Sierra Nevada Hydrologic Observatory

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Introduction

Several recent reports, including *Water 2025: Preventing Crises and Conflict in the West*, highlight the need for new water information to enable better decision-making for water resources management, and for the myriad of other decisions that are influenced by water. Explosive population growth and changing climate are combining to create supply-demand mismatches that threaten water supplies across the West. Collaborative approaches and market-based transfers can help minimize conflicts between demands for water for people, for cities, for farms, and for non-human habitat. However, as water becomes a more valuable commodity, more accurate information than is currently available will be needed to support better estimates of natural water reservoirs (e.g. snowpack, groundwater); more complete understanding of water and contaminant fluxes (e.g. evapotranspiration, groundwater recharge, erosion, mercury transport, salinity sources); improved hydrologic modeling (e.g. streamflow forecasting, water quality predictions); and better informed decision-making. Observation technologies in current use are decades old, and the blueprints for modernization are lacking in most cases. These challenges have been brought home to most western land and water managers by hydrologic variability over the last two decades. In 2004, much of the west is in its 5th year of drought, with many surface-water impoundments at less than 20% of capacity. Nor is this just a western issue; the social, economic and environmental consequences of the West's water-supply crises affect economies and resources of national importance.

The Sierra Nevada (Figure 1) provides about 40% of the runoff for the whole state of California, and a much larger component for specific basins, including those draining into Nevada. The range serves water to over 10% of the U.S. population. The Sierra Nevada ecosystem has been described as "teetering on the edge" because of its summer aridity, encroaching development and air pollution. Snowmelt and streamflow timing are advancing earlier each spring in response to general warming (as much as +2°C in recent decades)(4). This seasonal shift implies increased risk of floods in springtime, and droughts and wildfires in late summer. These changes are not unique to the Sierra Nevada (7). 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 in Western mountains is notably weak. Information about water demand 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.

The proposed Sierra Nevada Hydrologic Observatory (SNHO) will provide infrastructure for advanced studies of the hydrology of the semi-arid west, and will provide the observational basis for a new generation of hydrological modeling and management tools. The SNHO represents an intersection of at least four factors on which to build a productive, high-impact hydrologic observatory: (i) compelling scientific need for new hydrologic understanding in the semi-arid West, (ii) urgent societal need, (iii) significant existing infrastructure and synergistic activities in regionally representative environments, and (iv) broad participation from both science and applications communities.

Figure 1. Sierra Nevada from southeast

Science Rationale for SNHO

In choosing the Sierra Nevada, the planning group first asked what science questions are driving the need for an observatory in the Western U.S., i.e. (i) what is changing that drives the need for new hydrologic understanding, (ii) what critical systems are a priority for the hydrologic science community, and (iii) what key questions require new infrastructure investments and sustained measurement?

As a platform for research, the SNHO will:

- Measure hydrologic phenomena over spatial scales that describe the range's intertwined hydrologic and ecological processes, long enough to identify inter-annual variability and explore natural vs. human-induced changes.
- Create a legacy of well-designed observations and experiments for present and future use.
- Foster collaborations among scientists from different disciplines and institutions.
- Provide baseline data and support process studies that will advance understanding and predictions of water and other resources.
- Provide information for the solution of societal problems through partnerships involving scientists, resource managers and other decision makers.

To best address hydrologic issues in the greater semi-arid west, we concluded that a Hydrologic Observatory must serve a broad community, but it also needs focus—it cannot contain every bit of complexity that is in the real world and still yield breakthrough research results. Rather than aiming for a mountain-to-ocean observatory, or trying to cover the wide variety of questions facing the region, the group concluded that the distinctive hydrologic opportunity in the region was a *mountain-range-scale research program exploring the hydrology of snowmelt-dominated systems*, which control much of the West's water supply. We recognized that there are already significant investments in hydrologic research below the mountain front (e.g. riparian system processes, sedimentation, salinity, water quality, groundwater-surface water interactions); many of these research initiatives extend only into the foothills, owing to the difficulties of hydrologic research in mountainous regions. The greatest knowledge gaps are in mountain hydrology. Water resource management in the lowlands is impaired primarily by our limited understanding of the hydrologic processes above the mountain front.

