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Hydrologic sensitivity of the Upper San Joaquin River Watershed in California to climate change scenarios

Zili He, Zhi Wang, C. John Suen and Xiaoyi Ma

ABSTRACT

To examine the hydrological system sensitivity of the southern Sierra Nevada Mountains of California to climate change scenarios (CCS), five headwater basins in the snow-dominated Upper San Joaquin River Watershed (USJRW) were selected for hydrologic simulations using the Hydrological Simulation Program-Fortran (HSPF) model. A pre-specified set of CCS as projected by the Intergovernmental Panel on Climate Change (IPCC) were adopted as inputs for the hydrologic analysis. These scenarios include temperature increases between 1.5 and 4.5 °C and precipitation variation between 80 and 120% of the baseline conditions. The HSPF model was calibrated and validated with measured historical data. It was then used to simulate the hydrologic responses of the watershed to the projected CCS. Results indicate that the streamflow of USJRW is sensitive to the projected climate change. The total volume of annual streamflow would vary between −41 and +16% compared to the baseline years (1970–1990). Even if the precipitation remains unchanged, the total annual flow would still decrease by 8–23% due to temperature increases. A larger portion of the streamflow would occur earlier in the water year by 15–46 days due to the temperature increases, causing higher seasonal variability of streamflow.

Key words | climate change, Hydrological Simulation Program-Fortran (HSPF), Mediterranean climate zone, snowmelt streamflow, southern Sierra Nevada

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INTRODUCTION

Global and regional climates have begun to change, likely due to excessive emissions of anthropogenic greenhouse gases (GHG). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) confirms that the climate is changing in ways that cannot be accounted for by natural climate variability. Regions that have a large fraction of runoff deriving from snowmelt are especially sensitive to changes in the climate (Xu 1999; Xu & Singh 2004; Barnett *et al.* 2005).

Since the last century, the average temperature in the USA has risen by a comparable amount and is likely to rise more than the global average over this century (Karl *et al.* 2009). In California, the average annual temperature has been increasing since 1920 (Moser *et al.* 2009). Recent simulations have shown that temperatures over the entire region of California will warm significantly during the 21st century, with end-of-century mean temperature rises from approximately +1.5 °C in the lower GHG emissions scenario to +4.5 °C in the higher GHG emissions scenario. A higher variability in precipitation has also been projected (Dettinger *et al.* 2004; Cayan *et al.* 2008).

Climate change will likely cause significant impacts on hydrology. Regions such as California that have a large fraction of runoff deriving from snowmelt will be especially vulnerable to climate change (Hayhoe *et al.* 2004; Barnett *et al.* 2005; Bates *et al.* 2008). Since the 1990s, many studies have shown that climate change has already been affecting different hydrologic basins throughout the western USA. Analyses of historical streamflow data indicate a definite shift towards earlier snowmelt (Fox *et al.* 1990; Aguado *et al.* 1992; Pupacko 1993; Dettinger & Cayan 1995; Cayan *et al.* 2001; Freeman 2002; Stewart *et al.* 2005). However,

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results for the southern Sierra Nevada basins were less statistically significant than for other regions (Roos 1991; Cayan et al. 2001; Stewart et al. 2004).

California is in the Mediterranean climate zone which typically has hot and dry summers and mild, wet winters. Precipitation is heavier during the colder months, and less or nearly none during the hotter months from May to October. Although numerous researchers have investigated the effects of rising temperatures on California's water availability, most of them have focused on global or regional trends with fairly coarse resolutions (Null et al. 2010). Less effort has been made to assess the sensitivity of local watersheds to global climate change. Relatively few studies have been performed for the Upper San Joaquin River Watershed (USJRW) above Millerton Lake (i.e. Friant Dam), which supplies the crucial amount of water for agricultural, urban and environmental uses in the San Joaquin Valley. To simulate the corresponding hydrologic system sensitivity to the projected climate change scenarios (CCS) in California, various hydrologic models have been used (Vicuna & Dracup 2007), including: topography-based hydrological model (TOPMODEL; Miller et al. 1999); US Geological Survey (USGS) precipitation–runoff modeling system (PRMS; Dettinger et al. 2004); US National Weather Service River Forecast System (Sacramento soil moisture accounting and Anderson snow model, or SAC-SMA; Miller et al. 2003); the variable infiltration capacity (VIC) model (VanRheenen et al. 2004); and soil water assessment tool (SWAT; Ficklin et al. 2009). Statistical regression models were also used in some cases (Duell 1994; Peterson et al. 2000; Stewart et al. 2005).

This study builds on previous studies by using the more detailed and physically based hydrologic model Hydrological Simulation Program-Fortran (HSPF) to simulate the hydrologic sensitivity of the snowmelt-dominated headwaters of the USJRW to climate change. Due to the large variation in temperature and precipitation over the Sierra Nevada caused by orographic effects (Meyers et al. 1992; Galewsky & Sobel 2005), a hypothetical set of CCS including temperature and precipitation variations within the projected ranges by IPCC (2007) were used as the input data for the HSPF. These simulations are not 'predictions', but rather a set of sensitivity analyses based on the projected CCS that could affect California in the 21st century. The goal is to address a critical question: to what extent is the hydrology of southern Sierra Nevada basins affected by the projected CCS?

Specific objectives of this study are: (1) to reveal the hydrologic sensitivity of the local watersheds in the rugged mountains to global climate change projections; (2) to investigate the effects of climate change on the Mediterranean climate regions such as the southern Sierra watersheds; and (3) to determine the sensitivity of the snowmelt-dominated USJRW to the projected CCS.

STUDY AREA AND DATA

Study area

The Upper San Joaquin River flows from the western slope of the Sierra Nevada Mountains (Figure 1(a)). The drainage area above Millerton Lake consists of approximately 4,500 km^2 of mountainous and foothill landscapes. About 90% of runoff-producing precipitation in this watershed occurs during November–April. Precipitation in the higher elevations above 2,000 m is primarily snowfall. The water is regulated by six main reservoirs which are operated with the objectives to minimize the spill-out, maximize the water supply reliability and generate hydroelectric power. Water from the river is used to irrigate 3,900 km^2 of highly productive farmland in the San Joaquin Valley.

