WATER AND ENERGY SECTOR VULNERABILITY TO CLIMATE WARMING IN THE SIERRA NEVADA: A METHOD TO CONSIDER WHETHER DAMS MITIGATE CLIMATE CHANGE EFFECTS ON STREAM TEMPERATURES

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ABSTRACT

In this paper, we provide a method for examining water quality objectives below dams at the mesoscale using a multi-model approach. Our method is a pilot application intended to leverage climate-forced hydrologies into reservoir inflows, combined with in-reservoir thermal dynamics, reservoir release operations, and downstream temperature changes driven by atmospheric conditions. Habitats for coldwater fish species, such as trout and salmon, have been reduced by water development, dam-building, and land use changes that alter thermal regimes of rivers. Climate change is an additional threat. Because regulated flows in California’s Sierra Nevada are complex and highly valued for downstream beneficial uses such as hydropower and water deliveries to municipal and agricultural uses, a multi-model method can potentially capture the complexities of changing flow regime and water quality. Changing hydroclimatic conditions will likely have associated changes to water temperature that will have cascading ecological impacts downstream (although we assume reservoir operations remain unchanged through time). We model hypothetical reservoirs of different sizes, elevations, and latitudes to examine the potential to manage stream temperatures for downstream coldwater habitat for 4 time periods representing a progressively farther outlook for climate change, and 2 climate models to illustrate climate model uncertainty. Climate-driven Variable Infiltration Capacity hydrologic data was input into a regional equilibrium stream temperature model. The Water Evaluation and Planning model was used to estimate reservoir outflow and develop generic operating rules for each reservoir and Water Quality for River-Reservoir Systems software was used to estimate water temperature within each reservoir. All models are 1-dimensional and operate on a weekly timestep. Our approach is useful as a proof of concept study, although we believe that stream temperature results are too cool and do not represent the current or future thermal regime. Air temperatures used as input data for this study are 3-7°C cooler than Daymet interpolated climate data, and NCARPCM1 air temperatures for the end of the 21st century are cooler than Daymet historical data. We recommend quantifying the accuracy of historical climate data in mountain regions and modifying reservoir operations to maintain hydropower and water supply benefits for more meaningful results.

Keywords: water management, climate change, regulated rivers, reservoirs, coldwater habitat, Sierra Nevada
RECOMMENDED CITATION

Please use the following citation for this paper:

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INTRODUCTION AND RATIONALE

Stream temperatures are an instrumental characteristic of lotic systems, directly influencing dissolved oxygen levels, nutrient cycling, chemical reaction rates, and productivity and mortality of aquatic ecosystems (Poole and Berman 2001). They are correlated with climate, making them particularly vulnerable to climate change (Mohseni and Stefan 1999). Stream temperatures are driven by heat exchange with the atmosphere and streambed, as well as source temperatures (i.e., groundwater, snowmelt, overland flow, and precipitation). 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), and modeling studies suggests that stream temperatures will increase further with climate warming, potentially causing habitat reduction for coldwater species (Battin et al. 2007; Jager et al. 1999). In California’s west-slope Sierra Nevada rivers, unregulated stream temperatures are anticipated to increase with climate warming (with uniform air temperature increases of 2°C, 4°C, and 6°C as a sensitivity analysis of stream temperature response to climate warming) (Null et al. Accepted) (Figure 1).

Figure 1: Average Annual Number of Weeks Unregulated Stream Temperatures Exceed 24°C, Where T0 Represents Historical Conditions and Incremental Air Temperature Increases of 2°C

In the west-slope Sierra Nevada, land use change and water development have fundamentally altered the natural flow and temperature regime, threatening the health and integrity of
freshwater ecosystems (Poff 2009; Olden and Naiman 2010). Aquatic and riparian habitats are often directly or indirectly managed by water operations with the quantity, quality, and timing of reservoir releases. Reservoir releases provide new boundary conditions for downstream reaches, with diminishing influence as distance from the dam increases. It is possible that dams could mitigate some of the stream temperature impacts of climate change, particularly where reservoir releases are colder than unimpaired conditions or where winter water is stored in the coldwater pool of deep reservoirs. The objective of this study is to 1) develop a method to evaluate a dam’s potential for mitigating climate change effects on stream temperatures at the mesoscale and 2) provide a method to improve understanding of potential changes to the volume and timing of coldwater habitat from baseline conditions.

It is likely that water will be managed more tightly in a future with climate change. This research begins to quantify the extent to which dams may provide thermal benefit under “normal operations”—meaning we used a generic operating rule curve and did not change operations to explicitly manage for cold water. Rather we compared the thermal regime of dam releases at various elevations and from reservoirs with various capacities while increasing the severity of climate change. This research is novel because it explores thermal management at the mesoscale, rather than analyze temperatures on a case-by-case basis for individual reservoirs. This study is intended to guide operations and help water managers who are relied on to provide water for multiple and competing uses. We provide baseline data regarding the duration of cold water available in reservoirs of different sizes, elevations, and latitudes, as well as how reservoir release affect downstream temperatures.

Most climate change research for water resource management in California focuses on human impacts such as water supply, hydropower generation, and flood control (Vicuna et al. 2011; Connell-Buck et al. 2011; Das et al. 2011; Null et al. 2010a; Madani and Lund 2010; Young et al. 2009; Medellin-Azuara et al. 2008; Tanaka et al. 2006). Fewer papers focus on potential climate warming impacts to water quality and quantity for environmental uses in regulated systems (Null and Viers 2012; Kaushal et al. 2010; Sinokrot et al. 1995; Johnson et al. 2004; Yates et al. 2008). Reservoir releases may present an opportunity to manage water temperature and provide suitable coldwater habitat for fish and wildlife, particularly by releasing water from the coldwater pool of thermally stratified reservoirs. Sinokrot et al. (1995) found that climate change effects on regulated stream temperatures were greater if reservoirs released from the surface rather than the deeper cold water pool. A study on the Blue Mesa Reservoir on the Colorado River showed that climate played the largest role in reservoir thermal structure and that a warmer climate may reduce the volume of the hypolimnion (Johnson et al. 2004). Yates et al. (2008) modeled California’s Shasta Reservoir and downstream Sacramento River, and determined the dam could provide a coldwater supply to offset the effects of climate change and maintain downstream habitat for native Chinook salmon.

