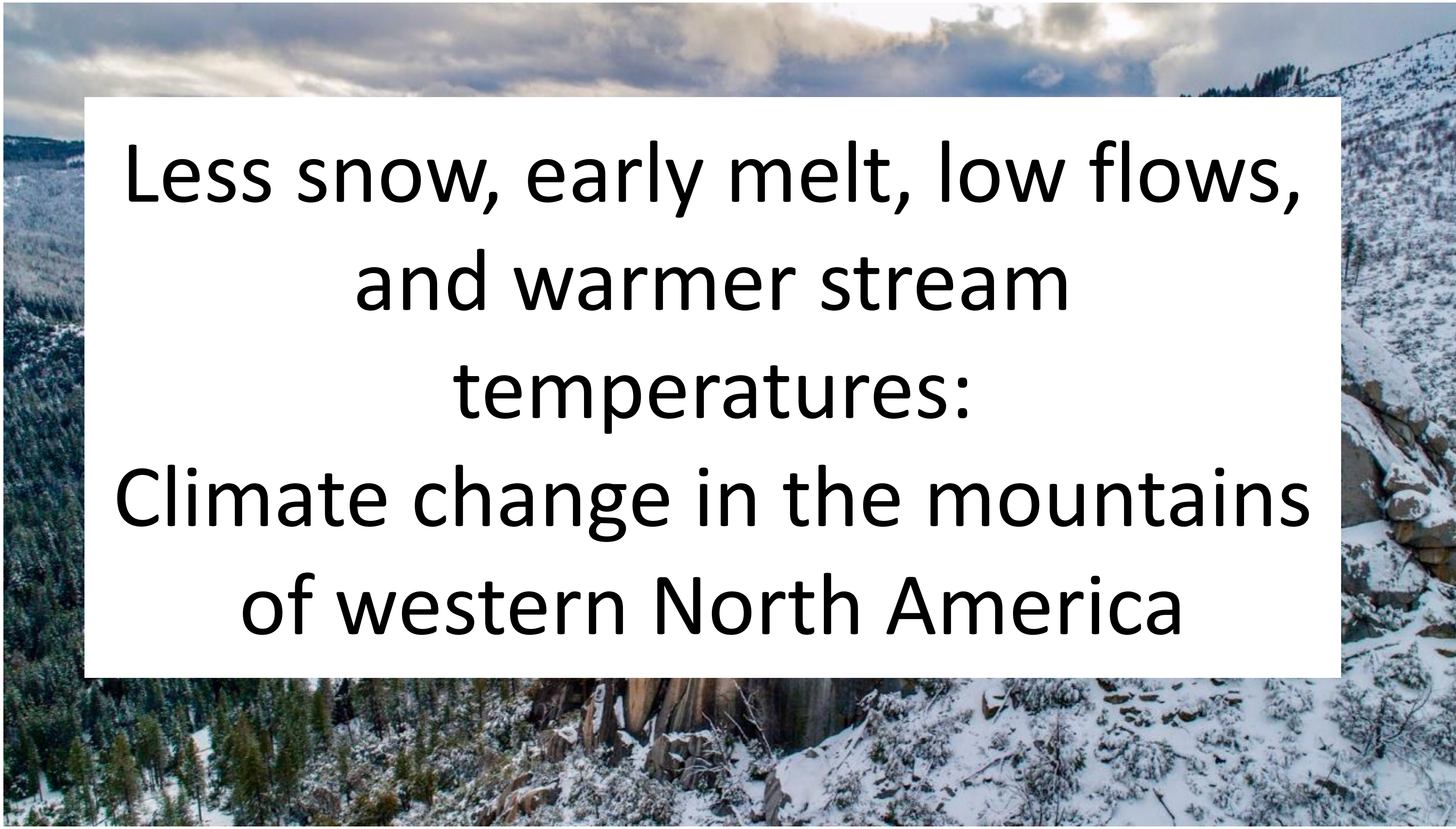


Less snow, early melt, low flows, and warmer stream temperatures: Climate change in the mountains of western North America

Iris Stewart

Alpine Hydrology Workshop

Obergurgl, November 21-22, 2019

Hydrology over the western United States is highly seasonal

- Much of the area semi-aris/arid
- Mountain water towers
- Summer dry season (May – October)
- Drought cycles
- Annual precipitation arrives with a few winter storms (atmospheric rivers)

California is the most extreme case in point. The overexploitation of groundwater has led to arguably the most complex water system in the world

California Department of Water Reources (2006)

Warmer temperatures by the end of the 20th century have led to earlier snowmelt runoff timing

- Warming in region is above global average
- Changes in timing are in addition to variability due to PDO/ENSO
- CT = Center Timing or timing of the center of mass

$$CT = \Sigma(t_i q_i)/\Sigma q_i,$$

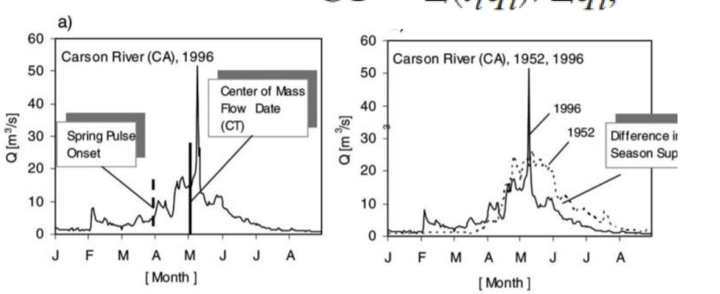


FIG. 1. Hydrographs of the (a) 1996 and (b) 1952 vs 1996 streamflow in the Carson River, West Fork, USGS gauge 10310000. In (a) the date of center of mass of annual flow (CT) and spring pulse onset timing measures of streamflow timing are indicated by the vertical solid and dashed lines, respectively.

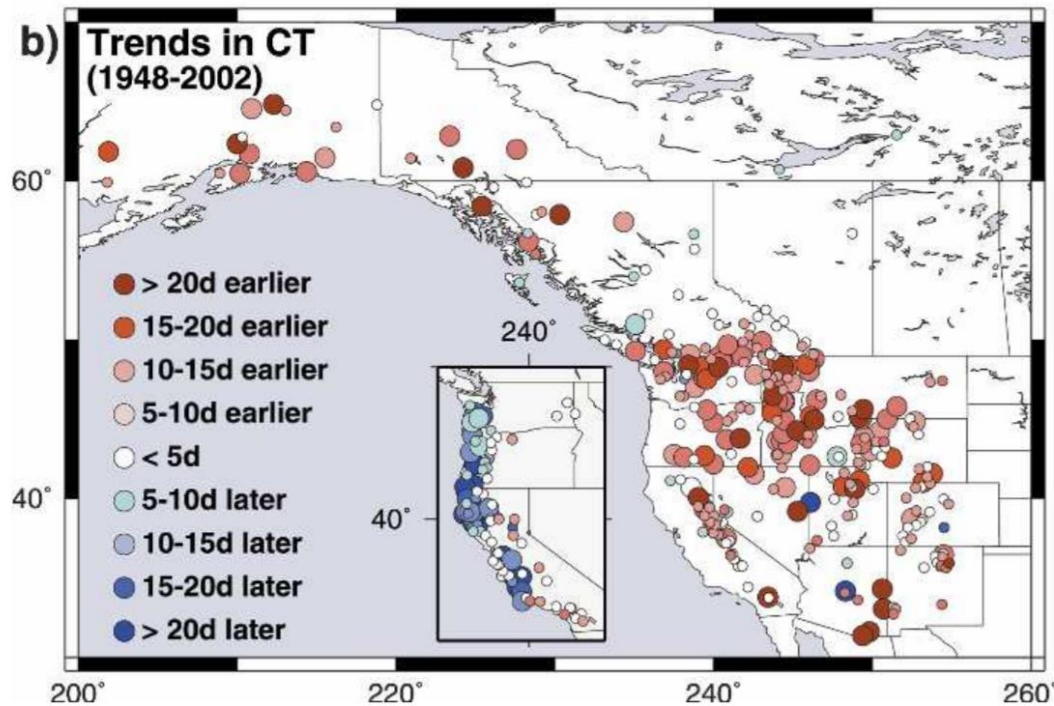
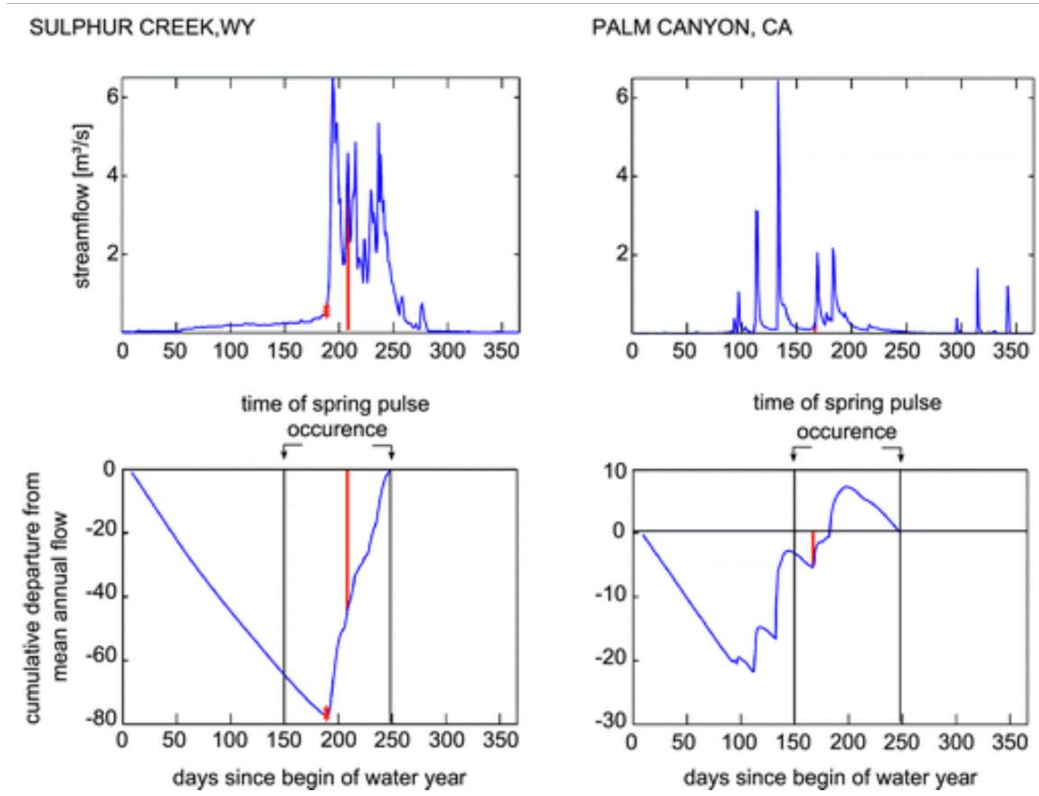


