MONITORING NETWORKS FOR LONG-TERM RECHARGE CHANGE IN THE MOUNTAINS OF CALIFORNIA AND NEVADA

A Meeting Report

Sam Earman, Desert Research Institute, Reno, NV
Mike Dettinger, US Geological Survey, La Jolla, CA

Presented at:
Willow Suite 1, Modoc Hall
California State University Sacramento
July 30, 2007

PIER WORKSHOP PAPER

DISCLAIMER

February 2008
CEC-500-2008-006

MONITORING NETWORKS FOR LONG-TERM RECHARGE CHANGE IN THE MOUNTAINS OF CALIFORNIA AND NEVADA--A Meeting Report

Sam Earman, Desert Research Institute, Reno, NV
Mike Dettinger, US Geological Survey, La Jolla, CA

Executive summary

Recent recognition that climate change may cause significant shifts in ground-water recharge in the mountains of the western United States suggests that long-term monitoring is needed to provide bases for prediction and early-warning of such changes. Although climate change has the potential to alter recharge processes in all parts of the world, the mountains of the western US may be especially vulnerable because much of the ground-water recharge in the West is derived from snowmelt, and a warming climate is expected to significantly change the distributions and volumes of western snowpacks. In the absence of long-term monitoring for changes in ground-water recharge, water managers might have to deal with significant and unexpected changes in water availability from both ground-water fed surface-water and ground-water sources.

A recent workshop convened 30 Earth scientists to discuss whether monitoring methods currently exist that could be used to begin gathering the observations needed to determine how ground-water recharge varies and changes in California and Nevada, and what the practical requirements for such monitoring would be. Methods based on ground-water hydraulics, geochemistry, geophysics, biology, and streambed physics were surveyed and considered. The consensus among workshop participants was that long-term monitoring for recharge change would be an effort of great value to the hydrologic community, and also would have a broad impact because of the societal importance of western ground-water supplies. In addition to tracking secular changes in ground-water recharge in the future, such a network has the potential to fill gaps in our understanding of ground-water recharge processes and ground-water occurrence and behavior in mountains. There was general agreement that a long-term monitoring network to detect changes in recharge should integrate multiple approaches, allowing more complete interpretations of the results from any one method and crucial independent checks on each that would not be possible using any single monitoring method. Unfortunately, the input received at the workshop indicated that the hydrologic community does not currently have the experience needed to establish a viable long-term multiple-approach monitoring network for recharge change in western mountain settings. While some available methods appear to be viable already in mountain settings, many of the methods deemed appropriate have never been applied in mountains, where long-term monitoring would be focused; other available methods have been used in mountains, but have never been applied more than once at any given site, meaning their use in a long-term, comparative context is untested. These deficiencies must be addressed, either through basic research or as part of a focused program, before a viable monitoring network based on integration of multiple methods can be established. More experience with characterization of recharge exists at the base of mountain, so that more immediate moves towards regional monitoring may be possible there.

Conclusions from the workshop include

- Mountain-recharge monitoring is necessary in at least some key and representative locations in California and Nevada if we are to detect and understand recharge change as early as possible
- A network that integrates several methods (hydraulic, geochemical, and geophysical, at least) would provide the most confident results
- Research applications of monitoring methods in mountain environments in some already well-instrumented watersheds would allow many current hurdles to widespread application in mountain settings to be resolved as quickly as possible, while leveraging existing investments for other purposes
- Locations like (but not restricted to) the Kings River Experimental Watershed and Sagehen Creek basin in the western and eastern Sierra Nevada would be good candidates for such research
- Monitoring at springs may provide a widespread and very sensitive initial approach to recharge monitoring, especially in Nevada
- More deep monitoring wells in mountain blocks (or equivalent structures like mines) may be crucial to understanding of high-altitude ground-water recharge processes; more paired streamflow gauging stations (to measure streambed seepage losses and gains) identified or established in mountain settings could provide immediate gains
- Networks of clustered monitoring wells sited at the foot of key mountain drainages could serve as focal locations for multi-method monitoring and may provide an opportunity for near-term steps towards widespread observation of recharge variability and change at the regional scale

1. Introduction

Recently, concerns have been raised as to whether recent warming trends, and the future warming that they appear to presage, threaten depletion or significant changes in ground-water recharge rates in western mountains and basins (Earman *et al*., 2006; Dettinger and Earman, 2007). Although large uncertainties cloud these concerns, the potential threats are significant. At present, however, observations needed to detect such depletions or changes, or even to provide strong bases for predicting such changes, are not being made routinely enough to establish baselines or changes. A workshop with approximately 30 attendees (Appendix 1) was held in Sacramento, CA on July 30-31, 2007 in an attempt to determine whether monitoring methods exist that could be used to begin gathering such observations and what the practical requirements for such monitoring would be.

Functions that could be provided by a long-term network monitoring recharge variability and change in western mountains include:

- A methods-development function: Can temporal variations of recharge be monitored in the long run?
- A monitoring function: How does recharge vary and change at selected sites?

- A research function: By what mechanisms is recharge varying?

With these network goals in mind, the objective of the workshop was to address two primary questions:

- What methods are now available for characterizing recharge and, especially, recharge change, and which methods seem suitable for transition to long-term monitoring purposes?
- What would be the proper characteristics of a network for monitoring recharge variability and change in the mountains of California and Nevada?

In retrospect, a 2004 report of the National Research Council (NRC; National Research Council Committee on Hydrologic Science, 2004) recommended that—for a variety of reasons—experimental sites should be established to improve our understanding of ground-water recharge, and to improve measurement techniques that can be applied to recharge quantification. A further recommendation was that a study or workshop be conducted, with focus on developing plans regarding the establishment of monitoring sites. The Sacramento workshop was thus also a step toward addressing the NRC's second recommendation.

The meeting began with background presentations from the workshop organizers, describing the current understanding of climate variability and change, and the potential for resulting recharge changes. Professor John Wilson from New Mexico Institute of Mining and Technology then provided an overview of recharge and terminologies for describing it, in order to provide a common language for subsequent discussions. A key definition was the distinction between "diffuse" and "focused" recharge, being, respectively, dispersed recharge over broad areas and recharge in concentrated locations or along narrow features (like streambeds).

Then, six tutorials on potential methodologies for detecting, quantifying and monitoring ground-water recharge variations were presented, covering hydraulic/well-based methods, geochemical and isotopic methods, dissolved gas methods, geophysical methods, stream-based methods, and biological methods.

A summary of the concerns that motivated this search for ways to monitor long-term variations of ground-water recharge in western mountains follows in section 2. Then a cursory listing of some of the observation methods that may be most suited for use in long-term monitoring for recharge change is presented in section 3. A more detailed synthesis of possible monitoring options makes up section 4, with a list of conclusions provided in section 5.

2. The risks of recharge change

All current projections of climate change by modern global climate models predict warming over the United States, with projected temperature changes over the conterminous States from about +3° to +6 °C. Predictions of precipitation change are less unanimous, but there is some consensus that moderately drier conditions will develop in the southwestern USA (conclusions by the authors from analyses of projections used in Intergovernmental Panel on Climate Change (IPCC) 2007; see also Seager *et al*., 2007). These predictions, especially the more-certain projection of warming, suggest that assessment of climate-change impacts on water supplies, including ground water, are urgently needed. Warming will likely reduce runoff generation, whether precipitation increases or decreases, because of likely attendant increases in the potential for evapotranspiration. In this context, water sources may become all the dearer, which also motivates the need to begin monitoring one of the main water sources in the West, ground-water recharge.