The broader, general science question posed by the planning group is, "how do mountain hydrologic processes vary across landscapes, spanning a range of latitudes, elevations and thus climate, soils, geology and vegetation zones?" Embodied are additional broad questions for the hydrologic science community as a whole: (i) How do hydrologic systems that are subjected to multiple perturbations respond? (ii) How do pulses and changes propagate through the hydrologic system? (iii) What are the time lags and delays of stresses in different systems? (iv) How can the predictive ability for these responses be improved? The water resources question is then "how can new information inform decision-making aimed at achieving water resources sustainability?"

HO science drivers for the semi-arid West:

- Dramatic changes in mountain snowpack as a result of climate warming, plus large interannual variability.(1,2)
- Vegetation changes across the landscape, particularly due to fire and climate.(3)
- Changing seasonal patterns of precipitation, snowmelt, runoff, evapotranspiration, and implications for groundwater recharge, streamflow, water quality, soil moisture, and ecosystems.(5,6)
- Land use change, driven by changes in and loss of land in agricultural production.
- Changes, both degradation and restoration, in riparian areas and aquatic habitats.

These questions motivated an observatory design with multiple 1,000-5,000 km^2 basins grouped into three transects across the Sierra Nevada, in three distinct latitude bands. 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. The study basins also make the greatest possible use of existing research infrastructure and ongoing monitoring programs. While the west-side basins are tributary to San Francisco Bay through the Sacramento-San Joaquin Delta, the proposed HO will focus on the mountain portions of this larger basin.

SNHO Site Characteristics

The Sierra Nevada, as defined by the Sierra Nevada Ecosystem Project (SNEP) is about 650 km long and 120 km wide, for an area of 80,000 km^2 (Figure 1). There are 24 main catchments that make up the Sierra Nevada, each of which drains from a few hundred to about 5,000 km^2 above the mountain front. Of the 20 main rivers draining the Sierra Nevada, 14 lie on the west side and 6 on the east. The greater San Joaquin (mountains & valley together) is on the order of 35,000 km^2, or 50,000 km^2 including the Tulare Lake basin. Much of the range is public land, and land cover includes significant forests, but also meadow, chaparral scrub, woodland, savanna, canyon land, alpine habitat, bare rock, water, and agriculture.

At its foundation, the Sierra Nevada is an enormous deposit of granitic rock whose exposed slopes are readily visible at the crest. The gradual west slope rising from the expansive Central Valley is dissected by deep, west-trending river canyons. At the eastern edge of the uplift, the high peaks dominate the uppermost elevations, forming rolling highlands in the north—with elevations mostly less than 2,700 m—and expansive, highly dissected mountains in the broad southern alpine zones, where Mount Whitney rises to 4,421 m. The range ends abruptly at the eastern escarpment, dropping with a shallow gradient in the north, but in the south plunging more than 3,000 m from the crest to the floor of the Owens Valley. In the northern Sierra the older rocks are overlain by younger volcanic rocks of the southern Cascades.

This juxtaposition of highly permeable and moderately porous Cascade volcanics with granites of low permeability and porosity makes the Sierra an excellent laboratory for testing geologic controls on groundwater flow, storage and the role of groundwater in surface water. Characterizing "geo-hydrologic landscapes" to better understand stream baseflow processes in mountainous regions like the Cascades is of primary importance (8). Drainage density and the frequency of alpine lakes in the Sierra are significantly greater in the granite regions as compared to the volcanics, probably reflecting the differing near-surface permeabilities. While this phenomenon is well known to hikers in the region, it has not been quantitatively studied. Granites and volcanics can be found as mixed assemblages in the Tahoe area of the Sierra, while monotypes of granite aquifers dominate in the southern Sierra. Volcanics dominate in the northern Sierra, but their properties vary significantly with their age.