FIG. 2. Trends in (a) spring pulse onset and (b) date of center of mass of annual flow (CT) for snowmelt- and (inset) non-snowmelt-dominated gauges. Shading indicates magnitude of the trend expressed as the change (days) in timing over the 1948–2000 period. Larger symbols indicate statistically significant trends at the 90% confidence level. Note that spring pulse onset dates could not be calculated

Stewart et al. (2005), JoC

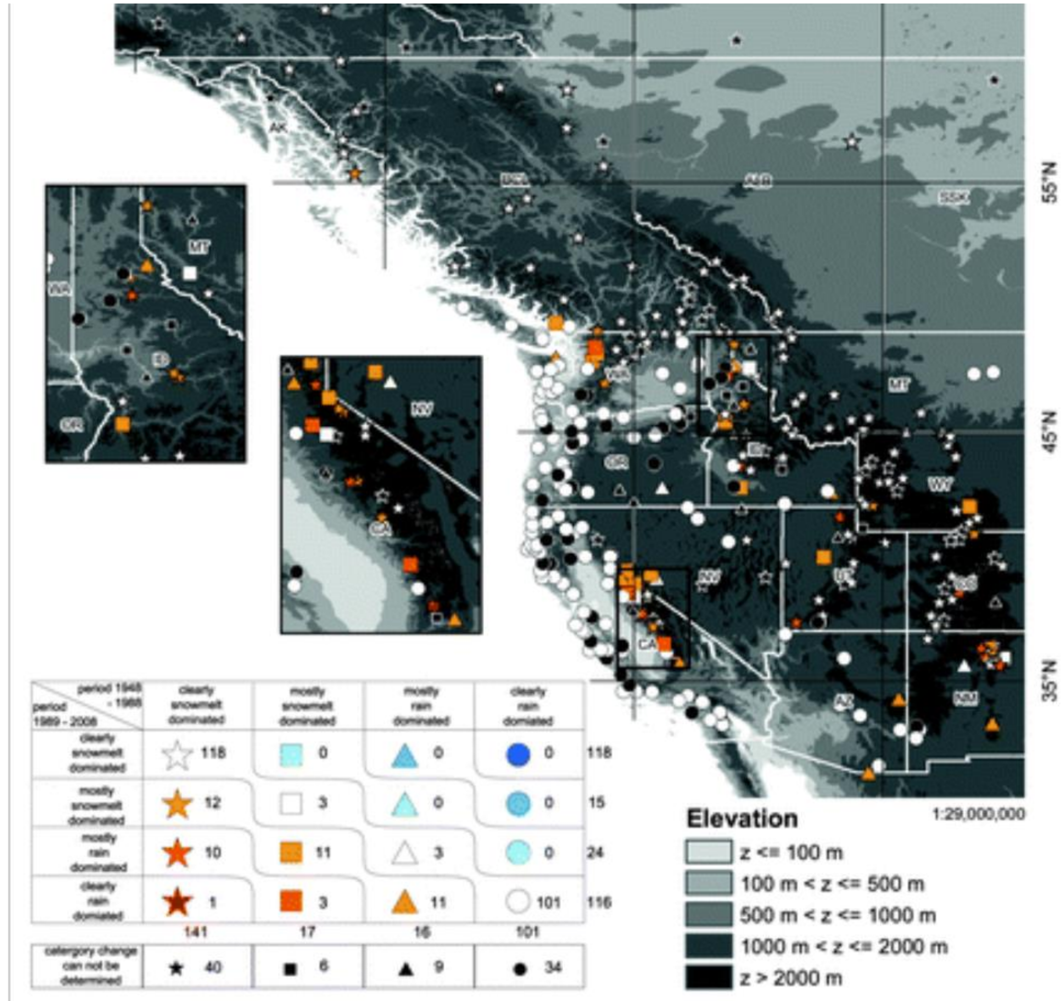
Using CT measurements to distinguish changes in snowmelt to rain-dominated regime

- Timing of spring pulse in late spring/early summer
- “False positives” are avoided if ratio of positive to negative departures from mean >=1



Fritze, Stewart, Pebesma (2011)

Changes from snowmelt to more rain-dominated regimes for lower altitude/southern streams



Fritze, Stewart, Pebesma (2011)

What further changes to streamflow are likely under projected climatic changes?

Model

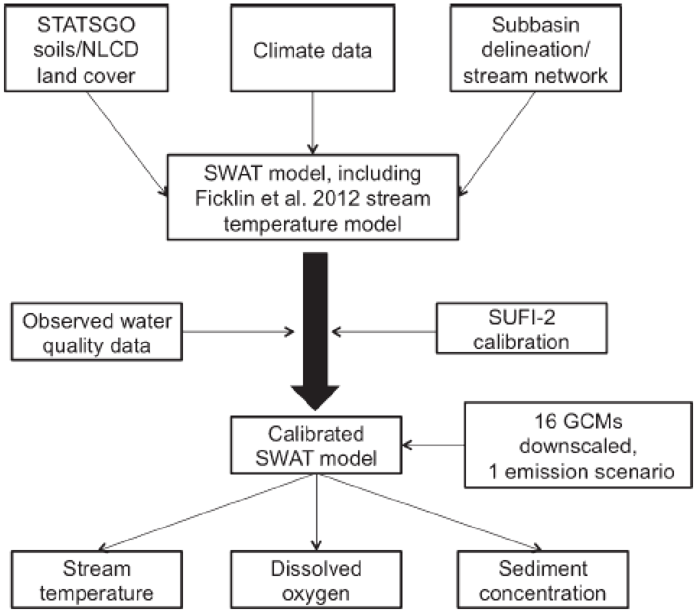


Figure 2. Overview of the methods used in this study.