In order to study the sensitivity of the system to climate change, this work was focused on an area at high elevations in the USJRW which consists of five headwater basins with natural flow condition (Figure 1(a)). This study area is located in the higher Sierra National Forest, west of the town of Mammoth Lakes, California. The integrated headwater basins cover an area of 647 km^2 with a mean elevation of 2,675 m. The annual average precipitation is 1,168 mm. Flow from these basins enters the Mammoth Pool Reservoir after merging with the South Fork of the USJRW. The South Fork in the east part of the watershed does not carry natural flow appropriate for hydrologic modeling. Two large reservoirs (Edison Lake and Florence Lake) in the South Fork intercept the flow; the water is then diverted through tunnels into the Huntington Lake for hydro-power generation. Eventually all streams in the

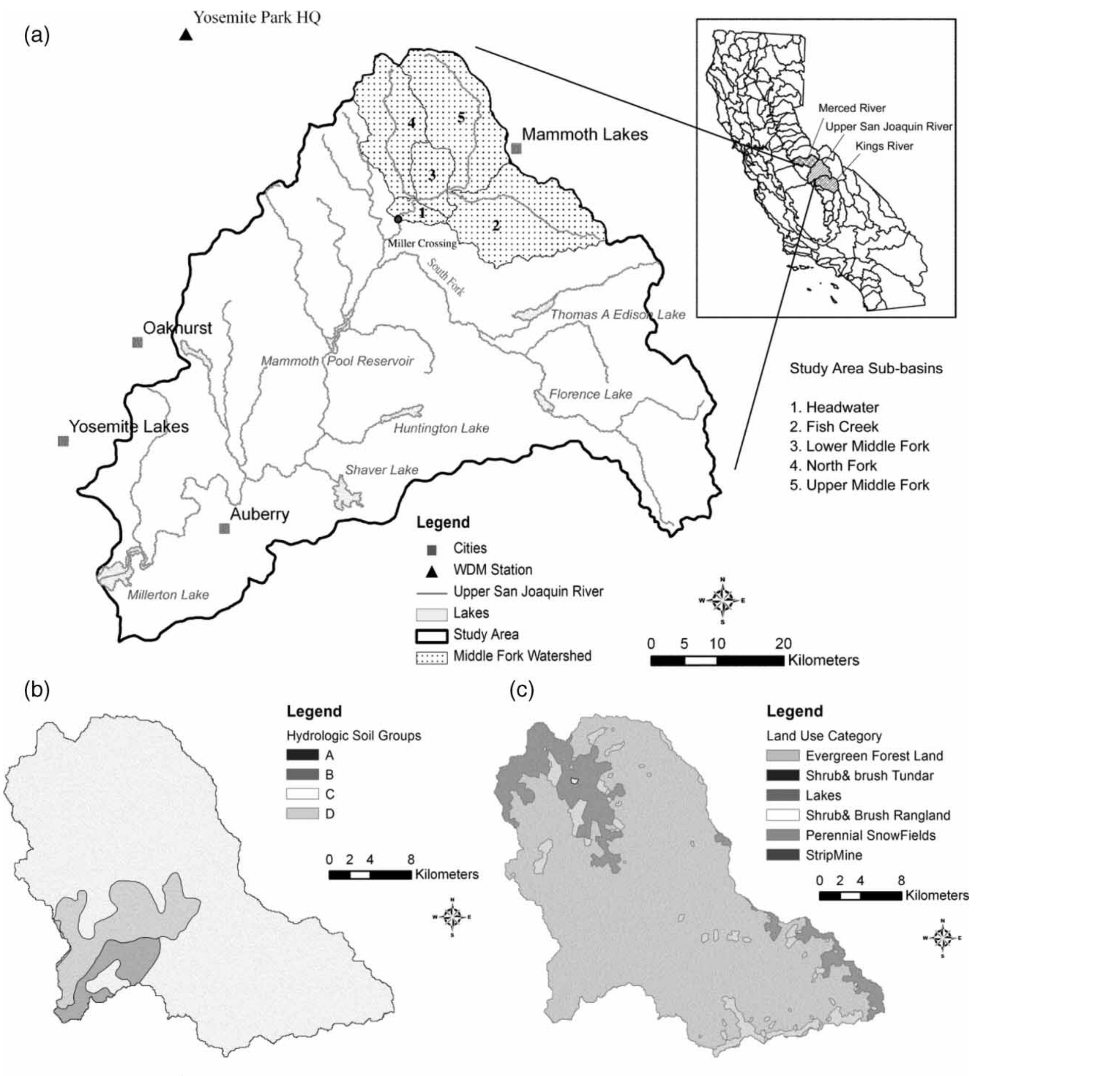

Figure 1 | (a) Map of the Upper San Joaquin River Watershed (USJRW) and the headwater basins; (b) hydrologic soil groups; and (c) land use types of the headwater basins.

USJRW flow into the Millerton Lake behind the Friant Dam at the lower end of the watershed.

Weather and runoff data

The availability of historical meteorological data from many stations in the mountainous area is limited. However, data from the nearest NOAA station CA049855 (which is the Yosemite National Park headquarters station) can be used. This station is approximately 25 km northwest of the study area. It is situated along the same mountain range and at a similar elevation, and represents the typical climate conditions in the southern high Sierra Nevada. The recorded meteorology data were archived by US National Climatic

Data Centers (NCDC) and available for the period 1970–2005. The measured and employed data include precipitation, air temperature, wind speed, solar radiation, potential evapotranspiration (ET), dewpoint temperature, and cloud cover. All data were stored in the Weather Data Management (WDM) format file.

The daily discharge data were obtained from the USGS Real-Time Water Data for California at the Miller Crossing gauge station (USGS Discharge Site NO.11226500) immediately below the study area. This stream gauging station maintained a 47-year record from 1921 to 1991 with missing data from 1929 to 1951. The record at this station has been discontinued since October 1991.

