Mountain hydrology, forest management & water security in the Sierra Nevada

How well can we estimate the mountain water cycle?

Roger Bales, Sierra Nevada Research Institute, UC Merced
Topics in this talk:

1. Southern Sierra Nevada CZO
2. The mountain water cycle – recent results
3. Water security & managing ecosystems
Motivating questions

How will this landscape & the hydrologic processes connecting it alter w/ climate warming & landcover change?

How do regolith development & properties control, limit or modulate effects of climate change, management or disturbance on hydrology, biogeochemistry & ecology?
Mountain hydrology – fluxes

- infiltration
- evapotranspiration
- precipitation
- snowmelt
- sublimation
- runoff
- ground & surface water exchange

How well can we estimate any of these fluxes & stores?

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

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Reservoirs:
- Snowpack storage
- Soil-water storage
SSCZO site location, gradients & infrastructure

4 instrumented sites along steep climate gradient: 12°C, 60 km

Co-located w/ USFS watershed research site: 8 headwater catchments ~ 100 ha each

Lower SSCZO site proposed for NEON core

Winter access to upper sites over snow

Encourage collaboration
SSCZO conceptual model

Feedbacks across time scales: regolith-atmosphere coupling along elevation transect

Glacial
- Subalpine forest 2700 m
- Mixed conifer forest 2000 m
- Pine/oak forest 1100 m
- Oak savannah 400 m

Daily

Hillslope to catchment

Feedbacks across spatial scales

Pore to plot

Basin to regional

3000 m elevation gradient
Oak savannah
$T_{ave} = 14.4^\circ C$
$P = 500 \text{ mm}$
$0 \text{ d snow}$
$H_{tree} = 11 \text{ m}$
$25\% \text{ tree cover}$

Pine/oak forest
$T_{ave} = 10.9^\circ C$
$P = 850 \text{ mm}$
$11 \text{ d snow}$
$H_{tree} = 29 \text{ m}$
$63\% \text{ tree cover}$

Mixed conifer forest
$T_{ave} = 8.9^\circ C$
$P = 1000 \text{ mm}$
$130 \text{ d snow}$
$H_{tree} > 30 \text{ m}$
$53\% \text{ tree cover}$

Subalpine forest
$T_{ave} = 4.1^\circ C$
$P = 1100 \text{ mm}$
$184 \text{ d snow}$
$H_{tree} = 22 \text{ m}$
$31\% \text{ tree cover}$
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Basic water balance

**Precipitation** = Evapotranspiration + Runoff

Evapotranspiration refers to evaporation plus water use by vegetation
Sierra Nevada precipitation & snow water equivalent (SWE) – climatological estimate

Bales et al., 2006
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 – index sites
Stations are on flat ground, in clearings, at mid elevations

Despite these limitations, snow pillows are widely used by modeling community as ground truth
What elevations provide the most snowmelt?

Values estimated from time series of satellite snowcover depletion & daily snowmelt.

Most snowmelt comes from elevations above most measurement of precipitation or snowpack.

Rice & Bales, 2013
LiDAR-derived snow depth, Kaweah R. basin

Kirchner et al., in prep.

B

Elevation, m

WY 2010

Kirchner et al., in prep.
Comparison of SWE measured by LiDAR w/ indirect estimates of SWE & precipitation, Kaweah R. basin

WY 2010

Future: data from distributed, wireless sensor networks, blended w/ remote sensing data

Calibrated T-index
Energy balance

Kirchner et al., in prep.
Basic water balance

Precipitation = **Evapotranspiration** + Runoff

Evapotranspiration refers to evaporation plus water use by vegetation
Evapotranspiration (ET) across an elevation transect

Mid-elevation forests show neither summer nor winter shutdown:
- deep rooting & resiliency to moisture stress
- warmer canopy-level temperatures despite snow

Goulden et al., 2012
Based on distributed, wireless sensor networks

About 1/3 of ET comes from deeper storage, below 1-m depth

Bales et al., 2011
Weathered material extends down at least 10 m – subsurface storage in saprolite & saprock

This deeper storage provides buffering against moisture stress & accounts for the year-round ET
Cumulative evapotranspiration

- **Subalpine forest (8900')**
- **Midmontane forest (6600')**
- **Oak/Pine woodland (1300')**

- Midmontane forest – year round ET results in high annual ET
- Subalpine forest – minimal ET in winter reduces annual ET
Basic water balance

Precipitation = Evapotranspiration + Runoff

Evapotranspiration refers to evaporation plus water use by vegetation.
KREW: 8 instrumented headwater catchments

- Providence Creek
- McKinley Grove
- Dinkey Creek
- Bull Creek

Catchment boundaries:
- P301: 99 ha
- P303: 132 ha
- P304: 49 ha
- D102: 121 ha
- B201: 53 ha
- B203: 138 ha
- B204: 167 ha
- T003: 228 ha

Mean elevation range: 1800 m to 2400 m

Rain + snow → snow

Stream gauge
Met station
Paved road
Secondary road
Private Land

Vicinity:
- Sierra National Forest
- Fresno
- KREW

M. Stuefky 2009-10-21
Water-year 2007 precipitation & discharge

Catchment characteristics
600-m average elevation difference across catchments
Total precipitation (rain + snow) same across this gradient
Mixed conifer → red fir

Features of hydrographs
Rainfall vs. snowfall events
Snowmelt dominance
ET dominance

Hunsaker et al., 2013
Decreasing elevation
Increase in water yield with elevation, from rain to snow dominated.

