Research vision: Mountain hydrology of the semi-arid western U.S.

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- Why mountain hydrology?
- Energy & water balance
- Biogeochemistry & ecosystem feedbacks
- Measurement strategy & data systems
Contributors & acknowledgements

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- Michael Goulden
- SNHO planning workshops
- SAHRA colleagues
Much of the semi-arid west derives its water supply from intensively managed mountain ranges.

News Focus

In a region already prone to water shortages, researchers now forecast that rising temperatures threaten the American West’s hidden reservoir: mountain snow.

As the West Goes Dry
Drought, snow cover & climate change

Being in a 6th year of drought has really focused attention on western water. It has made scientists & decision-makers alike push for new measurements & understanding of mountain hydrology to close critical knowledge gaps. This new understanding is needed for longer-term sustainable water management.
Estimating influence of possible +6°C on SNOW vs RAIN

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

"Great things are done when men and mountains meet." -- William Blake

USGS
Estimating influence of possible +6°C on SNOW-SEASON LENGTH

Derived from UW’s VIC model daily inputs, 1950-1999
Estimating influence of possible +6°C on RAIN-FLOOD STORMS

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

PROJECTED CHANGES IN ANNUAL TEMPERATURE, NORTHERN CALIFORNIA

NUMBER AMONG 10 LARGEST 5-DAY STORMS WITH TEMPERATURES IN THE RANGE: -6°C TO 0°C
[from 1950-1999 VIC 1/8-degree INPUT DATA]
Where does new understanding fit in?

Emerging scheme for water supply forecasting

digital elevation model

ground data

landcover information

snowcover maps

streamflow forecasts

precipitation forecast

decision making
Why the mountain hydrology: broader research questions

**Water resources sustainability**
- Effects of upstream watershed management practices vs. climate change & extended drought on down-gradient streamflow & water quality?
- How can better data & information promote cooperative decision-making?
Issue 1. Despite the hydrologic importance of mountainous regions, the processes controlling energy & water fluxes within & out from these systems are not well understood.

Particular areas for investigation
- precipitation patterns - orographics
- energy balance - modeling
- partitioning of snowmelt & rainfall on the ground
- water balance - scaling point to catchment to range
Example: Sierra Nevada precipitation

Orographic effects

- Tahoe City vs Sacramento: rain/snow mix
- Sequoia NP: snow dominated

Mixed signals — location dependent
**Orographic effects — Scaramento vs Tahoe**

1860 vs. 10 m elev., 135 km distance

[Graph showing the ratio of Tahoe City to Sacramento precipitation over time, with red and blue lines indicating Jul-Jun precip and 7-yr mean, respectively.]

**High ratio**


**Low ratio**

[Additional graph showing data points with mean 1.76.]

K. Redmond, Western Regional Climate Center.
La Niña

High ratio

El Niño

Low Ratio

K.. Redmond, Western Regional Climate Center.
Ratio of annual precipitation at 2 stations in Sequoia National Park, southern Sierra Nevada, 1949-2003

Orographic effects

Ratio = \frac{\text{precip at 2000 m}}{\text{precip at 600 m}}
Precipitation questions — research agenda

- Meteorological & climatic controls on precipitation in mountains?
- How large-scale circulation & mesoscale forcing influence the distribution & timing of precipitation?
- What mechanisms generate interannual variability in precipitation?
- Importance of rain shadow, both seasonally & storm to storm?
Energy balance modeling scheme

Data cube

- SWE
- Albedo
- SCA
- Incident solar
- Longwave
- Air temp
- Relative humidity
- Wind speed

Vegetation

Topography

Soils

Time

Basin potential runoff

Pixel by pixel SWE & SCA

Energy balance LSM

Pixel by pixel runoff potential

Time

Swine

Soils
Net radiation provided 75% of the energy for snowmelt, largely controlling the timing & magnitude of snowmelt.

Open issues: representation of surface albedo & atmospheric attenuation.