A detailed analysis of the hydroclimatic conditions in the USJRW was performed before conducting hydrologic modeling. Fluctuations in the annual data normally make it difficult to see trends in the data. To remove some of this variability, a 5-year running average was calculated and plotted. Once visual trends were detected, a statistical analysis was conducted on the original data. The Mann–Kendal trend test was used to detect the trend in historical data. It is a rank-based non-parametric test. When compared to other parametric tests, the Mann–Kendal test has a higher power for non-normally distributed data. It has been extensively used to determine trends in previous similar hydrologic studies; see a more detailed description in Helsel & Hirsch (1992), for example.

METHODOLOGY

Modeling approach

There are several different approaches used to determine local responses to global changes in temperature, precipitation and other climatologic variables. Most of the existing studies either directly use the outputs of the general circulation models (GCMs) for hydrologic studies, or by down-scaling the GCM to the smaller scales (Dettinger *et al.* 2004; Kim 2005). One major limitation of using GCM outputs is that the spatial resolution of GCMs (about 200 km) is too coarse to resolve the complex geographic changes locally and sub-grid scale processes such as convective precipitation, which is of major relevance to mountainous terrain such as the California Sierra Nevada Mountains (Wilby *et al.* 2003). Downscaling of these general trends to local scales is still subjected to large uncertainties. Given the complex climatology in the forested Sierra Nevada mountainous region, it is important to conduct the climate change modeling at a fine spatial resolution.

The selected HSPF model (Bicknell *et al.* 2001) is a public-domain geographic information system (GIS)-based watershed-scale hydrologic and water-quality simulator. It has been widely used to simulate watershed hydrology, water quality and climate change effects on water resources (Ng & Marsalek 1992; Göncü & Albek 2010). The HSPF model consists of a set of modules which permit the continuous simulation of a comprehensive range of hydrologic and water quality processes. It also includes a snowmelt algorithm which deals with runoff derived from the snow fall, accumulation and melting. The HSPF was built on a systematic framework in which various simulations and utility modules can be invoked, thus making it possible to integrate several sub-models for simulating a complete system.

The HSPF model can be calibrated manually with the support of the expert system calibration tool HSPEXP (Lumb *et al.* 1994) or automatically by using parameter optimization packages. To accelerate the calibration process, a model-independent and automated parameter estimation software (PEST; Doherty 2002) was used in conjunction with a model-independent time series processor utility for surface water (TSPROC). The PEST method implements a particularly robust variant of the Marquardt–Levenberg method which minimizes an objective function comprising the sum of weighted squared deviations between certain model outcomes and their corresponding field-measured values. It employs structured input files created for the parameters and selects calibrated values of the parameters by multiple runs of the watershed model and optimization of a selected objective function. In this research, a weighted multi-objective function similar to that used by Doherty & Johnston (2003) was adopted, in which the objective function combined daily flow with monthly flow volume and exceedance times. Weights were assigned to each sub-objective function to ensure that the contributions of each to the multi-objective functions were almost equal. Parameters are subjected to optimization by automatic calibration. The calibrated values and possible

Table 1 | Adjusted model parameters for hydrologic calibration

Parameters	Calibrated value	Range	Description (units)
LZSN	6.07	3–8	Lower zone nominal storage (inches)
UZSN	0.75	0.1–1.0	Upper zone nominal storage (inches)
INFILT	0.13	0.01–0.25	Index to infiltration capacity (h)
BASETP	0.01	0–0.05	Fraction of potential ET that can be sought from base flow
AGWETP	0.01	0–0.05	Fraction of remaining potential ET that can be satisfied from active groundwater storage
INTFW	1.31	1.0–3.0	Interflow inflow parameter
IRC	0.39	0.3–0.85	Interflow recession parameter
AGWRC	0.97	0.92–0.99	Groundwater recession parameter
DEEPFR	0.18	0.0–0.2	Fraction of groundwater inflow that goes to inactive groundwater
CEPSC	0.11	0.03–0.2	Interception storage capacity (inches)
TSNOW	31.69	31–33	The air temperature below which precipitation occurs in the form of snow (°F)
CCFACT	1.56	1.0–2.0	Correction of the melt equation for field conditions
SNOEVP	0.11	0.1–0.15	Correction of the snow evaporation equation for field conditions
MWATER	0.03	0.01–0.05	Water contents of the snowpack (inches)
MGMELT	0.04	0.01–0.03	Snowmelt rate due to ground heat (inch/day)
SNOWCF	1.35	1.1–1.5	Factor by which to account for poor gauge catch efficiency

variation ranges during the automatic calibration process are listed in Table 1.

Physical data and sub-watershed delineation

The physical data for model construction can be divided into three categories: topography, soils and land use. The topographic information of the study area was provided in the form of 10-m-resolution digital elevation model (DEM) data. The soil data were extracted from the USDA State Soil Geographic database (STATSGO) which contains soil maps at a scale of 1:250,000. Soils in the study area are predominantly decomposed granites and are classified into four hydrologic soil groups A–D based on their runoff potential and infiltration characteristics (Figure 1(b)). The dominant soil type in the study area is D which has the highest runoff potential, occupying 65.9% of the study area. The land use data (Figure 1(c)) was obtained from National Land Cover Dataset (NLCD), showing that the study area is characterized by 82% forest with relatively small proportions of tundra (12%), range land (5%) and water land (1%). The vegetation types range from alpine–sub-alpine meadows, to relatively dense and over-stocked coniferous forests to open range land.

The study area was delineated into five sub-basins using the watershed delineation tool based on the 10-m-resolution DEM data. Characteristics such as area, length, average slope and average elevation of the stream reaches within each sub-basin are listed in Table 2.