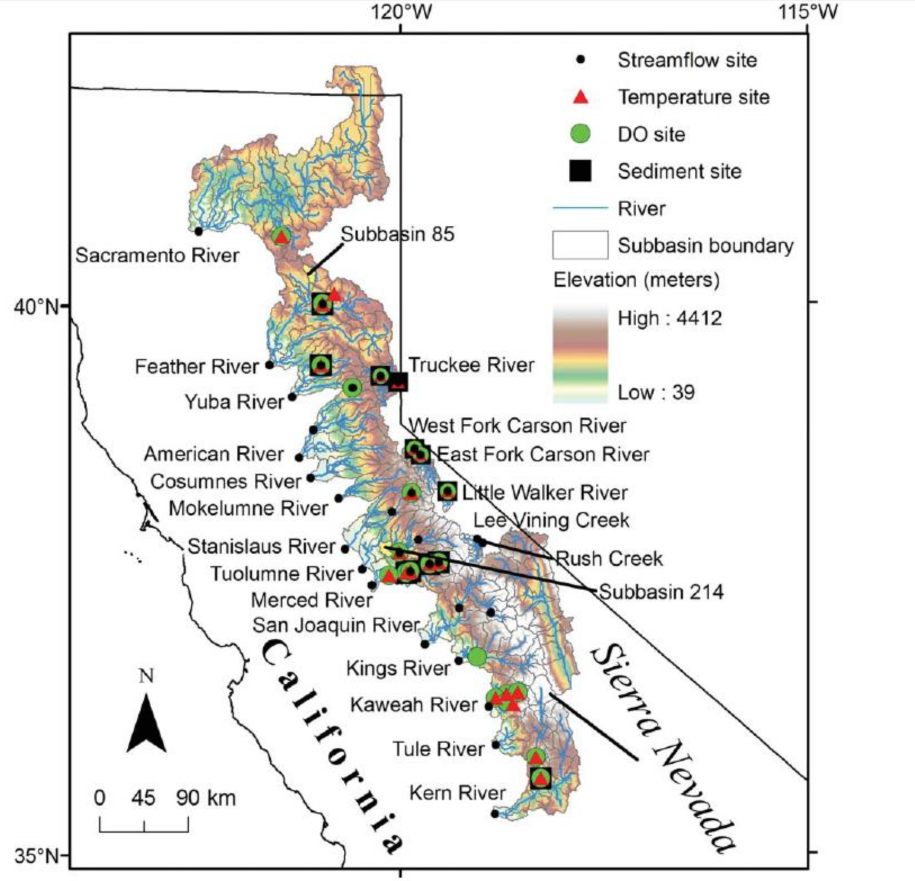


Figure 1. Boundary of the Sierra Nevada SWAT model along with calibration and validation locations. Yellow subbasins indicate the selected subbasins for the stream temperature discussion. Contributing area of subbasins 85 and 214 is 703 and 15,789 km^2, respectively. Average elevation of subbasins 85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

Modeled western North American Mountain ranges, focus here on Sierra Nevada

Model calibration & validation

TABLE 4. Western Sierra Nevada Monthly Streamflow Calibration and Validation Statistics.

			Calibration				Validation			
Site	Latitude	Longitude	Years	R^2	NS	ϕ	Years	R^2	NS	ϕ
Sacramento River	40.72	−122.42	1950-1979	0.81	0.80	0.74	1980-2005	0.80	0.76	0.75
Indian Creek	39.52	−121.55	1950-1974	0.75	0.72	0.45	1975-1993	0.80	0.77	0.59
Feather River	39.53	−120.94	1950-1979	0.88	0.87	0.70	1980-2005	0.93	0.89	0.81
North Yuba River	39.24	−121.27	1950-1974	0.81	0.78	0.62	1975-1995	0.85	0.74	0.76
South Yuba River	38.94	−121.02	1950-1974	0.82	0.78	0.75	1975-1994	0.86	0.83	0.60
Yuba River	38.68	−121.18	1950-1979	0.85	0.84	0.66	1980-2005	0.91	0.89	0.74
North Fork American River	38.50	−121.04	1950-1974	0.84	0.77	0.75	1975-1995	0.82	0.80	0.63
American River	38.31	−120.72	1950-1979	0.85	0.85	0.68	1980-2005	0.89	0.88	0.71
Consumnes River	38.19	−120.10	1950-1979	0.87	0.78	0.80	1980-2005	0.87	0.83	0.83
Middle Fork Stanislaus River	37.85	−120.64	1950-1975	0.87	0.84	0.61	1975-1994	0.82	0.78	0.53
Mokelumne River	37.94	−119.80	1950-1979	0.60	0.59	0.39	1980-2005	0.73	0.72	0.58
Middle Fork Stanislaus River	37.67	−120.44	1950-1974	0.78	0.76	0.52	1975-1995	0.68	0.66	0.52
Tuolumne River	37.72	−119.67	1950-1974	0.75	0.74	0.62	1975-1992	0.83	0.76	0.80
Stanislaus River	37.52	−120.33	1950-1979	0.82	0.77	0.51	1980-2005	0.89	0.85	0.65
South Fork Tuolumne River	37.32	−119.33	1950-1979	0.67	0.65	0.51	1980-2001	0.65	0.61	0.52
Merced River	37.27	−118.97	1950-1979	0.74	0.74	0.50	1980-2005	0.83	0.81	0.58
Merced River	36.98	−119.72	1950-1974	0.77	0.76	0.62	1975-1995	0.79	0.78	0.57
Tuolumne River	36.83	−119.34	1950-1979	0.85	0.84	0.65	1980-2005	0.88	0.85	0.75
South Fork Merced River	36.41	−119.00	1951-1965	0.72	0.65	0.52	1966-1975	0.77	0.72	0.56
Merced River	36.06	−118.92	1950-1979	0.76	0.47	0.72	1980-2005	0.81	0.66	0.70
San Joaquin River	35.43	−118.95	1950-1966	0.85	0.78	0.79	1967-1980	0.87	0.84	0.66
South Fork San Joaquin River	37.82	−120.01	1950-1966	0.74	0.68	0.69	1967-1980	0.69	0.68	0.49
San Joaquin River	40.08	−120.93	1950-1979	0.87	0.85	0.65	1980-2005	0.88	0.83	0.68
Kings River	39.32	−120.56	1950-1979	0.92	0.90	0.81	1980-2005	0.90	0.86	0.71
Kaweah River	38.36	−119.87	1950-1979	0.87	0.85	0.77	1980-2005	0.91	0.87	0.79
Tule River	37.65	−119.89	1950-1979	0.79	0.65	0.73	1980-2005	0.78	0.63	0.39
Kern River	37.73	−119.56	1950-1979	0.75	0.64	0.67	1980-2005	0.82	0.80	0.61

Notes: R^2, coefficient of determination; NS, Nash-Sutcliffe coefficient; ϕ, modified efficiency criterion.

Ensemble of climate projections:
Warming by up to 5.5 C
Variability in precipitation magnitude and direction, indication towards greater drying

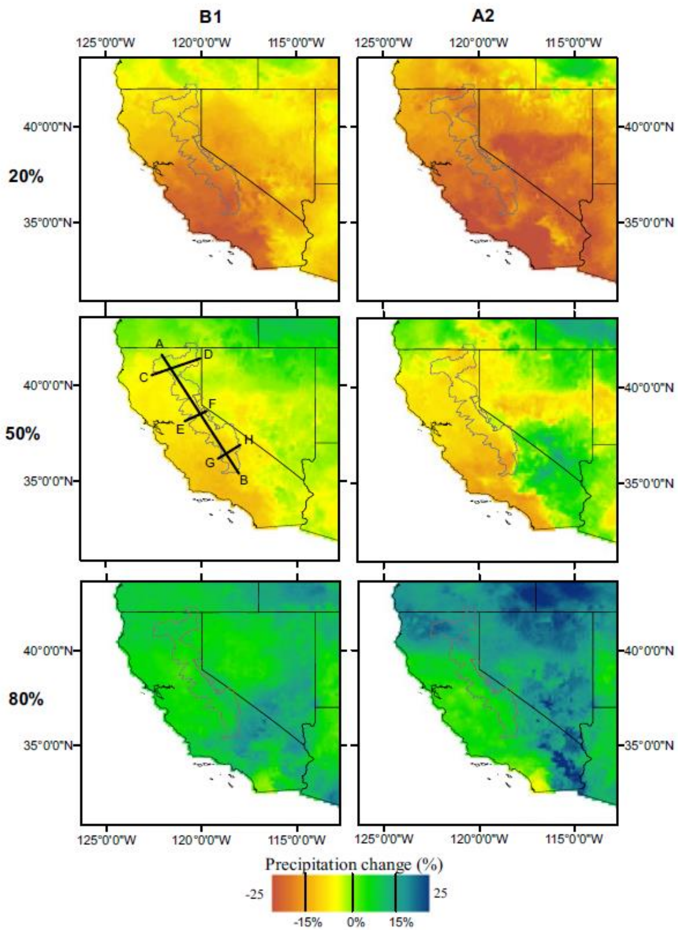
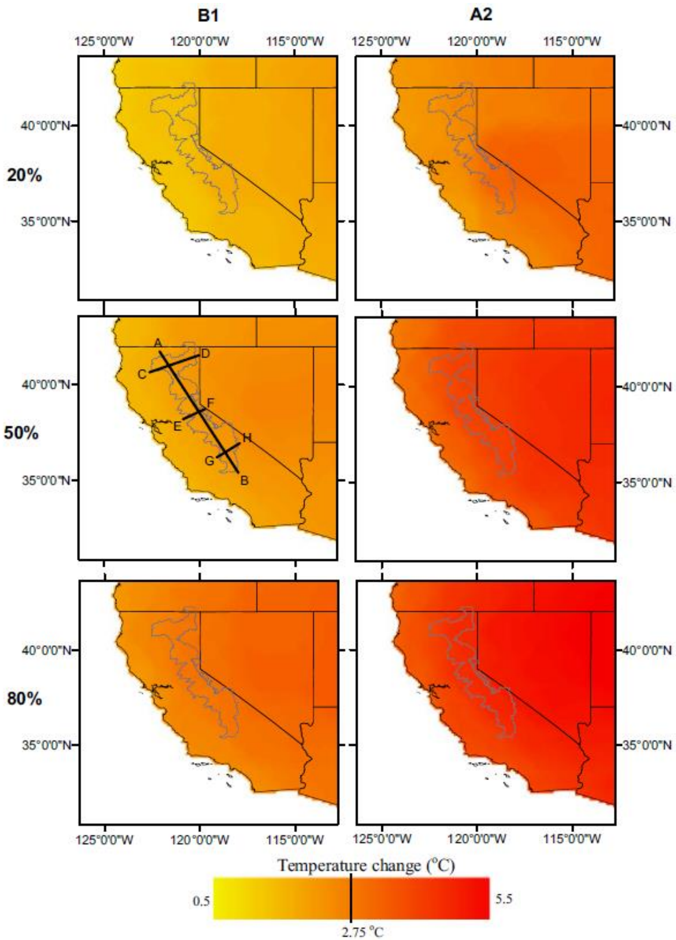


FIGURE 3. Quantiles of the Projected Annual Precipitation Change of the California Region. The gray outline shows the location of the Sierra Nevada study site and the black lines show the location of the transects.



