Project purpose

This project is a critical step in addressing the woefully inadequate observational infrastructure and understanding of mountain water balances. It provides important data for one area in the southern Sierra Nevada that is especially vulnerable to climate change (lower snow zone), but more importantly addresses broader questions of measurement strategy for larger basins and for the range as a whole. It addresses important water-balance questions, and provides data for a range of questions that others can take advantage of.

The specific aim of this project is to develop measurement strategies that blend remote sensing and ground-based data to achieve more accurate estimates of snowpack, snowmelt and the partitioning of snowmelt into runoff, infiltration and evapotranspiration (Figure 1). Our basic hypothesis is that strategically placed instrument clusters, designed to compliment satellite remote sensing information, provide the basis for more accurately and efficiently measuring and scaling water balance components, and thence basin-scale fluxes, than does an approach that relies on distributed snowpack and weather-station measurements of the type now available. A corollary to this is that water balance estimates provided by the prototype measurement system will improve forecasts of snowmelt runoff and other water balance components using emerging hydrologic models, and thence provide a more-accurate projection of mountain water supply and the timing of its runoff.

Our approach recognizes that hydrologic processes important at one scale may not necessarily be important at larger scales. At the point scale, surface energy exchange and storage of meltwater within the snowpack dominate snowmelt and runoff. At larger spatial scales, lateral movement of water through the snowpack, influenced by topography and linked to the stream network, affects the timing of runoff. At longer temporal scales, storage and routing will integrate short-term variations in runoff caused by variations in melt rates. To make these translations we will use the broader-scale coverage afforded by remotely sensed observations and the spatial detail coupled with the spatial and temporal integration provided by hydrologic models. While some spatial quantities can be estimated directly from remotely sensed information (e.g. snow-covered area (SCA), vegetation index, albedo), others depend on an integration of ground-based and remotely sensed information (e.g. snow water equivalent (SWE), radiation); ground measurements, together with modeling, will remain the primary means of measuring other quantities (e.g. soil moisture, turbulent energy) (Figure 2).

The need and demand for new hydrologic and climate information in the Sierra Nevada

Making more informed decisions to manage water resources drives the need for better hydrologic information. Mountain river basins, their associated reservoirs, and their underlying aquifers sustain the water...
demand of over 60 million people in the western U.S., including much of California. The Sierra Nevada provides about 40% of the runoff for the whole state of California, and a much larger component for specific basins. A large fraction of the runoff from Sierra Nevada basins, over 75% in some cases, comes from snow. Snowmelt and streamflow timing are advancing earlier each spring in response to general warming (as much as +2°C in recent decades) (Cayan et al. 2001). This seasonal shift implies increased risk of floods in springtime, and droughts and wildfires in late summer. The changing water balance and water distribution patterns, in both space and time, will radically impact ecosystems and water supplies in the Sierra Nevada and other western mountains in coming decades. Yet the knowledge base for implementing sound hydrologic management is notably weak. Information about the balance between water demand and supply is not easily accessible. The effectiveness of various water and land-management practices and restoration techniques are largely untested. Forecasting tools lack the measurement base to make major advances.

Water allocations in these supply-limited systems rely on complex decision-support systems that account for water laws and markets, flood control, agriculture, hydropower and municipal demands. Improvements in predicting the magnitude and timing of runoff—i.e. narrowing the considerable uncertainty in runoff estimates—directly benefit regional economies. Management of forests, fisheries and other resources that depend on mountain water sources also drives the need for new hydrologic knowledge. Montane forest dynamics rely on the spatial and temporal variability of hydrologic properties, especially the variability in snow water equivalent and snowmelt. Aquatic ecosystems are sustained by year-round flows of adequate quality, with summer baseflows being particularly sensitive to climate change. The West’s mountain regions also contribute significantly to the regional carbon budget (Schimel et al. 2002).

**Background on Sierra Nevada water balance**

Two fluxes (precipitation and streamflow) plus snowpack storage are the main components of the Sierra Nevada water balance that are measured at selected locations. None of these are measured adequately for basin-scale or range-scale water-balance models or studies, and other important reservoirs (soil moisture) and fluxes (evapotranspiration, groundwater recharge/discharge) are not measured.