Ground-water systems could be influenced by warming in many different ways. One of the major concerns for climate effects on water supplies in the western United States is the impact of warming on snowpacks. Because Western mountains are generally wetter and cooler than adjacent basins, most ground water is derived from mountain precipitation. Some of the recharge occurs as 'in-place' recharge in mountain blocks, and sustains important mountain ground-water supplies, springs, surface-water base flows and cool water temperatures. Infiltration into alluvial fans or basin floors from runoff that crosses from mountain blocks is an important source of ground water in basin aquifers, along with subsurface flows of ground water from within the mountain blocks to the basin aquifers.

Several studies in Western mountains have shown that snowmelt provides more in-place recharge than does rain, even when snow makes up a relatively small portion of the total precipitation at the sites (*e.g.*, Earman *et al*., 2006). In large part, this is because the accumulation of multiple precipitation events in the snowpack provides an amount of water for infiltration that is large enough to break through the thick unsaturated zones that are common in many western settings, while water from individual rain events may not be sufficient to overcome the evapotranspirative demands of the unsaturated zone. Studies in the Southwest indicate that 50 to 90% of mountain recharge originates as snowmelt (*e.g.,* Earman *et al*., 2006, Simpson *et al*., 1972, Winograd *et al*., 1998). For example, recharge-temperature analyses of dissolved gases in ground water suggest that recharge in the central part of the Chiricahua Mountains, Arizona, is derived only from altitudes above seasonal snowlines and not from lower altitudes (Earman and Phillips, 2003). Geochemical hydrograph separations in the highest basins of the Rockies demonstrate that, even during the peak snowmelt, 60% or more of the streamflow is supplied by ground water (Liu *et al*., 2004). On the other hand, recharge from streamflow infiltration through fans and basin floors depends on large, rapid, but generally infrequent, outflows of runoff from the mountains onto surrounding fans and basins. The mix of mountain vs. fan and basin recharge presumably varies from basin to basin and from year to year, but these variations are poorly understood in most of the West.

Western North America has warmed in recent decades (Cayan *et al*., 2001) and, as a result, precipitation has occurred more frequently as rain rather than snow (Knowles *et al*., 2006) and snowpacks have thinned (Mote, 2003). If warming continues, snowline elevations are expected to rise and snowpack water contents will continue to decline. If this happens, mountain recharge may also be expected to decline, because recharge areas will shrink and the amount of snowmelt available to infiltrate at any one time will dwindle. Using the University of Washington's VIC model (Maurer *et al*., 2002), recent simulations, by the authors, of near-surface water budgets in the western mountains, with and without warming, suggest that the partitioning of net precipitation between surficial runoff and subsurface runoff may respond to warming with declines in subsurface runoff of as much as 50%. These declines would likely also be reflected in ground-water recharge declines.

On the other hand, another simulated result of warming in the western mountains is relatively more surficial runoff. Declines in mountain recharge triggered by loss of snowpack would have immediate impacts on mountain water resources, including low flows and stream temperatures, and may also have serious impacts on long term ground-water supplies in surrounding basins due to reductions in the subsurface outflows from the mountain blocks to adjacent basins. Although recharge that supplies mountain ground water may decline, much of the water that fails to infiltrate into the mountains may run off onto the region's fans and basins and potentially may increase recharge on fans and basin floors. However, if the unrecharged water is instead mostly evapotranspired from the mountain soils, the overall recharge (mountain plus basin) may decline. In addition, the potential for increased recharge is dependent on the existence of sufficient 'accommodation' space in the aquifer that would receive the recharge (Phillips et al., 2004). Finally, changes in water temperature (should they result from the warmer climates) will affect the hydraulic conductivity of streambeds so that infiltration rates would change directly as a result, in as yet fairly uncertain ways. As indicated by this difficult chain of possibilities, at present, the extent to which the overall recharge will increase, decrease, or stay the same in response to warming is unknown at any scale in the West. Similarly, the impacts to ground water supplies due to changed locations and timings of recharge are poorly understood.

Given ground water's crucial role in western water supplies (both surface and subsurface), the potential impacts of warming on recharge deserve more attention than they have received to date. It is possible that ground-water supplies will fare well, overall, in a warming world, but they may also fare poorly. The projected climate changes are unprecedented in the modern era, and we lack the tools and data to confidently detect or predict ground-water responses to climate.

In order to address these concerns, and to move toward early-warning systems for possible ground-water responses to climate change, more long-term observations of ground-water processes, with particular focus on ground-water recharge, are needed. There are few locations where year-to-year fluctuations of recharge in the West are routinely observed or inferred. Sites where recharge fluctuations can be inferred from current hydrologic monitoring networks are generally along river channels where losses to infiltration can be inferred from synoptic measurements of river discharge. We have found no locations where recharge fluctuations in western mountains are being monitored regularly. Monitoring commitments like the USGS's national-scale Ground-Water Climate-Response Network (http://ogw01.er.usgs.gov/USGSGWNetworks.asp) are a start, but that network's focus on ground water level variations from days to years is likely insufficient to provide early warnings of recharge depletions in western settings. Such monitoring efforts need to be extended to address multidecadal time scales and beyond ground water level fluctuations to the full range of ground-water issues and processes, including recharge fluctuations. Otherwise, changes may come from unexpected directions to ground-water managers and users.

3. Available methodologies for monitoring mountain-recharge variations

In recent years, a number of scientific studies have used a variety of methods to detect and characterize ground-water recharge processes at locations around the western US. Typically, these studies have provided short-term snapshots of recharge rates and processes, or aquifer responses, rather than characterizing longer term temporal variations in these rates or processes. Such studies have used:

- Well-based methods
- Chemical and isotopic methods
- Geophysical methods
- Stream-based methods
- Biological methods

The primary question addressed by the workshop was whether or not any of the methods were suitable (and mature enough) for use in characterization of long-term recharge variations as parts of sustained monitoring networks.

3.A. Well-based methods

Ward Sanford, USGS, provided an overview of well-based methods for quantifying recharge. Because ground-water recharge variations will generally cause changes in the water table of an aquifer, monitoring changes in water levels in wells as a function of time can yield information on ground-water recharge processes (e.g., Hanson *et al.*, 2004). Current applications of well-based methods typically utilize available data, as opposed to a dataset specifically designed to examine ground-water recharge. Gathering high-quality data in a focused and sustained manner would afford a much better view of recharge and recharge changes than is currently available. Observation methods for monitoring water levels in wells are well established and, in recent years, the required instrumentation (e.g., submersible pressure loggers) has become compact, robust, and inexpensive. Boreholes and piezometers within which to make the water-level measurements remain relatively expensive to construct.

The simplest well-based method (after Healy and Cook , 2002) involves using the equation

$$\text{recharge} = S_y \frac{dh}{dt},$$

where S_y is specific yield, *dh* is the change in head, and *dt* is the change in time. Two disadvantages to this method are that it is a point measurement, and that S_y must be known or estimated in order to calculate a value for recharge. A number of point measurements could be interpolated to come up with larger-scale continuous estimates of recharge. If detecting recharge change rather than the absolute amount of recharge is the main goal of the measurement, then S_y would not need to be estimated.

Mountain fronts are probably the best places to use well-based methods, as observations at the mountain front integrate what is happening in the mountains above. In addition, changes in mountain-front recharge could occur over much shorter timescales and earlier than more distant changes in storage in basin aquifers resulting from shifts in mountain-block recharge rates. Sanford speculated that 20 to 30 well clusters at mountain fronts around the West could provide good indications of large-scale changes in mountain front recharge.