RE 2. Quantiles of the Projected Annual Temperature Change of the California Region. The gray outline ›ws the location of the Sierra Nevada study site and the black lines show the location of the transects.

Development of a new stream temperature module for SWAT

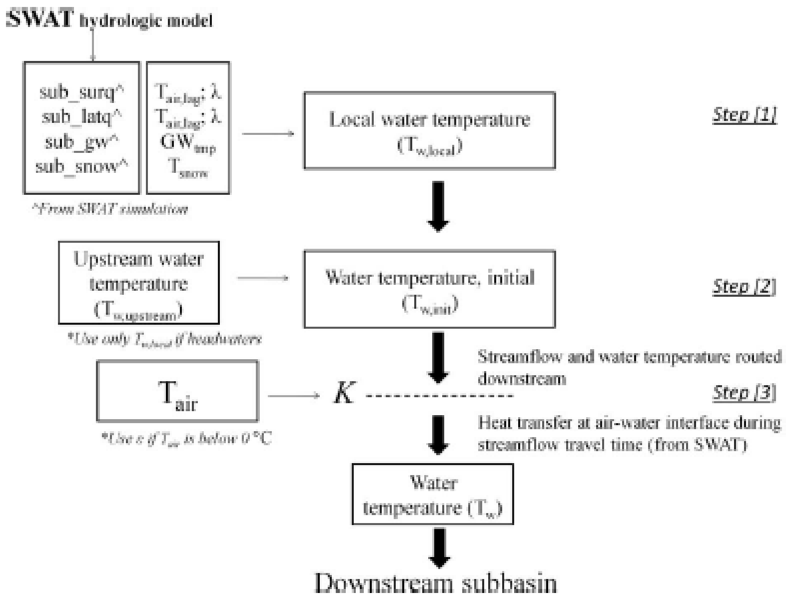


Figure 1. Schematic of new stream temperature model The following parameters are passed to the temperature module from the SWAT hydrologic model: sub_surq, sub_latq, sub_gw, and sub_snow.

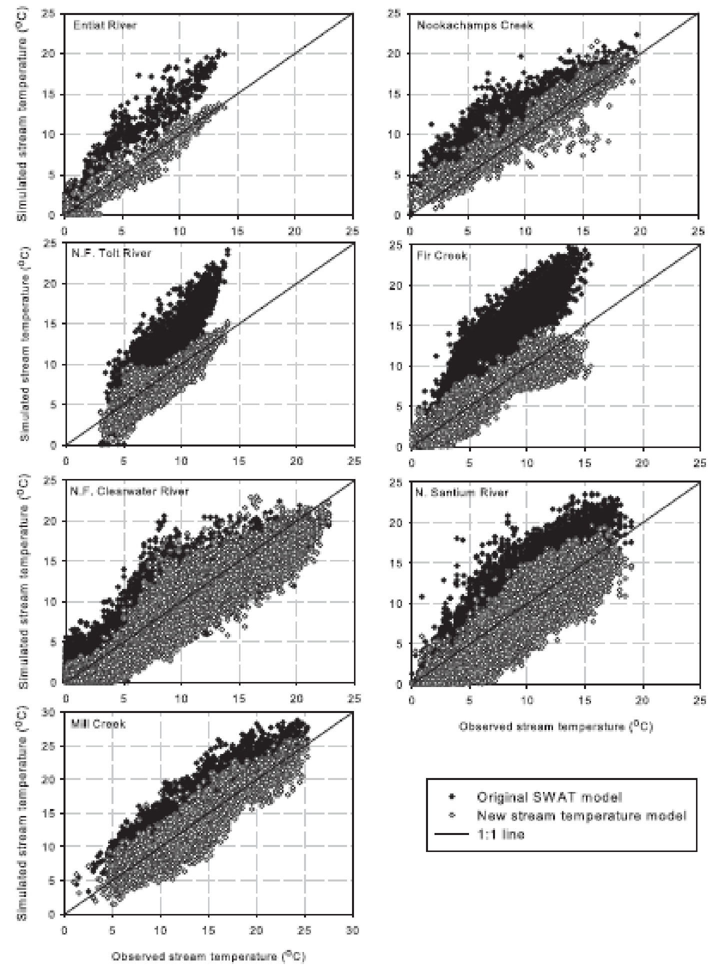


Figure 5. Scatterplots of daily stream temperature for the original and new SWAT stream temperature model for the seven study sites.

- Stream T not only based on air temperature relationship
- Incorporate upstream snowmelt fluxes and their temperatures

Modeled monthly streamflow,
Historic, 2050s, 2080s
Western and eastern Sierra Nevada Watersheds
Earlier melt, less snowmelt runoff

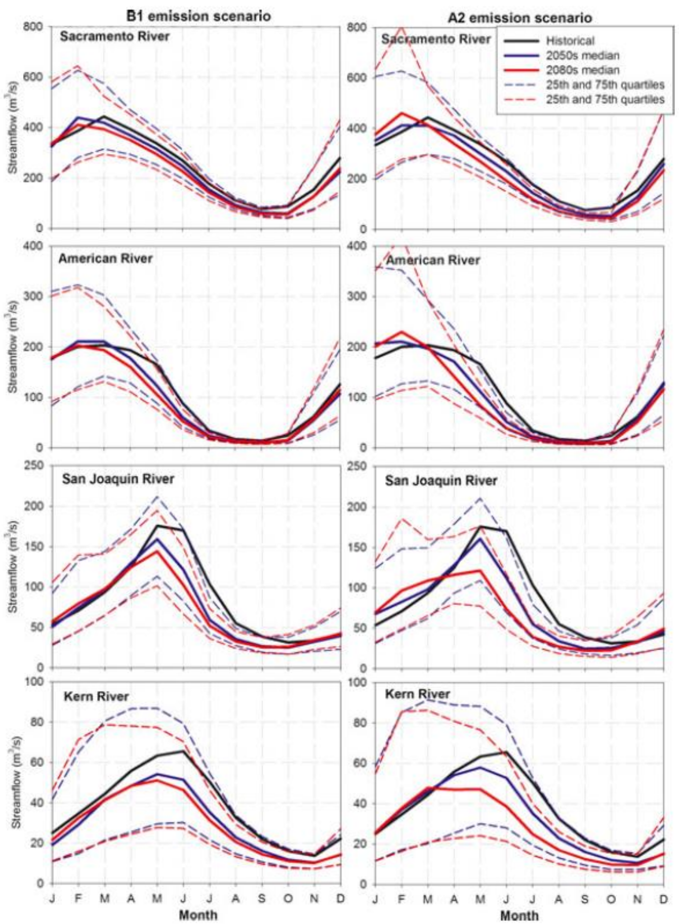


FIGURE 5. Average Median and Quartile Monthly Streamflow Projections for the 2050s and 2080s Under Each Emission Scenario for the Selected Western Sierra Nevada Watersheds.

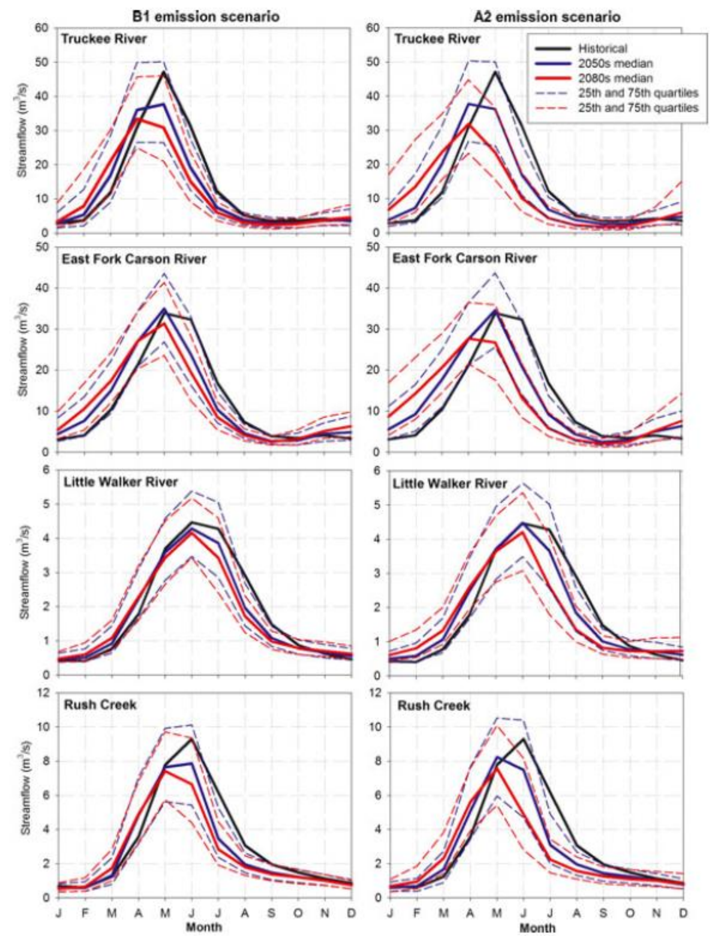


FIGURE 6. Average Median and Quartile Monthly Streamflow Projections for the 2050s and 2080s Under Each Emission Scenario for the Selected Eastern Sierra Nevada Watersheds.