Soils tend to be thin and rocky. Although soil fertility in general is low, the range contains some of the most productive conifer forests in the world. The rich and fertile soils that have formed on the western edges of the Sierra Nevada support a diverse agriculture.

The current Sierran climate is dominated by a Mediterranean pattern of a cool, wet winter followed by a long dry summer. High year-to-year variability in temperature and precipitation is also characteristic. Because of the influence of the Pacific Ocean and storm tracks from the west, strong climatic gradients develop with elevation from west to east. As elevation increases, so does precipitation. Winter storms are moisture-laden and release enormous precipitation on the west slope. The transition zone of rain to snow is an important determinant of vegetation types, stream characteristics and human settlement. Strong gradients of aridity also exist from north to south along the Sierran axis as a result of the location of the jet stream and subtropical high-pressure cells. Precipitation increases by a factor of two from south to north, and even more along elevational transects (Figure 2). Two extensive droughts, each lasting 100 to 200 years, occurred within the last 1,200

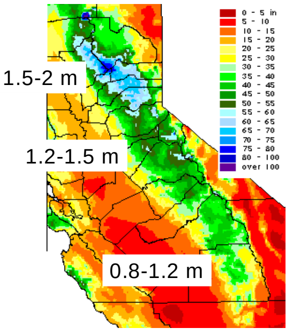

Figure 2. Annual precipitation

years. The last 150 years, by contrast, have been relatively warm and wet, containing one of the wettest half-century intervals of the past millennium. Many of the forests that stand today were established under these generally wet conditions.

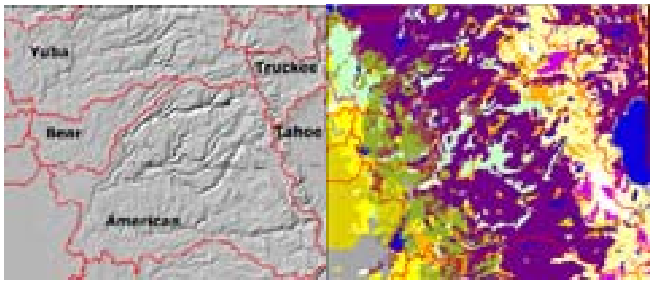

Figure 3. Shaded relief and vegetation maps for American River and Lake Tahoe area. See web site for legend, larger maps, other areas and description.

The Sierran crest divides water flow either west to the Pacific Ocean or terminating in the San Joaquin valley, or east into the Great Basin, where the water evaporates (Figure 3). Streams, creeks, and temporary waters define subwatersheds at increasingly smaller scales within these areas.

The major vegetation zones of the Sierra Nevada form large-scale elevational patterns, in north-south bands along the axis of the range (Figure 3). Major east-west trending watersheds that dissect the Sierra into steep canyons form a secondary pattern of vegetation. Diversity of regional and local plant species and vegetation types are highly influenced by climate, elevation (temperatures), and soil type.

Although the Sierra Nevada has been inhabited for over 10,000 years, the early 1800s began a period of increasingly intense resource use. Agriculture, mining, logging, and grazing were extensively practiced in many regions. The need to divert water to support resource extraction and settlement led to a major reordering of natural hydrologic processes through a vast network of ditches and flumes.

Although institutions are part of the ecology of the Sierra, nothing ensures that those institutions perceive the entire ecosystem, much less manage it in a sustainable manner. For example, the U.S. Forest Service and the National Park Service manage the land along the upper reaches of most Sierran rivers, while private landowners, the federal Bureau of Land Management, municipal utilities, and local irrigation districts manage much of the land along the lower reaches.