Hydrologic forecasts in the western U.S. are generated from SWE measurements at monthly manual courses and hourly/daily telemetry sites. However, precipitation in the western U.S. varies spatially and temporally because of topography—elevation, orientation, vegetation—and larger-scale synoptic processes. Therefore, substantial variations exist between snow measurements, even from sites close together (Carroll et al. 1999). Further, the monthly ground-based SWE measurements that supply the bulk of the data used in the Sierra Nevada provide inadequate temporal resolution to diagnose orographic effects or snowcover depletion patterns. Additional problems are that the snow courses, and since the late 1970’s also automated snow telemetry sites, are used as indices of streamflow, rather than for measuring snow volumes themselves. The locations are characterized by a homogenous snowcover and snowpack conditions specific to that elevation in that basin, and all of the courses are on flat or nearly flat ground that are not representative of the surrounding area.

The coupling of ground-based measurements with spaceborne satellite imagery provides a viable way to examine the critical physical processes controlling spatial and temporal distribution of seasonal snow in the mountains. The transfer of mass and energy fluxes to the snow and the changing climate dictate the seasonal and interannual distribution of snow that drives the seasonal transitions between cold and warm and wet and dry, which in turn drive the water and biogeochemical cycles and affect the response of the ecosystems. The measurement capabilities,
ground-based and spaceborne, will provide advancements in the physical process that drive the spatial and temporal distribution of the seasonal snowcover in mountain environments.

Streamflow is measured at USGS and other stream gauging stations, however, a number of gauges are no longer active. Most remaining gauges are on larger tributaries or main-stem rivers draining several hundred km$^2$. Recent deployments of continuous stage measurements at a number of smaller streams in the Upper Merced and Tuolumne basins are demonstrating the value of these distributed, low-cost measurements (Lundquist et al. 2003). A future strategy that blends a smaller number of larger, more-accurate emplacements, along with a larger number of telemetered, lower-cost sites needs to be developed to provide the sort of distributed data required by emerging hydrologic models (Bales et al. 2004, in preparation).

Precipitation measurements in the Sierra Nevada are also sparse and skewed toward lower elevations. Direct measurements of precipitation in mountainous environments are particularly difficult, given that so much of it falls as snow and that precipitation gauges have poor catch efficiencies. Although it is possible to infer precipitation rates from snowpack observations (Cherry et al., 2005), direct observations of precipitation are needed to explore changes in precipitation type associated with climate variability. Detailed observations of precipitation type and intensity, as well as the environmental conditions controlling them, are needed across latitudes, vegetation zones and climate regimes. Precipitation measurement strategies that employ new sensors as well as new network designs are needed. Many, if not most, of the stations that are now in the mountains were not sited to contribute to basin-scale water-balance measurements. Rather, they serve as climate reference stations, provide indexes of local precipitation, or were sited for convenience (e.g. at sites with AC power and road access).

**Background on satellite remote sensing and mountain hydrology**

Satellite remote sensing instruments and data-retrieval algorithms are now sufficiently well developed to provide snowcover information (SCA and albedo) that is useful for snow estimation and hydrologic forecasting. Vegetation properties can also be routinely estimated from remotely sensed data. While the potential exists for estimation of rainfall, SWE, soil moisture and streamflow from space, data are not routinely available and major barriers remain for routine use.

Remote sensing is the only practical way to routinely measure the spatial extent of snowcover and albedo, and over the past decade methods for retrieving snow-covered area from visible and infrared instruments on satellites have become well developed (Dozier and Painter 2004). Quantitative estimates of sub-pixel SCA and albedo for the Sierra Nevada are being routinely produced as part of a NASA-supported REASoN project (J. Dozier, PI; R. Bales, J. Frew, T. Painter, A. Nolin Co-I’s) ([http://www.snow.ucsb.edu/](http://www.snow.ucsb.edu/)).

**Background on research infrastructure for hydrologic sciences**

Through the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) ([http://www.cuahsi.org/](http://www.cuahsi.org/)), the National Science Foundation (NSF) proposes to establish a network of Hydrologic Observatories, or natural laboratories, as platforms for research in hydrologic and related sciences. A planning group has formed and is proposing a Sierra Nevada Hydrologic Observatory (SNHO) as the most compelling research infrastructure need for hydrologic science in the Western U.S. A preliminary prospectus and vision has been prepared for the proposed Sierra Nevada wide observatory (available at [https://ucmeng.net/snri/snho](https://ucmeng.net/snri/snho)). The proposed Sierra Nevada Hydrologic Observatory will provide infrastructure for advanced studies of the hydrology of California and the semi-arid west, and will provide the observational basis for a new generation of hydrologic modeling and management tools.
The group proposes a multi-scale observatory design with instrument clusters in multiple 1,000-5,000 km$^2$ and smaller nested basins grouped into transects across the Sierra Nevada, in 3-4 distinct latitude bands (https://ucmeng.net/snri/snho/snho_1204_agu). One of these bands falls in the southern Sierra. This design exploits the way that the prevailing climatic regime varies with latitude and altitude, to create a set of “natural experiments” that mimic anticipated effects of climate change in the Sierra Nevada.