Parameter description

As a comprehensive, partially lumped-parameter model, HSPF needs a significant number of parameters to properly simulate hydrological conditions of the watershed. These parameters are classified as physically based and calibration-based. The former are those that can be observed or estimated directly from the physical watershed and its sub-units and the

Table 2 | Characteristics of the selected headwater basins in the Upper San Joaquin River Watershed (USJRW)

Sub-basin name	Area (km^2)	Length (km)	Slope (°)	Elevation (m)
Fish Creek	225.86	31.40	30.3	2,831
Upper Middle Fork	198.30	36.97	28.2	2,920
North Fork	144.82	29.25	32.2	2,359
Lower Middle Fork	55.68	13.30	28.3	2,464
Headwater	23.04	9.57	34.1	1,525

latter are lumped single-valued parameters that cannot be quantified from direct measurements. They represent integrated spatially and temporally averaged conceptual approximations of system components. Although selection of parameter values that reflect watershed-specific physical processes can improve model calibration, estimation of actual parameter values from physical measurements is either difficult or impossible. The optimum parameter values are generally obtained through the model calibration process. Table 1 lists the key parameters and their values used in this study. Parameter selection was limited to this group based on the parameter sensitivity analysis presented in the literature (Donigian *et al.* 1984). The reasonable ranges of some parameter values were estimated based on local physical conditions and literature descriptions when possible. Notwithstanding the parameter uncertainties in the calibration process, Lawrence & Haddeland (2011) indicated that parameter uncertainty is less important in catchments where spring snowmelt dominates the generation of maximum flows.

Climate change scenarios as model input data

The warming projections from the IPCC Fourth Assessment Report (IPCC 2007) are described as 'virtually certain' but there is considerably less certainty about precipitation than temperature, especially for smaller regions. For California, most of the IPCC model outputs consistently projected an increase in temperature but exhibit greater variability in precipitation projections (Moser *et al.* 2009).

Based on multiple climate change model projections, Dettinger (2005) showed that most of the temperature change projections range from about +2 to +7 °C, and precipitation range from about −300 to +250 mm yr^{-1} in northern California over the course of the 21st century. Cayan *et al.* (2006) selected the lower and medium–high emissions scenarios, each of which was based on three state-of-the-art global climate models, to capture a range of uncertainty in climate change. The projection outputs show that temperatures over California warm significantly during the 21st century. Towards the end of the century, temperature increases will vary from approximately +1.5 °C in the lower emissions scenario to +4.5 °C in the higher emissions scenario. Precipitation projections for California show considerable differences from wet to dry years between models and between emissions scenarios.

Although the large majority of the IPCC model projections yield relatively moderate changes (from ±5 to ±20%) in total precipitation in California (IPCC 2007; Cayan *et al.* 2008), it yields no indication of significant changes in the seasonality of precipitation over the 21st century.

Based on the climate projections from the previous studies, we chose to focus on simple CCS similar to the method employed by Miller *et al.* (2003). The future CCS in this study are specified as possible combinations of temperature rises and precipitation variations, as shown in Table 3. The control scenario (or the baseline years from 1970 to 1990) represents the background weather conditions without the effects of climate change. Scenarios 1, 2 and 3 represent a fixed small temperature increase of 1.5 °C with three precipitation ratios at 0.8, 1.0 and 1.2 (i.e. 20% below, equal and 20% above the baseline year precipitation, respectively). Scenarios 4, 5 and 6 represent the same three precipitation ratios but at the moderate temperature increase of 3.0 °C. Similarly, scenarios 7, 8 and 9 represent the large temperature increase of 4.5 °C. These nine scenarios represent a range of future temperature and precipitation projections for the USJRW region that provide important insight regarding the response of the USJRW stream system to future climate change.

Model calibration and validation

During model calibration, values of several sensitive model parameters were varied within a reasonable range to

Table 3 | Climate change scenarios for the Upper San Joaquin River watershed

	Scenarios									
Climate parameter	**Baseline**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Temperature rise (°C)	0	1.5	1.5	1.5	3	3	3	4.5	4.5	4.5
Precipitation ratio	1.0	0.8	1.0	1.2	0.8	1.0	1.2	0.8	1.0	1.2

obtain the best practical agreement between observed and simulated streamflow data. The long-term water balance was calibrated first, followed by calibration for the monthly and daily flows. Complete and continuous runoff datasets for the study area were available for a 47-year period from 1921 to 1990 with missing data from 1928 to 1950. The meteorology datasets were available from 1970 to 2005. A 10-year period (1972–1981) was selected for model calibration and validation. This period was chosen because it includes 25–75% quartiles and represents a combination of dry, average and wet years. Streamflow data for the first 5-year period (1972–1976) were used to calibrate the HSPF model. Data from 1977 to 1981 were used for validation. Although it is generally more difficult for a model calibrated over a wet period to predict runoff over a dry period (Vaze *et al.* 2010), in the case of this study in the southern Sierra Mediterranean climate zone there is almost no rain in the dry period; this makes the calibrated model more reliable to predict runoff in the dry period which is solely dependent on snowmelt.

Comparisons of simulated and observed flows were performed for the calibration and validation periods using annual, monthly and daily values. Since there are no unique accepted model performance criteria to determine whether or not a model is properly calibrated, both graphical and statistical methods are used to evaluate the model performance in this study. Figure 2 shows graphical comparisons of simulated and observed annual flow for the calibration (1972–1976) and validation (1977–1981) periods.

During the calibration period (Figure 2(a)), the model reasonably reproduced each year's annual runoff with percentage volume difference (DV) varying from 9.23% (1974) to −18.65% (1975), which may be considered as very good to fair (Donigian *et al.* 1984). The annual time series of observed and simulated runoff data over the validation period (1977–1981) are shown in Figure 2(b). The DV values varied from 9.59% (1977) to −11.69% (1978), which can be considered very good. Despite the historical low-flow conditions in 1976 (within the calibration period) and 1977 (within the validation period), the model is sufficiently accurate for the annual water balance simulations.

Figures 2(c) and 2(d) depict the performance of the model in simulating the monthly flow. Generally, the model reproduces monthly runoff series with reasonable accuracies. The values of Nash–Sutcliffe simulation efficiency (E_c) are 0.86 and 0.97 for the calibration and validation period, respectively. The coefficients of determination (R^2) are 0.906 and 0.97, respectively. The goodness of fit for monthly flow is adversely affected by poor results in several months with relatively low streamflow, affecting the statistics of the data.

