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GROUNDWATER CONTRIBUTIONS TO BASEFLOW IN THE MERCED RIVER: PROCESSES, FLOW PATHS AND RESIDENCE TIMES

PROJECT REPORT

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Abstract

Preliminary evaluation of baseflow trends shows mean October flows have been declining significantly since 1984 in the Upper Merced River. Sources of baseflow (streamflow from August to October) in the Upper Merced River were determined using stable isotopes and specific conductance. Primary sources of baseflow are mountain-block recharge (groundwater recharge to the entire mountain body), lateral subsurface flow (occurs when infiltrating water encounters an abrupt decrease in hydraulic conductivity) and overland flow (directly from snowmelt and rainfall events). Contribution of mountain-block recharge was greater than 20% of total streamflow in 2006. Lateral subsurface flow and overland flow contributions responded to the quantity and timing of snowmelt in spring. After peak streamflow, contributions of lateral subsurface flow and overland flow were described using exponential decay functions. If snow quantity is reduced or snow starts melting earlier in spring, contributions of both flows would be significantly reduced in following months. The decline in baseflow may continue if regional changes in snow accumulation and timing of snowmelt shift in response to climate change. A study is needed to investigate responses of baseflow to climate changes throughout the Sierra, as the findings would benefit water resources management in California.

Key Words: Merced River, baseflow, groundwater, mountain-block recharge, lateral subsurface flow, overland flow, climate change, earlier onset of snowmelt, stable isotopes

Executive Summary

Introduction

Providing an adequate supply of water for California is already a problem, especially during dry years. Surface water from the Sierra Nevada provides 40% of the California surface water supplies. The central Sierra foothills are experiencing tremendous development pressures. Population in the mountain counties has doubled in the past thirty years, and this trend is predicted to continue. Much of this development depends on groundwater supplies. Climate change has also brought about concerns regarding water resources in mountains. Recent studies have shown that with a warming climate less precipitation would fall as snow and the melting of snow would start earlier. Observations and modeling results have shown that the earlier onset of snowmelt may lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when water demand is highest. Further understanding of the consequences of climate change on streamflow regime is hindered by the lack of information about surface water and groundwater interactions in mountains. The contribution of subsurface flow to streamflow is unknown. To improve water resources management for hydroelectricity generation, ecosystem protection, and water supply, it is critical to understand the interconnectedness of snowmelt, mountain-block recharge and streamflow, particularly during low flow period, and possible changes with climate change in mountainous areas.

Purpose

The purpose of this project is to develop promising, new scientific concepts about controls of baseflow and how it changes with climate warming, particularly the decline of snow water equivalent and the earlier onset of snowmelt in spring.

Project Objectives

The objectives of this project are to (i) understand the processes that link snowmelt, mountain-block recharge and baseflow using established and innovative techniques; (ii) estimate the contribution of mountain-block recharge to baseflow; and (iii) evaluate the impact of the change in snowmelt timing and snow quantity on baseflow. The Upper Merced River, including the Yosemite National Park, is selected for this project because its flow regime is representative of streams draining from the central and southern Sierra Nevada.

Project Outcomes

End-members (recharges that are derived from different hydrologic or geologic units with distinguished isotopic and chemical signatures) contributing to streamflow were identified and quantified using specific conductance and stable isotopes in the Upper Merced River Basin. The trend of baseflow was also analyzed and evaluated for the last two decades. Major results are summarized below.

- Using stable isotopes and specific conductance in end-member mixing analysis, it was determined that streamflow in the Upper Merced River was primarily controlled by three end-members: mountain-block recharge from fractured bedrock and alluvial aquifers, lateral subsurface flow from soil and the top of fractured bedrock zone and overland flow directly from rainfall and snowmelt storms.
- In 2006, contribution of mountain-block recharge to baseflow (streamflow from August to October) in the Upper Merced River increased downstream by percentage

of total streamflow: 13-47% at Happy Isles, 24-51% at Pohono Bridge, and 20-61% at Briceburg, and by absolute flow rate: 0.2-0.5 $m^3 s^{-1}$ at Happy Isles, 0.5-1.2 $m^3 s^{-1}$ at Pohono Bridge and 1.5-2.5 $m^3 s^{-1}$ at Briceburg.

- Based on tritium values, the mean residence time is estimated to be about 35 years for mountain-block recharge and 20 years for some of springs developed from or near the interface of soil and bedrock.
- The contribution of lateral subsurface flow and overland flow decayed over time (exponential function) from May to November 2006. The contribution of lateral subsurface flow peaked on July 19 with 55% of the total streamflow discharge at Happy Isles, two months after the peaking of snowmelt on May 19, indicating that the travel time for lateral subsurface flow was about two months. Lateral subsurface flow released faster and had a smaller capacity at higher elevations than lower elevations due to steeper slopes and thinner soils.
- Temporal changes in lateral subsurface flow and overland flow responded to snowmelt timing and quantity in May. The contribution of lateral subsurface flow and overland flow would decrease significantly in October if snow would start melting earlier (given the same quantity of snow at the beginning of snowmelt and no occurrence of precipitation afterward.) Lateral subsurface flow is also more sensitive to the changes in snowmelt timing at higher elevations than lower elevations.
- Both mean and minimum streamflow discharge in October have been significantly ($p < 0.05$) declining since 1984 at Happy Isles in the Upper Merced River. However, the decline in streamflow was not significant at lower elevations.
- In the Upper Merced River Basin, there was no significant trend for either annual precipitation or the August-October precipitation from 1984 to 2005 at all stations.

