



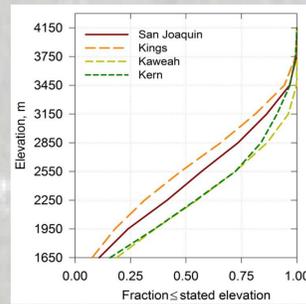
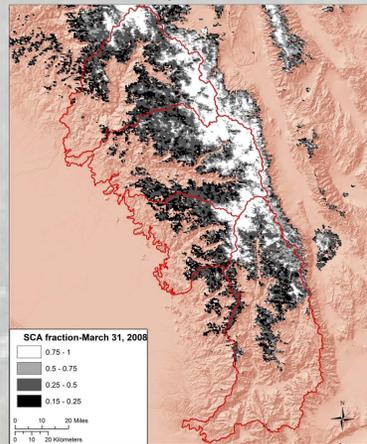
An assessment of snowcover in 4 major river basins of the southern Sierra Nevada and potential approaches for long-term monitoring

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Introduction

Snowpack is a critical resource that provides seasonal storage of water for soil moisture, lakes and streams. It is particularly important given the seasonal cycle of precipitation and long summer-fall dry period in the southern Sierra Nevada. Soil moisture is also a critical resource, which also provides seasonal storage for sustaining lakes, streams and vegetation year round. Daily snow water equivalent (SWE) was reconstructed for 2000-2009 using canopy-corrected fractional snow covered area (fSCA) from MODIS and a temperature-index snowmelt calculation. The MODIS fractional SCA was based on the MODSCAG (MODIS Snow Covered Area and Grain size/albedo) model, and provides a daily estimate of SCA across complex terrain. The few ground-based index sites for snow measurement can in many years provide good statistical estimates of total seasonal runoff in the basin; but they do not form the basis for spatial estimates of snowpack and snowmelt distributed over the year. The latter are essential for a number of critical resource-management decisions, and are critical inputs to more physically based hydrologic forecasts. Our analysis provided estimates of when the snow-covered area was at a maximum, when the snow started melting, how fast it melted and when melt was nearly complete.

Study Area

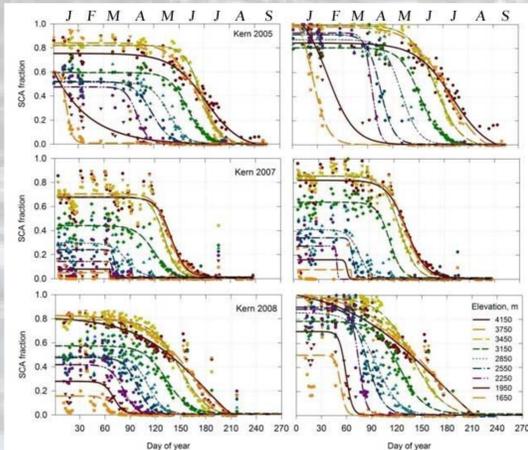


Elevation ranges in the 4 river basins, and have similar elevation distributions in their snow producing elevations, with mean elevations in the 2400 m range.

We analyzed the area that was snow covered, by 300-m elevation bands, in the San Joaquin, Kings, Kaweah, and Kern River basins. These basins range in size from 2846 to 6142 km², with snow occurring mainly above 1500 m. For ease of viewing, fSCA values are lumped in to 4 bins. Areas with no black/white shading have no detectable fSCA. Note: the MODSCAG SCA detection threshold is 0.15.