A growing literature links climate change specifically with water quality and quantity for salmonid species (salmon and trout), but does not always consider developed systems. For instance research indicates stream warming could reduce the total amount of coldwater habitat (Null et al. Accepted; Battin et al. 2007; Eaton and Scheller 1996; Mohseni et al. 2003; Tung et al. 2006; Isaak et al. 2010) shift it to higher elevations or latitudes (Jager et al. 1999; Isaak et al. 2010; Hari et al. 2006; Null et al. Accepted), alter the distribution and abundance of
coldwater species (Gooseff et al. 2005), or ease the introduction of invasive species that compete with natives (Rahel and Olden 2008). It is not well understood the extent to which dams can provide coldwater releases to maintain coldwater habitat, how climate change may impact release temperatures as climate change becomes more severe, or how dams of various sizes, elevations, and latitudes may be affected differently. We use climate-driven weather input from two global climate models (GCMs) to model generic (hypothetical) reservoirs at different elevations, latitudes, and of various sizes to examine how reservoir release temperatures may be altered with climate change. We assume that dam operations do not change with climate change.

This paper begins with a description of the Sierra Nevada study area, including a discussion of current water development. We explain our modeling approach, including Water Evaluation And Planning (WEAP), the rainfall runoff model used to simulate hydrology; Water Quality for River-Reservoir Systems (WQRRS), the one-dimensional water quality model used to estimate reservoir temperatures; and Regional equilibrium stream TEMPerature (RTEMP), the one-dimensional equilibrium stream temperature model. Results indicate that reservoirs release water that is cooler than upstream conditions, although the absolute temperatures of reaches below dams warm with climate change. Stream temperatures are sensitive to changes in reservoir volume, elevation, and latitude. Overall, the approach described here provides a method for dam operators or other stakeholders to incorporate water quality effects of climate change with water supply, hydropower, and flood control impacts for a more complete understanding of climate change impacts for water regulation. However, all modeled stream temperatures from this effort remain below 18°C for all simulations. These findings contradict previous research indicating stream temperatures are already nearing stressful or lethal temperatures for coldwater species (Yates et al. 2008; Null et al. Accepted). Climate input data used for this study may not adequately represent historical or future conditions (air temperatures are 3°C–7°C cooler than estimated Daymet air temperatures). We recommend comparing and analyzing modeled climate data to gauge which datasets are most representative of historical and future climatic conditions for California’s Sierra Nevada mountain region.

BACKGROUND

Study Area

West-slope Sierra Nevada rivers flow westward from the crest of the Sierra Nevada to their confluence with the Sacramento-San Joaquin Delta and out the Pacific Ocean (Figure 2). The Sierra Nevada region has a Mediterranean-montane climate with a dry season roughly from May to October and a wet season from November to April. Historically, the typical snowline was about 1,000 meters (m). Precipitation averaged about 100 centimeters per year (cm/yr) for the region, but varied greatly with latitude, elevation, and local weather patterns. Precipitation was greatest in the northern watersheds and the highest elevations of the southern Sierra Nevada. Typically, heavy snowpack persisted late into summer.
Sierra Nevada rivers have been extensively developed for water supply, hydropower generation, flood protection, and recreation. West-slope watersheds from the Feather watershed in the north to the Kern watershed in the south have about 24,590 million cubic meters (mcm) of water storage for all dams greater than 1.2 mcm (1 thousand acre feet [taf]), and approximately 8,751 megawatts (MW) of online hydropower capacity (Null et al. 2010a). Infrastructure consists of a complex network of dams, diversions, canals, powerhouses, and transmission lines. In general, the distribution of reservoirs is approximately equal by elevation, although storage capacity is much greater at lower elevations (Table 1).
Table 1: Major Sierra Nevada Reservoirs by Elevation, Latitude, and Average Volume (mcm)

<table>
<thead>
<tr>
<th>Elevation Group</th>
<th>Northern</th>
<th>Central</th>
<th>Southern</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Feather, Yuba, Bear, American, Cosumnes)</td>
<td>(Mokelumne, Calaveras, Stanislaus, Tuolumne, Merced)</td>
<td>(San Joaquin, Kings, Kaweah, Tule, Kern)</td>
<td></td>
</tr>
<tr>
<td>Very High</td>
<td>n = 12</td>
<td>n = 4</td>
<td>n = 6</td>
<td>n = 22</td>
</tr>
<tr>
<td>(&gt; 1600m)</td>
<td>avg. vol. = 50</td>
<td>avg. vol. = 82</td>
<td>avg. vol. = 137</td>
<td>avg. vol. = 80</td>
</tr>
<tr>
<td>High</td>
<td>n = 14</td>
<td>n = 7</td>
<td>n = 2</td>
<td>n = 23</td>
</tr>
<tr>
<td>(800-1600m)</td>
<td>avg. vol. = 206</td>
<td>avg. vol. = 171</td>
<td>avg. vol. = 102</td>
<td>avg. vol. = 186</td>
</tr>
<tr>
<td>Mid</td>
<td>n = 9</td>
<td>n = 6</td>
<td>n = 7</td>
<td>n = 22</td>
</tr>
<tr>
<td>(&lt; 800m)</td>
<td>avg. vol. = 800</td>
<td>avg. vol. = 1313</td>
<td>avg. vol. = 412</td>
<td>avg. vol. = 813</td>
</tr>
<tr>
<td>Total</td>
<td>n = 35</td>
<td>n = 17</td>
<td>n = 15</td>
<td>n = 67</td>
</tr>
<tr>
<td></td>
<td>avg. vol. = 305</td>
<td>avg. vol. = 553</td>
<td>avg. vol. = 261</td>
<td>avg. vol. = 357</td>
</tr>
</tbody>
</table>

Source: Null et al. 2010a.

Very high-elevation reservoirs are typically operated for hydropower generation, and larger, mid elevation reservoirs are more commonly operated for water supply and flood protection. Roughly 75 percent of California’s in-state hydropower is produced from more than 150 dams in the Sierra Nevada Mountains with elevations of over 300 m (Aspen Environmental and M-Cubed 2005). These high-elevation hydropower systems are primarily single-use and are mostly privately owned and operated solely for hydropower revenues (Vicuna et al. 2008). Winter rain and spring snowmelt is stored in relatively small reservoirs for within-year storage for generation primarily during summer. The remaining 25 percent of California’s in-state hydropower is produced in larger low elevation, multi-use projects owned and operated by the state and federal governments (Aspen Environmental and M-Cubed 2005).