3.B. Chemical and isotopic methods (including dissolved gases)

Concentrations and amounts of certain dissolved ions, gases, and isotopes (either as dissolved species or as parts of water molecules) from water samples can yield information about many processes that the water has undergone. In many recent studies, this information has provided insights into recharge processes. Professor Fred Philips of New Mexico Institute of Mining and Technology provided an overview of chemical and isotopic methods useful in characterization of western recharge. The type of recharge being investigated can drive the types of geochemical methodologies required. This is because some geochemical methods are more suited to determining signatures of, or changes in, near-surface water balances that commonly determine diffuse-recharge rates, whereas other methods mostly indicate ground-water ages and travel times. These ages and times are typically better suited to rapid transports associated with focused recharge.

Diffuse recharge typically results when overall precipitation and infiltration rates exceed collocated evapotranspiration rates sufficiently to provide deep and sustained infiltration of excess water for recharge. Two methods that can be applied to monitor the effects of evapotranspiration are chloride mass balance, and the use of δD and $\delta^{18}O$. Because chloride is often essentially conserved along ground-water flow paths, if precipitation amounts and the concentration of chloride in precipitation are known, an estimate of recharge can be made by using the concentration of chloride in ground water to determine the percentage of the original precipitation that was evaporated. Multiplying the non-evaporated percentage by the total precipitation volume yields the recharge estimate (*e.g.*, Dettinger, 1989). Values of δD and $\delta^{18}O$ are affected by evaporation; on a plot of δD vs. $\delta^{18}O$, evaporation will cause the remaining waters to plot along lines with slopes between approximately 3 and 6. The amount of ground-water recharge is inversely proportional to the square root of the length of these evaporation lines (Allison *et al.*, 1984).

Focused recharge is associated with the provision of water to vertical pathways of relatively high permeability that allow water to be concentrated and directly "injected" into the ground-water systems. Most often, water is provided for focused recharge by rapid accumulations of surface or near surface flows along stream channels, fractures, or local impoundments or surface depressions, with little time for evapotranspiration to modify the geochemical signatures of the waters. Under these conditions, travel times and ground-water ages may be the better indicators of recharge variability. Chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and tritium (^3H; sometimes used in conjunction with helium-3 (^3He)) can all be used to estimate water ages. Time-series measurements of water age at a given location could indicate changes in water velocity resulting from recharge-induced changes to the hydraulic gradient.

Andrew Manning (USGS) provided an overview of the uses of dissolved gases in characterization of recharge. In particular, concentrations of dissolved gases such as nitrogen, He, Ne, Ar, Kr, and Xe in water can be used to determine the temperature and elevation at which ground-water recharge takes place (e.g., Earman and Philips, 2003; Manning and Solomon, 2003). As discussed earlier, climate change might cause a shift in recharge from in-place mountain recharge to focused infiltration of runoff in alluvial fans and basin floors. As a result, monitoring inferred recharge elevations in distal areas of basin aquifers could yield insight into whether this process is occurring, and if so, the magnitude of the shift. Measurements of "excess air" in ground water can also be useful in understanding water table dynamics, especially in mountainous areas.

Geochemical methods have been used in many settings around the west to discriminate between ground water and surface runoff amounts, between recharge sources areas, and (less so) to detect rapid recharge pathways (*e.g.*, Liu et al, 2004). None of the workshop participants knew of instances where the methods had been repeated over time to detect changes in recharge in mountain environments or otherwise.

3.C. Geophysical methods

Don Pool (USGS) described a number of geophysical methods that might provide ways to monitor ground-water recharge, including electrical resistivity, gravity, seismic wave propagation, dielectric permittivity, and electro-magnetic methods. Geophysical methods are likely not the best tools for exact quantification of recharge, but they can be very useful for interpolating between points where other methodologies are applied, thus allowing recharge estimation on a relatively large scale.

Repeated microgravity surveys have been used to estimate amounts of water injected into alluvial aquifers by concentrated recharge events (Pool and Schmidt, 1997). Measurement of the gravitational potential at a site is influenced by the increases or decreases in the volume of water in the pore spaces in the subsurface below (or, in the case of sites in mines or tunnels, around) the instrument. If increased recharge adds 2.5 cm of water in the subsurface, the gravitational force measured above will be approximately 1 Gal (1 Gal = 1 m/s^2). A change of 1 microgal at a location would (with few exceptions) indicate that about 2.5 cm of water had been added to the subsurface by recharge or some other mechanism. Long-term monitoring of changes in gravity could thus yield information on temporal changes in ground-water recharge. The method could be especially powerful if at least one gravity-monitoring station was co-located with a water-level monitoring site. Using the relationship between gravity and water level, gravity data collected in the surrounding area could be used to interpret storage changes over a broad area without the presence of wells.

Gravity data could also be useful to delineate aquifer extent. In mountain-front areas, seasonal changes in water levels can be quite large; this could be the result of large volumes of water being added to the aquifer, or a relatively small volume of water being added to an aquifer of limited extent. Understanding reservoir extent via gravity data would aid in conceptual and numerical model development for each monitoring site.

The primary, known restriction on microgravity-based monitoring of recharge changes in mountains is a lack of experience with applying it in these rugged terrains and conditions using readily available equipment. One study has proven successful in using gravity measurements to understand water storage in mountainous terrain (Hassan et al., 2006), but it used a superconducting gravimeter with 1 μGal accuracy; non-superconducting gravimeters have accuracy of 2 or 5 μGal (for absolute and relative instruments, respectively). Gravity measurements using standard gravimeters have been quite successful at detecting and quantifying isolated recharge events in some western basins [e.g., Parker and Pool, 1998]. Gravity measurements for elucidation of ground-water conditions have proven to be most successful in areas that receive periodic recharge, which gives hope that mountain applications would be viable.

3.D. Stream-based methods

Detecting focused ground-water recharge through stream channels is an important component of recharge monitoring. As described by Jim Constantz (USGS), a number of stream-based methods could be applied, some of which overlap with other techniques (*e.g.*, chemical or isotopic methods). In addition, analysis of stream gauge records (preferably from multiple gauges at different locations on a stream), seepage runs, dye tracer studies, and measurements of heat conduction are all methods that could be of use in recharge estimation. Heat-based methods measure the relations between water temperatures in and beneath streams to determine when the stream is gaining water, losing water, or not interacting significantly with the subsurface (Stonestrom and Constantz, 2004). With detailed modeling of flow and heat transports, the temperatures can be used to infer recharging intervals and rates; without modeling, the temperatures can provide information about durations of recharge but typically not rates of recharge.

Heat-based methods and stream gauge monitoring have seen the most widespread use (among methods discussed here) and are the most cost-effective procedures for long-term recharge monitoring.

3.E. Biological methods

Don Sada (Desert Research Institute) provided an overview of the biology of western springs, indicating that observations of the organisms that inhabit spring pools and streams can yield insight into the past history of flow volumes relative to current rates.

Different organisms and communities prefer (or require) to inhabit settings with low flows or high flows, steady flows or variable flows, perennial flows or intermittent flows (Sada et al., 2001). As a result, surveys of organisms inhabiting spring pools could be used to identify springs with either long-term stability of discharge or a lack thereof; this could be an important screening tool when deciding which springs might be most immediately responsive to recharge changes for a long-term monitoring network. In addition to being used as a screening method to select springs for other types of monitoring, biological observations can be part of long-term monitoring efforts. Because organisms dwelling in spring pools are sensitive to parameters such as water depth and water temperature on time scales of days to months, long-term repeat monitoring of the biota associated with a spring can yield information on changes in spring discharge, which can be related to changes in recharge (although the quantitative relationship between changes in recharge and changes in discharge may not be known).

To date, this sort of inference of spring histories from their inhabitants has been applied mostly to basin-floor springs, rather than to high mountain springs. Thus application of biological methods to the detection of changes in mountain recharge will likely require some additional research and mountain-based case studies.

