Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California

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Received 7 March 2012; revised 8 April 2013; accepted 11 April 2013; published 28 May 2013.

[1] Warmer temperatures are expected to raise mountain stream temperatures, affecting water quality and ecosystem health. We demonstrate the importance of climate-driven changes in hydrology as fundamental to understanding changes in the local water quality. In particular, we focus on changes in stream temperature, dissolved oxygen (DO) concentrations, and sediment transport in mountainous, snowmelt-dominated, and water-limited systems, using the Sierra Nevada as our case study. Downscaled output from an ensemble of general circulation model projections for the A2 (higher greenhouse gas) emission scenario was used to drive the Soil and Water Assessment Tool with a new integrated stream temperature model on the subbasin scale. Spring and summer stream temperature increase by 1°C–5.5°C, with varying increases among subbasins. The highest projected stream temperatures are in the low-elevation subbasins of the southern Sierra Nevada, while the northern Sierra Nevada, with distinct impacts on snowmelt and subsurface flow contributions to streamflow, shows moderated increases. The spatial pattern of stream temperature changes was the result of differences in surface and subsurface hydrologic, snowmelt, and air temperature changes. Concurrent with stream temperature increases and decreases in spring and summer flows, simulations indicated decreases in DO (10%) and sediment (50%) concentrations by 2100. Stream temperature and DO concentrations for several major streams decline below survival thresholds for several native indicator species. These results highlight that climatic changes in water-limited mountain systems may drive changes in water quality that have to be understood on the reach scale for developing adaptive management options.

Citation: Ficklin, D. L., I. T. Stewart, and E. P. Maurer (2013), Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California, *Water Resour. Res.*, *49*, 2765–2782, doi:10.1002/wrcr.20248.

1. Introduction

[2] Water quality parameters such as stream temperature, dissolved oxygen (DO), and sediment concentration play a crucial role in the life cycle and habitat distribution of aquatic species and determine the suitability of water resources for human use. While increasing stream temperatures with climate change have been the subject of several recent studies, questions investigating how climate change will affect DO or sediment concentrations have not been resolved. Further, climate change stream temperature assessments at the watershed scale have to date been exclusively based on air temperature, without taking the critical role of the local hydrology, which drives changes in stream temperature and other water quality parameters, into account.

[3] Stream temperatures are primarily influenced by the amount of heat exchange at the air/water interface and secondarily by the temperature of the contributing hydrologic components to the stream reach such as groundwater, surface runoff, and snowmelt inputs [*Webb and Zhang*, 1997; *Mohseni and Stefan*, 1999; *Ficklin et al*., 2012a]. Therefore, any study that assesses the future impacts of climate change on stream temperature should consider changes in air temperature as well as changes in local hydrology. While stream temperatures in general have shown a strong positive correlation with air temperature [e.g., *Stefan and Preud'homme*, 1993; *Ducharne et al*., 2007], the relationship for snowmelt-dominated (often mountainous) basins is more complex, as in these basins, the seasonal spring warming results in snowmelt runoff to streams that temporarily lowers stream temperature [*Mohseni and Stefan*, 1999; *Brown and Hannah*, 2007; *Ficklin et al*., 2012a]. Due to the air temperature-stream temperature connection, increases in air temperature expected from future climatic changes are thought to raise stream temperatures in both lowland and mountainous streams. However, the

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0043-1397/13/10.1002/wrcr.20248

magnitude and seasonality of these future stream temperature increases and associated water quality impacts in connection with projected changes in hydrologic fluxes have to date not been systematically explored.

[4] Observed evidence suggests that streams have been warming with increasing air temperatures over the past several decades. For large low-elevation European and North American rivers, several studies found a 20th century increase in stream temperature of 0.01°C–0.1°C/yr [e.g., *Moatar and Gailhard*, 2006; *Webb and Walling*, 1992; *Ashizawa and Cole*, 1994]. For mountain streams, or those with a snowmelt component, increases in water temperature have been shown to exhibit a connection to seasonal shifts and decreases in streamflow, snowmelt, and changes in local hydrology contributions to streamflow in addition to rising air temperatures [*Constanz et al*., 1995; *Pekarova et al*., 2008; *Ficklin et al*., 2012a]. For example, a decrease in snowmelt contribution to streamflow from decreases in snowfall is likely to contribute to warmer winter, spring, and early summer stream temperatures, while earlier snowmelt times shift the timing of cold-water inputs to a stream to earlier in the year. Correspondingly, several studies considering mountainous North American and European Alpine streams through 2010 have reported annual stream temperature increases of 0.03°C–0.5°C/yr [e.g., *Pekarova et al*., 2008; *Hari et al*., 2006; *Swansburg et al*., 2004; *Isaak et al*., 2011], which have been attributed to the earlier onset of snowmelt and decreased summer precipitation. In addition, observations from 18 stream temperature sites in the northwestern United States between 1980 and 2009 found increasing stream temperature trends for the summer, fall, and winter seasons, with the highest rates of warming for summer and a decreasing trend during the spring season [*Isaak et al*., 2011]. Thus, stream temperature is a complex function of both climatic and hydrological changes, especially in mountainous regions, and stream temperature response to expected global changes is likely to substantially differ between watersheds [*Webb and Noblis*, 2007; *Ficklin et al*., 2012a; *van Vliet et al*., 2011].

[5] In addition to stream temperatures, projected climatic changes are thought to affect other water quality parameters. Stream DO is connected to stream temperature with the two variables generally inversely related. Therefore, warmer water temperatures affect the self-purification capacity of rivers by reducing the amount of oxygen that can be dissolved and used for biodegradation [*Intergovernmental Panel on Climate Change*, 2007]. Projected global changes will also likely impact rainfall and runoff patterns as well as vegetative cover, which in turn control soil erosion and sediment transport processes [*Chaplot*, 2007] and might affect the sediment concentration in streams [e.g., *Inman and Jenkins*, 1999; *Pruski and Nearing*, 2002; *Chaplot*, 2007; *Ficklin et al*., 2010]. The responses of sediment erosion with changes in climate are expected to be nonlinear and seasonal and vary in direction and by region largely due to the interaction between plant biomass growth timing and surface runoff/sediment erosion [*Pruski and Nearing*, 2002]. In regions where the land surface is covered by snow for a portion of the year, the shift of winter precipitation from less erosive snow to more erosive rainfall due to increases in air temperature will enhance sediment erosion.

[6] As stream temperature and other water quality variables are important contributors to ecosystem health, the effects of projected climatic changes on future stream temperature and water quality have become an important research focus in recent years. Several studies have used general circulation model (GCM) output or temperature and precipitation variations to drive hydrologic and stream temperature models for the United Kingdom [i.e., *Webb*, 1992], the United States [*Mohseni et al*., 2003], and worldwide [*van Vliet et al*., 2011]. Results from these studies suggest further rises in stream temperatures by several degrees by the end of the century and a significant reduction in thermally suitable habitat for cold-water fishes [*Mohseni et al*., 2003]. It should be pointed out that most of the regression models used in these studies are based on the relationship of stream temperature with air temperature alone and do not consider the impact of changing hydrologic flows on stream temperatures. Of particular importance for mountainous settings is that these models are not able to capture stream temperature changes that result from the influx of cold snowmelt into streams as a result of warmer air temperatures during the time of snowmelt runoff. While fully process-based models for stream temperature exist, they have not been applied to large-scale projection studies due to the lack of available data and intensive calibration requirements.

[7] Studies on the effects of climate change on stream DO and sediment concentrations are scarce within the literature. Several water quality modeling studies suggest a depletion of DO concurrent with future increase in water temperatures for basins in Europe and India [*Carmichael et al*., 1996; *Cox and Whithead*, 2009; *Rehana and Mujumdar*, 2011]. Simulations have shown [*Pruski and Nearing*, 2002; *Ficklin et al*., 2010] that increases in total rainfall are likely to increase sediment erosion and sediment loads in rivers, while temperature increases without concurrent precipitation changes resulted in decreases in sediment loads.

[8] Western North America is an area where potential water quality changes are of particular concern, given that this is already a water-limited region dependent on high-elevation snowpack for water resources [e.g., *Miller et al*., 2003; *Hayhoe et al*., 2004; *Maurer*, 2007; *Ficklin et al*., 2012b] and home to several high-profile aquatic species, such as salmon and trout, whose health and habitat distribution are dependent on particular flow patterns and comparatively cool stream temperatures [*Eaton and Scheller*, 1996]. Similar hydrologic stream systems exist in the Andes, Himalayan range, and arid mountains of the Mediterranean, Middle East, and Asia. Within western North America, the Sierra Nevada mountain range in California epitomizes several of the above conditions. Of the 40 aquatic and riparian species native to the Sierra Nevada, 6 are threatened or endangered and 12 others are candidates for listing [*Moyle*, 1996; *U.S. Geological Survey*, 1997]. Further, the higher-elevation streams in the Sierra Nevada are particularly important because many aquatic species are isolated in headwater streams [e.g., *Wiggins*, 1990; *Erman and Nagano*, 1992; *Hershler*, 1994].

[9] While little work assessing water quality changes due to global change has focused on the Sierra Nevada to date, several previous studies have used air-stream

temperature regression models to examine likely stream temperature changes for some important watersheds throughout western North America [e.g., *Morrison et al.*, 2002; *Bartholow*, 2005; *Mantua et al.*, 2010]. These studies project further increases in stream temperatures by the end of the century, with average summer temperatures in some basins exceeding 21°C, a threshold for fish die-offs [*McCullough*, 1999]. To the authors' knowledge, only *Null et al.* [2010a] has studied stream temperature sensitivity to climate warming in the Sierra Nevada using fixed air temperature increases. Overall, stream temperatures increased by 1.6°C for every 2°C air temperature increase, with the highest changes in temperature at the mid-elevations [*Null et al.*, 2010a]. While the study by *Null et al.* [2010a] represents an important advance, we would like to point out that fixed temperature increases do not capture the full range of climate changes modeled by GCM simulations. Additionally, as DO is inversely correlated to stream temperature, accurate stream temperature predictions are highly important for meaningful DO predictions. DO changes expected under climatic changes have, to the best of our knowledge, not been assessed for snowmelt-dominated basins, such as those found in the Sierra Nevada, using a stream temperature model that can account for the changes in hydrologic inflows.