Stream temperatures below dams are affected by reservoir release timing and temperatures, atmospheric conditions, and side contributions such as tributary inflow, snowmelt, or runoff. Hydropower releases typically occur from the bottom of the reservoir so that the weight of water in the reservoir pressurizes the penstock. This suggests that climate change impacts may be buffered somewhat by hydropower regulation. A reduction in volume of the hypolimnion could limit the ability of reservoirs (especially small reservoirs) to mitigate climate induced stream warming.
Methods

Our approach was to model a simplified, hypothetical watershed that has many of the physical characteristics found in watersheds of the Sierra Nevada such as hydropower, water supply and flood control infrastructure and unregulated tributaries. This approach required a series of models that, when linked via parameterization and sequencing, can be applied to a large spatial area such as the Sierra Nevada and have the ability to calculate multiple years and climate scenarios quickly.

Our hypothetical watershed has three main forks with a total drainage area of 2,341 square kilometers (km$^2$) (Figure 3). Elevation ranges from 325 m to 1,525 m, with three reservoirs in series. The Middle fork is the largest of the three forks and has two hydropower projects which influence the flow regime. The North fork and the South fork are undammed and have a natural flow regime. The lowest reservoir is below the confluence of all three forks near the bottom of the watershed representing a “rim” dam common in the Sierra Nevada which is managed for water supply and flood control.

Figure 3: Hypothetical Study Watershed with Modeled Infrastructure

Source: Authors
We used a weekly time step and with two GCMs, two management scenarios, and three watersheds (Table 2), which is further described below. Four 20-year time periods were modeled ranging from 1970 to 2090, and were labeled as historical (htp), near-term (ntp), mid-term (mtp), and far-term (ftp) time periods.

### Table 2: Model Run Matrix

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model Runs</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate models</td>
<td>A2-MIROC32med</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>A2-NCARPCM1</td>
<td></td>
</tr>
<tr>
<td>Time periods</td>
<td>htp (1970–1990)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>ntp (2010–2030)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mtp (2040–2060)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ftp (2070–2090)</td>
<td></td>
</tr>
<tr>
<td>Watersheds</td>
<td>Northern</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Central</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td></td>
</tr>
<tr>
<td>Management*</td>
<td>Regulated</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Unregulated</td>
<td></td>
</tr>
<tr>
<td><strong>Total Model Runs</strong></td>
<td><strong>48</strong></td>
<td></td>
</tr>
</tbody>
</table>

* Reservoir operation identical for all regulated runs (generic operating rules)

Source: Authors

### Overview of Modeling Steps

Many separate modeling steps were required to estimate stream temperatures below reservoirs. The complex interaction of hydrology, reservoir operations and climate variables were incorporated in this approach. Climate inputs were produced by the Scripps Institution of Oceanography by downscaling GCMs (Table 3). Climate and precipitation data drive the Variable Infiltration Capacity (VIC) rainfall-runoff model to produce surface runoff and groundwater flows on a spatially gridded format. WEAP software was used to produce river flows at specific locations. An equilibrium stream temperature model, RTEMP, was used to estimate stream temperatures upstream of reservoirs. Reservoir operations were modeled using WEAP and reservoir temperatures were modeled using WQRRS, a one-dimensional package developed by the Army Corps of Engineers. Regulated stream temperatures were again passed
to RTEMP with temperatures from the WQRRS model as upstream boundary conditions and flows from the regulated WEAP model (see modeling sequence in right side of Figure 4).

Table 3: Model Input Data and Sources

<table>
<thead>
<tr>
<th>Model</th>
<th>Input</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIC</td>
<td>GCM (MIROC32med and NCARPCM1 - A2 SRES) boundary conditions</td>
<td>California Climate Change Center</td>
</tr>
<tr>
<td>RTEMP</td>
<td>Meteorology</td>
<td>VIC (cloud cover user defined)</td>
</tr>
<tr>
<td></td>
<td>Hydrology (surface runoff, snow accumulation, snowmelt, groundwater)</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>Topography</td>
<td>USGS 10 m DEM</td>
</tr>
<tr>
<td></td>
<td>Reservoir Outflow</td>
<td>WEAP</td>
</tr>
<tr>
<td></td>
<td>Reservoir release water temperature</td>
<td>WQRRS</td>
</tr>
<tr>
<td>WEAP</td>
<td>Inflow hydrology</td>
<td>VIC</td>
</tr>
<tr>
<td></td>
<td>Reservoir operational rules</td>
<td>User defined</td>
</tr>
<tr>
<td>WQRRS</td>
<td>Meteorology</td>
<td>VIC (wet bulb temperature calculated, cloud cover user defined)</td>
</tr>
<tr>
<td></td>
<td>Geometry</td>
<td>User defined</td>
</tr>
<tr>
<td></td>
<td>Flow (Inflow, outflow, initial storage)</td>
<td>WEAP</td>
</tr>
<tr>
<td></td>
<td>Inflow water temperature</td>
<td>RTEMP</td>
</tr>
</tbody>
</table>

Source: Authors, RTEMP input from (Null et al. Accepted), WEAP input from (Young et al. 2009)
To assess latitude with the effects of climate change on stream temperatures, the entire theoretical watershed was shifted from the central Sierra Nevada (in the Stanislaus River) about 200 km north to the approximate location of the Feather watershed and about 100 km south to the approximate location of the San Joaquin watershed (Figure 4). Watershed size, shape, and infrastructure remained constant and only the climatic inputs and hydrology were changed with latitude.
GRIDDED CLIMATE INPUT DATA

We used two GCMs that represent extremes for possible precipitation and temperature, MIROC32MED and NCARPCM1. The two GCMs were run with the A2 emissions scenario which assumes fairly severe climate change and continuously increasing growth rate (Cayan et al. 2009). The GCM output was downscaled to 1/8° using the bias correction and spatial downscaling method described in Maurer et al. (2010). The VIC rainfall runoff model produced climate-forced surface runoff, baseflow, evapotranspiration, and soil moisture as described in Maurer (2007).

REGULATED WEAP MODEL

The infrastructure operations model represents a simplified example of water management infrastructure in the Sierra Nevada. The model incorporates three reservoirs in series with hydropower operations in the uppermost two, and flood control and water supply operations in the low elevation reservoir. We modeled reservoir operations and hydropower releases using WEAP, a priority based water management software package developed by the Stockholm Environment Institute. For simplicity and to focus on stream temperatures, we assume water operations remain constant with changing hydroclimatic conditions.

We modeled hydropower operations using a simple method of requiring a minimum release from the reservoir for each week (Figure 5). The weekly minimum instream flow requirement was based on average weekly hydropower releases from high-elevation hydropower plants in the Sierra Nevada. This method of simulating releases assumes that demand does not change with water year type or varying climate scenarios and therefore the annual pattern of releases remains constant.