4. Design of a recharge-change monitoring network

4.A. Operational vs. research network

There was consensus among workshop participants that long-term monitoring for recharge change would be an effort of great value to the hydrologic community, and would also have a much broader impact because of the societal importance of water supplies. In addition to possible insight into future changes in ground-water recharge, such a network has the potential to fill gaps in our understanding of ground-water recharge processes and ground-water occurrence and behavior in mountains.

However, it does not appear that observational technologies are currently ready to implement a "free-standing" long-term multi-approach monitoring network to detect changes in ground-water recharge within western mountain settings, where by "free standing" we mean capable being designed and operated without parallel research for ongoing development of methods and procedures. That is, it does not appear that a fully operational multi-approach network can be constructed at present; rather, any network initiated in the near future must incorporate a very strong research and development component. The main reason for this is lack of experience with using many of the appropriate methods in mountain settings or for long-term monitoring (rather than case study) purposes. For instance, gravity methods have been widely applied in alluvial/valley settings, but not in mountain settings, so the utility and at least some critical network design aspects of gravity data collection in mountain environments is unknown. Another example is geochemical water dating techniques. These methods have been used in a variety of settings, including within mountains, but the workshop group was unaware of any site where even a single set of repeated measurements was performed. As a result, the hydrologic community has no experience interpreting repeated samples, as would be required for long-term monitoring. The biological methods discussed earlier have not been applied in the mountain contexts in which they would be required for the proposed mountain-recharge monitoring network.

This leaves two main options that can be pursued at present. The first would be to retreat from the concept of establishing a long-term multi-approach monitoring network to detect recharge change; when (or if) enough experience is gained that the array of techniques believed appropriate to apply is ready to be used, the concept of a long-term monitoring network could be revisited. The second option would be to begin with scaled-back implementation (e.g., one or two sites instead of six or seven) of a long-term monitoring network, with all participants fully cognizant that the first several years of operation would be in 'learning mode' to gain experience in needed areas and fill in gaps in the current knowledge base. Once the knowledge gained allowed full-scale network implementation, the network could be expanded to its full size.

One possible drawback of the first option is that, for years, the hydrologic community has not addressed the problem on its own. As examples, the use of gravity measurements has been common within the geophysical community since at least the 1960s, and 'young' ground-water dating methods, such as $^{3}H/^{3}He$ dating have been in use since the late 1980s. Given that these two methods have not applied in the manner they would likely be used for long-term recharge monitoring during the ~50 and ~20 yr elapsed times from 1960 and 1988 (respectively) to the present, it is debatable whether the background knowledge required to start a long-term recharge monitoring network will ever be gained without specific intervention, such as focused RFPs from funding agencies. Thus, a sub-option for this scenario would be for agencies interested in development of a long-term recharge monitoring network to solicit and fund research in needed areas as part of the start-up cost of a monitoring network.

A drawback to the second option is that operating in learning mode makes it likely that some of the methodologies utilized initially might be discarded or changed significantly, as might sampling intervals and other parts of the initial plan. As such, some or all of the data collected during the initial period would not truly be part of long-term monitoring, as long-term monitoring requires data collected in a consistent manner. Furthermore, in the current state of uncertainty about how the methods will perform in mountain conditions, it is difficult to determine *a priori* what the best sites for monitoring will be. Thus, some sites used in the learning period may eventually be abandoned as unproductive.

Beyond the mountains settings, more technical experience exists with using well-based, gravity, stream-based, and some geochemical methods to characterize recharge variations in the surrounding basins and, in particular, at the base of mountain drainages (see previous discussions of individual methods). Thus monitoring for basin-recharge change may be more immediately feasible (although long-term applications of the methods even in basins have been uncommon). Basin-recharge change, however, may take longer to be detectable than the recharge changes nearest declining snowpacks.

Another concern was that changes detected by a long-term monitoring network could be part of natural variation. However, no monitoring of the type proposed here is currently underway, so, at present, we do not even have rudimentary knowledge of natural variations in mountain recharge. Thus, detection of long-term recharge variations is of at least as much importance to understanding ground-water systems under "normal" conditions as under changing-climate conditions. Furthermore, it is precisely because the community is inexperienced with even natural fluctuations of recharge that we have been so eager to initiate a long-term monitoring program rather than just more case studies; the need for such a program is not just to detect climate-change impacts but to monitor enough of both climate change and natural variability so that, as soon as possible, the two can be confidently distinguished from each other. Because ground-water supplies are critical to the western USA, we should be aware of any changes to ground-water systems, whether part of natural cycles or otherwise. Ensuring that at least some sites in the network have historical records of streamflow, temperature, precipitation, and other parameters dating back to at least the 1950s would also allow better evaluation of how changes observed in the future relate to past changes.

4.B. Network components

Although it does not appear that the hydrologic community is ready to launch a long-term "free-standing" network to monitor for changes to ground-water recharge directly within the mountain settings, the workshop participants outlined several characteristics that a long-term recharge-monitoring network should have.

In the face of current lack of experience with such monitoring and the need to mount the learning curve in a productive and economical way, a tiered network of sites was judged to be the best design strategy. The first tier would comprise a large number of sites where, at each, the number of different observations was relatively small and the monitoring interval relatively long; a second tier would be a smaller group of sites where many types of observations were performed, and the frequency of observations would generally be much higher. Still more intensive observations might be undertaken at still higher tiers in the network. One advantage of such a network design is that similar events observed at a small group of sites may have a too-strong possibility of being random chance. If, on the other hand, events documented by detailed observations at a small group of sites are found to be shared with related events indicated by less intensive observations made at a much larger group of (first tier) sites, it would be much more difficult to attribute the commonality (or geographic patterns) to chance. Workshop participants suggested that two to six intensely monitored mountain sites, and 30 to 50 or more sites with less intense monitoring, might be an appropriate target size at the scale of the Western States. Ward Sanford (USGS) proposed that well clusters at the foot of key mountain catchments could build upon the greater technical experience in such settings to begin the broader network component.

In addition, the same concept could be applied to individual high-intensity sites. In that scenario, high-quality data (many types of observations, high observation frequency) could be collected at a few clusters, surrounded by a halo of locations where fewer types of observations were made and observation frequencies were lower.

4.C. Co-location of observations

It will be important to monitor both ground water and surface water. Both are important resources; in addition, they are related through the hydrologic cycle. So, although the main concept behind the monitoring network would be changes in ground-water recharge, observations of both surface water and ground water will be needed to accomplish that goal.

An important step in selecting monitoring sites is a thorough evaluation of the current stream gauge network, as well as an assessment of former gauging sites that have long-term data. This would suggest locations with tie-ins to existing long-term data. While establishing long-term monitoring sites in conjunction with extant stream gauging locations would be ideal, compared to establishing a stream-gauging site from scratch, re-establishing a decommissioned site with a long-term record would be less costly, and would also have the advantage of historical data to which ongoing observations could be compared. Stream gauges located in bedrock control points at or near the mountain front would be valuable for integrating discharge coming from the mountain block, and would be likely to show changes on relatively short timescales. On the other hand, ground-water monitoring is also important because water levels tend to be smoother than surface water signals; smoother signals will make it easier to separate long-term trends from noise in the signal.

Where possible, observations by several means should be collocated. Because it is fundamentally a dispersed, subsurface (and thus hidden) process, recharge is never directly observed or measured, but rather is inferred by its influences on other aspects of the physical, chemical, or biological systems. The ability to draw accurate inferences is always a concern and depends on location, (often transient) hydrologic conditions, and methods used. Consequently, the most confident inferences are those bolstered by concurring (or at least consenting) inferences drawn by several different approaches. A network that uses several essentially independent methods to characterize recharge variations at a given location will provide the most confident results.

