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

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Whitney Crest from Kaweah Basin, copyright Tom Killion

Junction Peak, copyright Tom Killion
Topics in this talk:

1. Southern Sierra Nevada Critical Zone Observatory (CZO)
2. The mountain water cycle – recent research
3. Water security & managing ecosystems
Motivating questions

1. How will this landscape & the hydrologic processes connecting it alter with climate warming & landcover change?

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

precipitation

sublimation

evapotranspiration

snowmelt

infiltration

runoff

ground & surface water exchange

Storage:
Snowpack
Regolith

David Muench, Icon of the Sierra
My biases:

Improved predictions require better process understanding

The basis for process understanding is new measurements

We cannot just model our way out of these questions

David Muench, Afternoon Light, Temple Crag
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
- Millennial
  - Mixed conifer forest 2000 m
- Century
  - Pine/oak forest 1100 m
- Decadal
  - Oak savannah 400 m

Daily
- Pore to plot
- Hillslope to catchment
- Basin to regional

Seasonal

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

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

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

Subalpine forest
$T_{ave}$ 4.1°C
P >1100 mm
184 d snow
$H_{tree}$ 22 m
31% tree cover
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1. Southern Sierra Nevada CZO
2. The mountain water cycle – recent results
3. Water security & managing ecosystems
Basic water balance

Precipitation = Evapotranspiration + Runoff
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

Zoom in – network does not look so dense

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
LiDAR-derived snow depth, Kaweah R. basin

Kirchner et al., in prep.

15 cm per 100 m

Elevation, m

WY 2010

Snow depth, cm

0 50 100 150 200 250 300 350

Open snow depth
Visible under-canopy snow

Under-canopy COV
Open COV

Canopy cover fraction

Canopy over 2 m
Visible under-canopy area
Area (total 51 km²)

hectares

0 1 2 4 6 km

Snow depth, cm

Elevation

100 1000 1350 1700 2050 2400 2750 3050 >3300

Wolverton
Emerald
Panther
Topaz
M3

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

Kirchner et al., in prep.

SWE: Guan et al., 2013
Basic water balance

Precipitation = Evapotranspiration + Runoff

Evapotranspiration refers to evaporation, sublimation 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
Catchment-scale water balance

Snowmelt estimated from $\Delta$ SWE

0-100 cm soil

Based on distributed, wireless sensor networks

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

Bales et al., 2011
Porosity inferred from seismic refraction

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

Holbrook et al., 2013
End-member mixing analysis (EMMA) for CZO

EMMA results:
- Rainstorm runoff <6%
- Near-surface runoff <50% at 8 headwater catchments
- Significant baseflow: 30-80%

Other evidence for deep storage
Basic water balance

Precipitation = Evapotranspiration + Runoff
KREW: 8 instrumented headwater catchments
Water-year 2007 precipitation & discharge

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

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

Hunsaker et al., 2013
Decreasing elevation

Water-year 2007 precipitation & discharge

Rainfall vs. snowfall events

Snowmelt dominance

ET dominance
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 w/ 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

Hunsaker et al., 2013
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

**Stronger & more-adaptable INSTITUTIONS**

**Better & more-accessible INFORMATION**

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
Water management translates into managing ecosystem services. Adapting to climate change also means managing ecosystem services.
A new generation of integrated measurements

- Eddy correlation
- Embedded sensor networks
- Isotopes & ions
- Low-cost sensors
- Sap flow
- Sediment
- Lidar
- Satellite snowcover
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
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 w/ 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
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Extending flux-tower results to the basin scale

Precip based on PRISM
Runoff by difference
ET extended using satellite indices
Runoff

Goulden & Bales, in review
Runoff declines with higher temperature

- Longer growing season with temp. increase → more ET
- Average: 14% drop in runoff per 2°C
- Recall 10-40% drop at rain-snow transition catchments
Runoff declines with higher temperature

Note that current pattern of ET (P – Q) vs temp. for Sierra Nevada basins has similar slope
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Photos: J. Power & D. Buckley, USFS

Photos are Rim Fire area
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
Kyburz, S. Fork American R., 5000'
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 per ha

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

STEF snow survey
March 7, 2013

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 & RHESSys modeling
5-yr average, 2004-2008
What is the slope of this line in different forests???

Saksa et al., in prep
Motivating questions

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

2. How do regolith development & properties control, limit or modulate effects of climate change, management or disturbance on hydrology, biogeochemistry & ecology?
Research Summary

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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For bibliography of research presented contact rbales@ucmerced.edu