Conclusions

Baseflow was primarily controlled by mountain-block recharge, lateral subsurface flow, and overland flow from August to October, 2006 in the Upper Merced River. The contribution of mountain-block recharge increased from 10-20% of the total streamflow discharge in August to greater than 50% in October. The contribution of mountain-block recharge also increased with the increase in drainage areas, as expressed by flow rate, 0.2-0.5 $m^3 s^{-1}$ at Happy Isles, 0.5-1.2 $m^3 s^{-1}$ at Pohono Bridge and 1.5-2.5 $m^3 s^{-1}$ at Briceburg. Lateral subsurface flow dominated baseflow in August and September 2006 and accounted for more than 50% of the total streamflow. Overland flow primarily occurred at higher elevations above Happy Isles and accounted for less than 30% of the total streamflow from August to October. Surface water and groundwater interactions are a significant process in the Upper Merced River. Discharge (flow rate) of lateral subsurface flow and overland flow decreased gradually over time and could be described by an exponential function. The timing and amount of snowmelt in May appear to control these flows. The response of lateral subsurface flow to snowmelt lagged two months behind the peak snowmelt, indicating that the mean travel time was about two months. The baseflow in October has been significantly declining since 1984 at Happy Isles in the Upper Merced River. It is hypothesized that this decreasing trend is a result of the decline of snow amount and the earlier onset of snowmelt occurring in the Sierra Nevada. Lateral subsurface flow is more sensitive to the change in snowmelt timing at higher elevations than lower elevations. If the decline of snow and earlier onset of snowmelt continue as a result of climate warming in the region, however, decline in baseflow may continue and occur in all autumn months and across the entire Sierra Nevada. This trend could be exacerbated by groundwater withdrawals (e.g. for water supplies) interrupting or reducing the discharge of groundwater recharge to the Upper Merced River.

Recommendations

To develop an operational model to predict low-flow hydrology and evaluate the impact of low-frequency droughts on hydroelectricity generation, ecosystems and water supplies for the Sierra Nevada, two research projects are needed in future to (i) extend and validate the understanding of streamflow generation developed by this study using data from multiple years with different climates and several river systems, and (ii) develop a physically based, spatially distributed hydrologic model based on the conceptual understanding of streamflow generation to predict low-flow hydrology with a changing climate.

Benefits to California

The results of this study are of interest to broader communities, stakeholders and policymakers. The results can aid decision making regarding California's water resources, ecosystem management, electricity generation, irrigation and aquatic resources. This research leads to a better understanding of the relationship between the water cycle and climate change in the Sierra, and thus benefits the reservoir managers in their day-to-day operational decisions. The research also benefits the Federal Energy Regulatory Commission and the California Department of Water Resources and provides information relevant to decisions on the dam re-licensing and hydroelectricity strategies. Furthermore, information about the change in groundwater contribution to baseflow is critical for ecosystem managers to monitor stream temperature to protect some fish whose living is sensitive to stream temperature such as salmon and steelhead.

1.0. Introduction

Providing an adequate supply of water for California is already a problem, especially during dry years. The central Sierra foothills are an area of particular concern. These areas are experiencing tremendous development pressures; the population in the mountain counties has doubled in the past thirty years and this trend is predicted to continue [*Sierra Nevada Alliance*, 2006]. Due to prior surface water appropriations, these communities are dependent on groundwater supplies. With an increase in global temperature, a predicted consequence of rising levels of greenhouse gases, anticipated changes to mountain regions are that less precipitation falls as snow and the melting of snow starts earlier [e.g., *Knowles et al*., 2006; *Mote et al*., 2004]. Even without any changes in precipitation intensity, observations and modeling results have shown that less snow and earlier snowmelt leads to a shift in peak river runoff to winter and early spring, away from summer and autumn when water demand is highest [e.g., *Dettinger and Cayan*, 1995; *Barnett et al*., 2005; *Stewart et al*., 2005]. However, further understanding of the consequences of climate change on streamflow regime is hindered by the lack of information about surface water and groundwater interactions in the mountain regions [IPCC, 2001; *Wilson and Guan*, 2004; *Flint et al.*, 2001]. Uncertainties exist about groundwater flowpaths (pathways of groundwater discharge to river) and the volume of ground water contributing to streamflow. Mountain-block recharge (recharge that occurred in the entire mountain body from the slope of the highest peak to the mountain front) is also usually ignored [*Wilson and Guan*, 2004]. To improve water resources management for hydroelectricity generation, ecosystem protection, and water supply, it is critical to understand the interconnectedness of snowmelt, mountain-block recharge and streamflow, particularly during low flow period, and their probable response to climate change.

The goal of this project is to develop promising new scientific concepts concerning controls of baseflow and mountain-block recharge. The objectives of this project are to (i) understand processes that link snowmelt, mountain-block recharge and baseflow using established and innovative techniques, (ii) estimate the contribution of mountain-block recharge to baseflow, and (iii) evaluate the impact of the change in snowmelt timing and snow quantity on baseflow. This project was conducted in the Upper Merced River (Figure 1), a representative river draining the Sierra Nevada that is pristine at higher elevations and has reservoirs at lower elevations. The knowledge obtained from this project may be applicable to all rivers draining the Sierra Nevada. It may also lay the foundation for developing an operational model to predict baseflow with a changing climate. Furthermore, this research may foster similar research at large scales across the entire Sierra Nevada.

