Sierra Nevada snowcover patterns & watershed processes

from blended satellite & ground-based networks

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Topics covered in this talk

- Snow distribution
- Snowmelt generation & sources
- Stream & soil moisture response to ET
- Measurement design in mountain basins
Influence of \(+3^\circ C\) on SNOW vs RAIN

About 1/3 of current snow will be rain
Also earlier snowmelt – shorter snow season
And large snowstorms will become rainstorms, bringing more flooding

Currently about 2/3 of Sierra Nevada precipitation is snow

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

Bales et al., 2006
Likely loss of 3-5 million acre feet of snowpack storage in coming decades

Note: 3-5 million acre feet = 4-6 billion m$^3$
Estimating snow covered area (SCA) from satellite
Snow covered area (SCA) from MODIS satellite, 2004

DOY 131 – May 10

Tuolumne

Merced

% SCA
76-100
51-75
26-50
1-25
Filtering & smoothing of MODIS daily snowcover & grain size

Objective: produce time series that is spatially & temporally complete & consistent

Contributors to noisy values
- Data dropouts & sensor noise
- Cloud cover
- Sensor viewing angle (nadir to 65°)
  - Smearing pixels in cross-track direction
  - Off-angle views see less snow under trees
- Topographic variability within pixel
Need to interpolate & smooth to fill the space-time cube
Melt season SCA:

2004: snow 83% of average – ground became snow free relatively early

Each higher elevation band requires ~1 mo longer to become snow free

2005: snow 163% of average – ground became snow free ~1 mo later than in 2004
One source of error is vegetation

Note gap between accumulation season SCA & canopy fraction below ~2400 m elevation
Blending satellite & ground-based data to estimate snow water equivalent (SWE)
Snow measurements

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

Main basis for seasonal water supply estimates.

Errors in estimate of water balance components often exceed 20-30%.

Even 10% error is expensive.
Snow water equivalent (SWE) estimated from interpolation of ground-based measurements.

Measurements are sparse, but these are the only measurements of snow depth & snow water equivalent available.
Interpolated SWE from sparse ground-based data: little difference across elevations at beginning of snowmelt.

Sensors are clustered at mid elevations.

Blending SCA with interpolated SWE: shows distinct gradient with elevation, except at highest elevations.
Merced basin SWE depletion, 2004

Based on interpolated SWE

volume, $10^7$ m$^3$

3/1/04 4/1/04 5/1/04 6/1/04 7/1/04
Big problem: operational, ground-based snow measurements are not representative

- Snow pillow & snow course measurements provide limited information on spatial distribution patterns
- Sites are not representative of the terrain & thus fail to represent basin-wide snow depth or water equivalent
Alternate estimate of SWE & snowmelt: from SCA time series & snowmelt analysis

Determine “potential snowmelt” per elevation band based on temperature index (or energy balance) calculation.

Potential snowmelt quantity applied to all areas with snowcover, using fractional SCA per pixel.

That is, if an area has snowcover it is assumed to contribute melt at a rate equal to the potential snowmelt times SCA.

Amount of snowmelt calculated up to day when SCA is depleted equals beginning SWE.
Degree day factor estimated from snow pillow sites

No systematic variation of degree day factor with elevation

Strong seasonal change in degree day factor
2004 snowmelt based on degree day calculation

$melt \ flux = T_d \times a_r$
SWE based on SCA plus degree day snowmelt

Cumulative melt based on interpolated SWE
More rapid depletion
Interpolation over-estimates below 3,000 m & under-estimates above 3,000 m
SWE based on SCA plus degree day snowmelt

Interpolated SWE also shows rapid depletion at mid elevations
Less total melt for interpolated method because snow pillow sites melted out early
Findings: elevational contributions

36% of Tuolumne (34% Merced) snowmelt from > 3000 m.
   – Highest snow pillow is 2918 m
   – Main source of summer snowmelt

13% of Tuolumne (5% Merced) snowmelt from < 2100 m.
   – Lowest snow pillow is 2100 m.
   – Important mainly in March & April

50% of Tuolumne (60% Merced) snowmelt from 2100-3000 m.
   – All snow pillows melt out 1.5-2 mo faster
End-of-season SWE estimates are fine for process-level research, but fail to provide critical, real-time estimates for operational hydrology
Next step: design a better ground-based network
More than snow: also where the snowmelt goes
Gin Flat embedded sensor network, Yosemite NP
Gin Flat snow survey

February & April 2006

Grid of 144 points, 4 depth measurements at each point

4 km² - 64 points, 250-m interval

1 km² - 80 points, 25-m interval
Optimal locations for capturing spatial mean

error $\leq$ 10% of spatial mean
Whole-basin prototype planned
Whole-basin prototype planned
Understanding hydrologic processes in seasonally snow-covered mountain basins: our assumptions

Basis for process understanding is new measurements
Processes are coupled & best studied together
Spatial measurement design is a research area
Scaling processes requires multi-scale measurements
Following snowmelt will yield process insight
Prototype instrument cluster: Wolverton, Sequoia National Park
10 km² Wolverton basin

- Stream gage
- Water balance instrumentation
- Met station
- Meadow transects
Stream stage & discharge

Stream pressure transducers installed in summer 2006

Adjacent, higher elevation basins already monitored: Emerald Lake & Tokapah catchments
Wolverton meteorological stations

Two stations installed in fall 2006, at Wolverton & Panther Meadow
Soil moisture & temperature

Four locations (N/S, elev)
Three pits per location (canopy)
Four depths per pit
Snow depth sensors

Four locations (same as soil)
10 per locations
One over each soil pit
Meadow piezometers & wells

Three lateral transects
One longitudinal transect
Continuous logging
Soil volumetric water content response to snowmelt: Wolverton basin

Snow depth from acoustic sensors over each pit
Snow density from Panther Meadow snow course
Wolverton Creek, Sequoia NP: stream stage

Base-flow period, 2150 m elevation

August 14 - September 7, 2007
As we add measurements and integrate them, causal relationships become increasingly clear.
Wolverton Creek, Sequoia NP: stage, precip & air temperature

Base-flow period, 2150 m elevation

3 to 6 hour lag between daily low flow and Tmax or daily high flow and Tmin.
Peak sapflow occurs at solar noon about 1 hr before Tmax.
Southern Sierra Critical Zone Observatory (CZO): a community resource

Underlying hypothesis: The distribution of soil moisture throughout the catchments controls (bio)geochemical processes, including weathering & the extent of coupling among the carbon & nitrogen cycles.
Mixed conifer forest dominates the CZO, which crosses the rain-snow transition (1,500-2,000 m)
Current ability to quantitatively estimate water fluxes & reservoirs in mountains is woefully inadequate (also ecological & biogeochemical linkages)

Economic value of & societal demand for new knowledge & tools for mountain hydrology is very large

Advances will require sustained investments in new measurements & infrastructure, including data & information systems (for research)

Measurement strategies will rely heavily on remote sensing plus complimentary, distributed ground-based networks
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