Figures 2(e) and 2(f) show the model performance for simulating the daily flow. The E_c values are 0.771 and 0.882 for the calibration and validation periods, respectively, and the corresponding R^2 values are 0.83 and 0.897, respectively. The result of *t*-tests showed that calibration and validation of the daily flow had no significant differences at significance level SL > 95% ($t = 1.418$, $P = 0.156$; $t = 0.606$, $P = 0.545$). The model more accurately simulated the extremely high runoff in the spring of 1980 but showed poor agreement in the autumn of other years, especially in 1978 and 1975. The reason could be that the precipitations in the autumn of those years were mostly local events which did not necessarily occur in the broader mountain range including the study area. From the above comparisons and statistical tests, the simulated and observed results agreed adequately with each other and the model simulated the hydrologic conditions of the watershed reasonably. It is worth noting that, in Figures 2(e) and 2(f), there are several exceptionally sharp-increased high values in the observed discharge data (e.g. in 1972, 1976, 1978 and 1980). This was caused by the rain-on-snow events (Kattelmann 1997) which typically happen in the Sierra Nevada Mountains, producing large and sudden floods in the lower areas.

Method used to determine the shifting pattern of snowmelt streamflow

To quantitatively describe the shifting patterns of snowmelt streamflow, this study projects streamflow-timing changes in terms of the runoff center of mass (CT) rather than other measures (such as the beginning of the snowmelt period or the timing of the peak runoff sustained for a certain period of time). Although the value of CT is not consequently related to the timing of snowmelt compared to other measures, it provides a time-integrated perspective of the flow pulses and the overall distribution of the flow in the water year. It is comparatively insensitive to spurious

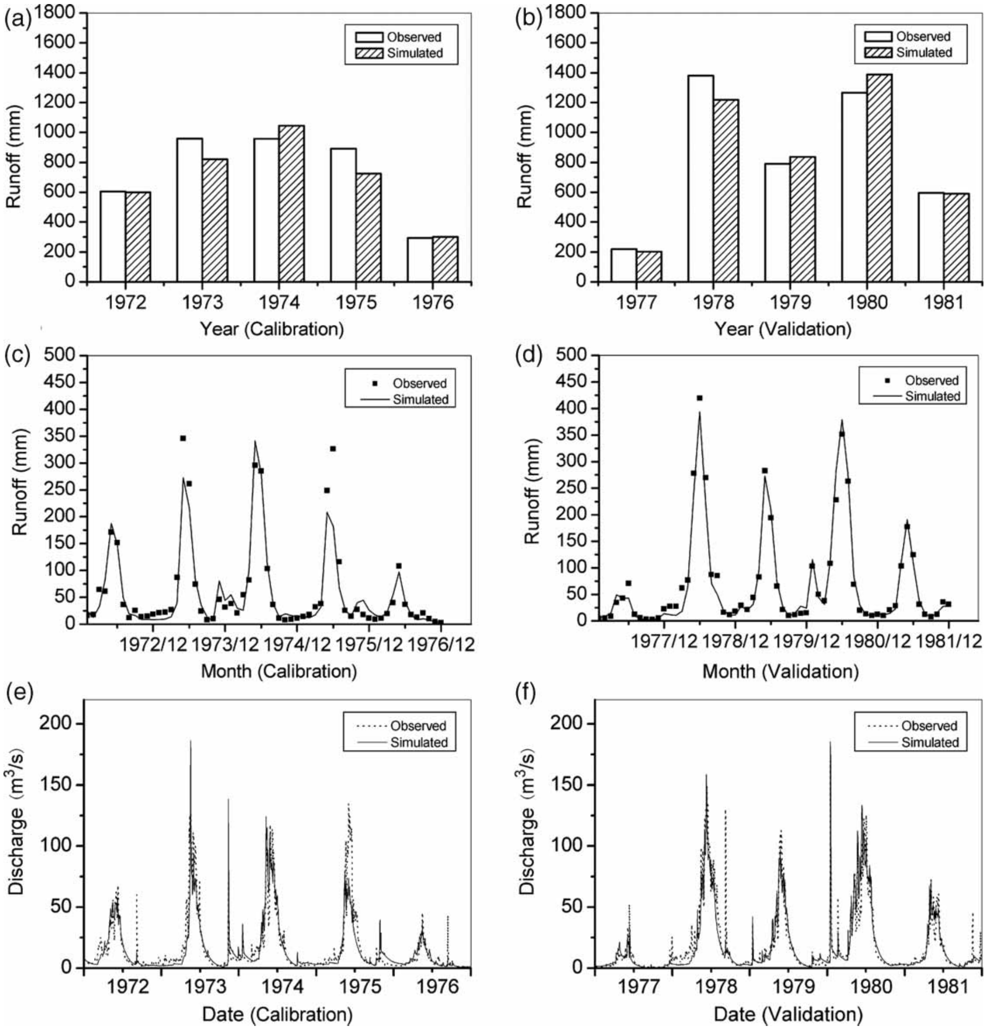

Figure 2 | Simulated and observed annual runoff for (a) calibration period (1972–76) and (b) validation period (1977–81); simulated and observed monthly runoff for (c) calibration period and (d) validation period; simulated and observed daily runoff for (e) calibration period and (f) validation period.

inter-annual variations. Furthermore, it represents a measure that is easily compared for basins in different climatic regimes, and has been used in evaluating changes towards earlier streamflow timing across western North America (Stewart *et al.* 2004). The CT is quantitatively defined as the discharge-weighted timing of streamflow:

$$\mathrm{CT} = \frac{\sum (t_i q_i)}{\sum q_i}$$

where t_i is the length of time period i in days from the beginning of the water year (1 October) and q_i is the corresponding average streamflow discharge for the ith period.