Figure 5: Flow Requirements to Upper and Middle Hydropower Plants, and Lower Reservoir

![Flow Requirements Graph]

Source: Authors
UPPER RESERVOIR

The uppermost hydropower project consists of a reservoir and a diversion to a hydropower plant downstream (Figure 3). The reservoir has an upstream drainage area of 63.3 km² and a storage capacity of 58 mcm, approximately the size of Ice House reservoir in the American River watershed (Table 4). The upper hydropower plant has a maximum turbine capacity of 9 cubic meters per second (m³/s).

Table 4: Physical Characteristics of Modeled Reservoirs

<table>
<thead>
<tr>
<th>Watershed Location</th>
<th>Reservoir</th>
<th>Size</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
<th>Capacity (mcm)</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>Upper</td>
<td>S</td>
<td>39.94</td>
<td>-120.31</td>
<td>1615</td>
<td>58.1</td>
<td>12</td>
</tr>
<tr>
<td>Northern</td>
<td>Middle</td>
<td>M</td>
<td>39.94</td>
<td>-120.94</td>
<td>1291</td>
<td>86.9</td>
<td>65</td>
</tr>
<tr>
<td>Northern</td>
<td>Lower</td>
<td>L</td>
<td>39.56</td>
<td>-121.44</td>
<td>300</td>
<td>1233.0</td>
<td>200</td>
</tr>
<tr>
<td>Central</td>
<td>Upper</td>
<td>S</td>
<td>38.31</td>
<td>-119.94</td>
<td>1615</td>
<td>58.1</td>
<td>12</td>
</tr>
<tr>
<td>Central</td>
<td>Middle</td>
<td>M</td>
<td>38.06</td>
<td>-120.19</td>
<td>1291</td>
<td>86.9</td>
<td>65</td>
</tr>
<tr>
<td>Central</td>
<td>Lower</td>
<td>L</td>
<td>37.94</td>
<td>-120.56</td>
<td>300</td>
<td>1233.0</td>
<td>200</td>
</tr>
<tr>
<td>Southern</td>
<td>Upper</td>
<td>S</td>
<td>37.31</td>
<td>-119.19</td>
<td>1615</td>
<td>58.1</td>
<td>12</td>
</tr>
<tr>
<td>Southern</td>
<td>Middle</td>
<td>M</td>
<td>37.06</td>
<td>-119.31</td>
<td>1291</td>
<td>86.9</td>
<td>65</td>
</tr>
<tr>
<td>Southern</td>
<td>Lower</td>
<td>L</td>
<td>37.06</td>
<td>-119.69</td>
<td>300</td>
<td>1233.0</td>
<td>200</td>
</tr>
</tbody>
</table>

Source: Authors

MIDDLE RESERVOIR

The middle hydropower project is similar to the upper project but larger in size. The middle reservoir has a storage capacity of 87 mcm, approximately the size of Bowman Lake in the Yuba River watershed. The modeled weekly hydropower demand for the middle hydropower project had a maximum turbine flow of 44.5 m³/s (Table 4, Figure 5).

LOWER RESERVOIR

The lower reservoir represents a Sierra Nevada watershed “rim” reservoir that is managed for water supply and flood control. The size of “rim” reservoirs in the Sierra Nevada vary from 86.3 mcm (Englebright on the Yuba River) to over 4,363 mcm (Oroville on the Feather River). We modeled a reservoir approximately the size of Folsom to assess climate change effects on rim dams (Table 4). Flood control operations were developed by simplifying the U.S. Army Corps of Engineers Folsom flood control curve. The top of conservation was drawn down to 500 mcm from week 41 to week 46 and held constant for the entire flood season regardless of what flood storage space was available upstream. From weeks 13–21 the flood control space is reduced to zero for the remainder of the year.
We simulated water supply operations in the lower reservoir by creating a demand that peaks in the summer and is at a minimum during the winter months, based on actual demand from "rim" reservoirs. WEAP allocates water at each time step based on a system of priorities. In our water management model, we placed the highest priority on water supply, second on hydropower generation and third on reservoir storage.

RESERVOIR WATER QUALITY MODELING – WATER QUALITY FOR RESERVOIR-RIVER SYSTEMS (WQRRS)

We simulated reservoir temperatures with WQRRS, a one-dimensional river and reservoir model developed by the U.S. Army Corps of Engineers (USACE-HEC 1986). WQRRS is a physically based, finite difference model based on the principles of conservation of heat and mass. The model operates on a daily time step, although we used weekly input and output data. We chose WQRRS because we could simulate 30 years of reservoir simulations in seconds. For this study, we used only the reservoir simulation component (not the river simulation component). Water temperature was the only water quality parameter modeled and was estimated using the heat budget method.

WQRRS has been used extensively through the past three decades to model water quality in lakes and reservoirs, with recent publications discussed here. It was used to aid decision-making by evaluating management alternatives for sustainable ecosystem management of Turkish coastal lagoons (Gonenc et al. 1997), and to aid conflict resolution over water allocation by modeling Iran’s Karkheh river-reservoir system (Karamouz et al. 2008). Deas and Orlob (1999) simulated water quantity and quality for restoration of anadromous fisheries below Iron Gate Dam on the Klamath River. Lopes et al. (2003) used it to simulate dissolved oxygen and water temperature in Portugal’s Aguieira Reservoir, and Meyer et al. (1996) altered meteorologic and hydrologic input conditions to estimate water quality effects on Shasta Reservoir and part of the Sacramento River from a doubling of CO$_2$.

Water temperature and other water quality parameters are simulated using the one-dimensional form of the advection-dispersion equation:

$$ V \frac{\partial C}{\partial t} + \Delta x Q_x \frac{\partial C}{\partial x} = \Delta x A_x \frac{\partial^2 C}{\partial x^2} + Q_i C_i - Q_o C + VS $$