[10] Previous assessments of the impacts of global climatic changes on water resources and quality emphasize broad regional changes or limited their scope to individual watersheds. By contrast, the objective of this study is to demonstrate how understanding the differences in the future changes in hydrology, which are projected from global climate changes at the subbasin scale, is critical for understanding the changes in local water quality which are of high ecological importance. In particular, we focus on stream temperature, DO concentration, and sediment concentration as key indicators of ecosystem health, in connection with local hydrologic changes in water-limited, snowmelt-dominated mountain stream systems. The subbasins of the Sierra Nevada mountain range in California are a key place to investigate the connections between changes in local hydrology and water quality, as well as the spatial variability of the projected changes. Its headwater streams are important to several native threatened or endangered species, it is an ecosystem highly sensitivity to moderate climate warming due to its geographic location, and it is the principal source of water for several urban centers of global importance and one of the most intensively farmed agricultural regions in the world. Similar hydrologic systems that supply water to large numbers of people exist in other arid and semiarid areas worldwide, such as in Southern Europe, the Middle East and South America. To accomplish our objectives, we use the Soil and Water Assessment Tool (SWAT) with a newly developed stream temperature model, which simulates stream temperature and associated water quality parameters based on air temperature and the effects of local hydrology [*Ficklin et al.*, 2012a]. The SWAT model was selected as it has, in contrast to other model options, the capacity to efficiently represent snowmelt and runoff processes, as well as incorporate a full range of water quality processes, and has successfully been applied in a wide variety of settings [*Gassman et al.*, 2007]. We drive SWAT at the subbasin scale with the downscaled output from an ensemble of 16 GCMs using one emission scenario (A2) through the end of the century. For all Sierra Nevada subbasins, we explore the spatially and temporally varying changes in stream temperature, DO concentration, and sediment concentration and interpret them in light of the changes in the hydrologic system. The analysis at the subbasin scale will aid in distinguishing between more and less vulnerable subbasins and could serve as a foundation for a comprehensive Sierra Nevada headwater aquatic ecosystem climate change assessment.

2. Methods

2.1. Study Area

[11] The study area occupies the eastern and western watersheds of the Sierra Nevada mountain range in California, an area that is particularly important for water resources and aquatic species habitat [*Moyle*, 1996] (Figure 1). The western watersheds modeled for this study span the Sacramento River to the north and the Kern River to the south, and the eastern watersheds span from the Truckee River to the north and Rush Creek to the south (Figure 1). Western Sierra Nevada rivers generally flow westward into the Sacramento and San Joaquin Rivers which then flow into the Sacramento-San Joaquin River Delta, while eastern Sierra Nevada rivers generally flow eastward into terminal lakes within the Great Basin of Nevada. The southern Sierra Nevada lies at higher elevations and reaches approximately 4400 m at the peak, while the northern Sierra Nevada generally remains below 3000 m (Figure 1). There were 478 subbasins simulated within the SWAT model, ranging from 0.03 to 1100 km^2. Sierra Nevada land cover is dominated by evergreen forest (51% of total Sierra Nevada area) and brush rangeland (29.9%), with minor areas of rangeland (8.0%), southwestern United States rangeland (4.7%), and open water (1.8%) [*U.S. Geological Survey* (*USGS*), 2007]. Generally, soils are thin and rocky and largely underlain by granite [*Pavich et al.*, 1986].

[12] The climate in the Sierra Nevada is Mediterranean-montane, with a large portion of the annual precipitation falling during the winter and spring seasons (November-April). The highest and lowest average annual precipitation rates in the study area are 180 and 30 cm/yr and occur in the high-elevation Yuba and low-elevation Kern River watersheds, respectively [*Maurer et al.*, 2002, Figure 1]. With an approximate snowline of 1000 m, snow plays a crucial role for water resources in California [*Null et al.*, 2010b]. For our study area, the percentage of area above the 1000 snowline is 54%. A large fraction of the precipitation received over the Sierra Nevada is stored as snow throughout the winter and spring and then released as a snowmelt runoff pulse as air temperatures increase in the spring and early summer.

2.2. Modeling Streamflow and Water Quality Using SWAT

[13] Figure 2 provides an overview of the methodology used in this paper. This study uses SWAT, an established hydrologic model that integrates processes of several other models, allowing for the simulation of climate, hydrology, plant growth, and erosion [*Arnold et al.*, 1998]. The surface water runoff and infiltration volumes are estimated using the modified soil conservation service (SCS) curve number method [*SCS*, 1984], and potential evapotranspiration was

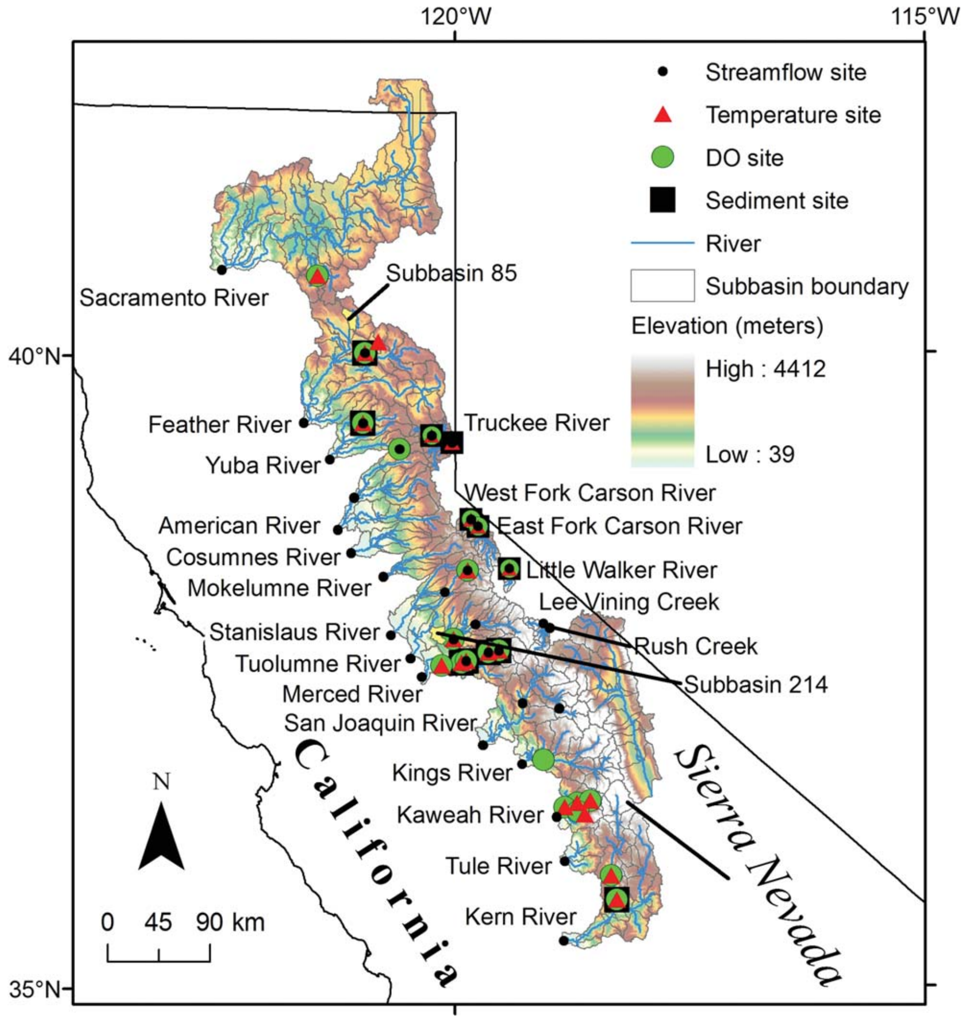

Figure 1. Boundary of the Sierra Nevada SWAT model along with calibration and validation locations. Yellow subbasins indicate the selected subbasins for the stream temperature discussion. Contributing area of subbasins 85 and 214 is 703 and 15,789 km^2, respectively. Average elevation of subbasins 85 and 214 is 1570 and 1717 m, respectively.

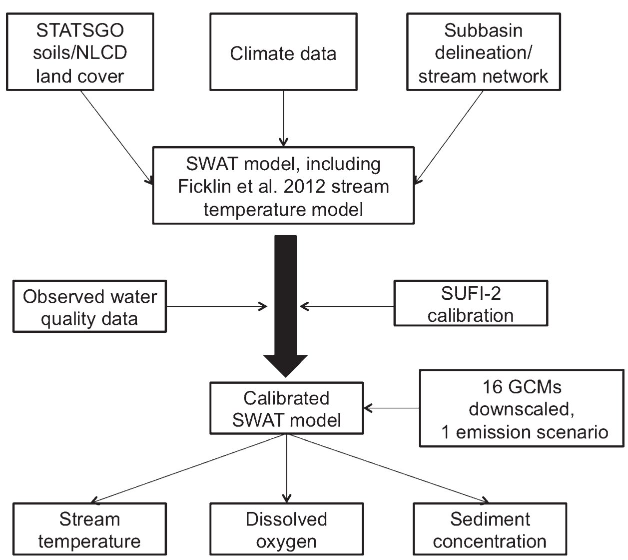

Figure 2. Overview of the methods used in this study.

estimated using the Penman-Monteith method [*Penman*, 1956; *Monteith*, 1965]. Air temperature and wind speed input data for the Penman-Monteith method were extracted from *Maurer et al.* [2002], while relative humidity and solar radiation were generated within SWAT [*Neitsch et al.*, 2005]. Stream temperature is calculated using the model of *Ficklin et al.* [2012a] that reflects the combined influence of meteorological conditions (air temperature) and hydrological inputs (streamflow, snowmelt, groundwater, surface runoff, and lateral soil flow) on water temperature within a stream reach. DO for this study is assumed to be completely saturated and is estimated by the equation developed by the *American Public Health Association* [1985]:

$$\mathrm{Ox}_{\mathrm{sat}} = \exp\left[-139.3441 + \frac{1.575701\times10^{5}}{T_{\mathrm{wat},K}} - \frac{6.642308\times10^{7}}{(T_{\mathrm{wat},K})^{2}} + \frac{1.243800\times10^{10}}{(T_{\mathrm{wat},K})^{3}} - \frac{8.621949\times10^{11}}{(T_{\mathrm{wat},K})^{4}}\right], \tag{1}$$

where Ox_{sat} is the saturated DO concentration (mg/L) and $T_{wat,K}$ is the water temperature in kelvin simulated by the *Ficklin et al*. [2012a] stream temperature model. The DO saturation assumption assumes that the streams and rivers are devoid of high organic activity and that the water within the stream or river channel is rapidly moving, which is an appropriate assumption for the mountainous streams in the Sierra Nevada [*Jarrett*, 1990]. SWAT simulates DO in terms of loads (kg/d or kg/month), which are then converted to a concentration (mg/L). Thus, the DO concentration is also contingent on streamflow volume in a reach. Sediment erosion on the landscape is estimated using the modified universal soil loss equation and then routed through the watershed using a modified *Bagnold*'s [1977] stream power equation developed by *Williams* [1980]. SWAT estimates biomass of terrestrial vegetation production based on the plant radiation use efficiency and the amount of intercepted photosynthetically active radiation on a given day, which is a function of solar radiation and the leaf area index (LAI). SWAT estimates LAI using the heat unit theory [*Boswell*, 1926; *Magoon and Culpepper*, 1932], which has proven to be a reliable predictor of plant growth for various plant types [e.g., *Cross and Zuber*, 1972; *Guerra et al*., 2004]. The growth temperatures for the various crops and plants were taken from the environmental policy integrated climate (EPIC) crop database [*Williams et al*., 1989]. The model was run at daily time step and then aggregated to monthly data for the historic (1950–2005) and future climate scenarios. A full description of the hydrology and water quality modules within SWAT can be found in *Neitsch et al*. [2005].