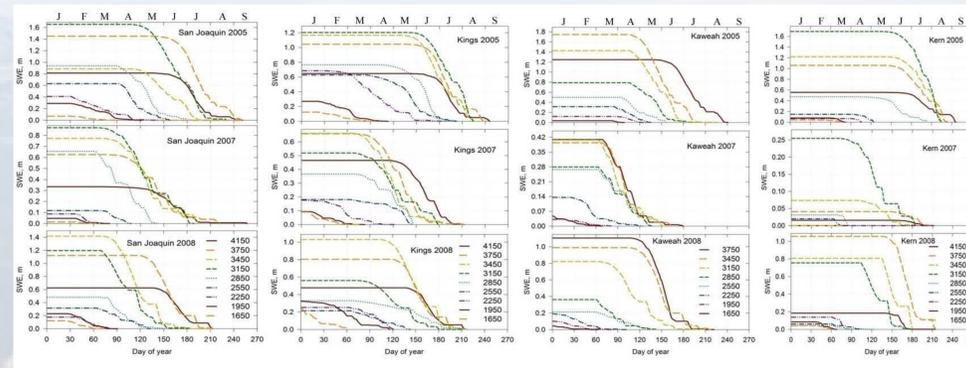
Results

Corrected MODIS fractional snow covered area



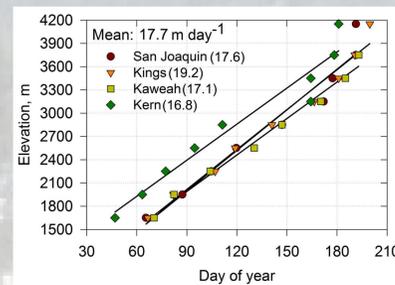
Empirical fSCA corrections of up to 40% were made in dense forests of the western Sierra Nevada to account for the satellite only detecting snow in viewable gaps in the canopy. The fractional snow-covered area (SCA) derived from satellite data was highest above 3600 m, often over 90%. SCA decreased with elevation, with values in the 1800-2100 m elevation peaking well below 50%. In some years SCA at this elevation was barely detectable.

Snowmelt estimates from snow depletion method

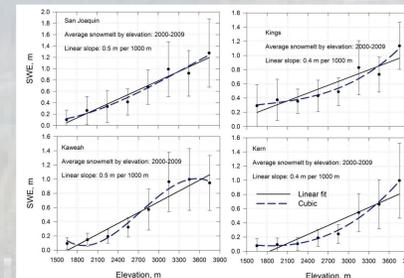


Snowmelt (expressed as SWE) by elevation band based on snow-depletion calculations using degree-day and MODIS SCA for the San Joaquin, Kings, Kaweah, and Kern River basins for 2005, 2007, and 2008. Daily snowmelt is summed back in time beginning with the day that SCA reaches zero.

Trends in snow covered area and snow water equivalent

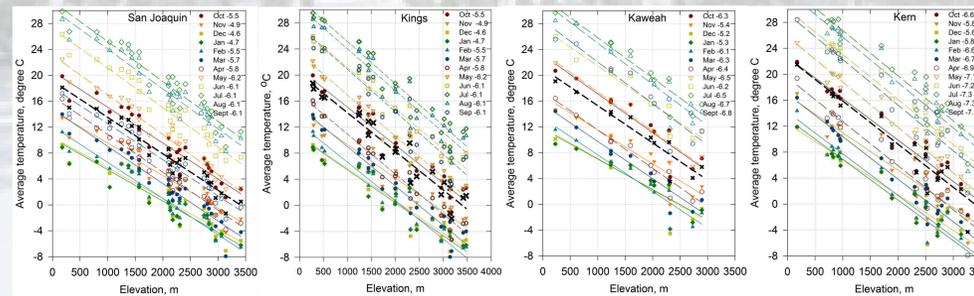


Evaluation of the historical MODIS SCA shows that the average snowmelt progression over the period 2000-2009 for the 4 basins is on average 17.7 m day⁻¹. Note that each successively higher 300-m elevation band melts out about 20 days later than the elevation band below it.

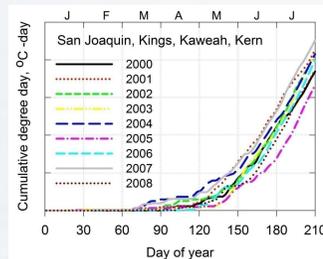


Elevation gradients of the back-calculated seasonal snowmelt showing ten-year means, standard deviations and best fit to means. Seasonal snowmelt increases a similar amount with elevation in all basins, despite the approximately 20% more snowmelt in the San Joaquin and Kings versus the Kaweah and Kern. The drop-off at the highest elevation in Kaweah is due in part to the very small fraction of the basin in that elevation band and thus limited range of physiographic variability in that fraction.