**Science questions**

While a number of science questions are addressed by the overall SNHO design, some of the specific hypotheses driving the prototype measurement system that is the subject of the current proposal follow:

- Increased accuracy in SWE estimation at scales of 1-1000 km$^2$ is possible with sensors placed to capture the variability in slope, aspect, radiation and landcover.
- Soil moisture patterns will follow the patterns for snowcover depletion. Soil moisture measurements may also help to discriminate snow versus rain.
- Canopy differences are as important as slope and aspect for variability in snowcover and soil moisture.
- Accurate estimates of change in spatial SWE across a basin can be developed using SCA and albedo from MODIS/MODSCAG plus canopy information and distributed energy balance modeling, with only limited ground-based SWE measurements.
- The reduction in uncertainty for a spatial average from additional nodes within a sensor web diminish slowly after a relatively small number of nodes are in place, i.e. measurement saturation will occur.
- Strategically placed sensor webs provide the basis for a scaling strategy that will provide more accurate basin-scale fluxes than relying solely on weather stations alone.
- Evapotranspiration is a dominant component of the water balance during much of the year, and is least in summer, after snowmelt is completed.
- Turbulent fluxes dominate the surface energy balance during much of the year in the forested systems, with that influence diminishing in areas with lower vegetation density.
- Evapotranspiration (and carbon exchange) continues through the winter at a significant rate, and increases in response to temperature during the snow-covered season and in response to soil moisture (precipitation) during the snow-free season.

**Description**

The approach involves developing a scalable measurement cluster, anchored by an eddy-correlation flux tower but with satellite measurements extending several km from the tower (Figure 3). Project data will be made available soon after acquisition through a web-based digital library. Measurements will be integrated with other available measurements in
the basin using MMS/PRMS for hydrologic modeling (Leavesley et al. 1996), which has recently been modified to use spatial data (Dressler et al. 2004).

**Task 1. Establish and maintain flux tower measurements and accompanying data system**

An eddy covariance tower will be established for measurement of water, energy and carbon fluxes in the Wolverton vicinity. Besides providing important measurements of evaporative and turbulent fluxes, it serves as the measurement and communications hub of the instrument cluster. Micrometeorological measurements and an embedded sensor network will be clustered around the tower.

Pending further on-site evaluation, the preferred site is Wolverton (Figure 4), which is outside the wilderness boundary. The Wolverton area (elevation 2100-2700 m) lies in the lower snow zone of the Sierra Nevada, the area that is most sensitive to temperature variability and changes in climate. The nearby Panther Gap snow course records on average about 0.95 m SWE on April 1, which is generally after the annual peak accumulation.

The terrain at the proposed site is similar in complexity to a tower that R. Bales and colleagues located and erected at MT. Bigelow, AZ, 2573 m elevation, on a small plateau on a saddle area ([http://www.sahra.arizona.edu/research/TA1/towers/](http://www.sahra.arizona.edu/research/TA1/towers/)) (Brown-Mitic et al. in press). Water vapor, carbon dioxide, sensible heat and momentum fluxes were measured using an eddy covariance flux system. The saddle has slopes of 10-17° for 1-2 km in all directions. Four micrometeorological stations equipped with wind, air temperature, relative humidity, surface and soil temperature, net radiation, precipitation and soil moisture sensors were installed in the vicinity of the eddy covariance tower, to characterize the variability in both atmospheric and surface characteristics.

![Figure 4. Wolverton and vicinity, showing preferred area for locating flux tower.](image-url)
Instrumentation on the proposed tower will be similar to that installed at Mt. Bigelow (Figure 5), and at seven sites that M. Goulden is installing along a 150-km transect in Southern California (coast to San Bernardino mountains). At Mt. Bigelow wind velocity and virtual temperature were measured with a three-dimensional ultrasonic anemometer and CO₂ and water vapor measured with an open-path infrared gas analyzer. Incoming and outgoing shortwave and longwave radiation components were measured above the canopy by a four-way radiometer and net radiation by a net radiometer. The tower was also instrumented to measure micrometeorological data at three vertical levels. Infrared thermometers were used to measure the skin temperature of the ground and canopy skin temperature. Operations on the tower were powered by four solar panels charging deep-cycle batteries. Data from the eddy covariance system was sampled at 10 Hz, and five-minute average values were recorded for all other hydro-micrometeorological variables. Our experience at Mt. Bigelow and at M. Goulden’s previous sites in the Boreal forest show that systems such as these can be operated year round on solar power, and can operate through winter snows and sub-freezing temperatures with only small losses of data.