Existing Infrastructure

Existing infrastructure that the SNHO will use and build on includes: (i) long-term operational monitoring networks (many with over 50-70 years of data), (ii) more than 20 years of Landsat and AVHRR remote sensing data, (iii) long-term research programs, (iv) over 20 field laboratories, most of which have staff in residence, (v) a maintained transportation system, (vi) an emerging backbone communication systems, (vii) data and information systems, (viii) analytical laboratories at over 30 institutions within a few hours drive of the SNHO, (ix) well-characterized study regions (e.g. detailed topographic, vegetation, soils and other data), and (x) paleoclimate data from tree-ring records and lake sediment cores. In addition, there are complementary efforts that will greatly expand the scope of research measurements and infrastructure well beyond what would be possible with just NSF-CUAHSI-HO support.

The proposed SNHO will make heavy use of existing data and networks. Significant data are already being collected, though far short of those needed for either research or operations. For example, there is a backbone network of precipitation, snowpack and streamflow measurement stations in the watersheds of the Sierra Nevada (see website for maps).

Figure 4. Emerald Lake watershed

One significant long-term measurement program on headwater catchments is the whole-watershed effort that began at the 1.2 km^2 Emerald Lake catchment (Marble Fork of Kaweah River,

Figure 5. Nested flumes, KREW

Sequoia National Park) in the early 1980s and later expanded to the 20 km^2 upper Tokapah (Figure 4). Though a number of other headwater catchments have 3-7 year records or intensive water and chemical cycles, the 20-year duration of this record in the Sierra Nevada makes it unique. Sequoia/Kings Canyon and Yosemite National Parks have active research programs, with both extensive and intensive long-term data sets on ecology and related ecohydrology issues. Researchers in the Parks have characterized them well, so detailed maps of topography, multiple vegetation characteristics, soils, fire history and other attributes are available. The several UC Natural Reserves, which are maintained as natural laboratories for field research, have a variety of long-term data sets, as does the Lake Tahoe research group. The USDA Forest Service, Sierra Nevada Research Center has various facilities in the Sierra Nevada, including the Kings River Experimental Watersheds (KREW), a set of 8 heavily instrumented catchments to study the effects of forest management practices (e.g. fire, logging) on hydrologic processes and aquatic ecosystems, as well as air-pollution effects (Figure 5).

Field laboratories where visiting researchers can live and work in the Sierra Nevada include: (i) UCSB's Sierra Nevada Aquatic Research Laboratory and Valentine Reserve in Mammoth Lakes, (ii) UCSD's White Mountain Research Station near Bishop, (iii) UCB's Sagehen Creek Field Station (Figure 6) near Truckee and Central Sierra Snow Laboratory west of Lake Tahoe, which are part of UCB's Central Sierra Field Research Station network, (iv) UCM's Wawona (Yosemite) facilities, (v) UCD's Lake Tahoe area facilities, (vi) University of Nevada System's Incline Creek Experimental Watershed in the Lake Tahoe Basin, (vii) UCD's Eagle Lake Field Station near Susanville, (viii) Sequoia-Kings Canyon and Yosemite research facilities and (ix) KREW's field laboratories. Most of these have high-speed internet access, along with office, laboratory and living space. Some additional facilities have measurement infrastructure and structures for working, but not on-site living quarters. Researchers from all over the U.S. use these field laboratories when doing research in the Sierra Nevada, and in all cases there is capacity to accommodate more usage. New facilities are also being developed and others upgraded. For example, UCM's Sierra Nevada Research Institute is working with the two national parks to develop additional field facilities as part of the UCM-NPS long-term cooperative agreement.

Figure 6. Laboratory building at Sagehen Creek

Figure 7. Continuous conductivity sensor in Tuolumne River, along Tioga Road

California and Nevada provide all-season and seasonal access to both field laboratories and high-mountain measurement networks and research sites. For example, California 120, a high volume seasonal road, transects Yosemite National Park, providing access during summer and fall to the high country of both the western and eastern Sierra (Figure 7). Interstate 80 connects Sacramento and Reno, providing all-season access to the Truckee/Tahoe region. There are three main airports at the base of the Sierra Nevada, Sacramento in the north, Fresno in the south and Reno on the east. Bus service is available to Yosemite and along Highway 395 on the east side of the range.