(1)

where $C$ is thermal energy (kcal), $V$ is volume (m$^3$), $t$ is time (s), $x$ is vertical distance in the reservoir (m), $Q_x$ is advective flow (m$^3$/s), $A_x$ is surface area (m$^2$), $D_c$ is the effective diffusion coefficient (m$^2$/s), $Q_i$ is lateral inflow (m$^3$/s), $Q_o$ is lateral outflow (m$^3$/s), and $S$ are sources and sinks (kcal/s). Internal transport of heat and mass occur only in the vertical direction through advection and effective diffusion mechanisms, with water well-mixed laterally and longitudinally. We assumed all reservoir inflow occurs at the upstream end of the reservoir, making the rate of advection slower than if the inflow occurred closer to the outlet. Effective diffusion between layers is based on temperature and includes molecular and turbulent diffusion as well as convective mixing based on density gradients. One dimensional models such as WQRRS work well for small to large reservoirs but should not be used for shallow reservoirs or reservoirs with small residence times (i.e., vertically mixed systems that would be better represented with a river model) (USACE-HEC 1986).
Reservoirs are represented as a series of one-dimensional layers, with user-defined surface area, thickness, and volume. For this application, layer thickness was 1 m. Inflows are instantaneously dispersed throughout a layer of similar density in the reservoir. Outflows are modeled using the selective withdrawal allocation method developed by the U.S. Army Engineer Waterways Experiment Station (WES method) (USACE-HEC 1986) to describe the vertical limits of the withdrawal zone and the vertical velocity distribution within the zone. For additional model detail, see USACE-HEC (1986). For this study we represented withdrawal outlets with a small (< 1 m³/s) withdrawal structure near the bed of the reservoir and a second outlet near the top of the coldwater pool for the remainder of outflow (modeled with WEAP). Spill events occur from the reservoir surface. The quantity and quality of reservoir releases form the boundary conditions for downstream river temperature models. See Table 3 for a list of input data and sources and Appendix A for a list of parameters and coefficients used for each reservoir model. Results from WEAP and WQRRS are passed to RTEMP to estimate stream temperatures, and the models are run sequentially (Figure 3).

STREAM TEMPERATURE MODEL – REGIONAL EQUILIBRIUM TEMPERATURE MODEL (RTEMP)

Stream temperatures were estimated with RTEMP, a one-dimensional equilibrium temperature model developed by Watercourse Engineering, Inc. (Null et al. Accepted). We used a weekly timestep and spatial resolution of 250 m vertical elevation bands for streams (the same resolution as WEAP). RTEMP is a physically based model, which uses meteorology, hydrology, boundary conditions, and stream length (Table 3) to estimate stream temperatures based on equilibrium temperature theory (Edinger et al. 1968; Bogan et al. 2003).

Stream temperatures are estimated using a simplified form of the advection-dispersion equation:

\[
\frac{\partial T_w}{\partial t} = \frac{H_{net}}{C_p \rho d}
\]

(2)

where \( T_w \) is water temperature (°C), \( t \) is time (wk), \( H_{net} \) is net heat exchange at both the bed- and air-water interfaces (W/m²), \( C_p \) is the specific heat of water (4185 J/kg/°C), \( \rho \) is water density (1000 kg/m³), and \( d \) is water depth (m). Equation 2 assumes rivers are advection dominated so dispersion is ignored, and that changes in longitudinal stream temperatures are driven by meteorological conditions, which change stream temperatures with respect to time. It further assumes a rectangular channel where water surface is the same width as the streambed. For a full derivation and additional model detail, see Null et al. (Accepted). Equation 2 produces a time series of dynamic stream temperatures where water seek equilibrium temperature, but is constrained by boundary conditions, travel time, and river geometry.

RTEMP reaches correspond to 250 m elevation bands, where stream temperatures are estimated separately for tributaries and mainstem rivers. This also allows attenuation of tributaries to be assessed. Mainstem and tributary channels mix at the bottom of each reach using a mass balance approach. In addition to boundary conditions for flow and stream temperature obtained from WEAP and WQRRS, we assumed snowmelt was 1°C, precipitation temperature is the
same as air temperature, and groundwater temperature is 7.5°C (mean annual air temperature for the west-slope Sierra Nevada at 2,500 m).

Equilibrium temperature is useful because heat flux at the water surface can be represented with only meteorological input variables, and it can be applied on a regional scale. RTEMP has previously been used to assess unregulated stream temperature sensitivity to climate warming in California’s west-slope Sierra Nevada, with an emphasis on impacts to coldwater habitat for anadromous salmon species (Null et al. Accepted). Other equilibrium temperature studies exist, including assessing the effects of climate change by examining the relationship between stream and air temperatures (Mohseni and Stefan 1999), predicting stream temperatures in Canada’s Miramichi River (Caissie et al. 2005), modeling Colorado River temperatures downstream of Glen Canyon Dam (Wright et al. 2009), and quantifying the effects of stream discharge on summer river temperature (Gu et al. 1998).

Model Calibration and Testing

We calibrated the models separately using observed stream and reservoir data. The RTEMP stream temperature model was calibrated prior to this study and is described in detail by Null et al. (Accepted). We calibrated the reservoir models using actual reservoirs in the Sierra Nevada; the upper reservoir was calibrated using temperature profiles from Icehouse Reservoir, Bowman Reservoir, and Folsom Reservoir for the upper, middle, and lower reservoirs, respectively. Reservoir calibration was challenging because few observed data were available, and calibration dates differ between modeled reservoirs depending on when measured data were available. Most stream and reservoir temperature studies in the Sierra Nevada are part of FERC relicensing, and therefore are limited to short-term collection efforts.

The upper reservoir calibration was completed using 13 thermal profiles. Daily average stream inflow and outflow temperatures from October 1, 2000, to October 19, 2004, were collected by SMUD and observed streamflow measurements were from the USGS.

The middle reservoir was calibrated with two years of measured data from Nevada Irrigation District’s (NID) Yuba-Bear project relicensing. Inflow and outflow temperature data included 15 minute temperature observations from June 3, 2008 to October 10, 2008, and June 12, 2009 to October 16, 2009. Reservoir thermal profile measurements were collected by NID in July, August, September, and October of 2008 and 2009. Inflow discharge was estimated with USGS measured daily outflows through the Bowman-Spaulding canal and Canyon Creek below Spaulding and Bowman storage.

The lower reservoir was calibrated with Folsom Lake inflow and outflow, as well as stream temperature data from the American River below Folsom Reservoir from September 30, 2000 to April 10, 2011 (CDEC 2011). No thermal profiles for Folsom Reservoir were available for calibration.

Evaporation coefficients and radiation absorption coefficients (listed in Appendix A) were adjusted so that the modeled profiles and outlet temperatures reasonably matched observed data (Figures 6 and 7). This assures that models stratify and mix correctly, and adequately
represent the complex physical processes of reservoirs in the Sierra Nevada. Calibration statistics are summarized in Table 5.