2.0. Methods

2.1. Research Site

This study was conducted in the Upper Merced River above the gaging station at Briceburg, including the Yosemite Valley (Figure 1). The Merced River is a tributary to the San Joaquin River and its flow regime is representative of streams draining from the central and southern Sierra Nevada. It is about 240 km long, drains 3,266 km^2, and ranges in elevation from 3963 m at its crest to 15 m at the San Joaquin River confluence. The Upper Merced River provides a catchment that is relatively undisturbed; much of the Upper Merced River flows through Yosemite National Park (YNP). The Merced River had been designated a Wild and Scenic River in 1987 by the U.S. Congress and has no significant water diversion until the

Central Valley/Sierra Nevada margin, which is below Briceburg. The Upper Merced River originates in high Sierran peaks and is a snowmelt-dominated river system[1].

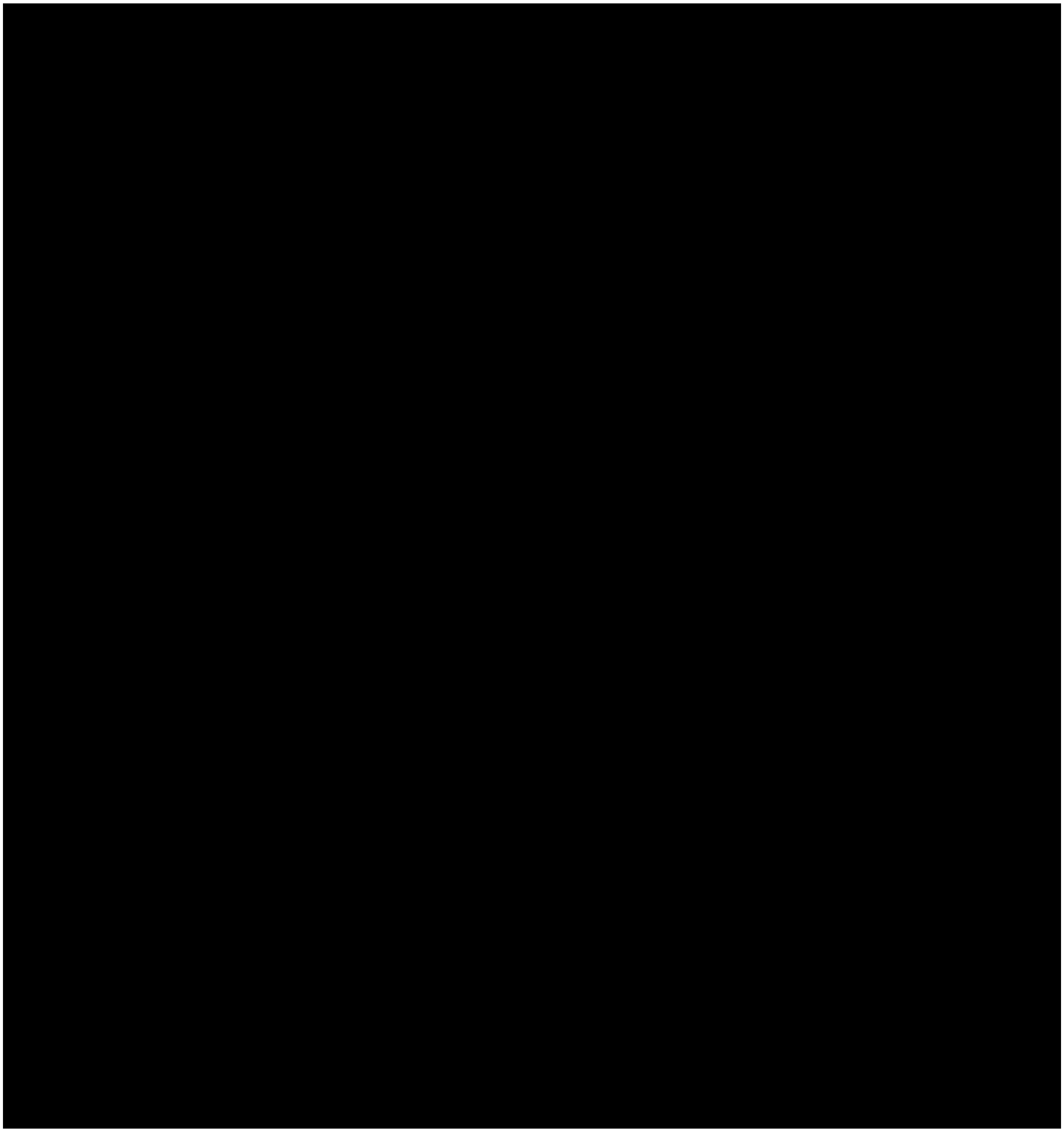

Figure 1. Topography of the Upper Merced River Basin and sampling locations (Note that four weather stations, one snowpit and one groundwater well are located outside the basin)

[1] From a practical aspect, the Merced River has road access for sampling the reach of interest.

The Merced River Basin experiences a Mediterranean climate, with moderately wet, cold winters and dry, hot summers. In 2006, the annual precipitation was 1,100 mm, 120% of the mean annual precipitation measured at Yosemite National Park Headquarters from 1916 to 2006. Precipitation occurred primarily in winter and spring months from November to March (Figure 2a). With rising in air temperature in late spring (Figure 2b), streamflow increased significantly due to snowmelt and peaked on May 19, 2006 at all three gaging stations (Figure 2c)[2]. Note that streamflow peaks also occurred on February 28 and April 4, 2006 at lower stations at Briceburg, but are not evident at higher station at Happy Isles. Two isolated snowmelt events apparently occurred earlier in lower elevations before the major snowmelt in May.