Niwot Ridge, CO — no trees!
Estimating distributed daily net radiation

Tokopah basin, Sierra Nevada: 19 km², 2630–3490 m elev, few trees

\[ R_n = S_\downarrow \times (1 - \alpha) + \text{net longwave} \]

Explicit measurements of incident & reflected solar radiation are needed across a range of physiographic conditions - combination of remote sensing & ground measurements

Molotch et al., GRL, 2004
Spatial variability of snow surface albedo

Measured albedo can be quite different from empirical estimates

Modeled snowmelt is very sensitive to albedo on slopes where solar radiation dominates

Small spatial variation in albedo measured by AVRIS — but large changes with grain size as snow ages — depends on elevation, latitude, orientation, wind exposure, dust deposition

Test basins for radiation balance & remote sensing needed across range of variability in mountains

α\text{mean} = 0.664

age = 11 dy

Molotch et al., GRL, 2004
Energy balance in mountain forest

Issues & research needs are somewhat different — turbulent fluxes, vegetation control on heterogeneity.

Daily cycles of turbulent fluxes at Mt Bigelow, AZ. 2400 m elevation, 2nd growth Ponderosa Pine-Douglas Fir forest.

Brown-Mitic et al., in press
Placing flux towers in mountains

Extending flux measurements of water, energy & carbon to the heterogeneous terrain of mountain forests is a priority.

Mt. Bigelow tower has ~1 km fetch in prevailing wind direction.
Has yielded consistent results in 1st 2 yr of measurement.

Brown-Mitic et al., in press
Research questions related to energy balance

- How to represent & scale basin-wide energy balance in complex, heterogeneous terrain — from sparse point measurements?
- How this scaling varies across climate/vegetation zones within a mountain range?
- What determines seasonal (transient) snowlines?
Partitioning snowmelt

Simplistic models & few measurements across range of scales, from hillslope to basin to mountain range

Hydrologic processes important at one scale may not necessarily be important at larger scales

Different approaches to gain understanding of snowmelt partitioning at point vs. basin vs. mountain range scales

- evapotranspiration
- infiltration
- snowmelt
- sublimation
- runoff
Partitioning snowmelt & rainfall on the ground: research questions

- How physical & ecological factors together determine the large variability in runoff vs. infiltration across a mountain range?
- How to accurately estimate sublimation?
- Relative contributions of evaporation & transpiration to total ET in mountain ecosystems?
- How to predict hydrologic response of perturbed systems, e.g. by fire?
Scaling from point to basin

surface characterization

snowmelt modeling

micromet network

basin-scale modeling
Scaling mountain water balance

snow distribution
  ↓
melt timing
  ↓
partitioning
  ↓
infiltration
  ↓
runoff
ET

Blending measurements from multiple scales

plot/hillslope

soil moisture

snow distribution

micromet

fluxes

infiltration & recharge

basin

remote sensing

SCA
albedo
vegetation
ground/RS

SWE
precip
radiation
EB
topography
ground

soil moisture
micromet
bedrock
soils

infiltration & recharge
Research questions: scaling

- What ground-based measurement strategy to validate remotely sensed information to enable its use in basin-wide modeling
- How to blend remotely sensed & ground-based observations with integrated modeling schemes?
Issue 2. There exists a need to realize, at various spatial & temporal scales, the feedback systems between hydrological fluxes & biogeochemical & ecological processes.

**Topics**
- carbon & nitrogen cycling
- flow paths & residence times
Mapped net ecosystem exchange (NEE)

Modeling suggests that in the Western U.S. NEE is greatest in the mountains.

Very few data available to evaluate fluxes.

C measurements should parallel those for water.

~75% NEE at high elevation, which is 85% complex terrain at 1750 m elev. How representative are flat high-elevation flux sites?

Long-term meteorological data sparse at elevations of maximum NEE – only SNOTEL sites.

Schimel et al., Eos, 2002
Carbon fluxes in a mountain forest

Note active uptake of carbon in all seasons except spring, when soil is dry & trees shut down for lack of water.

In winter soil does not freeze below 4 cm & vapor pressure deficit is low, making it a favorable time to sequester C.

Daily cycles of carbon fluxes at Mt Bigelow, AZ. 2400 m elevation, 2nd growth Ponderosa Pine-Douglas fir forest.