Furthermore, recharge and ground water are just one component of any hydrologic system, so that other crucial checks on inferences about recharge (including mechanisms of change) will depend on observations of other aspects of the hydrologic cycle, including precipitation, snowpacks, evapotranspiration, and runoff.

Thus there will be significant benefit from establishing network sites that collocate recharge-oriented observations by several different methodologies, and in conjunction with sites that already have significant hydrologic monitoring effort (for other purposes), such as Critical Zone Observatories (CZOs; Brantley *et al*., 2006), the Long Term Ecological Research sites (LTER; Long Term Ecological Research Network, 2005), and USGS Water and Energy Biogeochemical Budgets (WEBB) sites (http://water.usgs.gov/webb/). Notably, although they are generally the locations of large investments in research-grade hydrologic observations of shallow-subsurface to atmospheric boundary layer processes, these sites are not currently collecting data suitable for characterizing ground-water processes in their mountain settings. In particular, the kinds of observations being made are not the types of data needed for ground-water recharge evaluation. However, they do provide some of the best observational characterizations of other aspects of the hydrologic cycle available, so that they provide a strong context for closing hydrologic budgets with observations of recharge. At the same time, observations for recharge monitoring will only strengthen the interpretations of other monitoring efforts at these sites, so that collocation at those sites should be a welcome addition in many of these other networks. A significant amount of money is being spent at these sites to close the water balance, but the ground-water component of the hydrologic cycle is being ignored or given short shrift at many of these locations. As a result, ground-water monitoring data should help many of the existing monitoring sites to achieve their missions. Generally speaking, recharge observations collocated with observations of other aspects of the hydrologic budget are likely to be the best sites for testing and optimizing recharge-change network components and methods. In addition, conceptual models of many aspects of these sites (*e.g.*, impact of site geology on streams) have already been developed, requiring less effort to be expended in determining locations for data collection.

One possible risk of such a piggybacking strategy is that it assumes that these other networks will continue to be funded to pursue their present goals indefinitely. For instance, if some or all of the observations in a long-term recharge monitoring network are directly dependent on observations from co-located CZO sites, loss of funding for the CZO sites or a refocusing of CZO goals would deal a significant blow to the viability of the recharge monitoring network. In a sense, this can be considered a cost/risk issue during recharge monitoring network design: piggybacking onto existing monitoring sites would result in a significant cost reduction, but it would incur the risk of losing vital data streams in the future if other monitoring programs are changed.

4.D Site types

Recharge observations and inferences can be centered on either wells or springs. This is because springs can provide natural access to the conditions of ground-water flow through a portion of the mountain range, with the advantage of not needing to either site or pay for construction in most cases. Springs are generally the focus of nearby flow paths and thus integrate conditions over broader lateral areas than unpumped wells. Wells, on the other hand, provide access to a more vertical sample of the subsurface flow conditions and are less likely to dry up immediately if recharge rates decline. This same potential sensitivity of springs, however, makes them especially appealing as monitors of recharge variability, at least until they dry up. The advantage of hydraulic integration in springs can be a disadvantage with respect to geochemical sampling, as spring discharge can mix waters from different sources with different chemical and isotopic characteristics, which muddies interpretations, and often provides geochemists with much less control over mixing with the atmosphere where samples are being collected. This lack of specificity and control renders such springs poorer choices for methods such as $^3H/^3He$ dating. In other applications, e.g., for chloride-balance monitoring of recharge, having access to the broad lateral mix of waters from an area can be useful because the resulting recharge estimates are indicative of larger scale patterns. Wells would provide the opportunity to sample waters with less mixing, and thus less effect on the geochemical characteristics. Another advantage of wells compared to springs is that their locations can be planned; while it is unlikely that a series of springs with optimal lateral spacing will exist in along a flowpath, it would be possible to site wells in such a manner.

To allow timely detection of recharge changes, at least several springs at a monitoring site should have fast response times (< 1 yr) , discharging waters with short subsurface residence times (< 10 yr). Springs with longer response times will eventually also be valuable to monitor how changes in recharge propagate temporally, but rapid response will provide important experience with detection of variability and change in the near term, albeit amidst much short-term "noise". Because ground-water contributions are critically important to streamflow in the West, wells and/or piezometers should be installed such that an understanding can be gained of how different portions of the ground-water system (shallow versus deep flow) contribute to streamflow. Beyond that guideline, the current dearth of wells in mountains and alluvial fans means that the optimal distribution of wells is largely unknown. Elevational transects may be an important network design strategy because water tables will likely follow topography in the mountains and fans, as they tend to do in other areas. However, the number of wells needed to allow areal integration is not known. A minimum of three wells would be needed at any site, in order to determine the direction of lateral flow at all times, but our current understanding of mountain/fan systems does not allow determination of whether such a small number of wells is enough to make reasonable interpretations of areal integration, or whether a much larger number of wells would be needed.

Ideally, clusters of intensive monitoring should be large enough that they incorporate a significant range in elevation. This is important because processes and features that are major controls on recharge (*e.g.*, precipitation amount, precipitation type, vegetation, and soil cover) can change significantly with elevation. As a result, ground-water recharge processes can change from high to low elevation, even if the base geologic characteristics are the same. Incorporating data from a series of vegetation types (*e.g.*, high alpine, oak woodland/ponderosa pine, mixed conifer) would provide a window into the difference in recharge processes over the entire elevation range of a mountain. Ideally, all the different types of measurements performed at each site would be conducted at different elevations.

'Second-tier' sites would have less permanent instrumentation and might only be visited once or twice per year to observe temperature, discharge, electrical conductivity, and obtain an inventory of the biota. As a result, these sites could potentially have less-than-ideal accessibility, requiring a short hike from a road, for instance. These sites are likely to be at springs or existing wells so that construction costs are minimized in favor of widespread network coverage. However, sites for intensive monitoring must be accessible by road to allow installation of equipment and access for monitoring; consideration should also be given to the fact that some monitoring might need to take place during periods when significant snow cover remains on the ground. Installation of wells in mountain settings could potentially be carried out with track-mounted drill rigs, but use of these rigs will entail much more time and expense compared to sites where they would not be needed.

Another accessibility issue is that population growth near the site could have a major impact on data interpretation, as pumping of domestic or municipal supply wells could change the hydraulic characteristics of the system. As a result, sites in protected areas (*e.g.*, national forests) where population encroachment is unlikely would have an advantage over non-protected sites. On the other hand, the permit and paperwork requirements to install equipment in some protected areas (*e.g.*, national parks) can impose significant design limitations. In this respect, locating monitoring sites in conjunction with existing observation areas (such as CZOs or NEON sites) that are in protected locations but already have special-use permits for equipment installation would be desirable.

Joe Wang (Lawrence Berkeley Laboratory) proposed the use of abandoned mines in the recharge monitoring network. Tunnels into mountains provide unique opportunities to access water that has moved deep into the mountain system through the mountain block. The opportunity to recover tunneling costs through mineral extraction made these tunnels viable; without such an economic incentive, it highly unlikely that such access to the interiors of mountain blocks would be possible. In addition, mine tunnels into mountains would be good sites for installation of gravimeters to monitor changes in total water content in the mountain system above the monitoring point. However, mine tunnels bring disadvantages in addition to their advantages. The tunnels themselves represent an artificial alteration of the hydrologic system, creating areas with low hydraulic head that become unnatural sinks. The transient nature of these altered systems may make it hard to tease out information on long-term change from the data that are collected. Where available, paired catchments—one with a mine, one nearby with similar base conditions but no mine—could present partial solutions for dealing with the mine tunnels' impacts on the system. Because of these possible advantages and disadvantages and because of a lack of experience with using mines in this way, observations at mine sites should be pursued, but probably not as more than one or two of the original intensive monitoring sites.