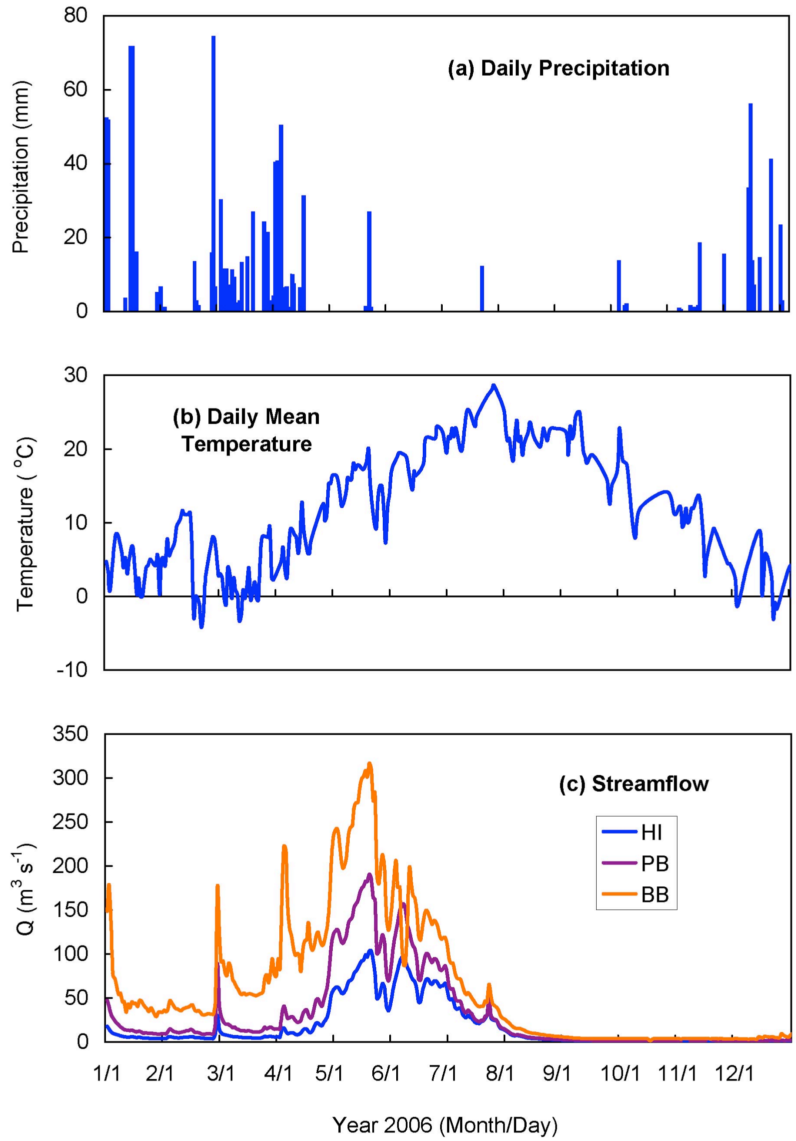

Figure 2. Temporal variation of (a) daily precipitation, (b) mean daily temperature, and (c) daily streamflow discharge in 2006

[2] The legends in the figures in this report are defined in the Section 7.0 (Sampling Location Acronyms), as well as Section 2.2 (below).

The Sierra Nevada mountain range is predominantly underlain by granitic rocks of the Sierra Nevada batholith. In the Merced River Basin, most of the plutonic rocks are granites and granodiorites from the Tuolumne Intrusive Suite (four concentrically arranged plutonic bodies) [*Bateman*, 1992]. These plutonic rocks are mostly composed of quartz, K-feldspar, plagioclase, biotite, and hornblende. Surficial deposits are primarily glacial tills that occur in the valley bottoms as lateral and recessional moraines. These tills have similar mineralogy to the granitic bedrock higher in the watershed. Downstream of Yosemite National Park, bedrock is primarily metavolcanic and metasedimentary rock, with thin soil development, and little to no glacial activity in the past. Those geomorphic and geologic variations (i.e., from alluvium to bedrock, and the transition from granite to metamorphic country rock) provide an excellent site to test geologic and hydrologic controls of streamflow generation.

2.2. Sample Collection

Samples were collected from snow, streamflow, spring and ground water through extensive field campaigns in the Upper Merced River Basin (Figure 1). Stream water samples were taken weekly to biweekly at Happy Isles (HI), El Captain Bridge (ECB), Pohono Bridge (PB), El Portal (EP) and Briceburg (BB) along the Merced River. Stream samples were also collected at waterfalls and confluences between major tributaries and the Merced River. Waterfalls that were sampled include Yosemite Falls (YF), Bridalveil Falls (BVF), and Cascade Falls (CAS). Tributaries that were sampled include Teneya Creek (TN), Crane Creek (CC), South Fork of the Merced River (SF140, indicated as the intersection of South Fork and Highway 140), Sweet Water Creek (SWC), and Bear Creek (BC). Samples were collected from springs, with a frequency varying from weekly to monthly, at Happy Isles (HISP), Trail Head (THSP), Fern Spring (FS), and Drinking Fountain (DF), a natural spring that was modified to accommodate a drinking fountain (now defunct) by the USDA Forest Service. These samples were stored in a 30-ml glass vial and high-density polyethylene (HDPE) bottles of 125 mL, 500 mL and 1,000 mL (only for tritium). All vials and bottles were soaked in deionized (DI) water overnight and rinsed with sample water three times at the time of collection. Once collected, samples were taken to the University of California, Merced and kept frozen until analysis. Tritium samples were collected using 1-L Nalgene Amber Wide-Mouth HDPE Bottles. After sampling, the bottles were sealed with Parafilm to minimize air exchange.