RESULTS

Climate trends in the past decades

The annual and 5-year running mean temperature changes are plotted in Figure 3(a). It shows that there is a strong and continuous temperature increase during the last decades from 1970 to 2005. After smoothing the curves by forming the 5-year running mean, the trend becomes highly significant (with significance level $\mathrm{SL} > 90\%$). The seasonal temperature changes as shown in Figure 3(b) are relatively uniform with an increasing trend ($\mathrm{SL} > 90\%$). Furthermore, there is a rapid increase in the winter temperature

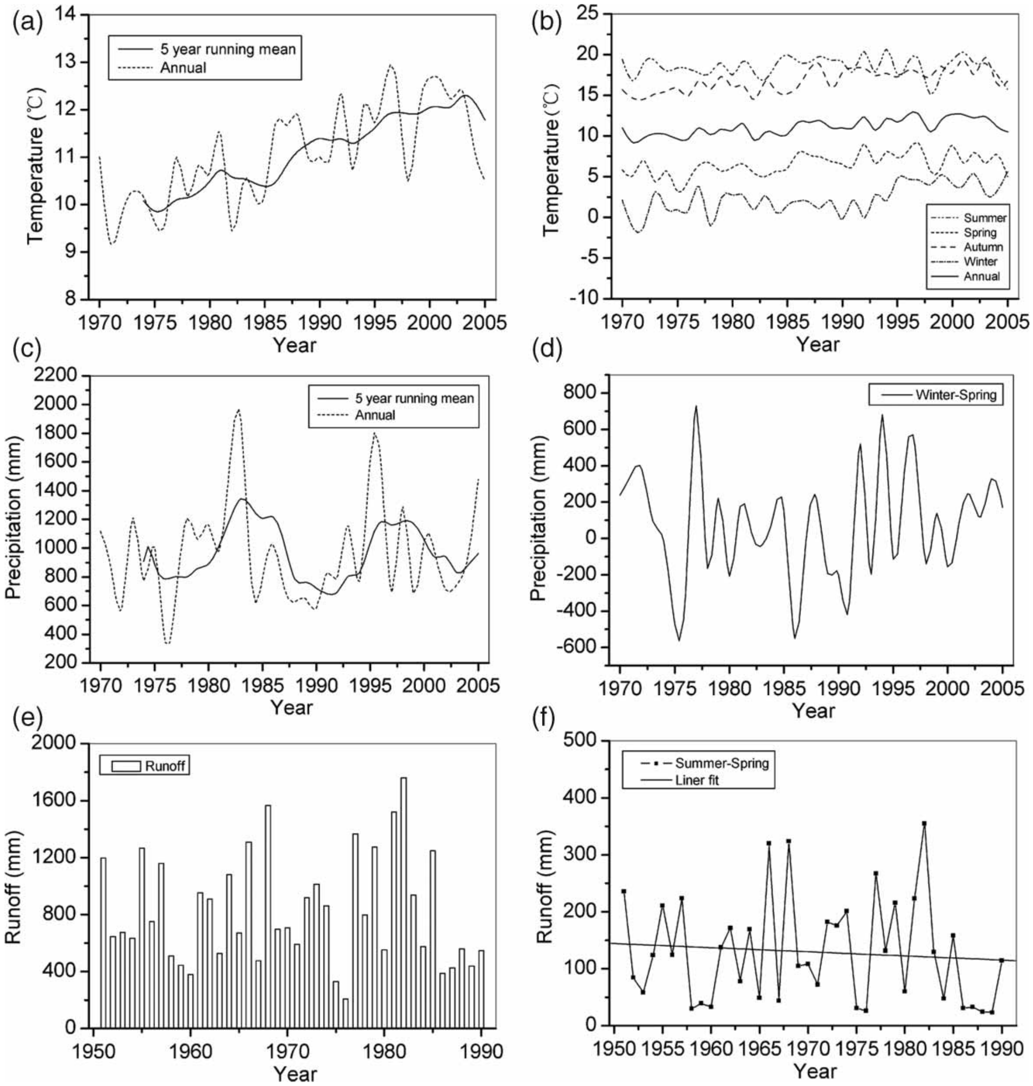

Figure 3 | (a) Evolution of the average temperatures in the study area during 1970–2005; (b) the seasonal temperature changes; (c) annual precipitation; (d) the difference between winter precipitation and spring precipitation; (e) annual runoff; and (f) difference between summer and spring runoff.

since 1992, showing a statistically significant step jump (SL > 90%) based on the cumulative deviation test. The annual and 5-year running mean precipitation changes are plotted in Figure 3(c). No significant trend is found for annual precipitation in the study period. However, a 10–12-year periodicity can be detected in the data based on frequency analysis. Since the precipitation in this watershed occurs primarily during winter and spring, the difference in precipitation in the wet season (winter and spring) was selected to reflect the seasonal change. It can be observed that the winter-time precipitation has likely been increasing, while the spring-time precipitation has been decreasing since the 1990s (Figure 3(d)). However, based on the cumulative deviation test, the suspected minor trends are not statistically significant (i.e. SL < 90%).

The mean annual runoff was highly variable and no clear trend can be observed for the dataset (Figure 3(e)). As for seasonal runoff, the primary runoff season (spring and summer) was selected for analysis as shown in Figure 3(f). It can be seen that there is a weak, increasing trend in the spring-time runoff flow and a decreasing trend in summer-time runoff.

Climate change effects on streamflow volumes

To assess the hydrologic sensitivity of the study area to CCS as shown in Table 3, the model was run under each of the scenario conditions for a full water year from October to September. The results in Figure 4 show that scenarios 1, 4 and 7, with reduced precipitation to 80% of the baseline, along with elevated temperatures of 1.5, 3.0 and 4.5 °C, cause severe reductions in the volume of streamflow (between −31 and −41%). Scenarios 3, 6 and 9, with increased precipitation to 120% of the baseline along with the same elevated temperatures, cause limited increases in the volume of streamflow (between +16.2 and +2.4%). Generally, temperature increases have a greater effect on annual runoff than precipitation increases in snow-dominated watershed, and the change and response of hydrological process have their own spatial characteristics in the tributaries of a headstream (Xu *et al.* 2011). With precipitation remaining unchanged, scenarios 2, 5 and 8 still cause minor decreases in annual streamflow (between −8.2 and −23.6%) purely due to temperature rises. The overall CCS cause the long-term average annual streamflow volume to vary in a large range, between −41 and +16.2%, and they show a clear trend of decreased overall streamflow.