2.3. Input Data

[14] SWAT input parameter values for topography, land cover, and soil data were compiled from federal and state databases (Table 1). Natural flow data for streamflow calibration were gathered from the California Data Exchange Center (CDEC) and the U.S. Geological Survey (USGS). The CDEC natural flow data are derived from climate/runoff relationships and correspond to the streamflow that would occur if no reservoirs were present and no streamflow diversions occurred. These data are only available at a monthly time step. The USGS data, from which water quality data were also extracted, are from the Hydro-Climatic Data Network, which is a streamflow and water quality data set specifically developed for the study of surface water conditions throughout the United States under fluctuations in the prevailing climatic conditions and hence suitable for climate change studies [*Slack et al*., 1993]. SWAT was run at a daily time step and aggregated to monthly values for streamflow calibration. Water quality components were calibrated at a daily time step.

Climatic projections from the 16 GCMs given in Table S1 in the supporting information and 1 Intergovernmental Panel on Climate Change emission scenarios (A2) were used to drive the calibrated SWAT model. The A2 emission scenario represents a high greenhouse gas emission scenario. The GCM data were obtained from World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) [*Meehl et al*., 2007a]. All GCM data were interpolated to a regular 2° grid and statistically downscaled using the bias-correction and spatial disaggregation method of *Wood et al*. [2002, 2004]. Data downscaled using this method have been widely used for studies in California and the western United States [e.g., *Barnett et al*., 2008; *Cayan et al*., 2008; *Hayhoe et al*., 2004; *Maurer*, 2007; *Maurer et al*., 2010; *Van Rheenan et al*., 2004; *Ficklin et al*., 2012b, 2012c]. The use of multiple GCM projections allows a better assessment of uncertainty and provides more quantitative climate change information for impacts studies [*Meehl et al*., 2007b]. GCM output data and SWAT input data include daily precipitation, maximum and minimum temperature, and wind speed from 1950 to 2099. The daily values of precipitation and maximum and minimum temperature are rescaled so that the monthly mean matches the bias-corrected and spatially disaggregated mean monthly value. Wind data are randomly resampled historic wind data. It is also important to note that the current CO_2 emissions are above projected emissions of the A2 emission scenario, and therefore, the A2 emission scenario can no longer be considered a "worst-case" scenario [*Raupach et al*., 2007]. The A2 emission scenario is often referred to as "business as usual," representing emissions growth rates [*Hansen*, 2006; *Lowe et al*., 2009].

2.4. SWAT Model Calibration and Validation Procedure

[15] The calibration and uncertainty analysis program, Sequential Uncertainty Fitting Version 2 [*Abbaspour et al*., 2007], was used to automatically calibrate the SWAT model at 35 streamflow, 13 DO, and 12 sediment concentration outlets within the Sierra Nevada (Figure 1). The stream temperature model was manually calibrated at 22 stream temperature outlets. These outlets include gauges within the lower and higher elevations and give a good representation of the different climates and environments within the Sierra Nevada (Table S5). Our previous work

Table 1. Data Sources for the Sierra Nevada SWAT Model Initialization, Calibration, and Validation

Description	Reference	Application	Source
30 m digital elevation model	*Gesch et al*. [2002]	Watershed delineation and stream slopes	http://ned.usgs.gov/
National Land Cover Database	*USGS* [2007]	Land use properties	http://www.mrlc.gov/
State Soil Geographic Database	*Wolock*, [1997]	Soil properties	http://soildatamart.nrcs.usda.gov/
1/8 degree resolution daily climate data	*Maurer et al*. [2002]	Precipitation, maximum and minimum temperature, wind speed input data	http://www.engr.scu.edu/~emaurer/data.shtml
Unimpaired observed streamflow data	*CDEC* [2011]; *Slack et al*. [1993]	SWAT model calibration	http://cdec.water.ca.gov/, http://pubs.usgs.gov/wri/wri934076/1st_page.html
Unimpaired observed water quality data	*Slack et al*. [1993]	SWAT model calibration	http://pubs.usgs.gov/wri/wri934076/1st_page.html

provides the details of the streamflow calibration procedure [*Ficklin et al*., 2012b].

[16] Sensitive initial and default parameters relating to water quality were varied simultaneously until an optimal solution was met. Sensitive SWAT and stream temperature model parameters are shown in Table S2 in the supporting information. Three optimization criteria were used to assess model performance: (1) the coefficient of determination (R^2), (2) the Nash-Sutcliffe coefficient (NS) [*Nash and Sutcliffe*, 1970], and (3) an efficiency criterion (ϕ). A perfect simulation will have R^2 and NS values of 1. The parameter ϕ is defined by *Krause et al*. [2005], where the coefficient of determination, R^2, is multiplied by the slope of the regression line, b. This function allows accounting for the discrepancy in the magnitude of two signals (captured by b) as well as their dynamics (captured by R^2). For ϕ, a perfect simulation is represented by a value of 1. A split-sample approach was used for calibration and validation. The calibration and validation years differed at each outlet depending on data availability. A model spin-up time period of 1 year was used from 1949 to 1950. Streamflow and water quality model parameters in regions that did not contain calibration data were extrapolated from the nearest region with calibration data. Streamflow and water quality were simulated on 478 subbasins in the Sierra Nevada.

[17] Many of the streams and rivers within the Sierra Nevada are severely impaired by dams and diversions for water resources development, and thus, streamflow and water quality calibration and validation were based on limited data. In some cases, insufficient data were available for validation, and results are only presented for the calibration time period. While the water quality calibration process for this study is imperfect, the calibration and validation results from the limited data calibration will indicate if the SWAT model is performing reasonably. After streamflow and water quality calibration, the SWAT model was forced using daily data from 16 future climate projections (16 GCMs with emission scenario A2) through the end of the 21st century.

2.5. Statistical Analyses

[18] The impact of potential climate change on streamflow and water quality was evaluated by comparing simulations using the GCMs in Table S1 in the supporting information under the A2 emission scenario for two future time periods: 2050s (2040–2069) and 2080s (2070–2099) to those of the historical time period (1950–2005; Table 2) by either absolute values or percent changes. Results are presented as the median of the 16 SWAT simulations forced with the 16 GCMs unless otherwise noted. The 25th and 75th percentiles of the 16 SWAT simulations forced with the 16 GCMs may also be presented. When results are presented as an average of the 2080s, for example, this value is the average of the median output from the 16 GCMs. Water quality changes were summarized for the spring (April-June) and summer (July-September) seasons because they are important for aquatic species (spawning and migration). Further, these seasons are important for agricultural, industrial, and urban water use, as this is the time period when (1) reservoirs are replenished and (2) the highest period of water needs. We do recognize, though, that excluding fall and winter from the analysis may exclude important storm events that may cause large changes in stream temperature, DO, and sediment concentrations. For the sake of brevity, however, we decided to exclude these seasons and only concentrate on spring and summer, which are thought to be the most affected by climate change. The Pearson correlation coefficient was used to measure the correlation between annual average of hydrologic and water quality changes during the 2080s with a target level of significance of $\alpha = 0.05$.

Table 2. Average and Standard Deviation of Subbasin Water Quality Values for the Historical Time Period (1950–2005)[a]

	Stream Temperature (°C)	DO (mg/L)	Sediment Concentration (mg/L)
Spring	8.6 (4.1)	11 (1.1)	12.4 (16.0)
Summer	14.6 (3.6)	9.8 (1.3)	6.9 (11.2)

[a]Standard deviation values are in parentheses.

3. Results and Discussion

3.1. SWAT Model Calibration and Validation

[19] The SWAT model was satisfactorily calibrated and validated for both streamflow and water quality simulations. Calibrated model parameter values or ranges can be found in Table S2 in the supporting information. Calibration and validation requirements were based on the work performed by *Moriasi et al*. [2007], where a calibration with NS value >0.5 (with other efficiency statistics used for confirmation) is considered to be a satisfactory calibration. Calibration and validation statistics for streamflow, stream temperature, DO, and sediments are given in Tables S3, S4, S6, and S7 in the supporting information. The average NS value for streamflow, stream temperature, DO, and sediments is in the 0.75–0.81 range for calibration and in the 0.74–0.77 range for validation. Similarly, R^2 calibration and validation values range between 0.75 and 0.87, indicating a strong linear relationship between observed and simulated streamflow values. Average ϕ values for all water quality components for the calibration and validation periods were 0.77 and 0.74, which indicate that the SWAT model satisfactorily captured the natural variability, including maximum and minimum observed values. For further validation, we compared water quality output from the observed historical time period (1950–2005) with the GCM-driven median historical simulations (1950–2005) at four outlets in the western Sierra Nevada (Sacramento, American, San Joaquin, and Kern River outlets; Figure 1). Results indicate that the differences between observed and GCM-driven historic simulated climate were negligible, with a percent difference of 1.9%, 0.7%, and 0.6% for stream temperature, DO, and sediment concentration, respectively.