Three snow pits were excavated at the maximum snow accumulation in late spring 2006 (before the onset of snowmelt) at Badger Pass (elevation 2,226 m), Gin Flat (elevation 2,150 m) and Ostrander (elevation 2,500 m) within or near the Yosemite National Park (Figure 1). The depth of snow pits ranged from 1.5 m to 2.5 m. Starting on top of the snow pit, a snow sample was taken every 10 cm using a standard snow density sampler and cutter. Snow samples were stored in plastic bags pre-rinsed with DI water and washed by sampling snow at the time of collection. Snow samples were melted at room temperature immediately upon arrival at the laboratory and handled in the same manner as the stream water samples.

Groundwater samples were collected in June and November 2006 from wells located in the Yosemite Valley (labeled as Valley Wells on Figure 1), Hogdon Meadow (HM), Crane Flat (CF), and El Portal (EPW's on Figure 1). Samples collected in 2005 by the same research team were also used in this study. The depth of wells is about 100-120 m in the valley and 30-60 m at the other locations. These wells are used for supplying drinking water to people who live in the valley and park. Samples were taken directly from a sampling port on the pump outlet, upstream of any treatment. In all cases, the wells were purged or were in production mode before sampling commenced. Once collected, these samples were handled identically to the stream water samples.

2.3. Sample Analysis

All samples were analyzed for specific conductance (conductance in the text hereinafter and Cond on figures) and stable isotopes in water molecules (^{18}O and D; the latter sometimes written as ^{2}H). A subset of samples was analyzed for tritium (^{3}H). Conductance was measured in-situ using a YSI conductivity meter at the time of sample collection and converted to equivalent conductivity at 25 ^{o}C. Analysis of $\delta^{18}O$ and δD were completed at the University of California, Berkeley (UCB), using a VG PRISM isotope ratio mass spectrometer. Oxygen isotopes were prepared using automated water-CO_2 equilibration, and hydrogen isotopes were prepared using a Cr reduction furnace. Their compositions are expressed as δ (per mil) values and calculated by $(R_X/R_{VSMOW} - 1)\times1000$, where R is isotopic ratio $^{18}O/^{16}O$ or D/H, *X* indicates sample and VSMOW stands for Vienna Standard Mean Ocean Water. The 1 σ precision was ±0.05‰ for $\delta^{18}O$ and ±0.3‰ for δD based on replicate samples. Tritium was analyzed at the U.S. Geological Survey in Menlo Park, California and expressed as tritium unit (TU). The 1 σ precision was ±0.2-0.3 TU for all samples.

2.4. End-Member Mixing Analysis

$\delta^{18}O$ and conductance were used in an end-member mixing analysis to understand pathways of streamflow. End-members refer to recharges or flow components that originate from various geologic and hydrologic units in the catchment, e.g., groundwater flow, shallow subsurface flow from soils and overland flow directly from snowmelt or rainwater (*Hooper and Christophersen*, 1990). $\delta^{18}O$ (or δD) is conservative and usually distinct over ground water and overland flow (*Kendall and McDonnell*, 1998). Only does mixing of different source waters change $\delta^{18}O$, not chemical reactions. However, $\delta^{18}O$ may not be distinguishable between overland flow and shallow subsurface flow if they originate from the same source water. Conductance, a measure of total solute concentration, is usually different between overland flow and shallow subsurface flow that has contacted with soils and rocks. Combining chemical tracers with stable isotopes is usually useful in identifying sources and pathways of streamflow [e.g., *Liu et al*., 2004]. The general expressions of three end-member mixing models, based on the mass balance for water and tracers, are as follows [*e.g., Genereux*, 1998; *Rice and Hornberger*, 1998], using fraction of streamflow discharge:

$$f_1 + f_2 + f_3 = 1 \quad (1)$$

$$A_1 f_1 + A_2 f_2 + A_3 f_3 = A_s \quad (2)$$

$$B_1 f_1 + B_2 f_2 + B_3 f_3 = B_s \quad (3)$$

where *f* is the fraction of total streamflow discharge due to an end-member contribution; *A* and *B* represent compositions of tracers *A* and *B*; subscripts *1*, *2*, *3*, and *s* represent end-members *1*, *2*, *3*, and stream water. To get solutions, a matrix is introduced, which consists of end-member compositions and constraints:

$$D = \begin{bmatrix} 1 & 1 & 1 \\ A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \end{bmatrix} \tag{4}$$

Its determinant is

$$|D| = -A_2B_1 + A_3B_1 + A_1B_2 - A_3B_2 - A_1B_3 + A_2B_3 \tag{5}$$

Based on the rule of mathematics, solutions for end-member contributions are

$$f_1 = \frac{1}{|D|}\left[(A_2B_3 - A_3B_2) + (B_2 - B_3)A_s + (A_3 - A_2)B_s\right] \tag{6}$$

$$f_2 = \frac{1}{|D|}\left[(A_3B_1 - A_1B_3) + (B_3 - B_1)A_s + (A_1 - A_3)B_s\right] \tag{7}$$

$$f_3 = \frac{1}{|D|}\left[(A_1B_2 - A_2B_1) + (B_1 - B_2)A_s + (A_2 - A_1)B_s\right] \tag{8}$$