Climate change effects on streamflow timing

Figure 5 shows the monthly streamflow in the study area corresponding to temperature and precipitation change scenarios (Table 3). The trend towards earlier arrival of the peak flow is evident. The peak time moves from mid-June

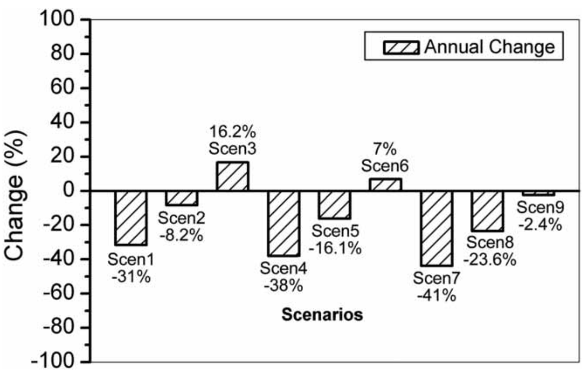

Figure 4 | Annual streamflow volume changes due to climate change scenarios, as shown in Table 3.

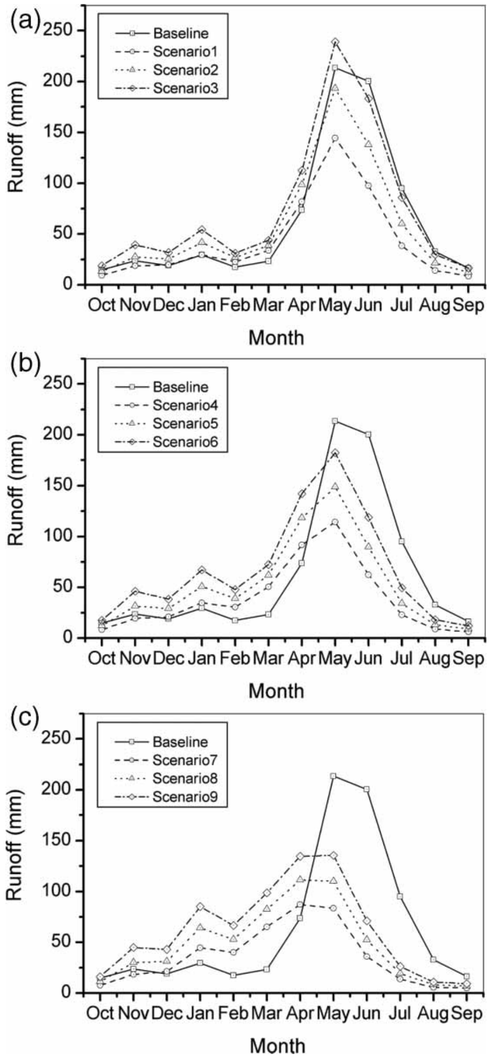

Figure 5 | Monthly streamflow due to climate change scenarios in Table 3: (a) scenarios 1, 2 and 3 with fixed minor temperature rise at 1.5 °C and varied precipitation ratios at 0.8, 1.0 and 1.2; (b) scenarios 4, 5 and 6 with fixed moderate temperature rise at 3.0 °C and precipitation ratios at 0.8, 1.0 and 1.2; and (c) scenarios 7, 8 and 9 with fixed severe temperature rise at 4.5 °C and precipitation ratios at 0.8, 1.0 and 1.2.

(baseline condition) to mid-May when the global temperature rise is 1.5 °C (Figure 5(a)). The peak time moves ahead to early May if temperature rise is 3.0 °C (Figure 5(b)), and to early April if the temperature rise is 4.5 °C (Figure 5(c)). Generally, the volume of monthly and annual flow decreases with precipitation declines and temperature rises. However, the temperature rise forces an even larger decrease in the total streamflow as indicated by the average heights of the curves in Figure 5. There is an apparent shift of the discharge peaks to an earlier time.

The variation of the timing of peak streamflow in the basin is characterized by the concept of seasonal fractional flow, which is defined as the ratio of the streamflow produced in a given season to the total streamflow in the water year. Table 4 lists the average seasonal fractional streamflow predicted for the study area with the outlet at Miller Crossing gauge station (Figure 1) for all the CCS (Table 3). The climate change will lead to a significant redistribution of the streamflow within the water year. The spring (February–April or FMA) and winter (November–January or NDJ) streamflow increases above the baseline while the summer (May–July or MJJ) and autumn (August–October or ASO) streamflow decreases below the baseline. For all the cases evaluated, there is a notable increase in spring streamflow volume (ranging from +2.2 to +29.9%) and a decrease in summer streamflow volume (between −4.6 and −35.9%). The greatest increase in seasonal flow occurs in scenario 7 with 29.9% above the baseline condition during the spring season. This scenario also produced the largest decrease in the amount of summer streamflow (−35.9%). Other scenarios show similar patterns of variation but smaller shifts in magnitude. The timing of spring and summer runoff is most strongly dictated by temperature and, to a lesser extent, by the volume of precipitation.

Table 5 shows the calculated CT for all the CCS, where ΔCT indicates the difference between CT of each scenario and that of the baseline. It can be seen that ΔCT is more sensitive to temperature rises than the precipitation variations. With precipitation unchanged (scenarios 2, 5 and 8), the temperature rises of 1.5, 3.0 and 4.5 °C cause CT to move ahead for 16, 31 and 45 days, respectively. With temperature rises fixed at 1.5 °C (scenarios 1, 2 and 3), 3.0 °C (scenarios 4, 5 and 6) and 4.5 °C (scenarios 7, 8 and 9), the variation of precipitation ratios causes ΔCT to vary within 4 days. The most unfavorable scenarios (1, 4 and 7) with the lowest precipitation ratio at 0.8 also lead to the most dramatic shifts in CT (by up to 19, 32 and 46 days ahead of the baseline times, respectively). Nevertheless, the highest temperature rise at 4.5 °C causes the largest shift in CT by up to 46 days ahead of the baseline average.

