Sierra Nevada snowpack, climate change & water management

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Topics in this talk

1. Sierra Nevada water cycle & climate change
2. Measuring the mountain water cycle
3. Snow covered area, snowpack water storage, snowmelt
Motivating questions

How will this landscape & the hydrologic processes connecting it alter w/ climate warming & land-use/landcover change?
Mountain hydrology – fluxes

My biases:
Improved predictions require better process understanding
The basis for process understanding is new measurements
Processes are coupled & best studied together

Reservoirs:
Snowpack storage
Soil-water storage
Relevant climate basics

The effects of temperature changes on the mountain/forest water cycle – snow vs. rain, soil moisture, evapotranspiration – go beyond historical levels

The water cycle in California’s mountains is undergoing long-term shifts

Land surface temperatures
5-yr average, departure from 1901-2000 mean
Observed changes in water cycle go beyond historical levels.

TRENDS (1950-97) in April 1 snow-water content at western snow courses.

Related effects:
- Earlier greenup, Cayan 2001
- Greater fire severity in warm/dry years, Westerling 2006
- Increasing forest mortality, van Mangten 2009
- Reduced summer streamflows, Stewart 2006
Influence of +3°C on SNOW vs RAIN

Derived from UW’s VIC model daily inputs, 1950-1999

Bales et al., 2006

More rain, less snow

Earlier snowmelt

More winter floods
Likely loss of 20-30% of snowpack storage with a 3°C temperature increase.

MAF: million acre feet

Data from DWR
The Department of the Interior, with its 67,000 employees and scientific and resource management expertise, is responsible for helping protect the nation from the impacts of climate change. In particular the Department must:

- Adapt its water management strategies to address the possibility of shrinking water supplies and more frequent and extended droughts to continue to supply drinking water to more than 31 million people and irrigation water to 140,000 farmers

Need to do things differently recognized at federal & state levels, & by many a the local/regional levels
Economic & societal forces define & constrain options for water management in the Sierra Nevada

– How do forest management actions influence water yield & runoff timing?

– What information is needed to effectively manage water resources & the ecosystems that influence water?

– Who benefits & who pays for ecosystem services?
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Hydrologic observations

Many of the existing systems are technologically obsolete, are designed to achieve specific, often non-compatible management accounting goals, and/or their operational and maintenance structures allow for significant data collection gaps. As a result, many of the data are fragmented, poorly integrated, and in many cases unable to meet the predictive challenges of a rapidly changing climate.

USCCSP, 2008
Current operational snow measurements

From a regional view, operational snow measurements look like a dense network

Main basis for seasonal water supply estimates
American River basin

2 snow pillows in N. fork, 1 in Middle Fork, 8 in S. Fork

Non-representative network

Stations are on flat ground, in clearings, at mid elevations
Seasonal forecasts of water supply are within +20% half of the time. Improved measurements will help most in years that depart from the long-term mean.

Uncertainties in forecasts have huge implications for the regional economy, hundreds of millions of dollars annually.
Enhancing seasonal water-supply forecasting

Empirical & regression methods

Precipitation forecast

Ground data

Volume forecasts

Decision making
Enhancing seasonal water-supply forecasting

- Streamflow forecasts
- Landcover information
- Enhanced ground data
- Integration & modeling
- Broader decision making
- Enhanced ground data
- Streamflow forecasts
- Broader decision making

- Digital elevation model
- Satellite snowcover
- Precipitation forecast
- Snowpack, soil moisture, ET estimates
Developing infrastructure for hydrologic research & applications

Enhanced, blended satellite & ground-based measurements
Basin-wide deployment of hydrologic instrument clusters – American R. basin

Strategically place low-cost sensors to get spatial estimates of snowcover, soil moisture & other water-balance components.

Network & integrate these sensors into a single spatial instrument for water-balance measurements.
Sierra Nevada Hydrologic Observatory – instrumented catchments across the rain-snow transition, along climate gradients. Research on:

- process understanding of water, nutrient & weathering cycles
- impacts of climate change
- hydrologic effects of forest management
Meteorological stations

In cooperation w/ CA-DWR

Data available on CDEC
Snow depth sensors
Wireless motes

Soil moisture
Stream stage & discharge
Meadow piezometers & wells
Stream instrumentation
Embedded sensor network technology – Providence Creek (CZO) prototype

Strategically placed sensors
Interpolated snow depth, 7 Apr 2010

- Uses network observations
- Variables: solar radiation, slope, aspect, elevation
- Gaussian process regression
- 30-m DEM

