resources are likely changing due to climate warming. With extreme climate warming in the T6 alternative, only the high elevations of the Tuolumne River watershed (regions higher than approximately 2,500 m, such as Tuolumne Meadows) retained stream habitat where stream temperatures never exceeded 21°C (Fig. 5). In all other locations, stream temperatures with natural flows increased above 21°C during the year, which could elevate stress, disease, and predation of coldwater fishes (Hari et al. 2006). Stream temperatures generally remained below 24°C throughout Yosemite National Park for basecase conditions, although this lethal temperature threshold was exceeded in a drastically warmer climate (T4 and T6), particularly at lower elevation river reaches within the national park.

We did not observe a habitat shift to higher latitudes (or a northward expansion) as has been reported by other researchers that have studied stream temperature on a national scale (Eaton and Scheller 1996; Sharma et al. 2007). California is the southern extent of the range of both Chinook salmon and steelhead trout. If distributions were historically limited from further southerly expansion by stream temperature, then it follows that even modest warming could lead to additional stress, and an overall habitat reduction in California. Where mountain ranges provide ‘islands’ of habitat and species cannot easily migrate to higher latitudes, climate warming is likely to reduce total habitat for coldwater species such as salmonids.

Anadromous salmonid species have adapted unique life history timing strategies to maximize river habitat and minimize exposure to warmer river temperatures during summer months (Moyle et al. 2002). Climate warming threatens to extend the seasonal duration of lethally warm river temperatures at watershed outlets (where large water supply reservoirs are currently located although lakes and their thermal influences were not modeled) (Fig. 7). Climate warming is projected to cause average annual stream temperatures to exceed 24°C slightly earlier in the spring, but notably later into August and September when peak numbers of fall-run Chinook salmon, the most abundant run in California, historically immigrated into freshwater streams to spawn. The percentage of years that stream temperatures exceeded 24°C at watershed outlets (for at least 1 week) is projected to increase with climate warming, so that if air temperatures rise by 6°C, most Sierra Nevada rivers would exceed 24°C for some weeks every year at watershed outlets (Table 4). The Feather River was a notable exception as discussed above.

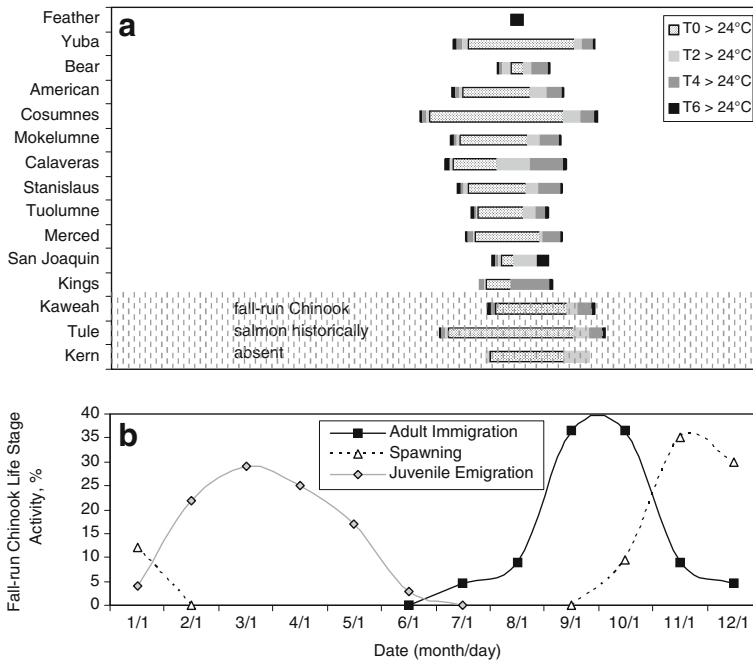


Fig. 7 Average annual weeks stream temperature exceeds 24°C at watershed outlets (north to south) by climate alternative (a), fall-run Chinook salmon freshwater life history timing (b). T0, T2, T4, and T6 represent climate warming of 0°C, 2°C, 4°C, and 6°C, respectively (fall-run Chinook salmon life history from Yates et al. 2008)

5.3 Water management implications

Although most major rivers in the study area are regulated, we used modeled natural flow hydrology to understand the potential impacts of regional climate warming and to separate climate induced changes from those of water operations and land use changes. Stream temperature conditions are dynamic with climate warming, yet regulated stream temperatures are typically compared with unregulated conditions from historical climate conditions, giving resource managers unrealistic baseline conditions to compare the effects of water development.