4.D. Instrumentation and data collection at intensive monitoring sites

In general, it is difficult to prescribe specific tasks to be performed at monitoring sites. As discussed earlier, the hydrologic community's lack of experience with many tasks that are desirable for long-term monitoring means that definitive guidelines cannot truly be developed at this time. However, during discussion at the workshop, a general consensus was reached that several methods or ideas hold enough potential that they should be applied at long-term monitoring sites. Some of these concepts will be discussed here as a starting point for development of detailed strategies for long-term recharge monitoring.

At intensive monitoring sites, instrumentation should be installed such that discharge can be measured at a minimum of two points on a major drainage, preferably with one located in bedrock; constant monitoring of temperature and electrical conductivity should also be conducted at these sites. Selected springs should also be instrumented for discharge monitoring; at least two monitored springs should have short response and residence times.

Monitoring wells and piezometers are woefully uncommon in western mountain settings. Wells or piezometers should be installed to allow direct access to subsurface flow paths and waters. At least one set of wells might be installed to form an elevational transect, with the lowest well being located adjacent to the main drainage for that watershed. Geophysical methods such as seismic surveys could be used to help plan well locations and depths. Access points at multiple depths in the wells will be desirable, and, to the extent possible with whatever funding is available, multi-well clusters capable of triangulating flow directions will be needed.

Water chemistry samples should be collected and analyzed on at least a seasonal basis from springs, wells, and streams. A quarterly sample suite for all waters should include major ion chemistry (plus bromide for Cl^-/Br^-, and aluminum concentrations if silicate rocks are present), δD and $\delta^{18}O$, and a suite of dissolved noble gases. Initially and during periods of significant change, much more frequent sampling to allow characterization of shorter-term flow and recharge events may be required. Emerging technologies, such as laser measurement of δD and $\delta^{18}O$, could make some samples cheap enough to analyze on these much more frequent schedules, even over the long term. At selected wells, some combination of CFSs, SF_6, and ^3H (or $^3H/^3He$) should be used to date the waters. Thought should be given to how appropriate each method is (for instance, does the background concentration of SF_6 allow good interpretation of results?). In addition, because $^3H/^3He$ measurements are expensive, it might be prudent to take these measurements only at the initial sampling to allow construction of the initial ^3H value (the recharge value prior to any radiodecay), then analyze only for ^3H thereafter. Electrical conductivity (EC) and temperature should routinely be measured along with discharge.

Temperature monitoring should be conducted to help trace the flow of water, both in and below streambeds, and in aquifers. These data can be used to delineate the depth of the active circulation zone, and the timing and magnitude of water fluxes. Temperature data can either be interpreted using a coupled heat and fluid flow model, or flux meters based on temperature could be deployed to yield direct flux measurements (*e.g.*, those currently being developed at Sandia National Laboratories).

Precipitation monitoring should be carried out at each site, both for amount and for chloride content. Because precipitation amount can vary significantly over short distances in Western mountains, several monitoring points would be ideal. Monitoring for other meteorological parameters (*e.g.*, temperature, wind speed) should be conducted at at least one point. Evapotranspiration monitoring via eddy covariance towers or some other method would also be advantageous, and is one of the main advantages to beginning the learning process at well-instrumented hydrologic research sites such as CZOs.

Gravity measurements should be conducted at the site. Ideally a high-resolution gravimeter could be permanently installed for constant monitoring, although this would add significant cost. Single-site monitoring should be augmented by multiple measurements collected several times a year. To allow effective long-term monitoring using portable instruments, monuments should be installed at the planned gravity monitoring points so that measurements can be repeated effectively without worry whether measurements are being collected at the same points each time.

4.E Synthesis of data

A calibrated ground-water flow (and transport) model will be a valuable tool for integration of different observations at most (if not all) sites. Because all available recharge-change observation methods are based on inferences, different observation methods will likely support different inferences and the network sites will generate as many hypotheses as conclusions. Models will provide "level playing fields" for comparing the different observations and for addressing many hypotheses. At the same time, the recharge-network observations can provide significant inputs for the development of models, especially since experience with ground-water flow modeling in rugged mountain settings is limited within the scientific community. Numerical model results could also help to identify further monitoring that could help refine the conceptual model of a site. Ground-water ages calculated from isotopic methods could be used to help constrain hydraulic conductivity values, and recharge rates based on chloride mass-balance estimates could be used to constrain model recharge. Finally, models would allow integrated assessment of surface water and groundwater systems, addressing a current weakness at sites such as CZOs, which tend to have a significant surface-water focus, in spite of the interconnection between surface water and groundwater (e.g., Winter et al., 1998).

Because mountain block systems are likely to conduct much of their flow through fractures rather than pores, estimating effective porosity will be important to relating water fluxes to changes in hydraulic head. In some mountain systems, seasonal fluctuations in the water table can be as high as 30 to 60 m, as observed at deep wells penetrating mountain blocks, such as Handcart Gulch, Colorado (Caine *et al.*, 2006), and Kyle Canyon in the Spring Mountains, Nevada (e.g., USGS well #361555115392901). If effective porosity is low because the porosity is primarily the result of fractures, then the total volume of water related to these fluctuations in the water table may be low; if the porosity is relatively high, a much higher volume of water may be involved. More such observation wells would be a useful addition for both tracking recharge variability in mountain settings and for the study of mountain hydrology, in general.

4.F Potential locations

A number of potential sites for intensive monitoring in the mountains of California and Nevada were suggested by attendees. Our two favored sites are:

- Sagehen Creek (Eastern Sierra Nevada, California)

  A Univeristy of California research basin with a history of strong support by the academic research community and much prior hydrologic interpretation. Advantages include a large number of springs and some streamflow records, a calibrated model of the watershed, good accessibility and existing infrastructure (including a road), a SNOTEL station in the watershed, some ET measurement equipment, protection from development. This site has perhaps the most complete (published) geochemical characterization of subsurface flow and recharge conditions (e.g., Rademacher et al., 2002) to be found in the Sierra Nevada, and in this regard, offers immediate opportunities for repeat sampling to begin characterizing variations and changes.

- Kings River Experimental Watershed (Western Sierra Nevada, California)

  A National Forest Service research basin with a large existing infrastructure for meteorologic and hydrologic monitoring, but limited current capacity for detecting recharge changes. Eight instrumented sub-watersheds, good access with protection from most development (although several sub-watersheds are slated for land-cover treatments as part of the experimental design). Long-term commitment to maintaining existing monitoring programs by the Forest Service and research collaborators; the site is also a proposed NEON monitoring location.

Other sites suggested and available for consideration include:

- Wolverton CZO site (Sequoia National Park, western Sierra Nevada)

  A developing NSF-funded Critical Zone Observatory of several instrument clusters using surface-hydrological monitoring methodologies, but currently lacking a strong ground-water component. Primary limitation here is a lack of much historical background, thus far.
- Merced River through and below Yosemite Valley (western Sierra Nevada)

  Ninety years of USGS records of daily river discharges above and below Yosemite Valley, with essentially pristine upstream watersheds. Geochemical studies in the past several years by Fenjing Liu and others at UC Merced, are providing a basis for distinguishing season to season and year to year differences in the surface-runoff, shallow ground-water, and deep-ground-water components of river flows at several points along the river from the head of Yosemite Valley to the Sierran foothills. Support to continue this geochemical monitoring, and to augment it with other monitoring methods, would yield early experience with geochemical detection of recharge variability. These studies may evolve into a useful counterpart to the recommended repeated geochemical assessments at Sagehen Creek.
- North Fork American Hydrometeorological Testbed (western Sierra Nevada)

Funded by NOAA and other agencies, monitoring and modeling of the Wild and Scenic North Fork American drainage is extensive. Intensive hydrometeorological monitoring infrastructure but (as yet) much less intensive surface (or ground) water monitoring framework. Location of the long-term Central Sierra Snow Laboratory where a number of the most fundamental classic measurements of snow properties and processes have been made.