For some data and instruments, timeliness is important. Such needs are apparent as an emerging backbone of communication systems is being deployed across the Sierra Nevada to meet demand for more efficient, robust, and reliable communication networks. An infrastructure is being built that relies on the GOES satellites, better cell phone coverage, and improvements in radio communication. For example, the Forest Service is using emergency radio frequencies for data (when there is no emergency) and Yosemite is planning a major upgrade to its radio communications system.

One of the challenges of the SNHO will be to capture the many historical and current data that researchers need in a way that promotes ready access. This is absolutely critical to the SNHO's success. Ongoing efforts such as UCD's Information Center for the Environment , the California Environmental Data Exchange Network, Alexandria Digital Library, the NASA REASoN project on Multi-Resolution Snow Products for the Hydrologic Sciences, the Western Regional Climate Center and others will contribute to the effort.

Several universities and government laboratories in and around the Sierra Nevada have expressed interest in contributing to the SNHO measurement effort. The demand for these laboratories as community resources will be explored.

Being in a semi-arid climate, the Sierra Nevada has many tree species that are sensitive to interannual variability in temperature and precipitation, resulting in excellent tree-ring records of climate for the past several centuries. Efforts are underway to expand those records, to reconstruct regional and even basin-scale precipitation and streamflow from paleoclimate records.

Proposed Core Data & Infrastructure

Our conceptual design for the SNHO involves a backbone measurement and communications system that provides intensive measurements in multiple nested basins along both the east and west sides of the Sierra Nevada. The backbone will involve elevational transects of measurement clusters through major ecosystems, extending from the foothills through the high Sierra. It is envisioned that each measurement cluster will have an eddy-flux tower for measuring water, energy and carbon fluxes, along with other properties. Where possible, the towers and instrument clusters will be located near streams that interact with groundwater, allowing quantification of fluxes at surface-subsurface and surface-atmospheric interfaces. As a strawman design, we have outlined a network of three elevational transects to be implemented with the initial NSF-HO investment. It would be desirable to implement a fourth transect in the north in a later phase, depending on availability of funds. Each transect crosses at least two of the basins draining the Sierra Nevada. We stress that this illustration is for conceptual purposes at this stage. Actual design of the system will take place over the next few months, and will involve considerations of latitude, elevation, precipitation, vegetation type, vegetation disturbance and regrowth status, existing measurement systems, and other variables. The core list of measurements (Table 1) continues to evolve.

Table 1. Measurement plan (preliminary)

Continuous
- Ground-based hydrometeorology instrument clusters
- Extended snow & soil moisture instrument cluster
- Flux towers along gradients
- Electrical conductivity, nitrate, silica, and otherspecies in selected streams
- Stream stage & groundwater levels

Periodic
- Snow cover, snowpack, soil moisture
- Stream, snow, rain, dry deposition, spring, groundwater chemistry
- Erosion

Characterization
- Topography, soils, forest canopy, land cover, geology
- Vegetation properties (LIDAR, mapping)

The Southern Sierra transect will build on long-term research in the Kaweah (Ash Mountain, Log/Tharpe Meadows, Marble Fork) and Kings (KREW, Teakettle) basins, and would have headwater basins in oak woodland, mixed conifer and subalpine ecosystems. Instrumentation placed in the Kaweah will provide nesting at scales from 1 to about 1,600 km^2. Including the confluence with the Kings River, the basin area is over 6,000 km^2. Most of the land is public, in Sequoia and Kings Canyon National Parks and the Sierra National Forest, with a variety of private landowners in the foothills. The presence of conservation trusts and active watershed councils at the lower elevations will facilitate research access.

Figure 8. Parker Pass Creek area, YNP.