Soil temperature will be measured with multilevel thermocouple probes located at the surface down to 60 cm, and soil heat flux will be measured using soil heat flux plates buried 2-cm deep in close proximity to the soil temperature probes. Soil moisture measurements will be made with nylon bocks located in the vicinity of the soil temperature arrays. Periodic surveys of soil moisture will be made using a portable soil moisture probe. Instrumentation on the satellite micrometeorological stations will be similar to that used at Mt. Bigelow (Figure 6).

It is also proposed to include measurement of carbon fluxes on the tower, providing a quite valuable addition to the growing measurement network in California, and providing the highest elevation site in the Sierra Nevada. The site will also become an important node in the Ameriflux network.

Data will be both recorded on site and telemetered to our laboratory in near-real time using a combination of GOES satellite uplinks and RF telemetry/spread spectrum.

**Task 2. Establish and maintain embedded sensor network for ground measurements**

We will deploy sensor webs, which are in-situ, spatially distributed instruments consisting of cooperating observational sensor pods, to record the seasonal evolution, accumulation through ablation, of snow depth, soil moisture, air temperature, soil temperature, relative
humidity and solar radiation. One distributed sensor web will be co-located with the flux tower, one will be located higher in the basin, in the Panther Meadow vicinity, and two others will extend along elevational transects.

The proposed suite of measurements will expand and leverage the existing research measurements in the nearby Tokapah basin.

This distributed sensor web network will take advantage of the varying topography to characterize the spatial variability of water-balance components at sufficient points to both develop and evaluate relationships between snow/soil measurements and topography, landcover and radiation features.

Sensor web network installations will be similar in design to the pilot network array at Gin Flat, along Tioga Pass Road in Yosemite National Park (Figure 7). Most sensors will be sampled hourly. Hourly temporal measurements are of sufficient resolution to capture accumulation rates without the dampening affects of settlement. Monthly site visits during the winter and spring will be used to verify accuracy and perform any necessary maintenance.

Within each of the sensor web clusters, a pod will be placed at randomly selected points to capture multiple trees and open spaces between trees. Since snow accumulation, densification and melting is affected by trees, it is necessary to sample distances from tree trunks and canopy in order to develop parameters to describe the local distribution of snow as a function of vegetation type and tree density. Manual depth surveys will be done in the general area of each cluster during the site visits to evaluate the representativeness of the sensor locations. We are using this same sampling design for snow, soil moisture and other parameters in the new deployment in the Valles Caldera, as a follow-up to our pilot study at Mt. Bigelow, and in our ongoing Gin Flat pilot study.

Having 10-15 pods within a cluster also provides for replication. We found that for snowcourse data at Gin Flat, 8 replicates were only slightly better than having 3 replicates in homogenous terrain. But for purposes of estimating spatial averages, uncertainty increased below 3 measurements (Figure 8).

We will also install a number of self-logging stream stage measurements in the basin (Figure 4), similar to those put in place in the upper Tuolumne and Merced basins (Lundquist et al. 2003). To the extent feasible we will include the data in our wireless network in order to have access to real-time information. Wolverton Creek drains into the Marble Fork.

Figure 7. Snow station with ultra sonic depth sensor and sensor web module (box) mounted above snow and 2 instrument rods, one to measure temperature profiles (open arrows) and one to add soil/snow moisture (solid arrows. Snow surface is shown as curved line.

Figure 8. Range of SWE estimates from choosing 1-8 points with identical physiographic features (flat, open) for 3 different years, as % on mean SWE: historical peak (1983), low (1988), & average (1982). Although there are 10 points in the snow course, 2 are close to trees. Data from Gin Flat.
Task 3. Develop remotely sensed data for mountain snowcover

Fractional snow-covered area and albedo for the upper Marble Fork basin will come from Moderate Resolution Imaging Spectrometer (MODIS) surface reflectance data, with products developed and delivered through our NASA-funded REASoN project, Multi-Resolution Snow Products for the Hydrologic Sciences. R. Bales is Co-I with responsibility for product applications. A limited number of LANDSAT Thematic Mapper (TM) scenes will also be available. With the launch of MODIS and completion of fractional SCA algorithms, satellite imagery has now improved to the point that the data provide accurate information on snowcover, but their role in hydrologic modeling is severely limited by the lack of adequate ground-based SWE measurement data, or the knowledge of how to design and deploy adequate SWE measurement systems to compliment remotely sensed data.