- Tuolumne Meadows (Yosemite National Park, Sierra Nevada crest)
  In 2006, about 20 boreholes were augered into this large high-altitude (8500 feet) meadow to allow monitoring of ground-water fluctuations. Nearby SNOTEL and some river stage recorders provide meteorologic and surface-water records for the area.
- Cold Creek (Eastern Sierra Nevada, California)
  Advantages include an existing stream gauge, a SNOTEL station in the watershed, and good access
- Elko area (Eastern Nevada)
  Advantages include a long-term stream gauge on Lamoille Creek (in operation since 1922), two SNOTEL stations, long-term precipitation data, and good accessibility from Elko.
- Martin Creek (Northwestern Nevada)
  A good site from many perspectives, but remote (6 hr drive from Carson City, 4 hr drive from Elko)
- Great Basin National Park (Eastern Nevada)
  Advantages include the gauges on Lehman Creek (the main drainage in the area) and 12 other streams, and the fact that all springs in the park are inventoried. Permitting issues related to well installation could be prohibitive.
- Pine Creek Mine (Sierra Nevada, California)
  The network of tunnels and shafts in the Pine Creek Mine would present a unique opportunity for in-mountain measurements, access is good, and existing stream gauges are located at the mountain front.

Some sites that could provide useful mountain-front anchors for monitoring at the foot of mountains are:

- Ash Canyon (Eastern Sierra Nevada, above Carson City)
  Advantages include good accessibility, a SNOTEL station nearby, a stream gauge in operation since 1977 that has been correlated to record from a gauge with ~100 yr of record, two wells and some nested piezometers located in association with the stream gauge. (Nearby Vicee Canyon also offers similar opporuntities.)
- Kyle Canyon (Spring Mountains, Nevada, above Las Vegas)
  Advantages include the fact that it is a vital site (the Spring Mountains are the main recharge zone for that area) and that the site is likely to be sensitive to climate change. A high-elevation shaft of the Paul Canyon Mine in the park would provide an opportunity for in-mountain measurements.

A well near the mountain front has long been observed to respond to seasonal cycles of snowmelt with water level changes of order 100 feet.

Design of a second tier of more numerous but less intensive monitoring sites was beyond the capacity of the workshop participants in the time allotted and with all the current uncertainties about which methods and locations would work and which would not. However, in Nevada, high-altitude springs are generally believed to provide important and economical access points to begin observing recharge variations. The Nevada State Engineer—as well as multiple entities motivated by water issues involving the Nevada Test Site, Yucca Mountain, past MX-Missile exploratory investigations, and assorted water-rights claims—have developed several extensive inventories of springs within the State (e.g., http://www.epa.gov/esd/land-sci/nv_geospatial/images/nv_springs.pdf). Such inventories could be culled to develop a list of springs suitable for regular "second tier" monitoring, to include discharge measurements, biological surveys, geochemical sampling, and perhaps some microgravity stations. We have been unable to identify a similar resource for design of second-tier monitoring in California.

Finally there is a great need for identification (or establishment) of more deep monitoring wells in mountain blocks, for water level monitoring and repeated geochemical sampling, in the heart of the mountain recharge zones themselves. Identification of well clusters at the mountain-front outlets of key mountain drainages, for similar purposes, should also be a priority, and could commence soon because there is more experience with characterizing basin recharge at the foot of mountains than in the mountains themselves.

5. **Conclusions**

Taken together, these discussions led the meeting organizers (Earman and Dettinger) to the following conclusions regarding near-term monitoring of recharge variability and change in California and Nevada:

- Mountain-recharge monitoring is necessary in at least some key and representative locations in California and Nevada if we are to detect and understand recharge change as early as possible

- A network that integrates several methods (hydraulic, geochemical, and geophysical, at least) would provide the most confident results

- Research applications of monitoring methods in mountain environments in some already-well-instrumented watersheds would allow many current hurdles to widespread application to be resolved as quickly as possible, while leveraging existing investments for other purposes

- Locations like (but not restricted to) the Kings River Experimental Watershed and Sagehen Creek basin in the western and eastern Sierra Nevada would be good candidates for such research

- Monitoring at springs may provide a widespread and very sensitive initial approach to recharge monitoring, especially in Nevada

- More deep monitoring wells in mountain blocks (or equivalent structures like mines) may be crucial to understanding of high-altitude ground-water recharge processes; more paired streamflow gaging stations (to measure streambed seepage losses and gains) identified or established in mountain settings could provide immediate gains.

- Networks of clustered monitoring wells sited at the foot of key mountain drainages could serve as focal locations for multi-method monitoring and may provide an opportunity for near-term steps towards widespread observation of recharge variability and change at the regional scale

References

Allison, G.B., C.J. Barnes, M.W. Hughes, and F.W.J. Leaney, 1984. Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils, *Isotope Hydrology 1983*: Vienna, International Atomic Energy Agency, pp. 105-123.

Brantley, S. L., White, T. S., Sparks, D., Richter, D., Pregitzer, K., Derry, L., Chorover, J., Chadwick, O., April, R., Anderson, S., Amundson, R., 2006. Frontiers in exploration of the critical zone: Report of a workshop sponsored by the National Science Foundation (NSF), October 24-26, Newark, DE. http://www.czen.org/system/files/CZEN+Booklet+July+06_0.pdf

Caine, J.S., Manning, A.H., Verplanck, PL, Bive, D.J., Kahn, K.G., and Ge, S., 2006, Well construction information, lithologic logs, water level data, and overview of research in Handcart Gulch, Colorado—An alpine watershed affected by metalliferous hydrothermal alteration: USGS Open_File Report 2006-1189, 14 p.

Cayan, D.R., Kammerdiener, S., Dettinger, M.D., Caprio, J.M., and Peterson, D.H., 2001. Changes in the onset of spring in the western United States. Bulletin, American Meteorological Society, 82, 399-415.

Dettinger, M.D., 1989. Reconnaissance estimates of natural recharge to desert basins in Nevada, U.S.A., by using chloride-balance calculations: *Journal of Hydrology*, 106: 55-78.

Dettinger, M.D., and Earman, S., 2007, Western ground water and climate change—Pivotal to supply sustainability or vulnerable in its own right?: Association of Ground Water Scientists and Engineers Newsletter, June 2007, 4-5.

Earman, S., A.R. Campbell, B.D. Newman, and F.M. Phillips, 2006. Isotopic exchange between snow and atmospheric water vapor: Estimation of the snowmelt component of groundwater recharge in the southwestern United States: *Journal of Geophysical Research*, 111: D09302, doi:10.1029/2005JD006470.

Earman, S., and Phillips, F. M., 2003. Groundwater recharge and movement in the central Chiricahua Mountains, Arizona, Geological Society of America Annual Meeting, Seattle, WA [*Geological Society of America Abstracts with Programs*, 35(7), 489].

Hanson, R.T., Newhouse, M.W., and Dettinger, M.D., 2004, A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States: Journal of Hydrology, 287, 252-269.

Hassan, S., Troch, P. A., Boll, J., and Kroner, C., 2006,. Modeling the hydrological effect on local gravity at Moxa, Germany, Journal of Hydrometeorology, 7(3) 346-354.

Healy, R.W., and Cook, P. G., 2002. Using groundwater levels to estimate recharge: *Hydrogeology Journal*, 10(1): 91-109.