50% more runoff in snow dominated vs. mixed rain-snow catchments.

Decreasing temperature
Increasing snow fraction
Decreasing LAI
Coarser soils

Hunsaker et al., 2013
Increase in water yield with elevation, from rain to snow dominated.

Implication for 2°C warmer climate: Reduce runoff by 10-40% in mixed conifer forest (assuming ecosystems adapt).

Decreasing temperature → Increasing snow fraction → Decreasing LAI → Coarser soils.
Topics in this talk:

1. Sierra Nevada hydrologic setting
2. Measuring the mountain water cycle
3. Water security & managing ecosystems
Making a water-secure world – the three I’s

INFRASTRUCTURE
to store, transport & treat water

INSTITUTIONS
Stronger & more-adaptable

INFORMATION
Better & more-accessible

Water security lies at the heart of adaptation to climate change.

Water security: the reliable availability of an acceptable quantity & quality of water for health, livelihoods & production, coupled w/ an acceptable level of water-related risks
Ecosystem services: managing forests, wetlands, rivers

Making a water-secure California

INFRASTRUCTURE: planning

INSTITUTIONS: collaboration & integration in planning, management

Ecosystem services: managing forests, wetlands, rivers

More INFORMATION-intensive decision support

Water management translates into managing ecosystem services. Adapting to climate change also means managing ecosystem services.
ACWA Policy Principles on Improved Management of California’s Headwaters

“... managing California’s headwaters is integral to optimizing ... water supplies ... Increasing water yield and quality; reducing the risk and impacts of catastrophic wildfire; and enhancing natural features and functions; are all benefits to be derived, locally and statewide, from improved headwaters stewardship. Enhancing the resiliency and adaptability of headwaters is overdue. California can no longer afford to relegate management of its headwaters to the margin.”
A new generation of integrated measurements

- eddy correlation
- embedded sensor networks
- isotopes & ions
- low-cost sensors
- sap flow
- satellite snowcover
- lidar
- sediment
Wireless embedded sensor network nodes

Sensor node

Hopper node
Embedded sensor network technology – Providence Creek

Wireless network layout & equipment

- Sensing node
- Hopper node

Node w/ antenna

Embedded base station
Integrate these sensors with remotely sensed data, forecasting tools & decision support

Platform for research & core element of new water information system
Strategically place low-cost sensors to get spatial estimates of snowcover, soil moisture & other water-balance components
Node construction at Alpha site
Some recurring questions around water & forests

1. How will the post-fire water yield differ from before?
2. What will be the water yield with climate warming, vs. today?
3. What was the historical water yield prior to fire suppression?

Photos are Rim Fire area

Photos: J. Power & D. Buckley, USFS
Some background questions

1. How different were forests prior to fire suppression vs. today, pre-fire and post-fire?

2. Can we take forests back to pre-fire-suppression conditions?

E. Branch, N. Fork Feather R., 3400’

Photos from G. Gruell
Some background questions

1. How different were forests prior to fire suppression vs. today, pre-fire and post-fire?

2. Can we take forests back to pre-fire-suppression conditions?

Strawberry, S. Fork American R., 5800’
Some background questions

1. How different were forests prior to fire suppression vs. today, pre-fire and post-fire?

2. Can we take forests back to pre-fire-suppression conditions?

Upper Yosemite Valley from Columbia Point, 4800’
Forest density, Stanislaus NF

Tree density, stems per ha

Live tree C, Mg ha

Collins et al., Ecosphere, 2011
Measuring forest effects on snow accumulation

1200 measurements

Stanislaus-Tuolumne Experimental Forest
Variable Density Thinning Study
Post-Harvest (2012)
Thinned unit w/ control in background
Impact of thinning on evapotranspiration & streamflow

P303 headwater catchment, Southern Sierra CZO/KREW, Sierra NF
Rain-snow transition, 2000 m elev
Results based on very-detailed pre-treatment data & hydrologic modeling
5-yr average, 2004-2008
What is the slope of this line in different forests???

Saksa et al., in prep
1. High ET across a wide swath of mixed conifer forest
   - Resiliency to water stress – combined snowpack & soil-water storage
2. Low water yield in rain zone, much higher in snow dominated
   - Product of longer-tem processes
   - Shorter growing season in snow zone
   - Timing & amount of runoff are sensitive to small $\Delta T$
3. Sustained forest management can provide measurable benefits for water supply – will require both investment & verification
4. Better information is a critical foundation for water security, especially in a warming & more-variable climate
   - Mountain water cycle is poorly measured
   - The technology is readily available to accurately & routinely estimate water-balance components
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