To maintain coldwater habitat with climate warming in California, it will likely be necessary to operate dams for thermal management, improve passage around dams, or remove some dams. While dams have fundamentally altered the natural flow regime in California and threatened some anadromous salmonids in the state, they also provide benefits for controlling the temperature of reservoir releases and may provide a critical coldwater supply to maintain habitat for coldwater species with climate warming (Yates et al. 2008). Thermal stratification in large reservoirs isolates the hypolimnion, often maintaining a coldwater pool through summer and into fall. Adapting reservoir operations to incorporate coldwater releases from the hypolimnion of large reservoirs may offset some of the thermal effects of climate warming and enhance thermal refugia in downstream locations for coldwater fish species, such as Chinook salmon and steelhead trout.

While managing reservoirs to maintain the thermal regime of downstream river reaches holds promise (Yates et al. 2008), many uncertainties remain and merit more research. For instance, climate warming changes the hydrodynamics of lakes and reservoirs, typically by

Table 4 Average annual maximum stream temperature (°C) and percentage of years that streams exceed 24°C at watershed outlets (T0, T2, T4, and T6 represent climate warming of 0°C, 2°C, 4°C, and 6°C, respectively)

Watershed	Average annual maximum temperature (standard deviation in parentheses)				Years water temperature exceeds 24°C			
	T0 °C	T2	T4	T6	T0 %	T2	T4	T6
Feather	18.7 (1.5)	19.8 (1.5)	20.8 (1.5)	21.8 (1.6)	0	0	0	5
Yuba	26.5 (2.1)	28.3 (2.3)	30.1 (2.6)	31.9 (2.6)	85	100	100	100
Bear	22.5 (1.1)	23.3 (1.2)	24.2 (1.4)	25.0 (1.4)	5	30	45	70
American	24.8 (5.5)	25.9 (5.8)	27.0 (6.0)	28.0 (6.2)	70	100	100	100
Cosumnes	27.1 (6.2)	28.8 (6.7)	30.5 (7.1)	32.7 (7.8)	100	100	100	100
Mokelumne	25.1 (1.4)	26.3 (1.1)	27.4 (1.0)	28.5 (1.0)	80	100	100	100
Calaveras	23.7 (1.1)	24.8 (1.1)	26.0 (1.1)	27.4 (1.8)	35	65	100	100
Stanislaus	24.7 (1.3)	25.8 (1.3)	27.0 (1.1)	28.1 (1.1)	70	90	100	100
Tuolumne	23.0 (1.5)	24.4 (1.4)	25.8 (1.2)	27.1 (1.0)	25	50	100	100
Merced	24.4 (1.4)	25.7 (1.1)	26.8 (1.0)	27.7 (1.0)	55	100	100	100
San Joaquin	21.8 (2.1)	23.5 (1.9)	25.0 (1.6)	26.5 (1.4)	20	40	80	95
Kings	20.2 (2.6)	21.8 (2.4)	23.4 (2.2)	24.8 (2.0)	5	15	30	65
Kaweah	24.7 (2.3)	26.7 (2.1)	28.3 (1.9)	29.9 (1.8)	60	85	100	100
Tule	28.7 (3.2)	30.8 (3.2)	33.1 (3.8)	35.0 (4.2)	100	100	100	100
Kern	18.8 (3.0)	20.4 (3.0)	22.0 (3.0)	23.6 (2.9)	5	5	15	55

lengthening the thermal stratification period, deepening the thermocline, and warming water temperature within the hypolimnion (Komatsu and Fukushima 2007). Thus, hypolimnetic reservoir releases could become warmer or the volume of water could become smaller, failing to provide adequate coldwater releases through summer and fall. Complicating matters is the expectation that climate change could result in greater competition for already scarce water resources in California. Harou et al. (2010) estimated that opportunity costs for environmental water releases could rise by at least an order of magnitude.