DISCUSSION

Several recent studies have been conducted to determine the hydrologic sensitivities of individual watersheds to climate warming scenarios within the Sierra Nevada mountain region. Generally, the above-mentioned results agreed with those of Stewart *et al.* (2004) who indicated that the projected runoff time shifts are most pronounced in much of the western North American regions, where the eventual CT change

Table 4 | Seasonal fractional streamflow percentages predicted for climate change scenarios

		Climate change scenarios (% changes relative to the baseline flow)								
Seasons	**Baseline (% annual flow)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Spring (FMA)	15.1	+2.2	+8.5	+6.1	+21.6	+19.3	+17.2	+29.9	+27.4	+25.3
Summer (MJJ)	67.0	−4.6	−10.8	−9.7	−24.6	−24.3	−23.8	−35.9	−35.7	−35.6
Autumn (ASO)	8.4	+4.2	−1.7	−1.1	−3.4	−3.0	−2.6	−4.3	−3.9	−3.6
Winter (NDJ)	9.5	−1.8	+4.1	+4.7	+6.5	+8.0	+9.2	+10.2	+12.1	+13.9

Table 5 | Centroids of the annual flow (center time, CT) and the shifts in days from baseline

	Scenarios									
Climate parameter	**Baseline**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Temperature rise (°C)	0	1.5	1.5	1.5	3	3	3	4.5	4.5	4.5
Precipitation ratio	1.0	0.8	1.0	1.2	0.8	1.0	1.2	0.8	1.0	1.2
Mean CT[a] (days)	221	202	205	206	189	190	190	176	176	175
Shift ΔCT (days)	0	−19	−16	−15	−32	−31	−31	−45	−45	−46

[a]Mean CT is the number of days in the water year starting from October 1.

amounts to 20–40 days in many streams corresponding to the projected regional temperature rises of about 2–3 °C.

More specifically, Miller et al. (2001) studied the Merced River and Kings River watersheds (next to each side of USJRW as shown in Figure 1) using another set of specified incremental temperature shifts (1.5, 3.0 and 5.0 °C) and precipitation ratios (1.00, 1.09, 1.18 and 1.30) as inputs to the SAC-SMA model. Simulation results showed that the long-term average annual streamflow varies between −48 and −8% for the Merced River and between −23 and +4.8% for the Kings River under all CCS. The average seasonal fractional streamflow for the Merced River shows a clear trend of increase in spring flow by +26.7% and decrease in summer flow by 35.9%, and for the Kings River an increase in spring streamflow by +19.2% and decrease in summer flow by 11.9%.

The change in the mean annual streamflow is driven by evapotranspiration and it is partly affected by the land cover of each watershed. Watersheds with lower mean elevation and relatively small area (such as Merced River) are most vulnerable to climate change, while watersheds located at higher elevations with a comparatively larger area (such as Kings River) are susceptible to moderate streamflow reduction and seasonal streamflow changes. The study area selected in this research is located at a higher elevation with relatively smaller watershed area, neighboring watersheds mentioned above. Our simulation results as shown in Figure 4 manifest the same trend with comparable annual streamflow changes between −41 and +16.2% under all CCS.

Changes in the magnitude of snow accumulation and timing of runoff in the Sierra Nevada have been studied from both historical and predictive perspectives. Stewart et al. (2004) reported that streamflow timing trends across much of western North America suggest even earlier springtime snowmelt than observed to date under 21st century warming trends (as predicted by the Parallel Climate Model under business-as-usual GHG emissions). The projected CT changes are consistent with observed rates and directions of change during the past five decades and are strongest in the Pacific Northwest, Sierra Nevada and Rocky Mountains where many rivers may eventually run 20–40 days earlier.

Young et al. (2009) implemented the Water Evaluation and Planning System (WEAP21) model for 15 west slope Sierra Nevada watersheds for climate warming scenarios with fixed increases of 2, 4 and 6 °C. The results indicated that the runoff center of mass shifted to earlier about 14–43 days for the USJRW under all CCS, and this shift was non-uniformly distributed throughout the Sierra Nevada. The same trend was confirmed again by Null et al. (2010) showing that, for every 2 °C rise in air temperature, average CT occurred nearly 2 weeks earlier for the Upper San Joaquin, Kings and Merced rivers. The runoff time change (indicated by CT) in this study generally agreed with those of previous investigations, showing a shift in CT to an earlier date by 15–46 days for USJRW under all CCS.

Considering differences in the hydrologic characteristics of each watershed, our results are generally in agreement with other climate forecasts in Sierra Nevada Mountains. Although the different degree of complexity in hydrology model structure and ways to define CCS generate diverse simulation results, the physical basis of process descriptions plays important roles when evaluating respective model results (Ludwig et al. 2009). Model formulation, resolution and calibration are significant factors in estimating projected changes in extreme flows, especially for low flows (Maurer et al. 2010) and for physically based hydrology models applied to snow-dominated basins in the Mediterranean climate regions, such as the Sierra Nevada of California.

CONCLUSIONS

It can be concluded from the modeling results that the streamflow of the USJRW is sensitive to the projected global CCS, similar to all other watersheds in the southern Sierra Nevada Mountains of California.

The projected CCS (temperature elevation from 1.5 to 4.5 °C and precipitation ratio change between 0.8 and 1.2) will lead to a large annual streamflow variation between −41 and +16.2%. The runoff center of mass (CT) will shift ahead by 15–46 days on average due to the temperature rises, and vary by 1–4 days with the change in precipitation ratios alone. Other scenarios lead to similar pattern of variation but smaller shifts in magnitude. It will effectively shift the runoff center of mass from the dry season (April–September) to the wet season (October–March), thus causing high seasonal variability of streamflow in the watershed. The temporal flow redistribution will most likely affect water availability and the management of downstream water conservancy projects. For example, reservoir operating plans and water resource management rules should be updated due to projected changes in hydrologic conditions.

Due to the overall uncertainty in climate change itself and the simulation models, the results of this paper cannot be viewed as accurate predictions of the true future climatic conditions as the input model parameters also depend on the changing climatic scenarios. However, these calculations do provide an important and reasonable set of upper and lower limits of hydrologic responses to climate change in the headwaters of USJRW. These results may help water resources managers to foresee the trends and pattern of streamflow change at the watershed scale and assess climate change impacts on USJRW.

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