Figure 6: Modeled and Observed Reservoir Thermal Profiles for the: (A) Upper (Icehouse), (B) Middle (Bowman), and (C) Lower (Folsom) Reservoirs

Source: Authors, SMUD, NID
Figure 7: Modeled and Observed Reservoir Release Temperatures for the: (A) Upper (Icehouse), (B) Middle (Bowman), and (C) Lower (Folsom) Reservoirs

Source: Authors, SMUD, NID, CDEC
Regulated Stream Temperatures in a Changing Climate

We discuss study results by focusing on the central watershed, although the northern, central, and southern watersheds are compared with longitudinal stream temperature profiles at the end of this section. Overall, modeled stream temperatures with anticipated climate change representing far-term conditions are cooler than current observed stream temperatures. We feel modeled stream temperatures for all time periods are too cool which reflect the input data used in this modeling effort, such as cool air temperatures. For more useful and believable results, input data should be scrutinized and high mountain regions in the Sierra Nevada perhaps should be recalibrated. However, this section illustrates the utility of our approach and the success of this research as a proof of concept study.

Reservoir Temperatures

Modeling suggests that annual average reservoir release temperatures will be resilient to climate change through winter (Figure 8). Beginning around early May, reservoir release temperatures warm with climate change. Simulations using MIROC32med input climate data were warmer than those using NCARPCM1 data. In fact, release temperatures for NCARPCM1 far-term period were similar to release temperatures for MIROC32med near-term period (Figure 8). This is indicative of uncertainty in climate models such as representation of physical processes and sensitivity to greenhouse gas forcings.
Figure 8: Average Weekly Central Watershed, Modeled MIROC32med and NCARPCM1 Reservoir Release Temperatures for (A) Upper, (B) Middle, and (C) Lower Reservoirs

Reservoir release temperatures were cooler for the middle reservoir than the upper reservoir, reflecting model calibration and reservoir depth. The upper and middle reservoirs were calibrated to Ice House and Bowman Reservoirs, respectively. Bowman Reservoir had exceptionally cold release temperatures (much colder than Ice House Reservoir), a result of the combination of outletworks infrastructure, reservoir operations, depth, and inflow temperatures. Because the middle reservoir is calibrated to Bowman Reservoir, some of the above factors are
implicitly included in this analysis. Additionally, the modeled middle reservoir (Figure 8b) is deeper than the upper reservoir (Figure 8a), potentially affecting the volume of the cold-water pool, with cooler release temperatures during summer.

On average, the warmest water is released in August to early September for the small, upper reservoir, late July to early August for the middle reservoir, and early October for the large, lower reservoir (Figure 8). However, there is considerable variability between years that is not depicted in the annually averaged figures. For the upper reservoir, the timing of the warmest releases generally became more consistent with more severe climate change (mtp and ftp). For all reservoirs, the warmest release temperatures coincided with extended periods of low reservoir storage which forced mixing of stratified waters within the reservoir, or less commonly, with spill events. The upper reservoir typically had low storage earlier in the year than the lower reservoir. For the lower reservoir, low reservoir storage most commonly occurred in early fall, which is consistent with observed storage levels in large rim dams (CDEC 2011).

**Modeled Unregulated Stream Temperatures**

For unregulated conditions, modeling suggests stream temperatures warm with more severe climate change represented with a farther outlook into the future (Figure 9 – first and third columns, time progresses from the historical, near-, mid- and far-term periods in the downward direction). For all unregulated runs, the middle river reach from approximately river kilometer (RKM) 150–250 is the warmest, before tributaries subsequently join the mainstem with cooler temperatures and higher flows that moderate mainstem temperatures. Toward the end of the 21st century, modeling indicates that streams not only become warmer, but that the average duration with warmer temperatures is extended as well (x-axes in Figure 9). Unregulated winter stream temperatures become approximately 2°C warmer as well. For MIROC32med unregulated simulations, maximum average weekly stream temperatures are 13.1, 14.4, 15.8, and 18.2°C for htp, ntp, mtp, and ftp, respectively. For unregulated NCARPCM1 runs, stream temperatures are 13.2, 13.2, 14.3, and 14.8°C for htp, ntp, mtp, and ftp, respectively. The warmer stream temperatures in the MIROC32med runs are largely driven by air temperatures that increase at double the rate of NCARPCM1 air temperatures for the ntp, mtp, and ftp.
Figure 9: Modeled Average Weekly Stream Temperatures for the Central Watershed with Regulated and Unregulated Conditions for All Time Periods

- MIROC32med
  - Unregulated
  - Regulated

- NCARPCM1
  - Unregulated
  - Regulated

Legend:
- 0 C
- 2 C
- 4 C
- 6 C
- 8 C
- 10 C
- 12 C
- 14 C
- 16 C
- 18 C

Modeled Dam
Modeled Regulated Stream Temperatures

This work reiterates existing research that dams alter the thermal regime of rivers in both space and time (Olden and Naiman 2010) (Figure 9 – second and fourth columns). The cool reservoir releases of the upper reservoirs (Figure 8) provide cooler stream temperatures and/or a shorter duration of warm stream temperatures than occur with unregulated conditions. However, the longitudinal length of cooler stream temperatures below dams is variable. For instance, cooler temperatures below the middle reservoir vary by approximately 10–90 RKM depending on GCM input data and modeled time period, and there is no clear trend as to whether that distance is increasing or decreasing with climate change (Figure 9). Below the large, lower dam there is a clear shift in the timing of yearly maximum stream temperatures from mid-summer toward autumn. For both GCMs and all modeled time periods, the lower dam cools summer stream temperatures, increases autumn stream temperatures, extends the duration of warm temperatures, and increases winter temperatures.

LONGITUDINAL STREAM TEMPERATURE PROFILES

Longitudinal profiles of stream temperatures show that dams reset thermal conditions for downstream river reaches (Figure 10). In headwater reaches in July, streams start with elevated temperatures, particularly in the northern watershed (Figure 10a – RKM 0 on x-axis). Tributaries join unregulated runs at the same locations as dams in the regulated runs, causing some warmer or cooler jumps in temperatures. Downstream of the middle reservoir, stream temperatures warm in response to July atmospheric conditions. Regulated streams warm more quickly than unregulated streams for all latitudes and time periods because flows are reduced with regulation. For example, for the central watershed far-term period, flow in the reach below the middle reservoir is 32–55 m$^3$/s with unregulated conditions (flow increases in the downstream direction as tributaries join the mainstem), but is 7.5–30 m$^3$/s with regulated conditions. Thus, longitudinal heating occurs more rapidly for the regulated runs because the river has a slower travel time (i.e., longer exposure to atmospheric conditions) and less volume to be heated. The lower reservoir causes another step decrease in downstream temperatures for all regulated simulations. Stream temperatures warm longitudinally below the lower reservoir, although at a slower rate than occurred below the middle reservoir because flows are higher. Overall stream temperatures increase more with the MIROC32med climate-driven input data than the NCARPCM1 input data.