The Central Sierra (Yosemite) transect will build on nearly 100 years of scientific research in the Park, several UC laboratories, and an already growing research measurement infrastructure using modern technology. There will be subalpine headwater catchments in both the Merced and Tuolumne basins, which, in contrast to the Kaweah basin, have better developed soils (Figure 8). Instrumentation placed in the Merced will provide nesting at scales up to about 3,200 km^2. Note that the Merced is tributary to the San Joaquin, which has a drainage area of 25,000 km^2 at that junction. We will leverage considerable research infrastructure in this greater San Joaquin basin, including an NSF-CLEANER planning effort that is designing an embedded sensor network for the basin, Bureau of Reclamation water quality measurement networks, and many local measurement networks operated by the State of California, irrigation districts, watershed councils and others. The groundwater part of this valley-wide network will be important to the SNHO for research on groundwater issues; we will evaluate the need for an SNHO investment in analyzing samples from groundwater wells, or other measurements needed to provide as complete a picture as possible of the subsurface flow system. The proposed SNHO will be of tremendous importance as valley researchers and decision makers try to put their studies in a whole-watershed context. This central Sierra transect will also continue over Tioga Pass to the east side of the range, down toward Mono Lake (Mono basin). It will link up with two intensive study sites, White Mountain research station and SNARL/Valentine, plus existing east-side networks (e.g. T-REX). The possibility of (re)establishing a headwater catchment site on the east side will be evaluated, possibly in the Rock Creek drainage just south of Mammoth Lakes. Headwater catchment research in that drainage began over 20 years ago, but the sites are currently inactive.

The Tahoe area transect will take advantage of considerable ongoing research in the American River basin, and extend east through the Truckee basin. Nesting in the American basin will be up to the scale of about 4,800 km^2. The Central Sierra Snow Laboratory has the longest-running snowpack data in the West (125 years of daily measurements), and Sagehen Creek Field Station has 50-year records of weather and streamflow, 35-year records of stream chemistry, and 50 years of research in fisheries and aquatic ecology. Sagehen and the adjacent Independence Creek provide paired headwater catchments, one in granitic and one in volcanic terrain, for studying the effects of lithology on hydrologic response. The Tahoe transect will also link up with the multi-million dollar per year research efforts on Lake Tahoe itself, including the surrounding watershed, being run out of UC Davis, University of Nevada-Reno, and its Desert Research Institute. Many other field facilities and measurement programs can contribute to the SNHO effort, including the Incline Creek Watershed (funded through NSF EPSCoR) in the northeast corner of Lake Tahoe, NV. Study components at Incline Creek have included biogeochemical cycling within upland forests, the effects that native plants have on soil water quality, snow pack distribution, temporal and spatial changes in stream water chemistry, and the impacts that urbanization has on surface water chemistry and stream habitat. At a larger scale, the Environmental Technology Lab (ETL) is planning a large-scale climate-weather connection experiment as the NOAA Hydrometeorological Testbed program, centered on the American River, involving *in situ*, aircraft, vertical profilers, upward pointing radar, and other fixed and movable measurement systems, for several years starting in 2005-06. SNHO will evaluate extending some of these measurements beyond ETL's study period, depending on interest from the community.

SNHO also plans to provide mobile observation platforms, which can be used on projects for shorter periods of time. These would be available to any scientist wanting to carry out research at the SNHO. Standard items will include similar suites of measurements as in the fixed installations, plus vehicles and technical support. Cooperation with the CUAHSI Instrumentation Technology initiative to provide specialty equipment for investigators using the SNHO would be ideal.

While this network will be the focus of the CUAHSI-SNHO investment, we are planning on considerable leveraging of resources. The network will both complement and include investments by other state, federal and private entities. We expect continuing commitments from non-academic partners to the SNHO, plus indirect support through the many researchers who will build the SNHO data infrastructure through their own grants. The Western Regional Climate Center at DRI is developing a California Climate Data Archive that will incorporate and provide data from SNHO, and deploying observational systems for long term climate monitoring. In some areas, we can co-locate surface instrument clusters with existing deep boreholes, water supply wells and other operational infrastructure. It is also our experience that measurements by volunteer groups, watershed councils and others can be quite valuable, filling important gaps in professional measurement efforts. There are over one hundred potential partner organizations in the Sierra Nevada with some capability to contribute to measurements.