3.2. Effects of Climate Change on Sierra Nevada Water Quality

3.2.1. Climate Projections

[20] Temperature and precipitation changes projected by GCMs indicate an average end-of-the-century increase in average annual temperature from the north to south by

4.0°C–4.3°C for the A2 emission scenario throughout the Sierra Nevada. Precipitation projections vary between GCMs, with an overall median decrease in precipitation compared to historical averages. Precipitation shows a median decrease by 5.5% in the northern Sierra Nevada and 14.5% in the southern Sierra Nevada. *Ficklin et al*. [2012b] discuss the expected climatic changes in greater detail.

3.2.2. Stream Temperature

[21] With few exceptions, stream temperature is likely to increase as a response to climatic changes through 2100 for all subbasins in the Sierra Nevada. The resulting projected stream temperature changes, however, are dependent on the season, subbasin location, elevation, and GCM. In general, the spring and especially summer seasons are likely to experience the greatest stream temperature increases and are examined in greater detail here, with less warming forecast for fall and winter (not shown). Historically, the spring season has been characterized by stream temperatures of less than 10°C in the headwaters and 10°C–15°C at the lower elevations. Median model results for all subbasins and all GCMs indicate stream temperature increases of, on average, 1.9°C and 3.2°C for the 2050s and 2080s spring seasons, respectively (Figure 3 and Table 3). As a result, spring stream temperature in all but the very highest elevations will likely rise above 10°C. By contrast, average summer stream temperatures to date have, on average, remained below 20°C for all but the very highest elevations. Our simulations show that the average summer subbasin stream temperature will likely increase by 2.5°C during the 2050s and 4.4°C for the 2080s (Figure 4 and Table 3). These increases imply summer temperatures of over 10°C and up to 13°C at the very highest elevations and up to 30°C in the low-elevation areas. Notably, model agreement on the direction of future changes in stream temperature is high across the ensemble of GCMs. As Figure 5 and Table 3 illustrate, stream temperatures are also expected to increase for the 25th and 75th percentiles. For the median model results, 59% of the Sierra Nevada subbasins had a high temperature increase (which was defined as any subbasin above the average spring stream temperature increase of 3.2°C) during the spring 2080s. For the percentiles, the percentage of subbasins during the spring that had a high temperature increase was 0% for the 25th percentile and 96% for the 75th percentile. For the summer 2080s, the percentage of subbasins above the average summer stream temperature increase of 4.4°C was 57% for the median, 0.3% for the 25th percentile, and 90% for the 75th percentile GCM projection (Figure 5).

[22] As illustrated by the patterns in Figures 3 and 4 there are great differences in current and future stream temperatures and projected warming rates between subbasins and seasons. Modeling results show that some of the highest historic and projected stream temperatures are found in the low-elevation subbasins of the southern Sierra Nevada, while subbasins in the northern Sierra Nevada have intermediate stream temperatures. For the spring season and both the 2050s and 2080s, warming was largest in the lower basins of the southern Sierra Nevada, parts of the Sacramento River basin, and parts of the Stanislaus River basin, where snowmelt is no longer a part of the hydrologic cycle. Further, hydrologic components are shifted to earlier in the season or shifted in magnitude [see *Ficklin et al*., 2012b] such that lower flows and higher stream temperatures result. For the summer season, and the 2050s, some of the highest subbasin increases are projected for the central and southern Sierra Nevada low-elevation subbasins, while the northern Sierra Nevada subbasins appear to possess generally lower vulnerability to stream temperature warming due to subsurface hydrologic inflows. By the 2080s, subbasins throughout the Sierra are likely to warm significantly, with notable exceptions in the Feather River basin (see Figure 1 for Feather River location). According to our simulations results, these warmer temperatures are mostly governed by large decreases of snowmelt inputs to the streams as well as decreases in summer streamflow. Some high-elevation subbasins in the southern Sierra Nevada appear more resilient to stream temperature changes because they are at a high enough elevation where the air temperatures remain cold under the climate change projected by the 2080s. For the summer season, the average projected subbasin temperature increase was 0.5°C higher for the western Sierra Nevada watersheds as compared to the eastern watersheds. In spite of the observed spatial variability, the magnitude of the changes in stream temperature with projected climatic change appears to be tied to elevation and season (Figure 6), such that warming is greatest for the spring and summer seasons and greater at lower elevations for all seasons. Correlations between elevation and stream temperature were statistically significant ($p < 0.05$).

[23] We suggest that the large differences in stream temperature response under similar air temperature changes are connected to changes in hydrology, such as shifts in groundwater or snowmelt resulting from climatic shifts. To illustrate the influence of hydrologic changes on stream temperature, we present two example subbasins (Figure 7): one subbasin (85) representative of basins in the northern Sierra Nevada (subbasin of Feather River basin) which experienced an average median increase of 2.5°C and 2.0°C during the 2080s spring and summer seasons, respectively, as compared to the historical time periods, and another subbasin (214) representative of basins in the central Sierra Nevada (subbasin of Tuolumne River basin) where there is a likely average median increase of 3.5°C and 5.1°C by the 2080s spring and summer seasons, respectively. These subbasins are indicated in Figure 1. The main differences between the two subbasins are the snowmelt and subsurface flow components of streamflow (Figure 7). For subbasin 214, which experienced a greater change in stream temperature, the snowmelt component, albeit historically small, is completely removed from the hydrologic cycle during the 2080s and therefore no longer contributing to a decrease in spring stream temperature. By contrast, even though snowmelt for subbasin 85, which experienced less stream temperature change, is significantly decreased, it is still a portion of the hydrologic cycle (~25% of historical volumes), even during the summer, and acts to moderate stream temperature. Further, for the subsurface flow component of subbasin 85, an advance of 1 month of the subsurface flow compared to the historical snowmelt peak is projected. Due to this shift, future winter subsurface flow for subbasin 85 is likely greater than during the historical period and will contribute to warmer winter and cooler summer stream temperatures. In general, the northern Sierra Nevada regions are more dependent on subsurface

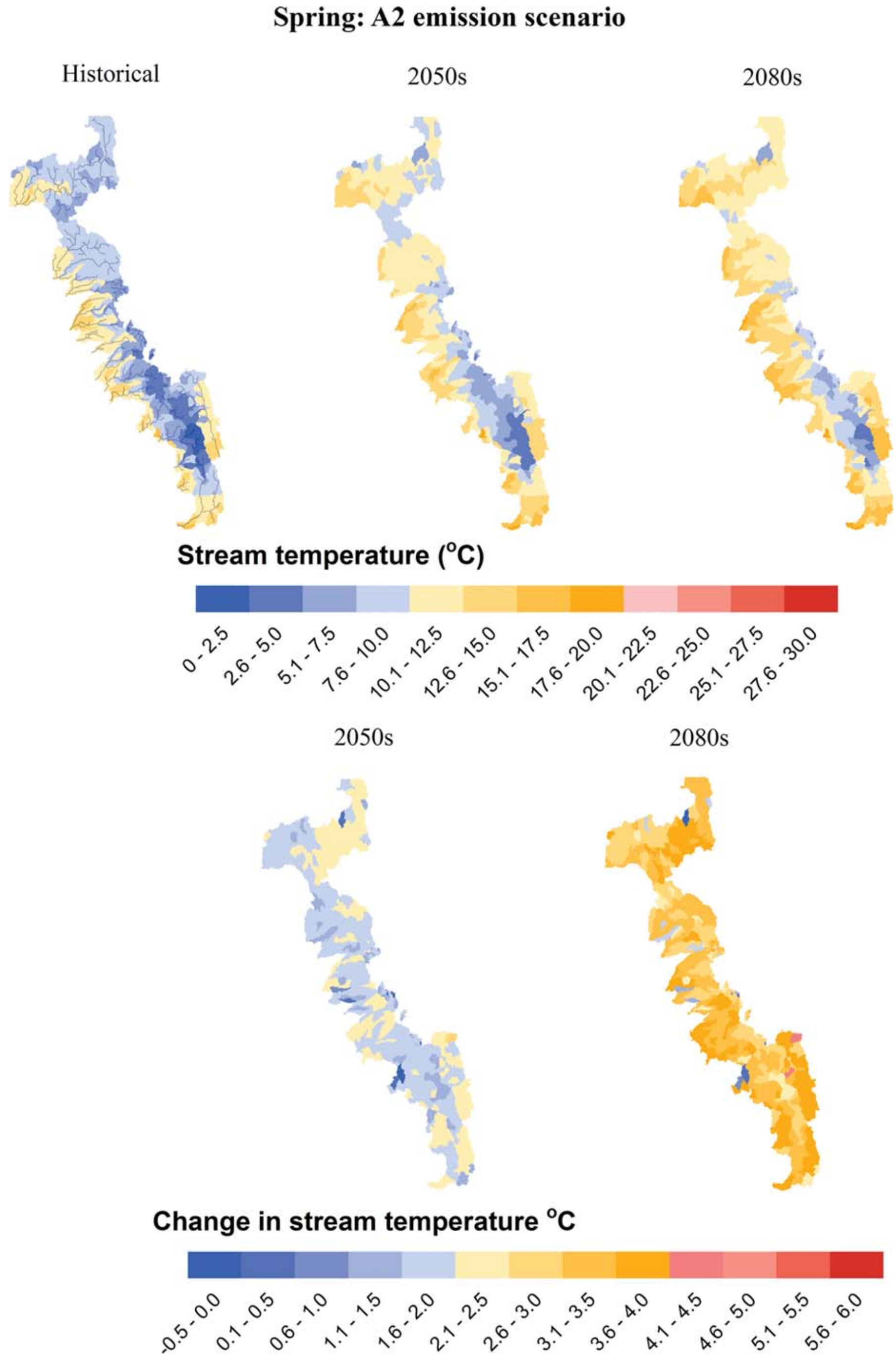

Figure 3. Stream temperature simulation results for the spring season GCM median ensemble A2 emission scenario. Historical period represents 1950–2005, 2050s represent 2040–2069, and 2080s represent 2070–2099.

flow than others [*Ficklin et al*., 2012b] and thus have a continued larger inflow of water with cooler temperatures. These areas can serve as climate change refugia and could be very useful for natural resource management. By contrast, for subbasin 214, the moderating subsurface flow component for the 2080s time period is less than the historical time period for all seasons, thus exacerbating summer stream warming. Figure 7 illustrates the importance of understanding the local hydrology as a key to changes in local water quality.