Ficklin, Stewart, Maurer, JAWRA 2012

Earlier snowmelt affects timing and magnitude of other components of the hydrologic cycle

- Earlier subsurface flow
- Decrease in summer soil water
- Ecological impacts and wildfires

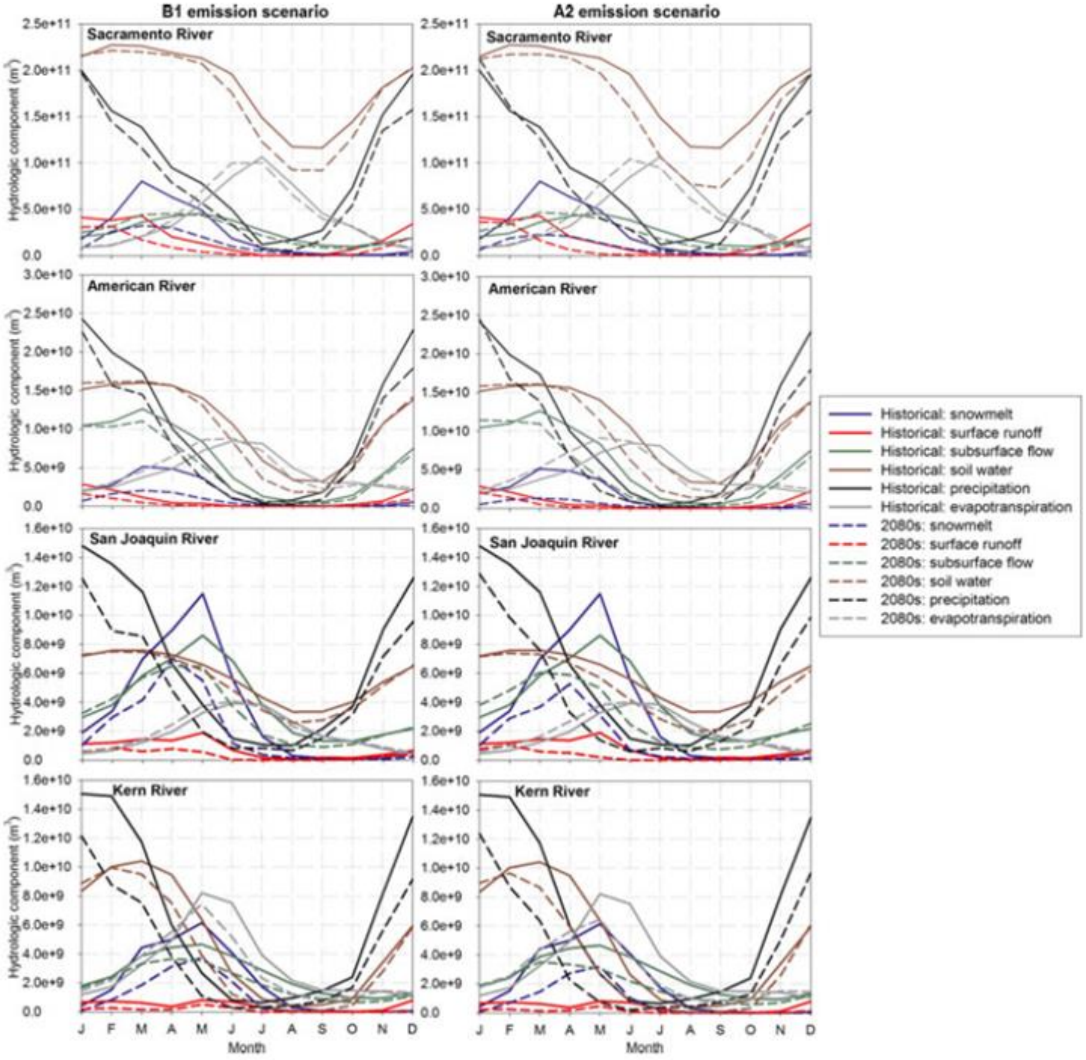


FIGURE 8. Total Hydrologic Component Volumes for the Selected Western Sierra Nevada Watershed for the 2080s Under Both Emission Scenarios.

Decreases in spring and summer streamflow and snowmelt

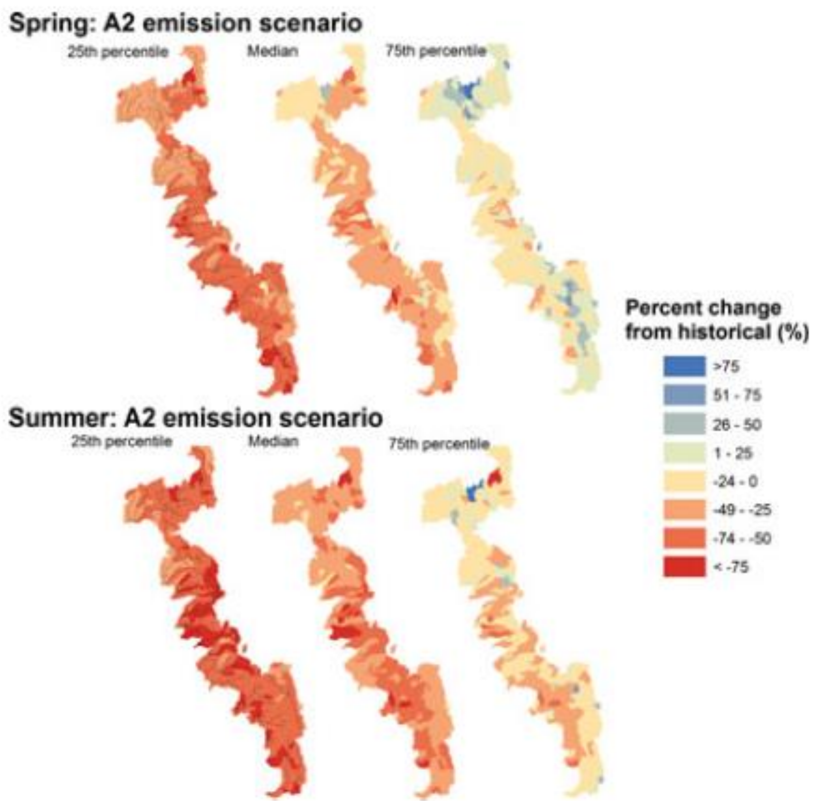


FIGURE 11. Spatial Average Median Streamflow Discharge Percent Changes for the Spring and Summer Seasons Under the A2 Emission Scenario.

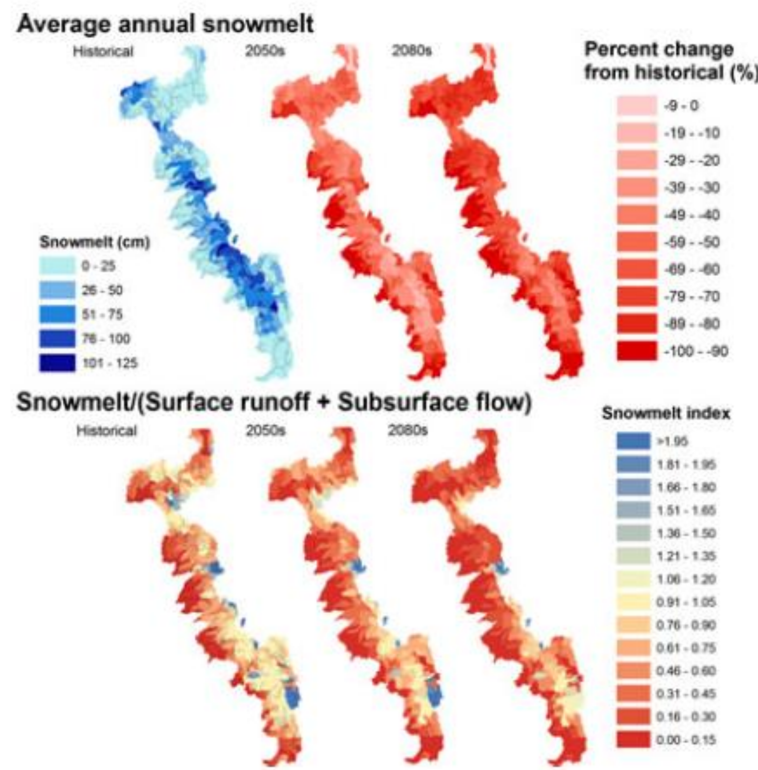


FIGURE 12. Percent Changes in Average Median Annual Snowmelt and Hydrologic Component Indices Under the A2 Emission Scenario.