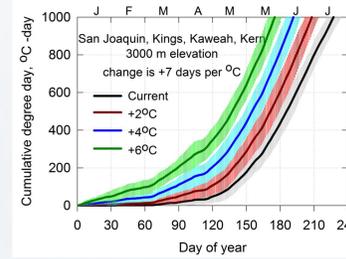
Monthly and average annual lapse rate



Monthly and annual average ground-level lapse rates for the ten-year period 2000-2009. Monthly values ranged from -4.6 to -7.3 °C per 1000 m. For the main snowmelt season, April through June, the average ranges from -5.9 to -6.3 °C per 1000 m, corresponding to approximately a 1.7 to 2.2 °C change in average temperature for each 300-m elevation change in the San Joaquin, Kings, Kaweah, and Kern.

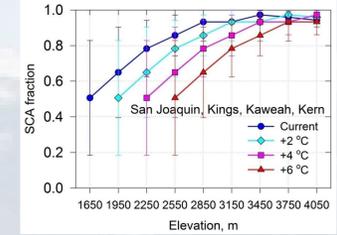


Using variability in current temperatures for individual years for one elevation (3000 m), expressed as cumulative degree days, shows that in a warmer year (2001), a given value of cumulative degree-day is reached about 20 days before the same level is reached in a colder year (2005).



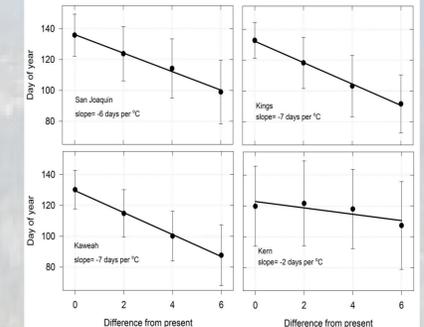
This same 20 day or 2-3 week advance in snowmelt per 2 °C of warming noted above also shows up in examining the projected cumulative degree days for the 3000-m elevation.

Winter SCA by elevation, current and projected with increased temperature.



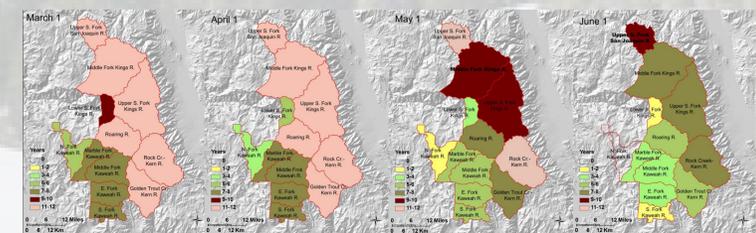
Temperature increases will shift the amount of snow covered-area as less precipitation falls as snow. To a first approximation, this can be viewed as a shift of 300 m in current SCA patterns as being equivalent to 2 °C. Currently across all six basins there is an elevational dependence of winter SCA with each successive lower 300 m elevation band having greater inter-seasonal variability (e.g. error bars). That is, higher elevations, which are consistently below freezing much of the winter, have more consistent snowcover than do lower elevations.

Snowmelt timing based on the depletion method



The day of snowmelt is projected based on depletion methods for current conditions, and achieved by imposing a temperature change of 2, 4 and 6 °C and by shifting the corrected SCA fractions up by 300 m per 2 °C change in temperature. This is consistent with the current observations that each 300 m corresponds to a 2 °C shift in temperature. The timing of snowmelt shifts toward earlier in the spring at a rate of -6 to -7 days per °C in the San Joaquin, Kings, and Kaweah.

Average snowcover persistence



Areas with persistent snowcover on May 1 or June 1 for 11-12 years are the areas with least potential for change, and areas with the most accumulation and/or slowest melt rates. Areas with persistent snowcover for 6 or fewer years on May or June 1 would be more vulnerable to change. Areas with snowcover for 6 or fewer years on April 1 are the most vulnerable to change.

Conclusion

Management of water dependent resources should consider an adaptive-management approach, involving a continual cycle of investigation and synthesis to inform decision-making. Developing more-definite scenarios for temperature, precipitation, snowpack, snowmelt and streamflow that are specific to the relatively small sub-basins and complex topography should consider the following elements: (1) an expanded and enhanced measurement program of mountain temperature, precipitation, snowpack, soil moisture and selected other energy-balance components to augment the current system; (2) improved characterization of forest vegetation from satellite and aircraft data in support of hydrologic data analysis and modeling; and (3) an ongoing program of assessment of hydrologic conditions, trends, forecasts, and outlooks, with particular emphasis on extreme events and years; integrating this program with decision support.

Acknowledgements

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