2.5. Residence Times Using Tritium

Tritium is a radioisotope of hydrogen with a half life of about 12.43 years [*Ingraham*, 1998]. Tritium is produced naturally in the upper atmosphere by the bombardment of nitrogen with cosmic-ray-produced fast neutrons and anthropogenically by above ground thermonuclear testing. The cosmogenic tritium level was determined to be 5-10 TU (1 TU = 1 tritium atom per 10^{18} hydrogen atoms), while the peak tritium concentration in precipitation was measured to be as high as 10,000 TU prior to the cessation of extensive above ground thermonuclear tests. If the tritium concentration in groundwater recharge is known, the groundwater residence time can be calculated by the decay function:

$$T = T_0 e^{-\lambda t} \tag{9}$$

where T and T_0 are tritium concentrations at time *t* and at the time of recharge, respectively, and λ is the tritium decay constant (0.05576 yr^{-1}).

3.0. Outcomes

3.1. Identification of End-Members Controlling Streamflow

3.1.1. Isotopic Composition and Conductance

$\delta^{18}O$ and δD were highly correlated in all samples collected from streams, springs and wells, and followed a local meteoric water line (LMWL, a line that is established based on isotopic values in precipitation (i.e., meteoric water) within the region) determined using all snow samples, except for three samples collected at Yosemite Falls (Figure 3). The LMWL has a slope of 8 and an intercept of 11, similar to those of *Craig* [1961] for the global meteoric water line (the standard meteoric water line established using continental precipitation samples collected all over the world). This result showed that stream water, spring and ground water were all developed from meteoric sources (snowmelt and rainwater) and did not experience significant evaporation after recharge. Samples at Yosemite Falls were collected downstream of a small pond below the falls. Three samples falling to the right of the LMWL were collected later in the summer at low flows. Their deviation from the LMWL indicates that there has been substantial evaporation in the outflow of Yosemite Falls at these sampling times.

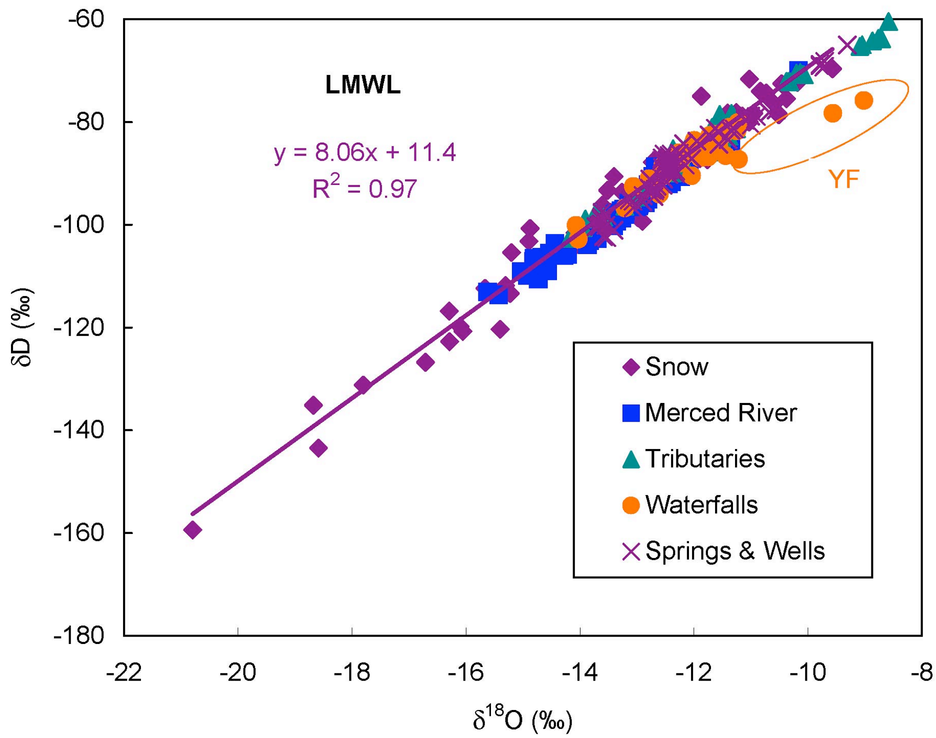

Figure 3. Scatter plot of δD vs. δ^{18}O in snow, stream water, springs and groundwater wells, with a local meteoric water line (LMWL) established using snow samples. Samples in the orange ellipse labeled YF were collected during low-flow periods downstream of a pond near Yosemite Falls, and appear to have been impacted by evaporation.