**Grid distance north, m**

**Grid distance east, m**

Avg network depth = 101 cm  
Avg predicted depth = 106 cm

Meadows et al., 2010
Estimation error of interpolated snow depth, 7 Apr 2010

Uses network observations
Variables: solar radiation, slope, aspect, elevation
Gaussian process regression
30-m DEM

Avg network depth = 101 cm
Avg survey depth = 103 cm
Avg predicted depth = 106 cm
Mean error = 35 cm
More on the CZO water balance at Wed seminar

Strategic sampling results are encouraging
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Satellite data provide a spatially continuous time series of Sierra Nevada snowpack – but how accurate is an issue.
Sierra Nevada fractional snow covered area (SCA) from MODIS MODSCAG algorithm – Painter et al., 2008

SCA is binned into 4 classes for ease of viewing
Pixel size: 500 m
Data available for 2000-present

Despite differences in elevation, latitude & accumulation, there is a remarkable consistency to rate & extent of snowmelt with elevation & latitude – Eastern Sierra Nevada example

SCA for March 10, 2008
Consistent rate of SCA depletion with elevation, during snowmelt

Each 300-m elevation band melts out about 3 weeks later than the next lower band.

Inter-annual differences are about 6 weeks.

Bales, in preparation
Rate of SCA depletion with elevation during snowmelt – varies with latitude

Data based on 20 Eastern Sierra Nevada basins, years 2000-08

Bales, in preparation
Maximum winter SCA also increases with elevation & latitude.

- Based on 20 Eastern Sierra Nevada basins, 2000-08

Precipitation increases about 30% per degree latitude.

At a given latitude, SCA increases about 0.15 per 300 m elevation.

Bales, in preparation
Satellite views snow in canopy gaps
To get total SCA need to correct for canopy
Canopy correction varies during snowmelt
Snow surveys give ground truth to correct MODIS for underestimate of SCA.
Gin Flat, Feb 2006

Survey: >90% SCA
MODIS: 29% SCA
LANDSAT: 32% SCA

Canopy closure
SCA canopy corrections by 300-m elevation band – Bishop Creek basin, Eastern Sierra Nevada

MODIS fractional SCA products require bias corrections of 0.1-0.5 for Sierra Nevada, depending on time of year & forest cover
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Two approaches to estimate snow water equivalent (SWE) across a basin

1. Back calculated
2. Interpolated

Energy balance

Met station time series

Landscape data

Snow vs. rain

Precipitation

Local SWE

Potential SWE
Fraction of annual snowmelt from various elevations

Snowmelt estimate based on interpolation of SWE from existing, ground stations (snow pillows) underestimates snowmelt at highest elevations

Rice et al., in review
Reconstructed snowmelt by elevation band for wet, average & dry years

NE-SW transect across Sierra Nevada

Note: precipitation timing not included

Bales, in preparation
Comparison with snow-pillow measurements

Elevation adjusted value from reconstructed snowmelt compared to snow-pillow SWE for peak accumulation.

It is well established that sparse snow-pillow measurements do not accurately represent the amount of snow in a basin.
Comparison with station precipitation measurements

Seasonal total values from reconstructed snowmelt compared to precipitation gauges at meteorological stations

Gauges are also not representative of spatial precipitation
Comparison with PRISM data along a NE-SW transect

PRISM 4-km data overestimate precipitation in snow zone & fail to capture inter-annual variability.
Projected impact of climate warming on snow, Eastern Sierra Nevada – based on data analysis

Bishop Creek
slope = -0.040 m per °C

Bishop Creek
slope = -0.019 m per °C

Bishop Creek
slope = -12 days per °C

Bales, in preparation
Water in a changing climate is at the center of management issues affecting ecosystem services.

Reduced snowpack, earlier snowmelt & altered hydrology associated with warmer temperatures & altered precipitation patterns will complicate Western U.S. water management & affect other ecosystem services.

Possible responses:
- More information-intensive decision support
- Collaborative & integration in planning, management

California is trying to do some of both.
Research summary

Measurement programs & high-quality data for process understanding, water balance, improved predictions & decision support in the Sierra Nevada & other mountains – blending ground-based & remotely sensed data

Southern Sierra Critical Zone Observatory & other instrumented catchments are platforms for collaborative, multi-disciplinary research: ecohydrology, snow hydrology, (bio)geochemistry …
Mountain Hydrology Research Group: Bob Rice, Xiande Meng, Sarah Martin, Peter Kirchner, Ryan Lucas, Phil Saksa, Matt Meadows, Patrick Womble, Reza Ghanbari, Allyson Smith

Collaborators: Jeff Dozier (UCSB) & Tom Painter (JPL), Martha Conklin (UCM)

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Remote analysis supported by NASA & LADWP

Ostrander, YNP