Brown-Mitic et al., in press
Observations:
- Mountain catchments are receiving increasing fluxes of N & other pollutants in deposition
- The organic N pool in catchment vegetation, litter & soils is quite large relative to fluxes in atmospheric deposition

Issue: role of snowpack & catchment water balance in N cycling & export — how system responds to water balance
- snowmelt as source of soil moisture
- snowcover attenuation of soil freezing
- snowcover influence on plant growth & microbial activity
Nitrogen cycling — snowpack feedbacks

Hydrologic control over N export & source-sink relationships in Rocky mountains vs. Sierra Nevada

In CO Rockies deeper snow mitigates soil freezing, resulting in active soil biomass & greater uptake of N released in snowmelt

Soil freezing not the issue Southern Sierra — DIN retention less in years with deep, late snowpacks — need overall water balance

Sickman et al., 2001
Carbon & nitrogen cycling research questions

- What is the importance of seasonal transitions to carbon & nitrogen biogeochemistry at the scale of a mountain range, i.e. across elevational & longitudinal gradients?
- How do changing seasonal transitions affect carbon & nitrogen cycling in & export from aquatic ecosystems?
- How do they differ in rain vs. snow dominated areas?
Flow paths & residence times

Do subsurface flow paths & residence times increase with scale, from headwater catchment to a river basin?

How does baseflow respond to climate variability across the various geologic & vegetation regimes in a mountain range?

Principal geologic factors controlling groundwater storage, discharge to streams & chemical composition in mountains?
Issue 3. Lack of integrated measurement strategies & data/information systems for mountain hydrologic data hamper improvements to understanding the aforementioned processes

Topics:
- precipitation & snowcover — blend of remote sensing & ground-based measurements
- integrated water balance measurement strategies
- measurements as a research area
SCA can be measured accurately at the basin scale

%SCA from AVHRR

Recent advances enable estimating fractional snowcover
Snow under trees remains a challenge — ground truth needed for research
Hydrologic models & water resources resources are only beginning to evaluate this information

Bales et al., in preparation
MODIS fractional SCA & grain size

MODIS has sufficient spectral resolution to estimate grain size & thus albedo, as well as fractional SCA, within a 500 m pixel.

Mountain snowcover is generally not continuous at the 500-m scale — binary snowcover models consistently overestimate basin-wide SCA & albedo.

The question remains: how to knowledge of snowcover from remote sensing as part of an integrated measurement & modeling strategy.
Remote sensing of SWE remains a future challenge

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Resolution</th>
<th>Domain</th>
<th>Purpose</th>
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<tr>
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<td>full</td>
<td>snow cover</td>
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</tbody>
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Mountain precipitation

Research needs cover most aspects of the problem:
- Measurement at a point
- Ground-based network design
- Integration of remotely sensed & ground-based measurements

The accuracy provided by existing networks simply is not adequate
Snow course & snow telemetry sites

- Point measurements of SWE — not quantitative measures of basin-scale SWE
- Established as index sites to estimate seasonal runoff using statistical models — located at sites with persistent snowcover
- Emerging water resources decision support systems & hydrologic models are based on mass balance — quantitative SWE estimates are a top priority
SWE distribution: SNOTEL bias

Map showing the distribution of SWE across various states in the western United States, including Colorado, Utah, New Mexico, Arizona, and Wyoming. The map highlights the Del Norte Gauge with an arrow pointing towards it.

Key states:
- Wyoming
- Utah
- Colorado
- New Mexico
- Arizona

Scale bar:
0 10 20 30 km

Direction indicators:
N (North)
April SWE bias at 4 Colorado sites

SNOTEL site generally has much more snow than does surrounding area

How to design representative network?

Molotch et al., in preparation
Based on topography, vegetation, energy balance factors, it is possible to design a network to minimize the error in spatial estimates. Existing sites generally do not fall within that area. Network design is still a research issue. New technology must also be used to extend point measurements — lower cost, less intrusive.

Molotch et al., in preparation
There are very few data — need to instrument & routinely survey representative areas
Need to capture variability in interannual climate, latitude, elevation, topography, vegetation ...
Need more automated methods for larger scales

Maybe do not need?
Network design for integrated water balance measurements

Back to basics: streamflow

The tradeoff: many faster, lighter, cheaper measurements or measurements at a few points with high accuracy
Measurement clusters: flux towers & associated surrounding instrumentation

Pilot deployments over past 4 yr to develop concept

Need to find Bigelow soil moisture photo

Similarity in $T_{air}$ & RH — differences in net radiation (reflected in surface temperature) & potential for heat transfer