The core measurement approach will make heavy use of automated, in-situ measurements and telemetry to reduce costs and make data available in near real time. Data will undergo automated quality control tests and then be immediately posted on the web and archived. Weather stations, stream flow gauges, in-situ chemistry systems, flux towers, and snowpack depth gauges will be linked in a near real-time network similar to the RAWS/SNOTEL networks of weather stations and the USGS real-time streamflow network. The SNHO will need to coordinate data archiving, access and retrieval protocols with the CUAHSI Information Systems group. We would like to see a data archive and distribution system with multiple user interfaces that will allow researchers anywhere to query, order, and download data with ease. These should include, for example, a GIS-based interface, a relational database and other interfaces adapted to user demand. In addition, this system should offer online interactive plotting and analysis tools for data visualization and manipulation. Examples of partial capability are the Climate Diagnostics Center and the Microsoft TerraServer.

Hydrologic processes in mountainous regions are highly variable in time and space, requiring remotely sensed data to observe local to regional processes and intensive field observations to observe hillslope-scale phenomena. Current understanding of the processes at these two scale extremes is largely disconnected, inhibiting the transferability of studies at the different scales. Further, the spatial and temporal non-linearity of hydrologic and biogeochemical processes requires simulations tailored to the scale of the application. While the SNHO budget will support only the modeling needed for quality control of the data, it will develop hydrologic observations to drive, validate, and calibrate models that simulate and couple hydrologic and biogeochemical processes at a variety of spatial and temporal scales. Modeling scientists are involved with the SNHO design, with the aim of making it the best test-bed possible for modeling research.

The measurement plan will take advantage of remote sensing data to characterize the spatial and temporal distribution of hydrometeorological variables that vary over large spatial scales, including: (i) a variety of vegetation characteristics, (ii) snow-covered area and (iii) radiation. We will make available historical and current data from Landsat, AVHRR, AVIRIS and MODIS. The combination of remotely sensed and ground based data will enable calculating a number of other spatial fields needed for model testing, site selection and data interpretation. We expect considerable leveraging of resources from other agencies to develop these remotely sensed data.

The baseline data and infrastructure will be community resources, and will be readily and widely available to the community. Individual investigators need ready access to the observatory data and facilities in order to do their own modeling, initiate their own intensive measurement campaigns and enhance their individual research. In this regard, a close working relationship between the CUAHSI Information Systems facility and all hydrologic observatories is essential for success of this collaborative, integrative research in the hydrologic sciences.

Example Science Questions

Science drivers motivate more specific science questions, which must pass peer review. The planning group has assembled a compelling (though not necessarily exhaustive) list of high-priority, candidate questions. These questions: (i) stem from the science drivers, and reflect rapidly changing components of the hydrologic cycle, (ii) require infrastructure investments, particularly long-term measurements to address the critical unknowns, (iii) are closer to the level of specific testable hypotheses and long-term research proposals, and (iv) may require field campaigns and modeling, but infrastructure needs stand out.

The SNHO aims to address the five science topics put forth by the CUAHSI HO planning group: (i) linking hydrologic and biogeochemical cycles, (ii) hydrologic extremes, (iii) sustainability of water resources, (iv) transport of chemical and biological contaminants and (v) hydrologic influence on ecosystem functions.

Many more specific questions and testable hypotheses can be posed within the larger science framework noted on page 2. An abbreviated list is presented here, in six overlapping categories, with more detail on our planning website.