Intergovernmental Panel on Climate Change, 2007. Climate change 2007, The physical science basis. Summary for Policymakers: IPCC Secretariat, http://www.ipcc.ch.

Knowles, N., Dettinger, M., and Cayan, D., 2006. Trends in snowfall versus rainfall for the western United States. *Journal of Climate* 19(18), 4545-4559.

Liu, F., M. W. Williams, and N. Caine, 2004. Source waters and flowpaths in a seasonally snow-covered catchment, *Water Resources Research*, Vol. 40, W09401.

Long Term Ecological Research Network, 2005. Celebrating 25 years of excellence in long-term ecological research. <http://intranet.lternet.edu/archives/documents/Publications/brochures/LTERNetworkBrochure1.pdf>

Manning, A.H., and D.K. Solomon (2003) Using noble gases to investigate mountain-front recharge. Journal of Hydrology, 275, 194-207.

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P., and Nijssen, B., 2002. A long-term hydrologically based data set of land surface fluxes and states for the conterminous United States. *Journal of Climate* 15(22), 3237-3251.

Mote, P.W. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters* 30. DOI 10.1029/2003GL0172588.

National Research Council Committee on Hydrologic Science, 2004. *Groundwater Fluxes Across Interfaces*, National Academies Press, Washington, D.C.

Parker, J.T.C., and D.R. Pool, 1998, Use of microgravity to assess the effects of El Nino on ground-water storage in southern Arizona: USGS Fact Sheet FS-060-98, 4 p,

Phillips, F.M., 2004. Effects of environmental change on groundwater recharge in the desert Southwest, *in* Hogan, J.F., F.M. Phillips, and B.R. Scanlon, eds., *Groundwater Recharge in a Desert Environment: The Southwestern United States*: Washington, D. C., American Geophysical Union, pp. 273-294.

Pool, D.R., and W. Schmidt, 1997, Measurement of ground-water storage change and specific yield using the temporal-gravity method near Rillito Creek, Arizona: USGS Water-Resources Investigations Report 97-4125, 29 p.

Rademacher, L.K., J.F. Clark, and G.B. Hudson (2002). Temporal changes in stable isotope compositions of spring waters—Implications for recent changes in climate and atmospheric circulations: Geology, 30, 139-142.

Sada, D.W., J.E. Williams, J.C. Silvey, A. Halford, J. Ramakka, P. Summers, and L.

Lewis. 2001. A guide managing, restoring, and conserving springs in the western United States. Technical Reference 1737-17. Bureau of Land Management, Denver, CO. BLM/ST/ST-01/001+1737.

Seager, R., M.F. Ting, I.M. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, N. Naik, 2007: Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America, Science, 316, (5828), 1181 - 1184 DOI: 10.1126/science.1139601

Simpson, E. S., D. B. Thorud, and I. Friedman (1972). Distinguishing seasonal recharge to groundwater by deuterium analysis in southern Arizona. Pages 623-633 *in* World Water Balance: Proceedings of the Reading Symposium, July 1970, Volume 3.

Stonestrom, D., and J. Constantz, 2004, Using temperature to study stream-ground water exchanges: USGS Fact Sheet FS-2004-3010.

Winograd, I. J., A. C. Riggs, and T. B. Coplen (1998). The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada, USA, Hydrogeology Journal, 6, 77– 93.

Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M., 1998. Ground water and surface water: A single resource, U.S. Geological Survey Circular 1139.

Appendix 1
Workshop Attendees/Affiliation List

Bill Alley (US Geological Survey)
Mike Anderson (California Department of Water Resources)
Thomas Armstrong (US Geological Survey)
Roger Bales (University of California, Merced)
Martha Conklin (University of California, Merced)
Jim Constantz (US Geological Survey)
Bill Cunningham (US Geological Survey)
Mike Dettinger (US Geological Survey/Scripps Institution of Oceanography)
Sam Earman (Desert Research Institute)
Alan Flint (US Geological Survey)
Devin Galloway (US Geological Survey)
Phil Gardner (US Geological Survey)
Justin Huntington (Nevada State Engineer's Office)
Andy Manning (US Geological Survey)
Joe O'Hagan (California Energy Commission)
Fred Phillips (New Mexico Institute of Mining and Technology)
Don Pool (US Geological Survey)
Dave Prudic (US Geological Survey)
Chris Reeves (Bureau of Indian Affairs)
Don Sada (Desert Research Institute)
Ward Sanford (US Geological Survey)
Michael Tansey (US Bureau of Reclamation)
Sushel Unninayar (National Aeronautics and Space Administration)
Joseph Wang (Lawrence Berkeley National Laboratory)
John Wilson (New Mexico Institute of Mining and Technology)
John Woodling (California Department of Water Resources)

Appendix 2
Meeting agenda

Agenda

Workshop on Networks for Recharge Change

Willow Suite 1, Modoc Hall
California State University Sacramento Campus

Sponsors: US Geological Survey Office of Ground Water and California Energy Commission

Objective: Develop a conceptual design for networks of hydraulic, geochemical, geophysical, and biological monitoring sites to detect and track long-term variations in sources, mechanisms, and rates of present-day and future ground-water recharge in California and Nevada mountain settings *(a strawman outline of such a design/white paper will be circulated before the workshop)*

July 30, 2007

1. **Opening remarks and introductions** (8:00 - 8:15 am)
2. Brief tutorial and discussion of **climate variability and change** (Mike Dettinger , 8:15 – 8:40 am)
3. Brief tutorial and discussion of **potential for recharge change** (Sam Earman, DRI, 8:40 – 9:00 am)
4. Tutorials:

   Recharge overview and terminology (John Wilson, New Mexico Institute of Mining & Technology (NMIMT); 9:00 – 9:30 am)
   Hydraulic/well-based methods (Ward Sanford, USGS; 9:30 – 10:00 am)
   [Break 10:00 – 10:15 am]
   Geochemical and isotopic methods (Fred Phillips, NMIMT; 10:45 - 11:15 am)
   Dissolved gas methods (Andy Manning, USGS; 10:15 – 10:45 am)
   Geophysical methods (Don Pool, USGS; 10:45 am – 11:15 pm)
   Stream-based methods (Jim Constanz, USGS; 11:15 – 11:45 pm)
   Biological methods (Don Sada, DRI; 12:15 – 12:45 pm)

5. **Lunch** (12:45 – 2:00 pm)
6. **Plenary discussion** of network requirements to detect and monitor in-place mountain recharge variations and change of recharge sources, mechanisms, and rates (2:00 – 3:15 pm)
7. **Plenary discussion** of network requirements to detect and monitor remote (in-stream) recharge variations and change of recharge sources, mechanisms, and rates (3:30 – 4:45 pm)
8. **Plenary goals** of Day 2 activities and identification of a core leadership team to carry the issue forward (4:45 – 5:30 pm)

July 31:

9. **Disciplinary breakout discussions** to outline network designs for each of the technical approaches (8:00 am – 10:00 am)
10. **Plenary discussions** of which methods and settings would provide most information, which methods are most feasible, how to design an overall (merged) network, what minimal and maximal networks might look like (10:00 am – 12:00 pm)
11. **Working lunch** to begin action items and discussion of potential funding issues (12:00pm – 1:30 pm)
12. **Optional continuation of previous discussions** and action items (1:30 – 5:00 pm)

Please make arrangements to stay into the afternoon of the 31st if you can, but we will understand if you have to leave before end of day.

Logistical and other contacts:

Sam Earman (searman@dri.edu; 775-673-7415)
Mike Dettinger (mddettin@usgs.gov; 858 822-1507 or 619 368 2896)