Ficklin, Stewart, Maurer, JAWRA (2012)

Increases of spring and summer stream temperature

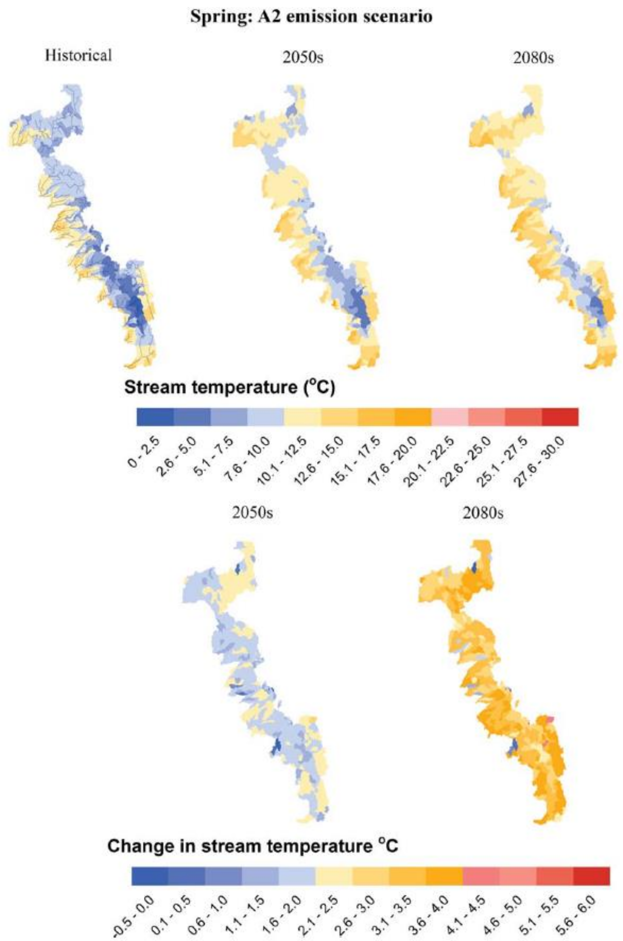


Figure 3. Stream temperature simulation results for the spring season GCM median ensemble A2 emission scenario. Historical period represents 1950–2005, 2050s represent 2040–2069, and 2080s represent 2070–2099.

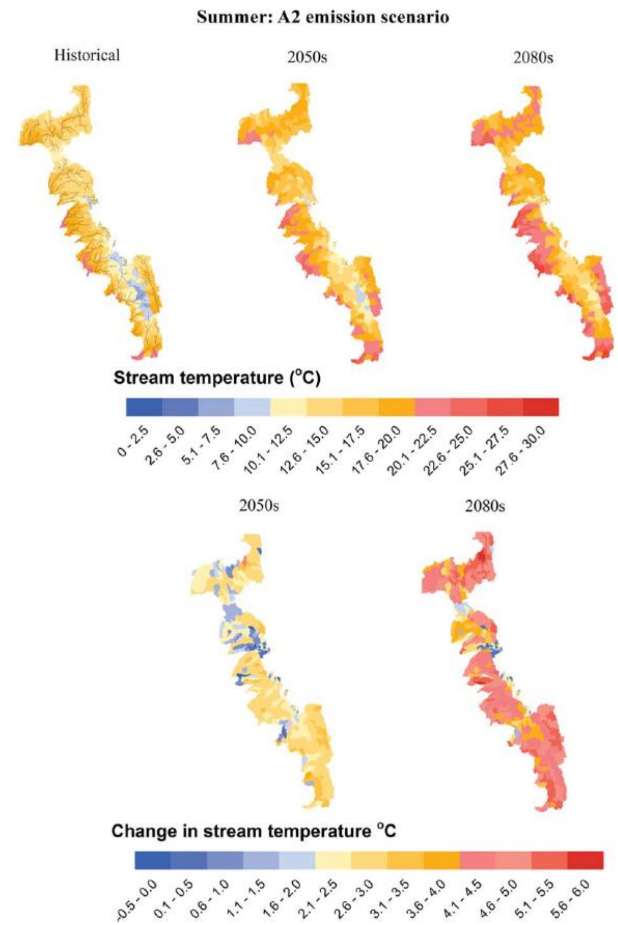


Figure 4. Stream temperature simulation results for the summer season GCM median ensemble A2 emission scenario. Historical period represents 1950–2005, 2050s represent 2040–2069, and 2080s represent 2070–2099.

Ficklin, Stewart, Maurer (2013)

Increases in winter streamflow as more precipitation arrives as rain and due to earlier melt

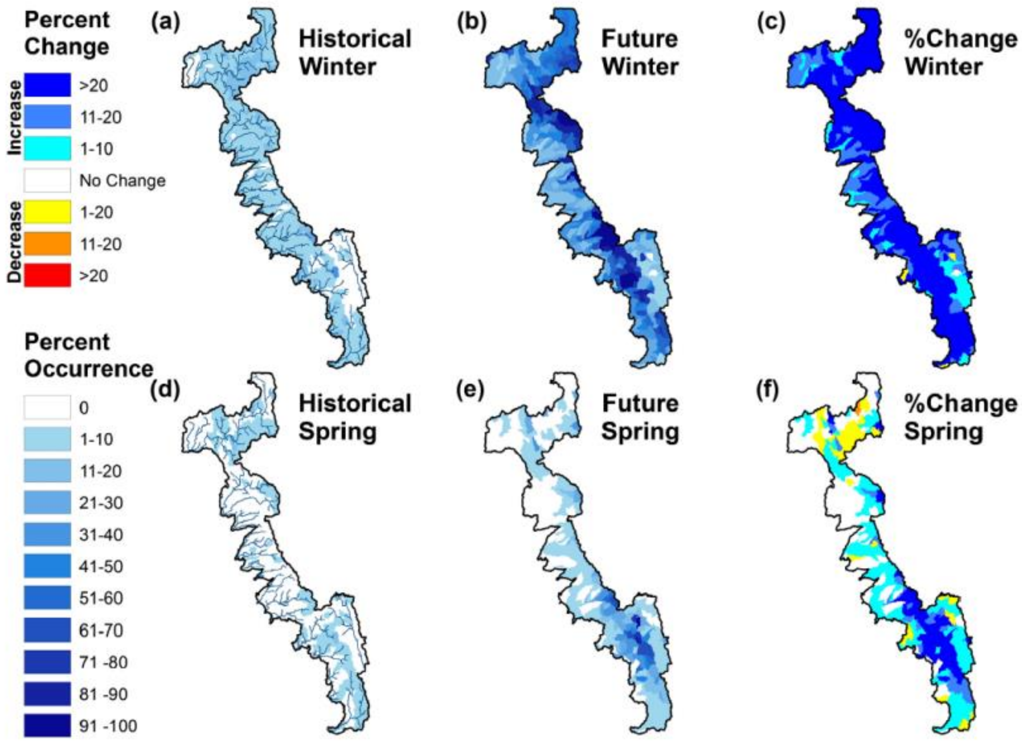


Fig. 2. The percent occurrence of monthly flows exceeding historical average monthly values by 150% or more for the Sierra Nevada mountainous region. The upper/lower row is for the winter (December–February)/spring (March–May) season, respectively. Shown are the frequency of occurrence for the historic (1961–1990) period (a,d), future (2070–2099) period (b,e), and the percent change (c,f).