5.3.1 Limitations of study results

Modeling inherently simplifies real-world systems. Our approach used fairly coarse spatial representation, with separate mainstem and tributary channels. Water was assumed to be well-mixed within reaches, and small-scale thermal variability was not assessed. We used a weekly timestep, so estimating diurnal fluctuations was outside the scope of this study. We show that weekly stream temperature estimates are sensitive to air rising air temperature, although seasonally-adjusted air temperature increases would likely improve results. We assumed snow cover completely covered reaches, or was completely absent, so the weeks during spring with partial snow cover were poorly represented in RTEMP. Lakes were not modeled, nor the thermal influences of lakes.

RTEMP struggled to adequately estimate stream temperatures with very low flow conditions (e.g., streamflow <0.3 m³/s). When low flow conditions occurred, we constrained atmospheric heating with upper bounds. In real systems, micro-topographic shading, hyporheic flow, partial snow cover, and snowmelt likely moderate stream temperatures when low flow conditions exist.

Measured unregulated stream temperature data were limited. Modeled domain included diverse thermal conditions in terms of elevation, latitude, hydrology, and atmospheric conditions, and we aimed to test the model at sites representative of this variability. Given the extensive modeled domain of this application, model performance was appropriate for the objectives of this study.

We applied lethal maximum temperature tolerances as an initial assessment to understand likely habitat shifts from climate warming. Fish population modeling would better delineate mortality by life stage and species, and could also incorporate anticipated flow changes, which previous research indicates may have non-additive effects on the distribution and abundance of coldwater fish species (Jager et al. 1999). Impacts to the health and distribution of some coldwater fish species may not be as dire as predicted here if other environmental factors such as food availability compensate for thermal impacts (Matthews et al. 1994). Additional research is needed to understand the potential of coldwater species to respond to a warming climate through evolution, since little is currently known about the capacity of salmonids to adjust to climate change (McCullough et al. 2009).

6 Conclusions

The regional equilibrium temperature approach applied here is well-suited for climate change analysis because it retains mechanistic heat exchange at the air-water interface, but is not overly data or computationally intensive. This study modeled stream temperatures at the mesoscale, improving understanding of the differential impacts to regional stream temperature from climate warming. This method could be applied to other regions to improve understanding of the relative vulnerability of neighboring watersheds to climate change. It is a useful approach for water managers because it indicates which watersheds, sub-basins and elevations are resilient to climate warming. This application assesses stream temperatures with natural flow conditions, although dams or other infrastructure can be incorporated by changing boundary conditions (Wright et al. 2009). Once watersheds or sub-watersheds that are promising for restoration have been identified with our approach, finer resolution equilibrium or deterministic water temperature modeling may better represent diurnal variability and sub-reach spatial variability.

In this application, stream temperatures increased by approximately 1.6°C for each 2°C rise in air temperature, although thermal heterogeneity existed within and between basins. The high watersheds of the southern Sierra Nevada and the northern Feather River watershed were less vulnerable to changes in the thermal regime of rivers from climate warming, while the low elevations from approximately the Yuba to the Tuolumne watersheds, as well as the Kaweah and Tule watersheds were the most vulnerable to increasing stream temperatures. Precipitation shifts from snowfall to rainfall, and low flow conditions were two characteristics that drove water temperatures dynamics with climate warming. Elevation was a good predictor of the shift from snowfall to rainfall, while season, water year type, and mean annual flow of watersheds were good predictors of low flow conditions. The largest thermal change from climate warming occurred during spring, when stream warming could exceed 5°C for each 2°C rise in air temperature.

We applied lethal maximum temperature tolerances to evaluate likely habitat shifts from climate warming. Results indicate that stream habitat for coldwater species declined with climate warming, and that remaining habitat existed at higher elevations. If maintaining coldwater habitat is a priority in California, it will likely be necessary to operate dams for thermal management, improve passage around dams, or perhaps remove some dams for fish

to access coldwater habitat. This indicates that climatic changes must be considered and incorporated when studying and planning stream restoration projects, preparing environmental impact statements, or licensing operations of hydropower facilities. Assessments of stream habitat viability that do not incorporate anticipated effects of climate warming are unlikely to provide desired outcomes or promote changes in behavior that buffer against future climate warming.

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