Task 4. Estimate water balance using flux tower and sensor network data plus modeling

This task involves integration of the remotely sensed data, other spatial information, point flux tower data and sensor web data to estimate the spatial water balance. Research involves developing and evaluating a strategy and approach that can be scaled beyond this pilot area, as much as estimating the actual water balance for the basins that are the subject of the current study. Hydrologic modeling, carried out initially under our REASoN project, will be used to help integrate measurements and provide estimates of derivative quantities.

Daily snowmelt is a primary water balance component that will be estimated from spatially interpolated data (Figure 9). It is planned to assess the snow and energy mass balance, and the consistency between them, across the different scales of the study area. Consider the data cubes (x-y-t) illustrated on Figure 9. Analysis of precipitation will be mainly at the smaller scales, based on measurements; a basin-wide assessment of precipitation quantities (other than from snow data) is beyond the scope of this project.

Radiation components will be estimated for the topographically diverse terrain using our point measurements and TOPQUAD to spatially distribute the measurements, as noted above. Canopy effects will be measured both at the tower and more generally at the scale of a sensor web and extended to broader areas using the available vegetation (canopy opening, NDVI) information. For this analysis we will evaluate the approach that we recently used in the 19 km$^2$ Tokapah basin (Sequoia National Park), with the turbulent energy terms lumped into a melt factor (Brubaker and Rango 1996, Molotch et al. 2004). A 30-m grid will be used for calculating the radiation components, aggregated to 500 m to match the scale of the satellite/snow information. The snowpack evaluation at the different scales, as noted above, applies to the snowmelt and snowpack mass balance analysis as well.

One factor not well accounted for in the modeling scheme of Figure 9 is sublimation. The tower and surrounding meteorological measurements offer the possibility to accurately estimate sublimation in the context of any number of energy balance and simpler models. For interpreting
the snowpack mass balance in the vicinity of the tower it is proposed to use the data intensive,
multi-layer SNTHERM (Jordan 1991). In the larger sensor web and cluster areas, a simpler three-
layer model (Jin et al. 1999) will be used.

Our approach to integrating the soil moisture data will follow that for snow. To our knowledge
this sort of spatial estimation has not been done for a mountain environment. At the moment we
are aware of soil moisture being measured at one point in the Southern Sierra Nevada (3 depths), at
Gin Flat.

We will use the Precipitation Runoff Modeling System (PRMS), within the framework of the
Modular Modeling system (MMS) for integration of basin-scale data and estimation of
streamflow(Leavesley et al. 1996). This USGS modeling approach involves a semi-physically based
hydrologic model that is designed to accept spatial inputs and track water balance across a
catchment. It lacks some of the complexity and thus parameter estimation issues of more fully
physically based land-surface models. PRMS includes partitioning the watershed into hydrologic
response units (HRU’s) based on hydrologic properties of the watershed (e.g., slope, aspect,
elevation, soils, etc.). The scale of the HRU’s, compared with the basin scale, should reflect the
spatial variability of important hydrologic processes (e.g., precipitation, evaporation, infiltration,
etc.). For the current application it is proposed that the model be run on a 0.5-km to 1-km grid
across the watershed, following the approach that we are using for two basins in the Southwest
(headwaters of Salt and Rio Grande) (Dressler et al. 2004). In that application we have modified
PRMS to assimilate spatial, gridded SWE data, and update the water balance on each component
accordingly. Besides the remotely sensed SCA data, streamflow data from available measurement
points will provide points of comparison with the PRMS modeling.

Evapotranspiration (ET) at the nested scales will be evaluated using the tower data,
meteorological data, spatial soil moisture data and remotely sensed information. We will evaluate
the consistency of the flux measurements across time, and in relation to soil moisture, snowpack and
precipitation. This analysis will influence parameterized values/indices of vegetation and ET in our
hydrologic modeling. While it is beyond the scope of this project to develop or even parameterize a
detailed model of ET, it will address questions of seasonal and diurnal cycles that must be covered
before a meaningful effort at modeling can proceed.
Literature cited