Colorado River Watershed is the largest source of water in the arid southwest

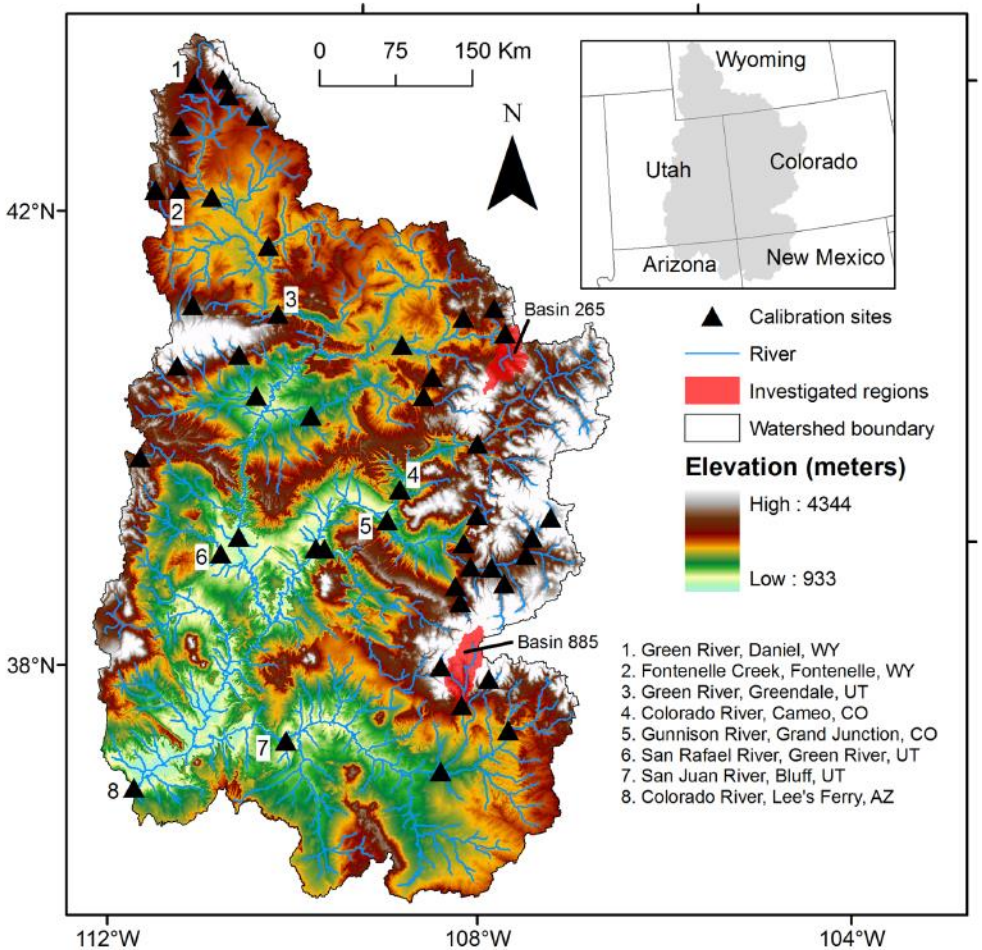


Figure 1. Upper Colorado River Basin study area showing calibration sites, investigated regions, and examined outlets.
doi:10.1371/journal.pone.0071297.g001

- Water generating part in the upper altitudes

Water in the Colorado River is overcommitted, even in a good year

Years used to calculate how much water can be allocated

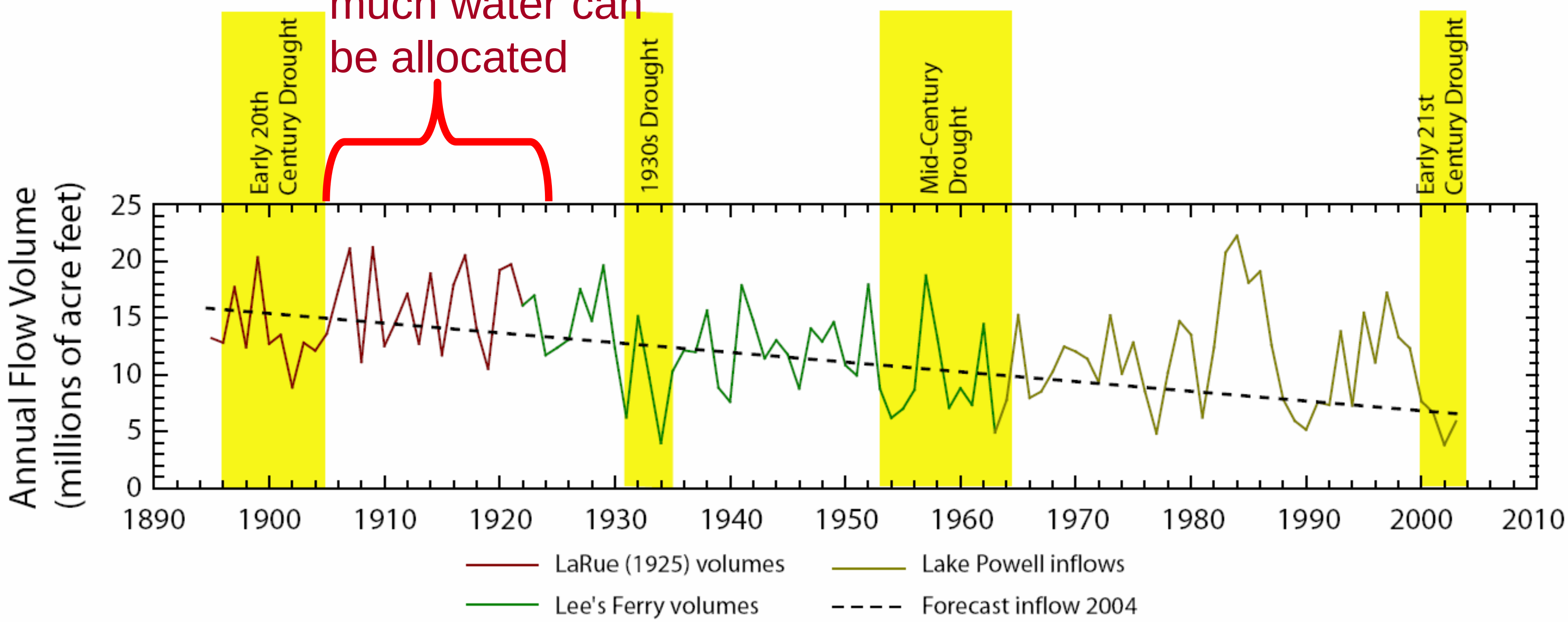
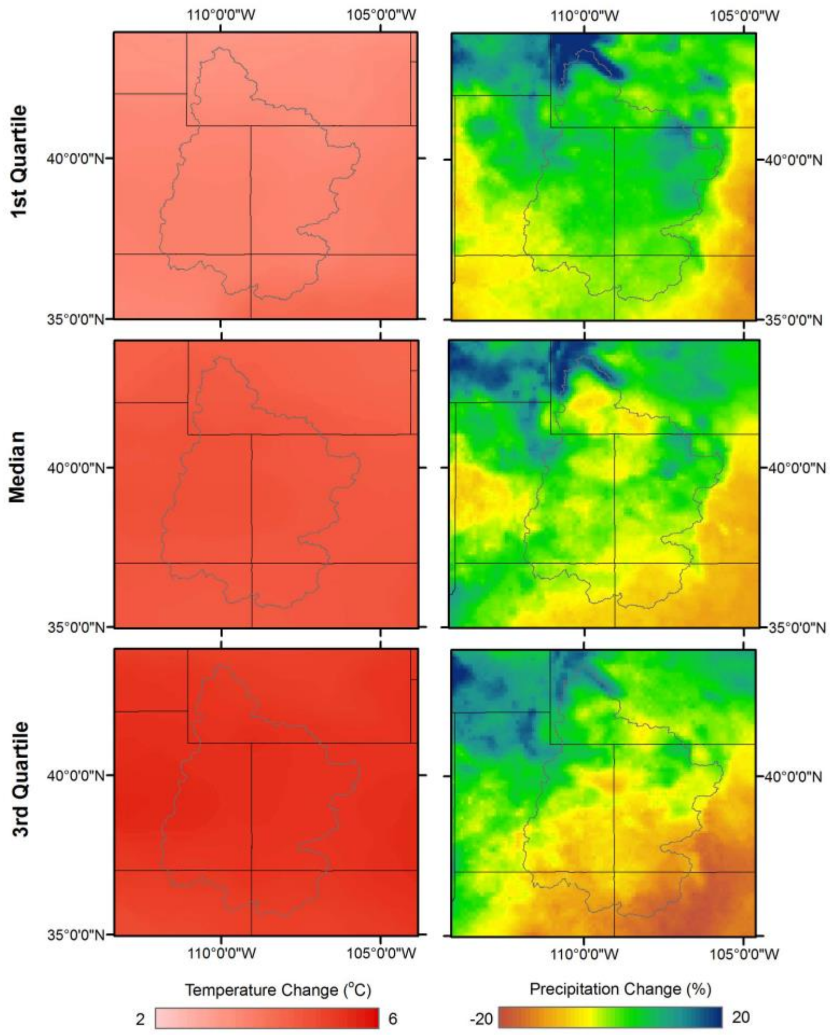
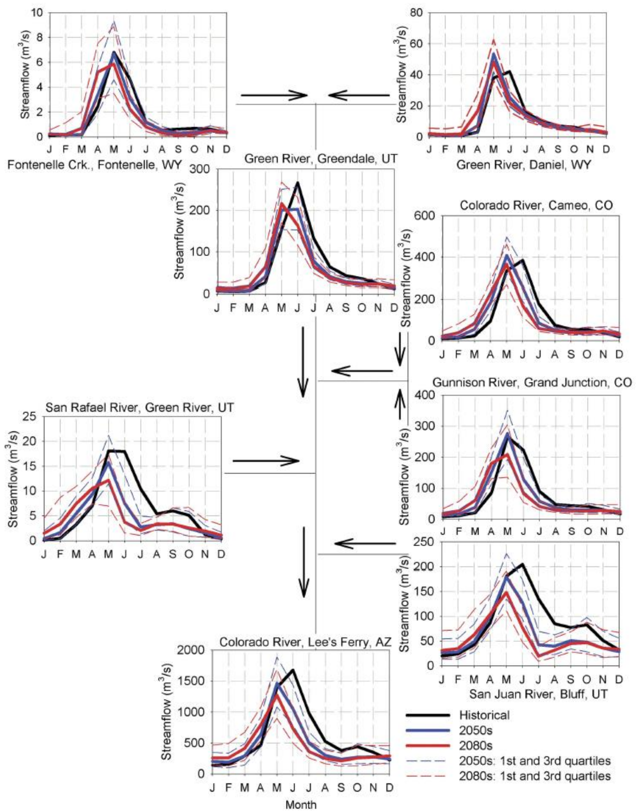


Figure 3. Time-series plot of the annual flow volume (in millions of acre-feet) for the Colorado River at Lee's Ferry. Dashed line is the linear trend for the period. Vertical bars and shading delineate drought periods as defined using the Palmer Drought Severity Index for the climate divisions encompassing the upper Colorado River basin.