1. *Range-scale precipitation meteorology & climatology*
   - What are the meteorological and climatic controls on precipitation in mountainous regions?
   - How is large-scale circulation modified by mesoscale forcing to influence the spatial and temporal distribution of precipitation?
   - What mechanisms generate interannual variability in precipitation?
   - How important is the rain shadow, both seasonally and from storm to storm? Does most precipitation fall on the top of the range, or part way up the slope? Is the location of the rain shadow changing?
   - What are the links between meteorological/climatological controls and extreme events such as major floods and wildfires?
2. *Snow distribution & snowmelt patterns*
   - What determines the seasonal (and transient) snowlines?
   - What role do snowlines play in the geomorphology, ecology, aqueous geochemistry, and hydrology of mountain catchments?
   - How (and why) do the seasonal snowlines vary from year to year? Are snowlines trending?
   - What role do geomorphology and ecology play in setting snowlines?
3. *Land surface hydrology and hydrology-vegetation interactions*
   - How do land-surface biophysical processes control partitioning of water into surface (including snow) and subsurface storage, and partitioning of rain and snowmelt into runoff, infiltration, evapotranspiration and recharge?
   - What controls the spatial distribution of vegetation/biophysics; how would this distribution change with changes in water availability and hydrologic extremes of flooding and drought?
   - How have land-use and land-cover changes affected these hydrology-vegetation interactions?
   - How do fire suppression, fires, stand thickening and logging affect land-surface biophysics, water balance, and nutrient cycling?

- How are the snow accumulation and ablation, and the partitioning of snowmelt and rainfall, affected in burned landscapes?

4. *Mountain block aquifer systems & their hydrologic linkages*
   - What are the principal geologic factors controlling groundwater storage, groundwater discharge to streams and groundwater chemical composition in mountains?
   - To what extent is large-scale groundwater flow in volcanic versus granitic regions occurring, and what is the effect of deep groundwater flow on hydrology and heat flow?
   - What are the impacts of land use management and distributed groundwater withdrawals during watershed urbanization on both nearby low-order stream habitats and distant, down-gradient aquifers?
   - To what extent do subsurface flow paths and residence times increase with scale in going from headwater catchments to the scale of a river basin?

5. *Biogeochemical cycling*
   - What is the importance of seasonal transitions to carbon and nitrogen biogeochemistry at the scale of a mountain range, i.e. across elevational and longitudinal gradients?
   - How do changing seasonal transitions affect carbon and nitrogen cycling in and export from aquatic ecosystems? How do they differ in rain vs. snow dominated areas?
   - How does lithology determine the sensitivity of catchments to climate warming and changes in the partitioning between rainfall and snowfall?
   - How do changes in the timing and duration of stream flows affect the formation and transport/fate of pollutants such as methylmercury in aquatic systems?
   - How do erosion patterns vary across the landscape and what is the response to disturbances?

6. *Water resources sustainability*
   - What are the effects of upstream watershed management practices versus climate change and extended drought on down-gradient streamflow and water quality?
   - What are the effects of changes in overall snowpack water content on sustenance of down-gradient surface water reservoirs and subsequent water availability for downstream urban, agricultural and ecological needs?
   - How can better data and information about hydrologic phenomena promote cooperative decision-making among competing water constituencies?
   - How can the SNHO stimulate development and use of comprehensive modeling frameworks that will empower communication between stakeholders?

References

(1) Mote, P. W. *Geophysical Research Letters* **2003**, *30*, 1601, doi:1610.1029/2003GL017258.
(2) Stewart, I. T.; Cayan, D. R.; Dettinger, M. D. *Climatic Change* **2004**, *62*, 217-232.
(3) Brown, T. J.; Hall, B. L.; Westerling, A. L. *Climatic Change* **2004**, *62*, 365-388.
(4) Cayan, D. R.; Kammerdiener, S. A.; Dettinger, M. D.; Caprio, J. M.; Peterson, D. H. *Bulletin of the American Meteorological Society* **2001**, *82*, 399-415.
(5) Knowles, N.; Cayan, D. R. *Geophysical Research Letters* **2002**, *29*.
(6) Miller, D.; Luce, C.; Benda, L. *Forest Ecology and Management* **2003**, *178*, 121-140.
(7) Cayan, D. R., Dettinger, M.D., Redmond, K.T., McCabe, G.J., Knowles, N., and Peterson, D.H. In *Climate and Transboundary Issues*; Diaz, H., and Woodhouse, B., Ed., **2003**; pp 237-262.
(8) Tague, C.; Grant, G. E. *Water Resources Research* **2004**, *40*.

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