[24] In Table 4, correlation analysis showed that stream temperature change is significantly ($p < 0.05$) and negatively correlated to groundwater, snowmelt inflow, and precipitation, indicating that decreases in these components contribute to increases in stream temperature. Groundwater and snowmelt inflows in late spring and summer are below air temperatures and result in lower stream temperatures. Decreases in these hydrologic components contribute toward stream temperature warming. Decreases in precipitation, which is assumed to be at air temperature, result in

Table 3. Average Median Subbasin Changes in Water Quality Components for All Time Periods Under the A2 Emission Scenario[a]

	2050s			2080s		
	Stream Temperature (°C)	DO (mg/L)	Sediment Concentration[b] (%)	Stream Temperature (°C)	DO (mg/L)	Sediment Concentration[b] (%)
			25th Percentile			
Spring	0.9 (0.2)	−0.8 (0.1)	−60.0 (35.5)	2.1 (0.4)	−1.4 (0.3)	−64.6 (34.8)
Summer	1.5 (0.5)	−1.2 (0.3)	−57.2 (38.7)	3.1 (0.7)	−1.6 (0.5)	−59.7 (37.0)
			Median			
Spring	1.9 (0.3)	−0.6 (0.5)	−45.7 (34.2)	3.2 (0.5)	−1.3 (0.5)	−53.9 (35.6)
Summer	2.5 (0.6)	−0.9 (1.0)	−49.8 (44.1)	4.4 (0.9)	−1.3 (1.0)	−49.4 (44.5)
			75th Percentile			
Spring	2.9 (2.5)	−0.3 (0.1)	−11.7 (35.1)	4.4 (0.6)	−0.6 (0.1)	−20.4 (75.2)
Summer	3.4 (0.6)	−0.6 (0.2)	−30.4 (50.5)	5.5 (0.8)	−0.9 (0.2)	−22.7 (101.2)

[a]Standard deviations are shown in the parentheses.
[b]Percent change from historical time period.

overall decreases in streamflow and more rapid stream temperature warming in summer and spring, as smaller volumes of water require less energy to heat up. Other than sediment concentration, air temperature was the only other significant and ($p < 0.05$) positive correlation on stream temperature, which is to be expected.

3.2.3. DO Concentration

[25] Concurrent with increasing stream temperatures, model predictions suggest that DO concentration will decrease throughout the Sierra Nevada with projected climatic changes for the median and percentile GCM projections (Figures 5 and 8 and Table 3). The historical Sierra Nevada average for all subbasins for DO was 11.0 mg/L in spring and 9.8 mg/L for summer. The subbasin average of the GCM median projection decreased during the 2080s by 1.3 mg/L for spring (11.8% decrease) and 1.3 mg/L for summer (13.1% decrease) from the historical time period. Decreases were projected across the model ensemble for the 25th and 75th percentiles for the summer season (Table 3). The largest projected summer DO subbasin decreases were found for lower elevation subbasins in the southern Sierra Nevada, while small DO increases were found for the high-elevation subbasins in the southern Sierra Nevada due to increases in streamflow volume and small changes in stream temperature (Figure 8). The summer displayed larger percent decreases in DO compared to the spring, with decreases of 0.9 mg/L during the 2050s (8.2% decrease) and 1.3 mg/L during the 2080s (13.1% decrease; Table 3). The largest DO decreases were found in the central Sierra Nevada. It is important to note that the SWAT simulations of DO did not vary appreciably between the GCMs throughout the study area (Figure 5 and Table 3). DO showed a positive significant correlation ($p > 0.05$) to changes in streamflow, groundwater, and snowmelt and a significant negative correlation ($p > 0.05$) to stream temperature (Table 4).

[26] Some of the largest decreases in spring and summer DO are likely to take place in the American, Cosumnes, and Mokelumne River watersheds in the central Sierra Nevada (see Figure 1 for location), where DO for some subbasins is likely to decrease to an average of 3–4 mg/L from 8–9 mg/L during the summer (Figure 8), well below the lower limit to maintain aquatic life of 5 mg/L [*Crisp*, 1993]. However, the projected DO concentrations for the 2080s spring season are not likely to go below the 5 mg/L threshold. On the other hand, for the 2080s summer seasons, DO concentrations for 3% of the subbasins (a total of 10 subbasins) are projected to decrease below the 5 mg/L threshold, while 7% (26 subbasins) decrease below 7 mg/L, the concentration needed to maintain aquatic ecosystem health. The decreases in these watersheds are connected to large (up to 75%) decreases in streamflow [*Ficklin et al*., 2012b] by the 2080s as compared to the historic period.

[27] It should be noted that even if seasonal DO values remain above 5 mg/L, these values represent seasonal or monthly averages, and one can expect lower values, possibly for extended periods, throughout the season. Further, the DO simulated by equation (1) is the saturated oxygen concentration, which is the total amount of DO that can be dissolved within the streamflow volume. Therefore, the role that biological activity such as growth, productivity, respiration, and decomposition exerts on DO is not accounted for within this study. Generally, DO concentrations are below the saturation level due to biological activity [*Krenkel and Novotney*, 1980], and thus, it can be expected that the DO concentrations presented in this study represent the ceiling of potential DO levels. In headwater streams with low levels of organic material, the DO concentration may drop by only 10%–20% below saturation levels. By contrast, in rivers or streams with high amounts of organic material, the DO concentration can drop by 90% [*Volkmar and Dahlgren*, 2006; *Sullivan et al*., 2010]. Further, increases in temperature will increase biological activity within a stream reach, and therefore, future DO concentrations will be likely lower than the concentrations presented within this paper.

3.2.4. Sediment Concentration

[28] As sediment concentration calibration data were limited (calibration data for 12 outlets out of 478 potential outlets), simulated sediment concentrations based on land surface and in-stream erosion simulations have large uncertainties associated with them. In addition, there was large variation between modeling results for the different GCM projections (Figure 5 and Table 3). Therefore, the sediment concentration results presented here give only a general indication of the magnitude and direction of change and

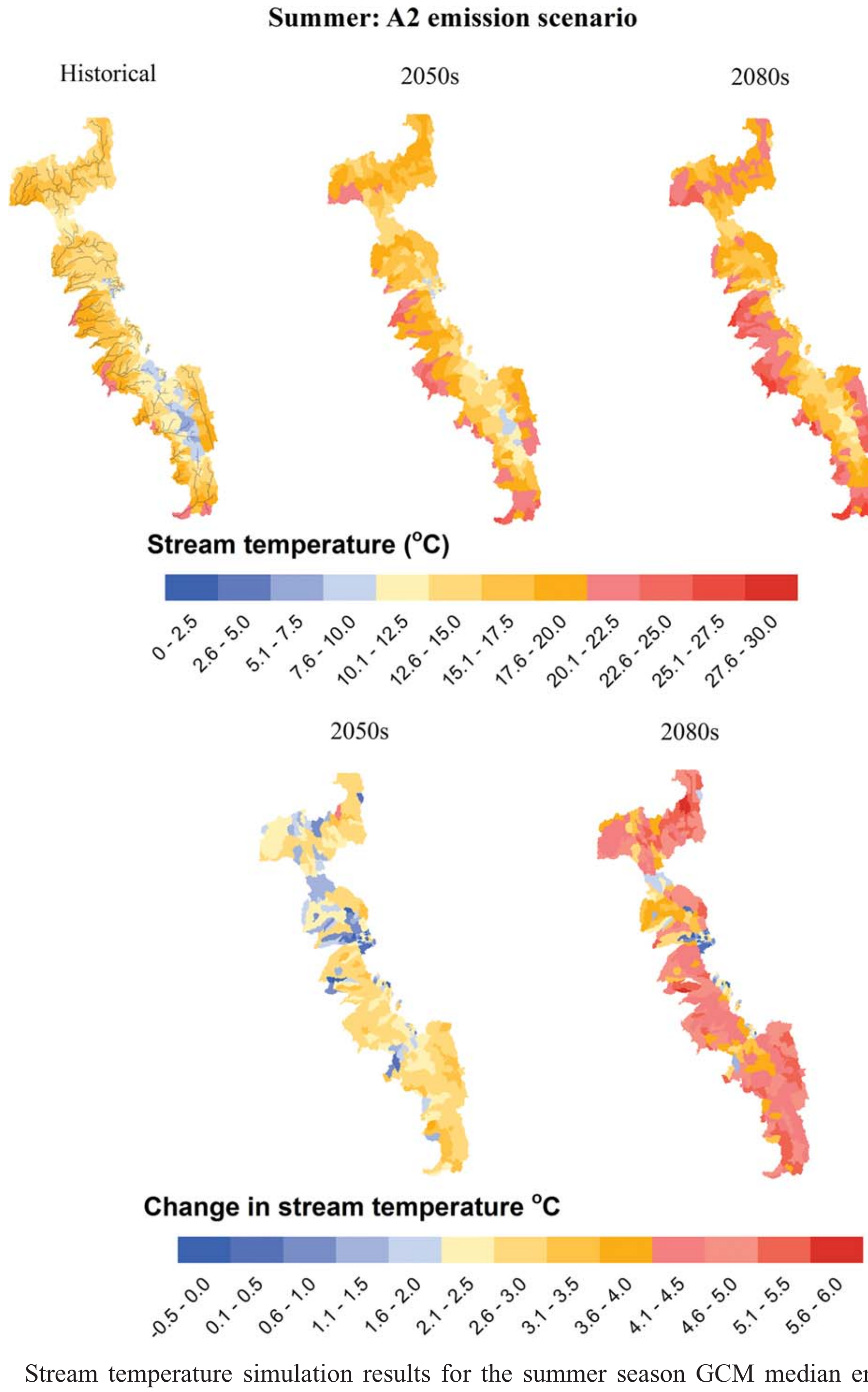

Figure 4. Stream temperature simulation results for the summer season GCM median ensemble A2 emission scenario. Historical period represents 1950–2005, 2050s represent 2040–2069, and 2080s represent 2070–2099.