Source: USGS Fact Sheet No. 202004-3062

Model results show similar trends as in Sierras
Warmer temperatures and increases in ET dominate over some precipitation increases in water generating high elevation areas





Reductions in snowmelt (% of historical, especially at lower elevations by end of century

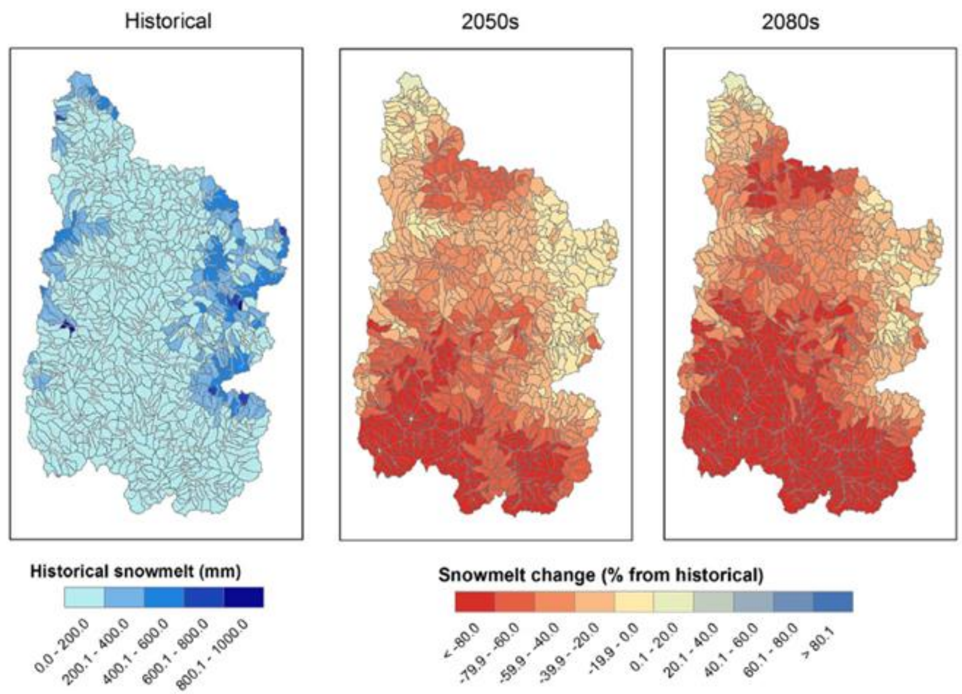


Figure 7. Subbasin snowmelt changes for the 2050 s and 2080 s for the Upper Colorado River Basin under the A2 emission scenario.
doi:10.1371/journal.pone.0071297.g007

Changes in the aridity index

- Shrinkage in the size of the water generating region
- Increases in the size of the arid and semi-arid region

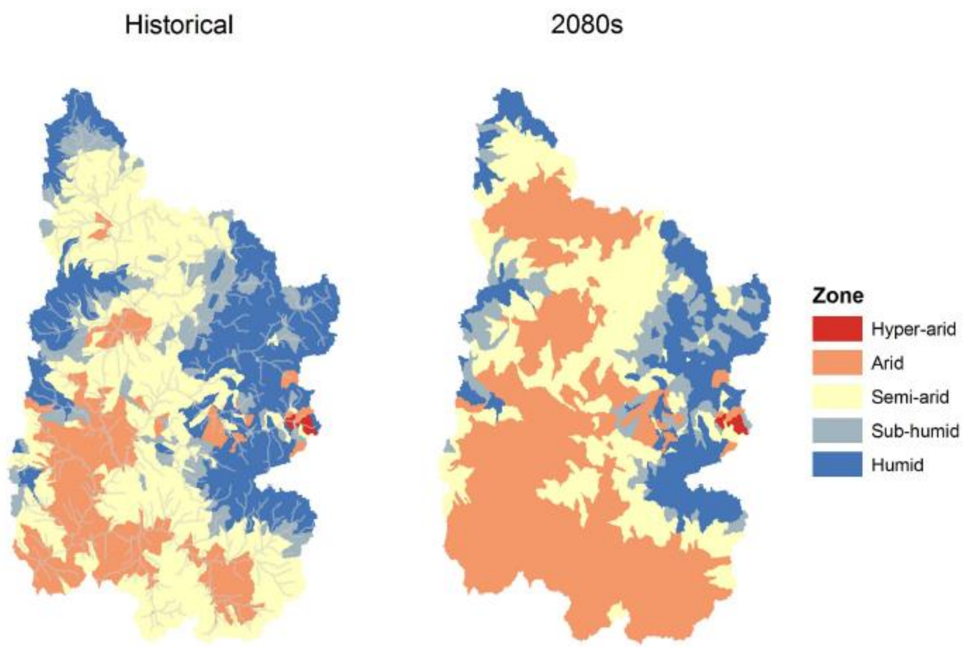


Figure 11. Changes in aridity indices for the 2050 s and 2080 s under the A2 emission scenario for the 2050 s and 2080 s in the Upper Colorado River Basin under the A2 emission scenario.
doi:10.1371/journal.pone.0071297.g011

Increases in the frequency of extremes

Winter flow > 150 % of historical average

Summer flow < 50% of historical ave

Summer stream temp > 3 °C historical ave

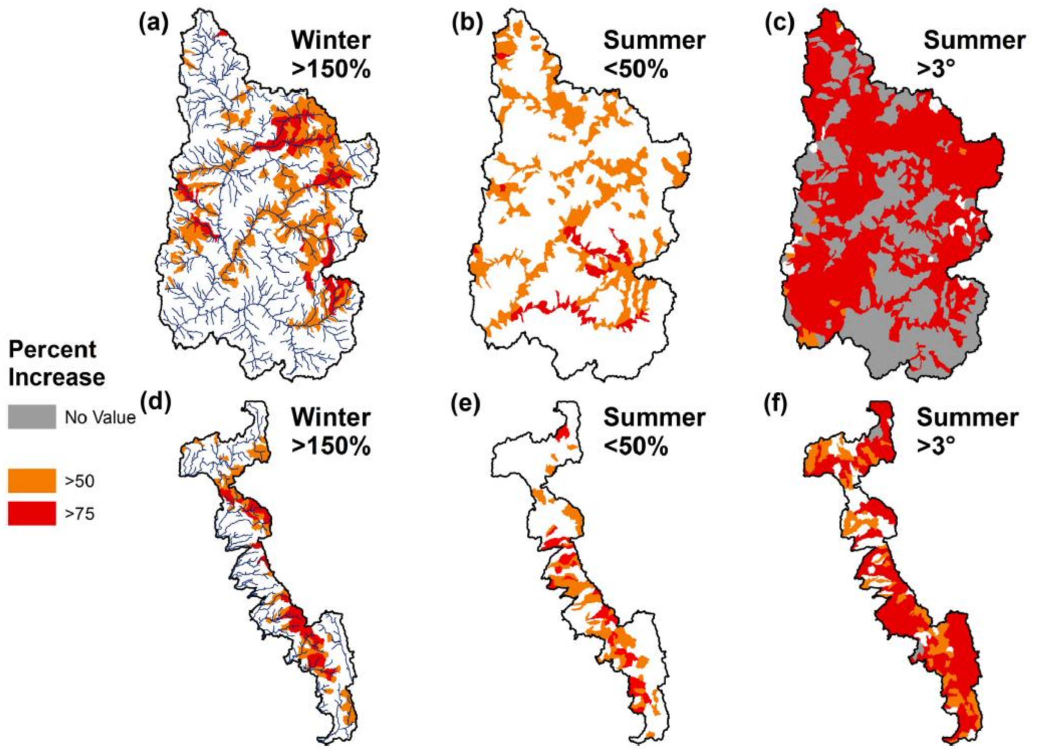


Fig. 8. Areas with the greatest increases in the percent occurrence of extreme conditions in the Upper Colorado River Basin (above) and the Sierra Nevada (below).

Colorado River Basin

Sierra Nevada

Impacts for water supplies and environmental flows

Stewart, Ficklin, Carrillo, Russell (2015)