Values of conductance and stable isotopes varied significantly as a function of time and location in stream water, spring and ground water in the Upper Merced River Basin. Values of conductance and stable isotopes in stream water at the Merced River gradually increased downstream (Figure 4a and b). Mean values of conductance and δ^{18}O from May to October 2006 were about 17.7 µS cm^{-1} and -13.9‰ (respectively) at Happy Isles, and increased to 23.4 µS cm^{-1} and -13.5‰ at Pohono Bridge and 49.6 µS cm^{-1} and -12.5‰ at Briceburg, about 15 and 56 miles downstream of Happy Isles. Stream water in tributaries and waterfalls in the Yosemite Valley above El Portal had a range of conductance from about 6 to 50 µS cm^{-1} and δ^{18}O from -14 to -11‰, lower than those in tributaries below El Portal (Figure 4c and d). Conductance was usually less than 40 µS cm^{-1} at Fern Spring, Hardin Spring, and Cascade Spring in the valley but 6-8 times higher at Happy Isles in the valley and Drinking Fountain near Briceburg. δ^{18}O was about -13.6‰ at Happy Isles Spring and became gradually more enriched with decrease in altitude from Trail Head Spring to Drinking Fountain (these sites, among the points in Figures 4e and f, which are arranged from higher to lower elevations with highest elevation on top). Conductance and $\delta^{18}O$ in ground water at Valley Wells (VW's and AR) did not vary much with location. Conductance in ground water at El Portal wells (EPW's, CF, and HM) varies significantly as a function of location, with a range of 80-210 μS cm^{-1}. Variation of $\delta^{18}O$ in ground water at the El Portal wells ranged from -10.5 to -13.0‰. It is evident that groundwater sources and stream flow controls were different in the valley from before El Portal.

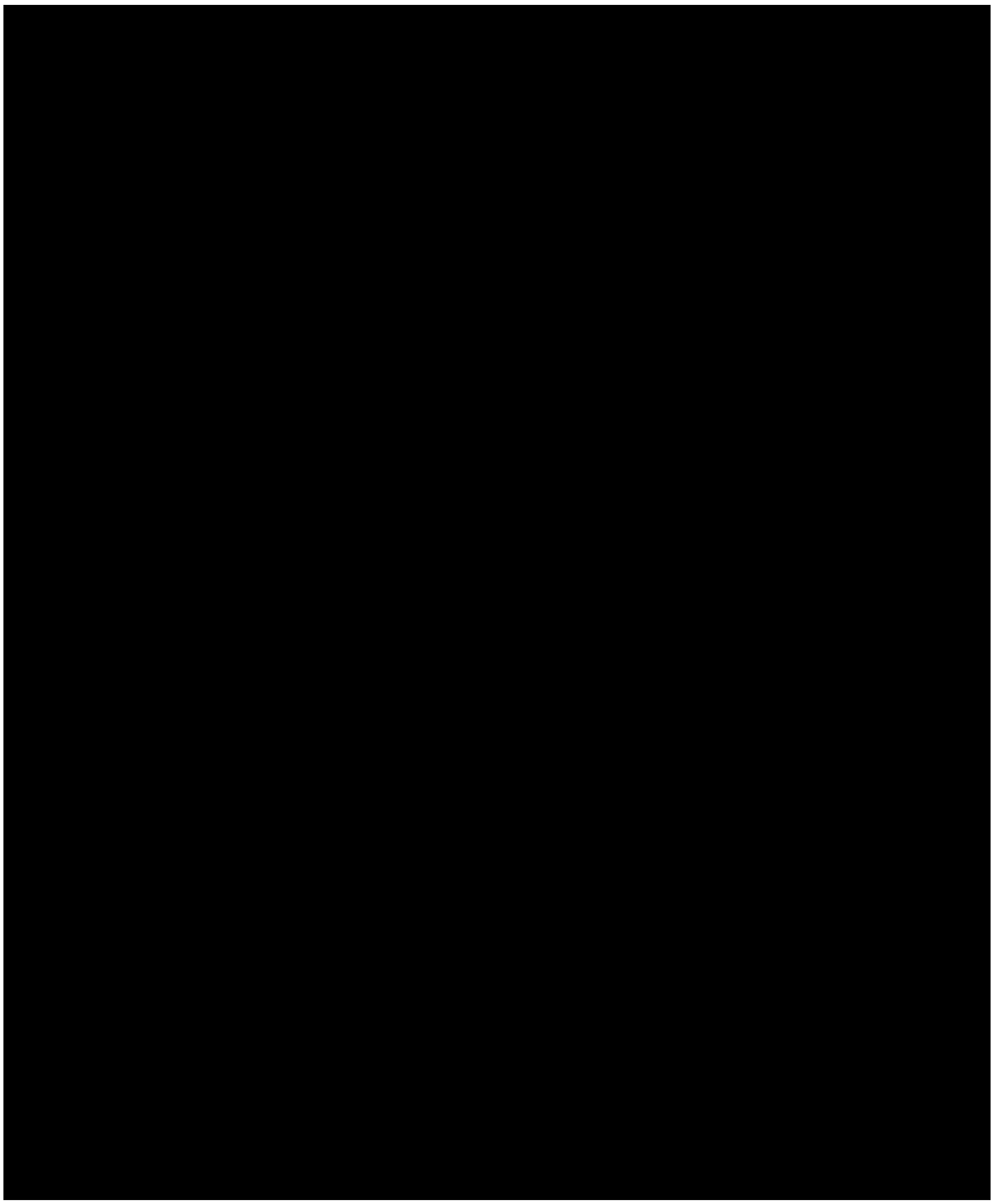

Figure 4 Box and Whisker plot showing conductance and $\delta^{18}O$ values in snow, streamflow, springs and groundwater wells (bar = median, box = 25 and 75% quartiles, whisker = 5 and 95% quartiles)