should be viewed with caution. Projected sediment concentrations under expected changes in climate were significantly lower than historic values throughout the Sierra Nevada (Figure 9 and Table 2). Average historical sediment concentration values were 12.4 mg/L for the spring and 6.9 mg/L for the summer. Average subbasin spring sediment concentration of the GCM median projection decreased by 45.7% during the 2050s and 53.9% during the 2080s with large variation between GCMs, as compared to the historical time period (Figure 9 and Table 3). Sediment concentration decreased similarly during the summer season, with decreases of 49.8% and 51.4% during the 2050s and 2080s, respectively (Table 3). There was no discernible spatial trend in sediment concentration decreases. Most of the eastern and western small headwater streams have historically been relatively sediment-free, and therefore, any decreases in simulated sediment concentrations lead to large percent changes (>50% for some subbasins). By comparison, large rivers outlets such as the Sacramento (area of 18,835 km^2), American (4,815 km^2), San Joaquin

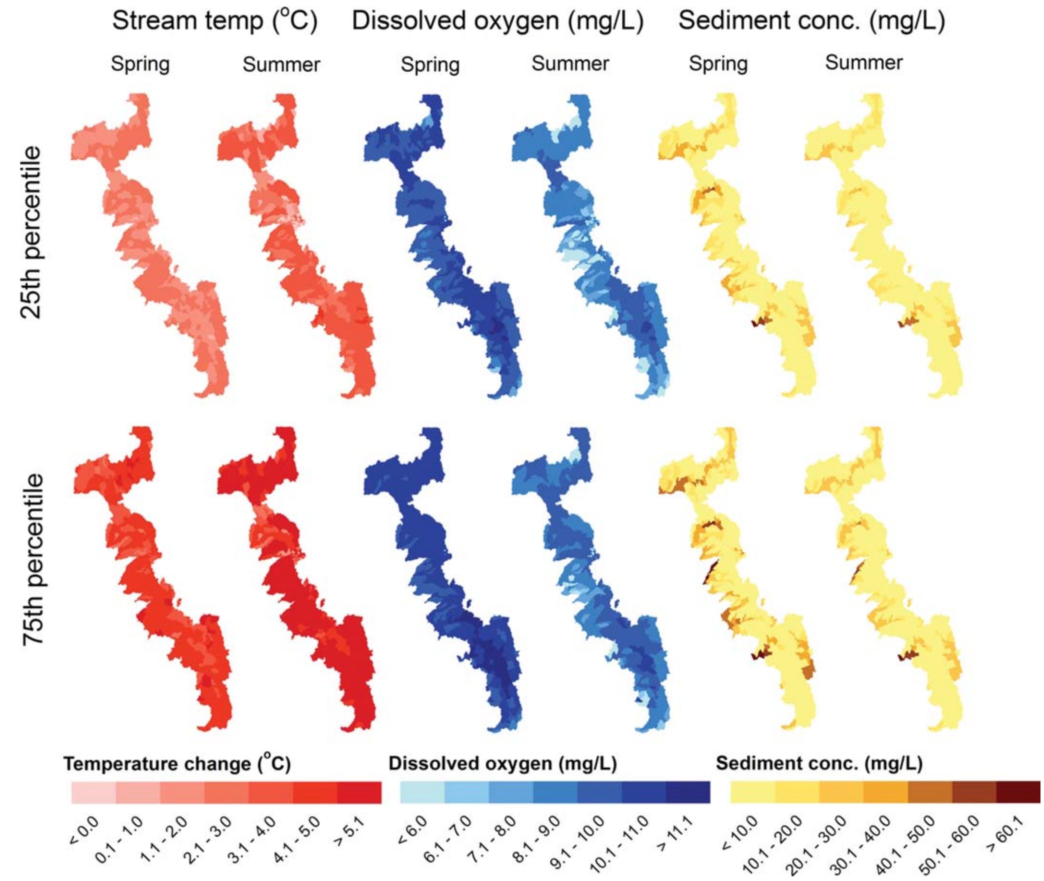

Figure 5. The 2080s A2 emission scenario spring and summer water quality changes for the 25th and 75th percentiles of the GCM ensemble; 2080s represent 2070–2099.

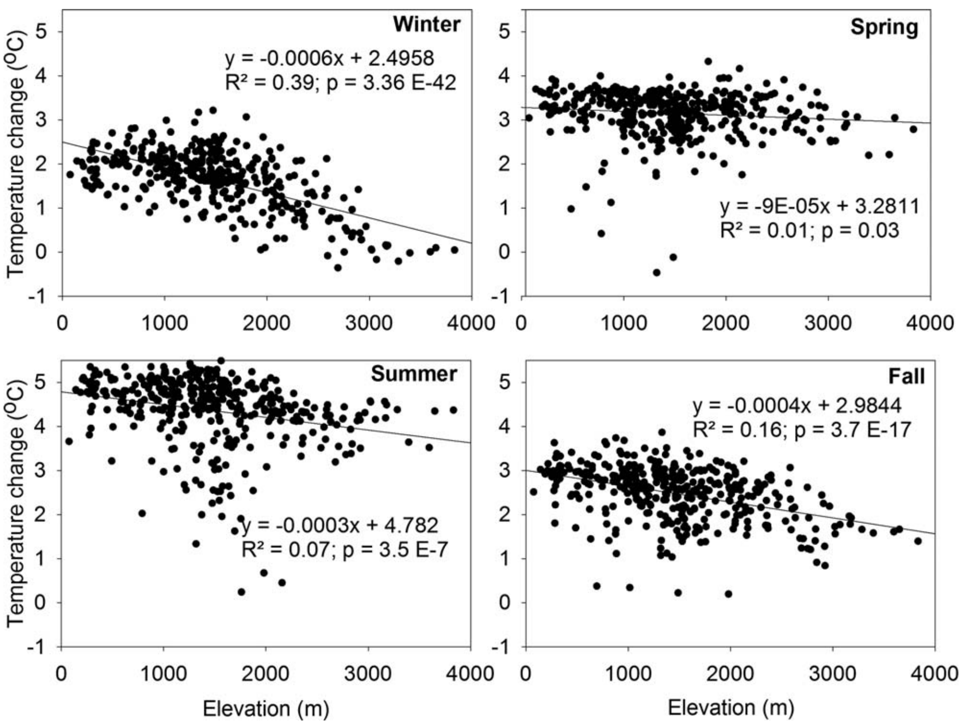

Figure 6. Scatterplots of elevation and temperature changes for all subbasins for the A2 emission scenario during the 2080s.

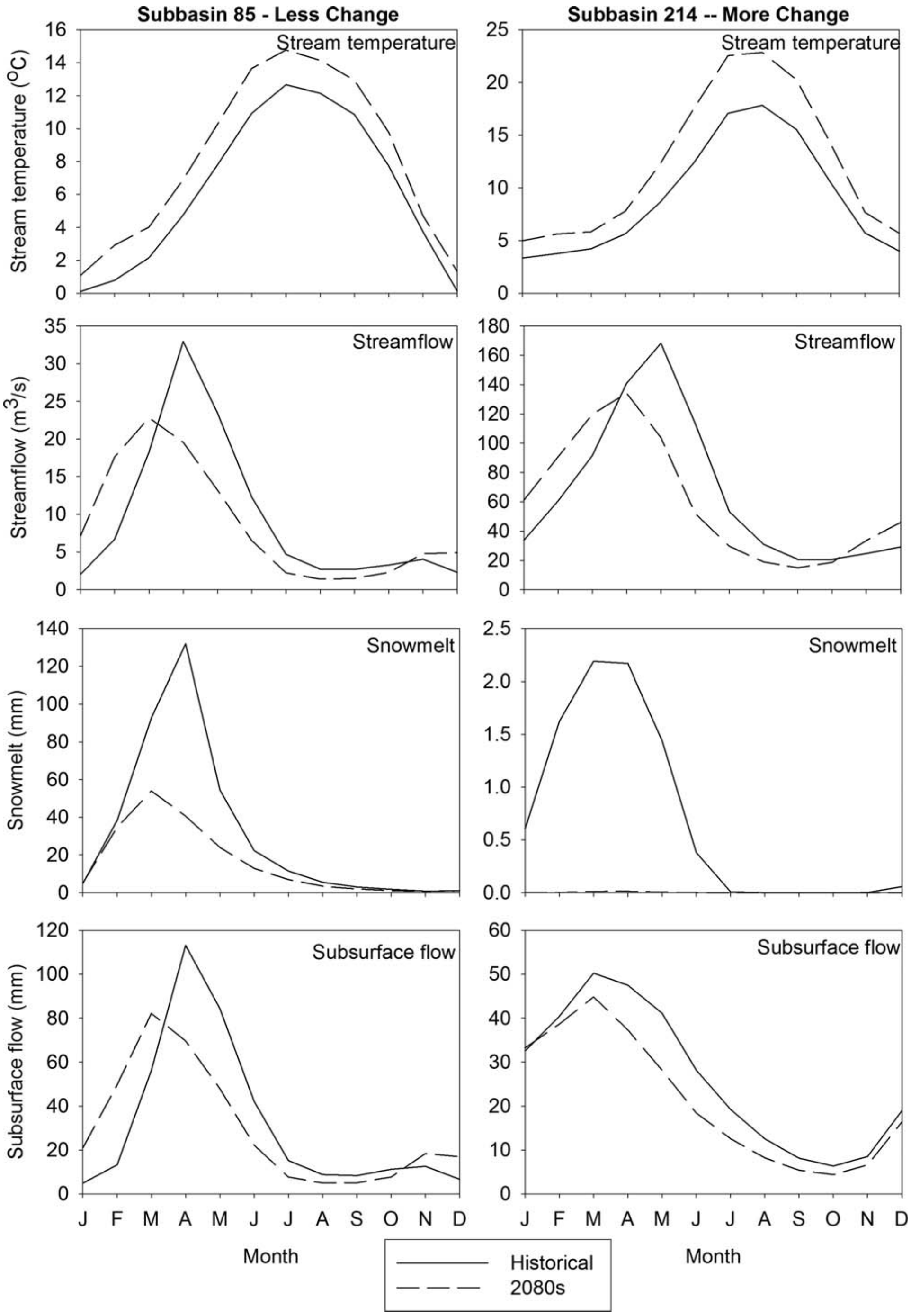

Figure 7. Subbasin examples of GCM median ensemble temperature changes related to hydrologic changes. Subbasin 85 is located in the northern Sierra Nevada, while subbasin 214 is located in the central Sierra Nevada.

(4,333 km^2), Kern (6,091 km^2), and Truckee (1,098 km^2) rivers (locations shown in Figure 1) exported less sediment under climate change, with percent decreases of 8.9%, 9.7%, 0.3%, 22%, and 17%, respectively, during spring season.

