Wireless-Sensor Technology for Basin-Scale Hydrology

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BIOGRAPHICAL SKETCH

Dr. Roger Bales joined the University of California, Merced, as Professor of Engineering in June 2003, and is one of U.C. Merced’s inaugural faculty. Prior to joining UC Merced he was Professor of Hydrology and Water Resources at the University of Arizona, and prior to that served as a consulting engineer. Dr. Bales received his B.S. from Purdue University, an M.S. from the University of California, Berkeley and his Ph.D. from the California Institute of Technology. He has published over 120 papers in diverse fields of research including mountain hydrology and biogeochemistry, water resources, polar snow and ice, and water quality. At UC Merced, Dr. Bales organized the Mountain Hydrology Research Group, which is deploying new research instrumentation at several Sierra Nevada sites, and has multiple ongoing, collaborative projects investigating mountain hydrology. In 2007 he was named Director of UC Merced’s Sierra Nevada Research Institute. He Bales is a fellow of the American Association for the Advancement of Science, of the American Geophysical Union and of the American Meteorological Society. He serves on a number of advisory committees, and professional society boards.

ABSTRACT

A basin-scale observatory is being developed in the main seasonally snow-covered portion of the American R. basin, which is over 2000 square kilometers in area, to make comprehensive water-balance measurements in support of research by multiple investigators. This basin-scale “instrument cluster” will consist of over 20 local sensor groups, following the design for a local sensor group, or “headwater-catchment-scale observatory” developed at the Southern Sierra Critical Zone Observatory (CZO).

Each local instrument group will have 10-20 “sensor nodes” consisting of a snow-depth and temperature sensor, with solar radiation, soil moisture, soil temperature and sap flow measured at a subset of the nodes and local groups. All local groups will have a meteorological station, including precipitation measurements. Individual sensors within local sensor group will be deployed to measure the quantities of interest across variable aspect, slope and vegetation cover. Local sensor groups will be arrayed within the basin to measure attributes across the same variables, plus account for elevation and soil differences.

The inter- and intra-group communications will be provided by a sophisticated wireless sensor network. Locations for the local sensor groups for measurement of snow depth and water equivalent was evaluated using rank-based clustering, which proved superior to random placement or geographic clustering. Rank-based clusters remained stable inter-annually, suggesting that rankings of pixel-by-pixel snow water equivalent exhibit stationary features that can be exploited by a sensor-placement algorithm. Locations of wireless-sensor nodes within each local sensor group follows a three-phase design procedure to overlay a wireless network onto strategically placed sensor nodes. An iterative procedure is necessary, with specific metrics for network performance, as network performance in vegetated, complex terrain can be much different from that in flat, open areas. Data and analysis from these catchment-scale and basin-scale observatories provides unprecedented, detailed accounting of water fluxes and storage, and insight into catchment-scale and basin-scale processes.
Wireless-sensor technology for basin-scale hydrology

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

1. Sierra Nevada hydrologic context
2. Measuring the mountain water cycle
3. Sensor deployment strategy
4. Current deployments & future directions
Sierra Nevada precipitation & snow water equivalent (SWE) – climatological estimate?
Seasonal runoff forecasts are based on historical observations & have some skill in a stationary climate.

Forecasts use a few point measurements as indices of snow accumulation.
Percent bias of April 1 forecast of annual streamflow

Absolute values of percent bias

75th %

mean

Fraction of forecasts ≤

American River at Folsom
mean & stdev

Percent bias

wet  med  dry

Wet years tend to be under-forecast, dry years over-forecast

Shorter-term forecasts of water supply based on historical data have similar limitations on prediction skill

Decrease forecast skill w/ climate warming?
Some additional points re water supply context

1. We cannot model our way out of this uncertainty
2. Improvements in forecast skill require new observations
3. The technology to support new observations is available
4. This technology has matured over the past 5-10 years
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Current operational snow measurements

From a regional view, operational snow measurements look like a dense network
3 snow pillows in Merced, 7 in Tuolumne; a few more snow courses

Non-representative network – index sites

Stations are on flat ground, in clearings, at mid elevations

Despite these limitations, snow pillows are widely used as spatial ground truth
Relative snowmelt contributions by 300-m elevation band

Estimated based on satellite snowcover & snowmelt calculations

Snowmelt contributions by elevation band consistent between wet & dry years

Inter-basin differences depend on elevation patterns & latitude

Most snowmelt comes from elevations above most measurement of precipitation or snowpack
Myth:
We can, with a high degree of skill, estimate or predict the magnitude of these quantities.