---

1 RTEMP struggles to accurately estimate stream temperature in headwater reaches with very low flow conditions (< ~0.3 m$^3$/s). In real headwater systems, micro-topographic shading, hyporheic flow, partial snow cover at high elevations, and snowmelt likely moderate stream temperatures somewhat; although observed August stream temperature data show warmer stream temperatures above high-elevation reservoirs such as French Meadows and Hell Hole than below them (American watershed) (PCWA 2007).
Figure 10: Average July Stream Temperature Longitudinal Profile for MIROC32med and NCARPCM1 htp and ftp for the (A) Northern, (B) Central, and (C) Southern Watersheds

Source: Authors

EFFECTS OF LATITUDE ON STREAM TEMPERATURES IN A CHANGING CLIMATE

Stream temperatures vary by latitude (watershed), although clear trends are not obvious. Differences in stream temperatures appear to be sensitive to local differences in climate input data rather than different rates of heating by latitude. While there is variability in stream temperature reductions below each dam, overall reductions become more pronounced with
more severe climate change, represented as mid- and far-term time periods (Figure 11). Absolute stream temperatures still increase with climate change (Figure 10). The large, lower dam reduces stream temperatures most in the central and southern watersheds (Figure 11b and c). The small, upper reservoir always reduces downstream temperatures least. Interestingly, although the MIROC32med simulations consistently have warmer stream temperatures than the NCARPCM1 runs (Figure 9, Figure 10), reductions to stream temperatures from dam releases are approximately equal for the two GCMs (Figure 11).
Figures 10 and 11 imply that flow and temperature can be managed with dam releases to maintain and enhance suitable instream habitat for coldwater species with climate change. Further, modeling suggests larger, lower-elevations dams provide greater temperature reductions than higher, smaller dams. We were unable to analyze changes to the longitudinal distance of coldwater habitat in this study because all modeled stream temperatures remain
under 18°C for both regulated and unregulated, within the ideal temperature ranges for coldwater species such as native salmon and trout. The weekly average lethal threshold for salmonids is approximately 24°C–25°C (Eaton and Scheller 1996; Myrick and Cech, Jr. 2001). Overall, simulated stream temperatures seem optimistically cool and are significantly cooler than unregulated conditions modeled with Daymet climate data and WEAP hydrologic data (with all other data and parameterization unchanged). Regardless, the findings described in this paper are offered as a proof of concept study to demonstrate the usefulness of this approach.

Input Data Discrepancies

MIROC32MED- AND NCARPCM1-DRIVEN VIC VS. DAYMET-DRIVEN WEAP DATA

Climatic and hydrologic input data were used to estimate both instream flow conditions and heat budget conditions which drive stream temperatures. The cool stream temperatures suggested by this modeling effort, where maximum average annual stream temperatures remain under approximately 18°C for all climate alternatives, time periods, and management alternatives (regulated vs. unregulated) are representative of this data.

We compared the unregulated RTEMP MIROC32med- and NCARPCM1-driven VIC stream temperature runs with unregulated RTEMP runs which use Daymet-driven (Thorton et al. 1997) hydrology for the WEAP rainfall-runoff model (Young et al. 2009; Null et al. 2010a). Daymet data is daily, interpolated surface data (aggregated to a weekly timestep here). The runs with Daymet/WEAP data estimate climate warming by modeling uniform air temperature increases of 2°C, 4°C, and 6°C as a sensitivity analysis of unregulated stream temperature response to climate warming (Null et al. Accepted). The different climatic and hydrologic input data lead to very different stream temperature results (Figures 12 and 13) (all other data and parameters are identical). Figure 12 shows historical conditions at the outlet of the Stanislaus River. Average annual maximum stream temperature is 23.8°C using the Daymet climate data, but is over 10°C cooler, at 13.1°C with the MIROC32med climate data. Stream temperatures reach their average annual maximum in the first week of August for both simulations. Figure 13 illustrates unregulated average weekly stream temperature differences longitudinally (y axes) and through time (x axes). These data show that stream temperature estimates from the VIC model are almost always cooler than the Daymet data, and that temperature differences are most pronounced toward headwaters, where VIC-driven stream temperature estimates can be more than 13°C cooler than Daymet-driven stream temperatures for far-term predictions. Climate is notably difficult to model in mountain regions due to orographic microclimates and these data suggest future modeling and research should focus on improving accuracy of climate predictions for the Sierra Nevada mountain region.
Figure 12: Modeled Stream Temperatures at the Outlet of the Stanislaus River (500 m Elevation) for Historical and Future Climate Conditions Using MIROC32med and Daymet Input Data (T0 is Historical Conditions and T2, T4, T6 are 2°C, 4°C, and 6°C Climate Warming, Respectively)

Source: Authors, unregulated stream temperatures with Daymet input data from Null et al. (Accepted)
Figure 13: Difference in Average Weekly Unregulated Stream Temperature for the Central Watershed for (A) MIROC32med minus Daymet, (B) NCARPCM1 minus Daymet

Source: Authors, unregulated stream temperatures with Daymet input data from Null et al. (Accepted)
Although future climate assumptions are different in Figures 12 and 13 (the GCMs explicitly model physical processes whereas Daymet data is increased by 2°C increments as a sensitivity analysis), stream temperatures with unregulated conditions (black lines) differ markedly and thus call into question the believability of the results from this study. To sidestep this problem, we plotted stream temperature differences between regulated and unregulated conditions using MIROC32med and NCARPCM1 climate data (Figure 14). Plots show the effect of dam regulation on stream temperatures with temperature differences. For MIROC32med runs, reservoirs cool downstream reaches by up to 4°C during June through August. Stream temperatures below reservoirs are nearly 9°C warmer during autumn and early winter with regulation, illustrating potential changes when cold-water pools have been depleted. The progression of time (htp, ntp, mtp, and ftp) shows that trends are becoming more pronounced with more severe climate change. Reservoir releases during summer months can cool stream temperatures relatively more with more extreme climate change (ftp) than for the historical period (htp), although climate change causes the 0°C isotherms to be warmer overall for both regulated and unregulated conditions with more extreme climate change. These values could be used to approximate the effect on stream temperatures from river regulation in a changing climate using measured stream temperatures or other modeled data. The NCARPCM1 runs show similar trends, but with less pronounced summer cooling downstream of reservoirs. Temperature differences between the MIROC32med and NCARPCM1 plots represent uncertainty from climate modeling assumptions.