[29] Decreases in sediment concentration are largely related to changes in hydrology. Changes in streamflow and surface runoff showed a significant positive correlation ($p < 0.05$) to changes in sediment concentration (Table 4), as decreases in streamflow will result in less streamflow energy for stream bank and streambed erosion and also a lower capacity for transporting sediment. Similarly, decreases in surface runoff may result in less land surface erosion due to a lower energy and capacity of the surface runoff to transport sediment. Changes in snowmelt showed a significant negative correlation ($p < 0.05$) to changes in sediment concentration (Table 4). When snow cover is present, the erosive power or rainfall and runoff within a

Table 4. Correlation Matrix of Hydrologic and Water Quality Components for the 2080s A2 Emission Scenario

	Stream Temperature Change	DO Change	Sediment Concentration Change
Stream temperature change	1.00		
DO change	−0.40[a]	1.00	
Sediment concentration change	0.19[a]	−0.16[a]	1.00
Streamflow change	−0.06	0.16[a]	0.20[a]
Groundwater change	−0.09[a]	0.09[a]	−0.02
Snowmelt change	−0.11[a]	0.28[a]	−0.27[a]
Surface runoff change	0.07	−0.01	0.32[a]
Air temperature change	0.16[a]	−0.06	−0.19[a]
Precipitation change	−0.11[a]	0.00	0.06

[a]Significant at $\alpha = 0.05$.

watershed is reduced according to the SWAT simulations, resulting in less land surface sediment erosion. Solely decreasing snow cover due to climate change will likely lead to increases in sediment concentration according to the SWAT simulations; however, other hydrologic components may play a larger role in sediment generation.

[30] Air temperature and sediment concentration were found to be negatively correlated, largely due to the increases of biomass from increases in temperature. Biomass increases mostly took place due to the earlier start of the warm season with warmer air temperatures, resulting in more land cover throughout the year which will decrease sediment runoff. An example of this is shown in Figure 10. In the top region of Figure 10, a plant is shown with a base

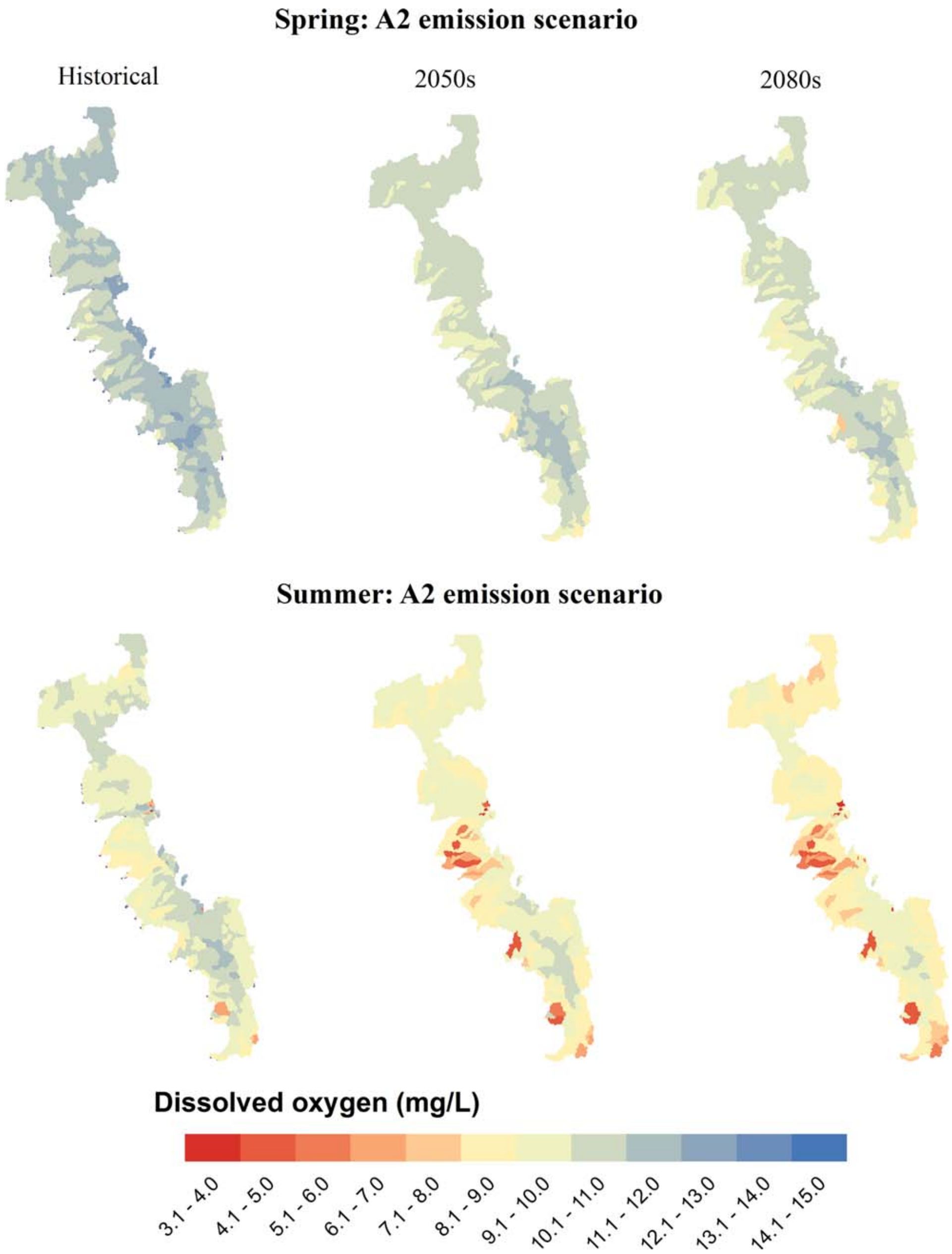

Figure 8. DO simulation results for the spring and summer seasons GCM median ensemble A2 emission scenario. Historical period represents 1950–2005, 2050s represent 2040–2069, and 2080s represent 2070–2099.

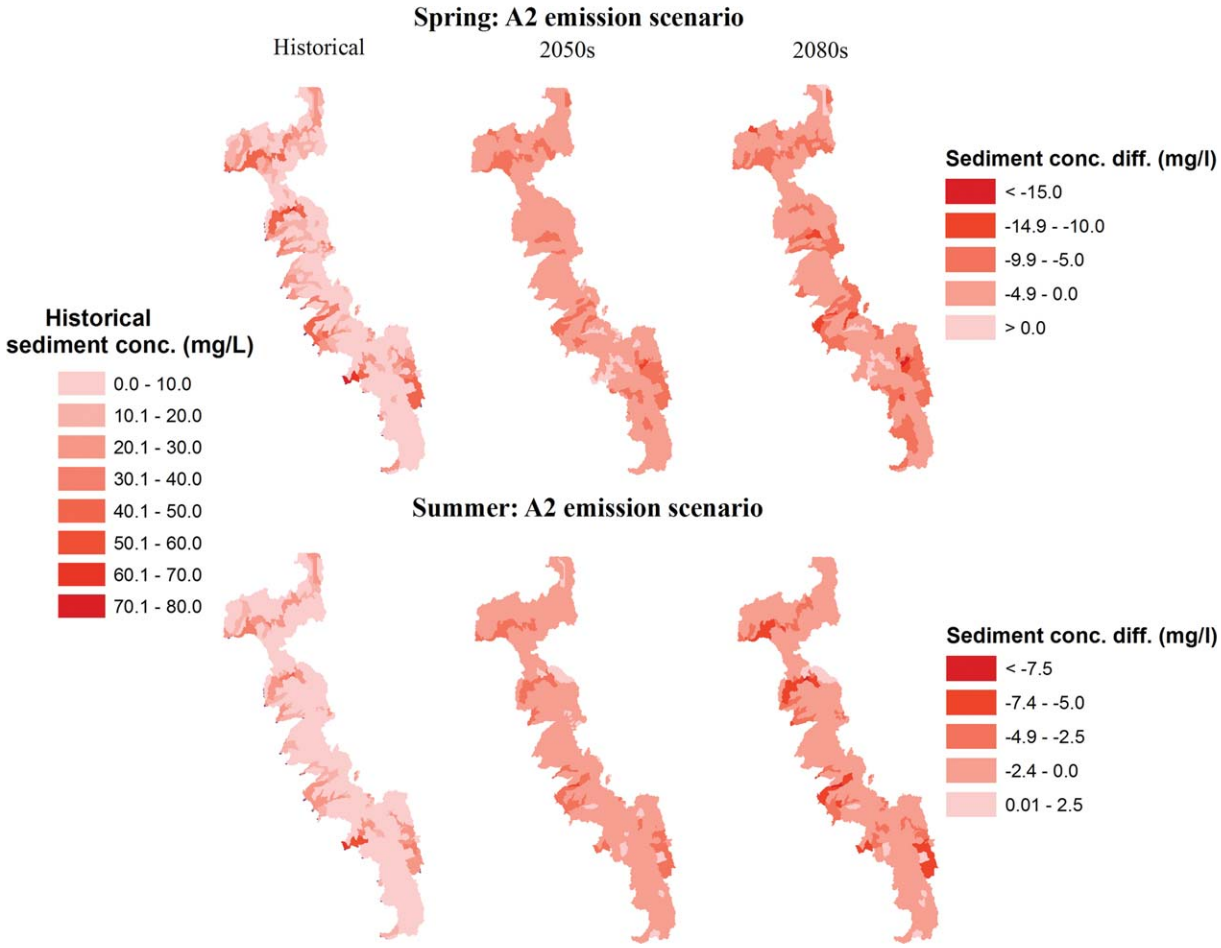

Figure 9. Sediment concentration simulation results for the spring and summer seasons GCM median ensemble A2 emission scenario. Historical period represents 1950–2005, 2050s represent 2040–2069, and 2080s represent 2070–2099. Please note the different sediment concentration scales for the spring and summer seasons.