Reservoirs:
Snowpack storage
Soil-water storage
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Measurement technology

Available now: blending data from satellites, aircraft, wireless sensor networks, advanced modeling tools

Together these add up to Big Data challenges
Sensor networks: 5-10 yr ago, wired sensor networks

Met station
North, south facing sensor nodes; <45 m wire lengths
– snow depth, temp, soil moisture
Current setup: *wireless* nodes

Improved representation of the landscape: topography & vegetation
Strategy to instrument snow-covered portion of American R basin

Deployment of sensors in progress
Snow depth, temperature, relative humidity
Soil moisture, radiation
Elevations above 1500 m elevation
Divided into approximately 7000 500-m square pixels
Near-optimal sensor locations

American River Basin above 1500 m elevation, divided into approximately 7000 500-m square pixels
Strategically place sensors using 2001-2011 snow water equivalent (SWE) estimates during snowmelt.
Rank-based cluster analysis of SWE during snowmelt

Cluster mean & standard deviation

American River Basin above 1500 m elevation divided into approximately 7000 500-m square pixels
Average RMSE vs. spatial sensors placed, averaged over 2008-2010 melt seasons (5 clusters)

**Mutual information**: when maximized seeks to reduce the error of estimates for unobserved locations.

Approach estimates the entropy, or uncertainty, at un-instrumented locations, given a set of selected sensing locations.

Mutual information more stable than random through melt season.
Average RMSE vs. number of rank-based clusters

At least two spatial sensors per cluster
Basin-wide deployment of hydrologic instrument clusters – American R. basin

Rank-based cluster much better than random placement or geographic placement. Little improvement beyond 5 clusters w/ 4-5 sensor groups per cluster. Also place to take advantage of existing infrastructure.

Network & integrate these sensors into a single spatial instrument for water-balance measurements.

In progress
Placement of sensor nodes within local scale instrument clusters

Providence Creek – main CZO instrument cluster

3 headwater catchments w/ stream gauges & water-quality measurements
2 met stations
60-m tall flux tower
60-node wireless embedded sensor network
214 EC-TM sensors for volumetric water content
113 MPS sensors for matric potential
57 snow-depth sensors
Meadow piezometers & wells
Sap-flow sensors
Three phases of WSN deployment

- Pre-deployment:
  - Deploy Prototype
  - Collect WSN Statistics
- Deployment:
  - Analyze RSSI vs. PDR (waterfall behavior)
  - Analyze RSSI vs. path distance
  - Determine site-specific path distance
- Post-deployment:
  - Deploy/Adjust Network
  - Collect WSN Statistics

Kerkez et al., in review
Three phases of WSN deployment

1. **Pre-deployment**
   - Deploy Prototype
   - Collect WSN Statistics
     - Analyze RSSI vs. PDR (waterfall behavior)
     - Analyze RSSI vs. path distance
     - Determine site-specific path distance

2. **Deployment**
   - Deploy/Adjust Network

3. **Post-deployment**
   - Collect WSN Statistics

![Path Occurrences](image)
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Sierra Nevada hydrologic research infrastructure

American R. basin

N-S transect of research catchments, 39°N to 36.5°N

E-W transect of flux towers

San Joaquin Exper. Range 400 m
Soaproot Saddle 1100 m
CZO P301 2000 m
Shorthair Creek 2700 m
Main CZO site

MODIS image
Node construction at Alpha site
Concluding points

1. Technology is sufficiently mature to invest in systems for operational use
2. American R basin is both research platform & core element of new water-information system
3. Forecasting water supply using spatial data & appropriate modeling could reduce uncertainty due to land-surface fluxes & stores by ~50%
4. Even a few % improvement in high-elevation hydropower ($1.5 billion per yr) would provide significant gains
5. Better information is a critical foundation for water security, especially in a warming & more-variable climate
6. Water information system also provides verification for benefits of sustained forest management
Some additional concluding points re knowledge gaps

7. Research is still needed on several basic engineering, hydrologic-science, social-science questions, e.g.:
   – Systems for accurate spatial measurement, blending remotely sensed & ground-based data
   – Blending of data w/ modeling tools to improve forecast skill – including advances in predictability & better process understanding
   – Economic value & use of better information for hydropower operation, water allocation, flood forecasting, infrastructure planning, markets ...
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For bibliography of research presented contact rbales@ucmerced.edu
Wireless sensor networks are central components of a new water information system for California.