**Figure 14: Average Weekly Regulated minus Unregulated Stream Temperature Difference for the Central Watershed for All Time Periods**
Results 30

Source: Authors
It is beyond the scope of this study to thoroughly analyze the climate datasets or quantify their accuracy. However, we have provided mean annual air temperature and precipitation for both GCMs used in this study as well as the Daymet dataset for the Stanislaus watershed (Table 6). We have also included the future change for each model projection. This shows that for historical conditions, mean annual air temperature (averaged across the entire watershed) is nearly 3°C warmer with the Daymet dataset than either GCM, and in fact air temperature by the end of the twenty-first century is cooler for the NCARPCM1 dataset than for Daymet’s historical conditions. We recommend future analysis of input GCM data to quantify accuracy for historical conditions in Sierra Nevada watersheds.

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<tr>
<td></td>
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<td>Daymet</td>
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</table>

Source: VIC data from Cayan et al. (2009); Daymet data available online and climate assumptions described in Null et al. (Accepted)

**LIMITATIONS**

Estimating stream temperatures from GCMs involves millions of calculations, some of which are highly uncertain. In this modeling effort we apply atmospheric projections on a global scale to regulated stream temperatures at a watershed scale, which is unprecedented. Results were presented to show the type of outcomes from this proof of concept study, and focus was on relative changes rather than absolute stream temperatures. This method complements existing reservoir operations research and incorporating our approach with those studies could provide valuable insights into the potential of existing infrastructure to mitigate the effects of climate change.

As with any model, the results are only as good as the boundary conditions and input data. The input climate and hydrologic data from the California Climate Change Center was discussed above in detail and should be noted as a limitation of this study. Calibration has primarily been completed for lower elevation locations in the Central Valley, with less certainty for high-elevation locations of the Sierra Nevada. While this compromises results, it is also a major finding of this study.
WQRRS is a 1-D reservoir temperature model that assumes homogeneity in the longitudinal and lateral directions. This assumption is reasonable for Sierra Nevada reservoirs because of the long, deep nature of the flooded river canyons. Many simplifications were made to reservoir and stream temperature models. More complete input and calibration data would improve results.

Reservoir operations are modeled very simply to assure that changes in stream and reservoir temperatures are due to climate as opposed to reservoir operations. This study is about stream temperatures not about changes in reservoir operations and therefore we held flood control, hydropower, and water supply demands constant. A limitation of this simplification is a lack of weekly variability in streamflow that would be the result of a more complex hydropower simulation model. Also, because water and power demands do not change with future climate scenarios, our approach does not represent realistic conditions. Climate change will affect reservoir operations, which will alter reservoir temperatures. Previous hydropower studies in the Sierra Nevada have shown that reservoirs will fill earlier and empty earlier as inflow shifts from springtime snowmelt to winter snowmelt and rain events (Tanaka et al. 2006, Vicuna et al. 2008, Null et al. 2010a). The strength of our method is that it complements existing reservoir operations studies (that typically ignore water quality). A reservoir operations model that included our stream temperature modeling module could provide valuable insights into reservoir operations that include environmental uses with human uses.

**Discussion and Major Findings**

The thermal regime of rivers has been fundamentally altered by humans from water development, land use changes, and increasingly, climate-induced changes to the heat budget driving stream temperatures. Many aquatic ecosystems are thermally-sensitive and have had significant reductions in habitat with these changes. In California's Sierra Nevada, stream temperatures often increase with water development and land use changes, and maintaining coldwater habitat with anticipated climate change is a future challenge.

Overall, our approach was useful as a proof of concept study; although, the input data used in this effort result in stream temperatures that remain optimistically cool for all time periods, climate, and management alternatives (regulated versus unregulated). The effects of dams on downstream temperatures vary by season, longitudinal distance, reservoir size, outlet structure, and reservoir elevation. During summer, dams provide a step reduction in stream temperatures, which then warm longitudinally in response to atmospheric conditions. Increasingly severe climate change (represented with a longer future outlook) indicates that although the absolute temperature of stream temperatures increase from historical conditions, the thermal reduction from reservoir releases grows somewhat more pronounced. This implies that reservoirs may be useful for releasing cooler water throughout the year than occurs with unregulated conditions, and offers a potential mitigation strategy for climate change induced stream warming for short distances downstream. Changing water and power demands will also impact operations, and should be considered in future work.

In California, water is tightly managed. Economic-engineering modeling suggests in a warmer and drier future, competition for already scarce water could increase by an order of magnitude (Harou et al. 2010). This means that attention should focus on managing water quality to maintain and enhance aquatic ecosystems, especially when maintaining water quality may
reduce the need for environmental instream flows (Null et al. 2010b). With more water scarcity, it may be increasingly important to understand the factors limiting aquatic ecosystems in Sierra Nevada rivers and manage those specific problems.

In a non-stationary climate, the geographic distributions of habitats and ecosystems are also likely to change (Hanak et al. 2011). This study indicates that summertime coldwater habitat is anticipated to exist immediately downstream from dams but stream temperatures rise as the distance from dams increases. This indicates coldwater habitat may persist in regulated rivers with climate change (particularly if dams are operated to preserve winter water in stratified reservoirs), although possibly not in the same locations as coldwater habitat historically existed. This presents future challenges for water managers since many of the laws and regulations to protect ecosystems (such as the Endangered Species Act) were created with the assumption of ecological stationarity.

Given the generally cool stream temperatures estimated in this effort with the MIROC32med- and NCARPCM-driven VIC input data (and the incongruence with previously modeled unregulated conditions in west-slope Sierra Nevada rivers) (Null et al. Accepted), it is beyond the scope of this paper to analyze the extent of coldwater habitat from river regulation with climate change.

Modeling studies such as this are needed to better understand the thermal effects from dams with climate change and the potential to mitigate for anticipated changes. Here we illustrate the thermal regime of rivers differs between unregulated and regulated conditions in a changing climate. This proof of concept study shows the mesoscale modeling approach utilized here is worthwhile for assessing the potential for thermal management of reservoir releases to maintain and enhance downstream coldwater aquatic ecosystems. MIROC32med stream temperature projections are consistently warmer than NCARPCM1 projections. However, step reductions in stream temperatures from reservoir releases are approximately equal between the GCMs. Major discrepancies exist between climate input data sources (Daymet-WEAP vs. GCM-VIC) and the accuracy of historic climate data should be quantified in the future to assess the effects of dams to manage coldwater habitat in Sierra Nevada rivers with climate change.
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## APPENDIX A

### WQRRS Input Parameters and Coefficients

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<th>Coefficient</th>
<th>Reservoir Size</th>
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Source: Parameter valued by the authors. Parameter IDs and notes from USACE-HEC (1986)