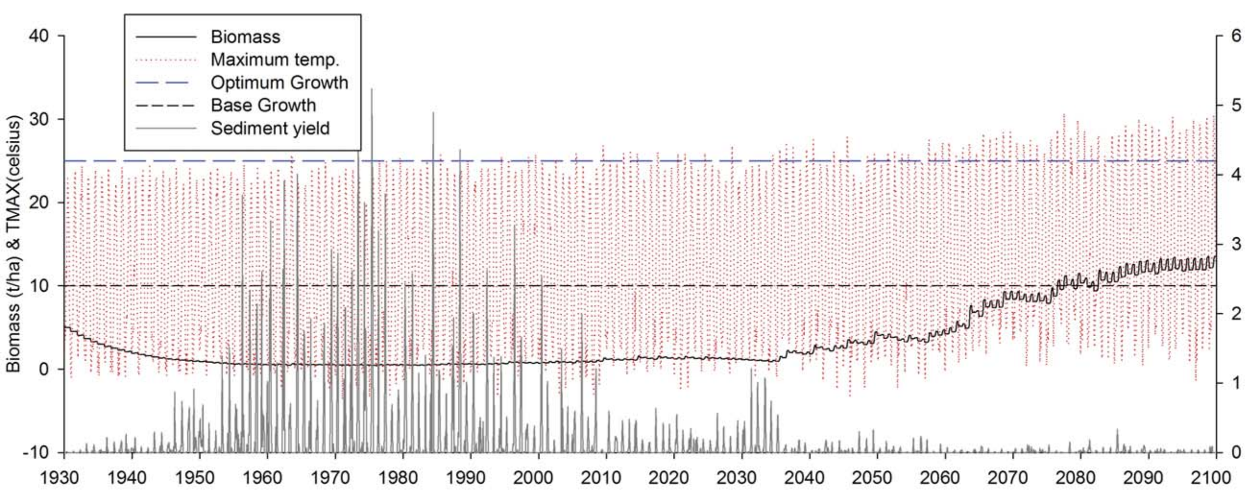

Figure 10. Plot showing the effects of biomass (black line) on sediment yield (gray line) with an increasing temperature (red dashed line). Base and optimum growth temperatures are shown by the dashed black and blue lines, respectively.

(dashed black line; minimum temperature for plant growth) and optimum growth (dashed blue line; optimum temperature for plant growth) temperature of 10°C and 25°C, respectively. During the historical time period of 1930–2010, the base growth temperature is exceeded, but the optimum growth temperature is rarely exceeded, indicating the vegetation rarely reaches its optimum biomass (black line) potential. As a result, large sediment runoff events occur (gray line) as less land cover is present. However, after 2020 the optimum growth temperature is likely to be exceeded more frequently, resulting in more biomass land cover and less sediment erosion. For other vegetation with lower base and optimum temperatures, large sediment runoff events may not decrease with increases in temperature, as the lower base and optimum temperatures may already be met under current climatic conditions.

4. Conclusions

[31] The objective of this study was to demonstrate how an understanding of the differences in the future changes in hydrology at the subbasin scale is critical for understanding the changes in local water quality under projected global climate changes. The resulting water quality impacts may be of high ecological importance and relevant for watershed adaptive management. In particular, we examined stream temperature, DO, and sediment concentration in a water-limited, highly seasonal, and mountainous system, the Sierra Nevada mountain range in California, which is the principal water source for several urban centers of global importance, and for one of the most intensely farmed agricultural regions worldwide. The Sierra Nevada aquatic ecosystems are thought to be highly sensitive to even modest amounts of warming, as most of the annual snowpack is expected to vanish by the end of the century. In addition, the Sierra Nevada has historically represented the southern border of several high-profile cold-water fish species, which have substantially declined over the past several decades and are likely to be affected by further changes in hydrology and water quality. Thus, results from the Sierra Nevada may be used as indication of the potential effects of climate change on cold-water fish habitat. To this end, we used downscaled output from 16 GCMs through 2100 and one emission scenario to drive the SWAT hydrologic model, which has been successfully applied throughout the world for hydrology and water quality modeling [*Gassman et al.*, 2007]. The SWAT hydrologic model used in this study is implemented with a recently developed stream temperature model that relies on air temperature and the local hydrology of each subbasin [*Ficklin et al.*, 2012a]. Simulations of hydrology, stream temperature, DO, and sediment concentration were performed for 478 mountainous subbasins in the Sierra Nevada that are unaffected by dams and diversions and are home to important aquatic species such as the Chinook salmon and brown trout.

[32] Our modeling results suggest that for the highly seasonal, water-limited, and mountainous basins such as exist in the Sierra Nevada, substantial changes in water quality can be expected under future climates. These changes appear especially significant for the spring and summer seasons and include stream temperature increases of up to 6°C for summer, reaching close to 30°C in the lower-elevation reaches, decreases of DO by 2%–12%, and overall decreases in sediment concentrations. For all seasons, stream temperature increases were elevation-dependent, with the largest changes in the lower (<1000 m) basins. Geographically, the low-elevation subbasins in the southern Sierra Nevada are likely to experience the greatest effects on stream water quality, with the upper elevation southern and the northern subbasins affected to a lesser degree. We suggest that the differences in vulnerability of subbasins, in spite of very similar future climatic drivers, can be explained through the differences in how watershed hydrology at the subbasin scale is likely to respond to global changes. For example, the northern Sierra Nevada subbasins are less likely to experience stream temperature increases and DO declines due to timing shifts in groundwater and subsurface flow inputs to the stream. This local scale matters, because decisions about water, other natural resources, and species are made at this level. By contrast, subbasins that appear highly vulnerable to future water quality changes are likely to experience a decreased or time-shifted snowmelt component, a decreased summer subsurface component, and overall decreases in streamflow, all of which contribute to stream temperature increases, particularly for summer. Decreases in DO are mainly the result of increases in stream temperature and decreases in streamflow volume, thus decreasing the saturation and carrying capacity for DO. For a number of lower elevation subbasins in the Sierra Nevada, especially within the American, Cosumnes, and Mokelumne watersheds, DO levels are likely to, on average, cross below the 5 mg/L DO levels to maintain aquatic life [*Crisp*, 1993], and drop as low as 3–4 mg/L during the summer months. Decreases in sediment concentration were largely a result of changes in hydrology, where decreases in streamflow reduced the energy for stream bank and streambed erosion as well as an overall lower sediment transport capacity. Increasing temperatures enhance terrestrial biomass production, which reduces surface erosion, and decrease snow cover increases vulnerability to erosion, though we find the latter effect to be smaller than the others.

[33] The impacts of the projected sediment changes are not well understood and largely dependent on the species and the timescale. For water resources, decreases in sediment concentration in streams and rivers that replenish reservoirs are beneficial, as the reservoir capacity is no longer being reduced due to high sediment infill rates. Previous studies for coho salmon found that aquatic species health is largely dependent on the type (fluvial and well-rounded versus anthropogenic and angular) and timing (i.e., short-term pulses) of sediment in stream rather than its concentration [*Berg and Northcote*, 1985; *Crisp*, 1993; *Lake and Scott*, 1999]. *Crisp* [1993] also suggests an ideal concentration range for free-swimming salmon and trout species of 25 mg/L. While the simulated sediment concentration results from this study are not ideal for individualized aquatic species assessment, the results do give an idea of the general temporal and spatial trends of sediment concentration with a changing climate.

[34] Due to data and modeling constraints, the simulation results for this study are presented as averages over 30 year periods, 16 different GCM models, and 1 emission scenario

and aid in differentiating between more and less vulnerable basins. The estimation of impacts we present here is subject to the "cascade of uncertainties" inherent in any scenario-based analysis [e.g., *New et al*., 2007; *Wilby and Dessai*, 2010]. There are uncertainties associated with unknown future greenhouse gas trajectories, uncertain climate response as represented by climate model output, the local manifestations of the large-scale climate change as implied by the downscaling applied to the GCM output, and the water resources impacts of the projected changes, as simulated by the SWAT hydrologic and water quality models. By including 16 climate model projections for one emissions scenario, we are able to capture some of this uncertainty, at least to the extent that the GCM "ensemble of opportunity" captures the range of climate responses [*Stainforth et al*., 2005; *Mote et al*., 2011]. While not all sources or ranges of uncertainties are included in our study, some projected changes are still large enough to allow robust conclusions: even if conservative future water quality changes are assumed, those changes are likely to decrease the quality of aquatic habitats.

[35] Many important statistics affecting ecosystems, such as the number of consecutive days' specific water quality thresholds are exceeded, would be important for a more detailed analysis. In this study we focus on aggregate statistics over longer time periods to draw more generalized regional conclusions on future projections of water quality, reserving more specific and higher temporal resolution analysis for future work. Although the timescales used here are not sufficiently small enough to distinguish the likelihood of extreme events on the weekly or daily basis, the averages nonetheless allow for some important insights. The magnitude of the average changes projected by our simulations would be sufficient to substantially affect species adapted to cooler spring and summer stream temperatures and higher sedimentation rates. For example, maximum weekly upper thermal tolerances for salmonids lie between 19°C and 24°C [*Eaton and Scheller*, 1996], with temperatures around 14°C favorable for spawning, rearing, and migration. As our results show, these thresholds would be exceeded, on a monthly or seasonal average, for approximately 22% and 91% of the subbasins during the spring and summer seasons, respectively, for the high greenhouse gas (A2) emission scenario during the 2080s. It should be noted, however, that disaggregating the monthly and seasonal averages presented to daily or diurnal timescales is likely to produce critical temperature increases and DO and sediment decreases for days and weeks in more of the watersheds under consideration.

[36] The insights gained from the work presented here could aid in prioritizing the management of particular mountain streams in the Sierra Nevada and other arid and semiarid regions. For example, providing riparian shading may mitigate some of the effects of global change on stream temperature.

[37] In addition, results from the Sierra Nevada could give an indication of how other arid mountain systems may be affected by global changes in the future. One important transferable result is that climate-driven changes exhibit a large degree of spatial variability and that the local hydrology needs to be characterized in order to protect water quality. Another insight is that the magnitude of the impact of climatic changes is highly dependent on the season. For seasonal, snowmelt-dominated, arid basins, low-flow reaches at the mid- and lower elevations without a significant groundwater component are likely to experience not only a shift in the timing of flow with global warming, but also substantially higher stream temperatures during the low-flow season, concurrent with a significant decline in water quality and the associated impact on freshwater reserves and native species.

[38] **Acknowledgments.** The authors gratefully acknowledge financial support for this work from the U.S. Environmental Protection Agency through EPA STAR grant RD-83419101-0. The authors acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multimodel data set. Support of this data set is provided by the Office of Science, U.S. Department of Energy.

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