Temporal variation of conductance and δ^{18}O in stream water, spring and ground water is shown in Figure 5, along with discharge at Happy Isles and Briceburg. Both conductance and δ^{18}O had their lowest values on May 19, 2006 in the Upper Merced River at Happy Isles and Pohono Bridge when streamflow discharge peaked. With decrease in streamflow discharge from May to July, conductance increased and δ^{18}O rapidly became more enriched. From early August to November, conductance continued increasing rapidly, while δ^{18}O became relatively invariant. Conductance and δ^{18}O in tributaries and waterfalls in the valley followed a similar temporal pattern to that of streamflow at Happy Isles and Pohono Bridge over the entire season, but were consistently distinct from those at Happy Isles and Pohono Bridge. The temporal variation of conductance in springs was similar to that in streamflow, but δ^{18}O did not seem to change significantly at Fern Spring and Trail Head Spring. Temporal variations of conductance and δ^{18}O in streamflow at Briceburg had similar patterns as those at Happy Isles and Pohono Bridge. Due to the closure of Highway 140 during the spring and summer 2006 caused by a land slide, samples were not collected from tributaries and springs below El Portal. Samples taken from August to October indicated that both conductance and δ^{18}O changed slightly over time in tributaries and springs, and were slightly lower than values from ground water at El Portal, except for Sweetwater Creek, Drinking Fountain, and Bear Creek (Figure 5c and d).

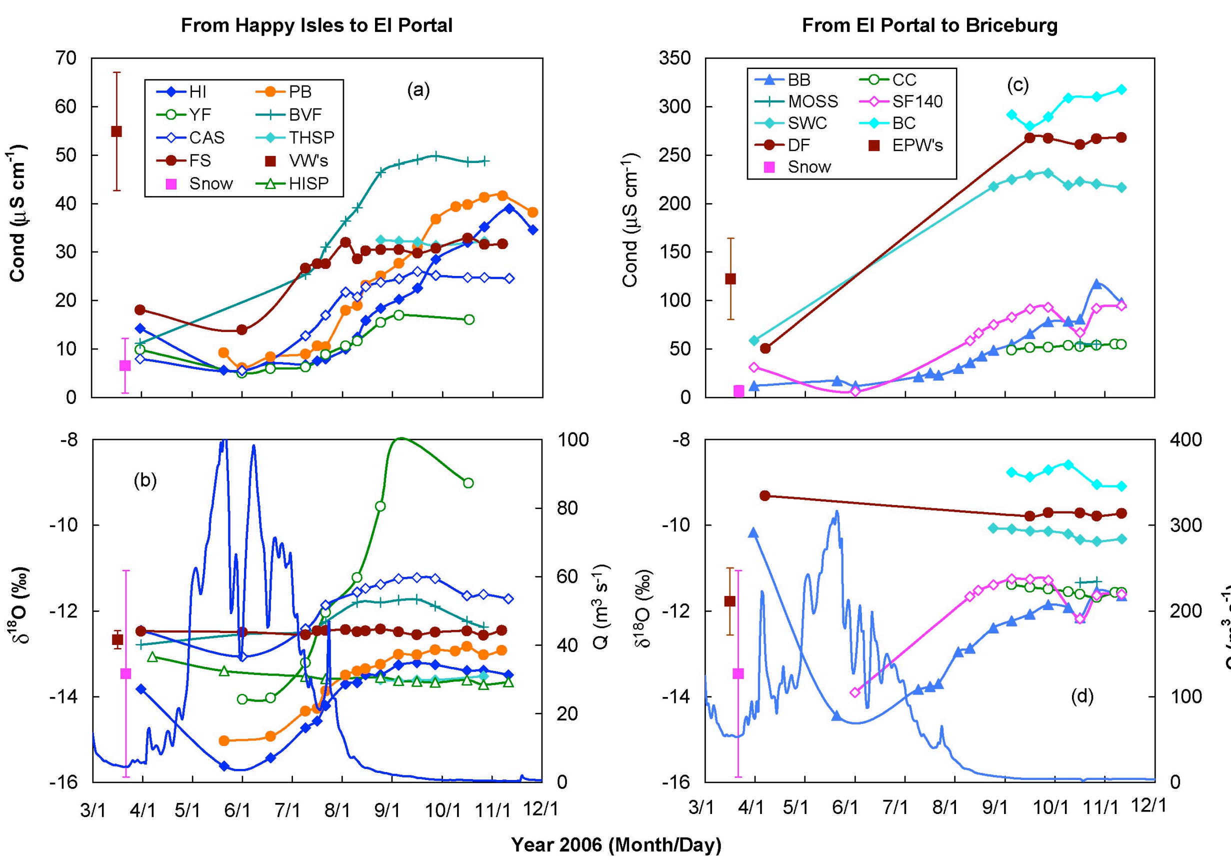

Figure 5 Temporal variations of conductance and δ^{18}O values in streamflow and springs (a) and (b) from Happy Isles to El Portal and (c) and (d) from El Portal to Briceburg; Snow and ground water shown by mean values with 1σ standard deviation; Streamflow discharge at Happy Isles and Briceburg also shown

3.1.2. Mixing Diagrams

Mixing diagrams, geometrical expression of mixing models, were constructed using conductance and $\delta^{18}O$ (δD was highly correlated with $\delta^{18}O$ and basically has the same result as $\delta^{18}O$) following *Christophersen et al.* [1990] and *Hooper et al.* [1990]. To determine end-members, all streamflow samples must be bounded by a convex polygon with end-members at vertices in this bivariate plot. The number of end-members needed to form the mixture is determined by the shape of the streamflow sample distribution. Groups of samples with a linear pattern indicate two end-members and a curvy or scattered pattern mean more than two end-members contributing to the mixture. Since the pattern of samples at Happy Isles, Pohono Bridge and Briceburg follows a parabola (Figure 6), a triangle is adequate to bound all streamflow samples, suggesting that streamflow was a mixture of three end-members at those locations.

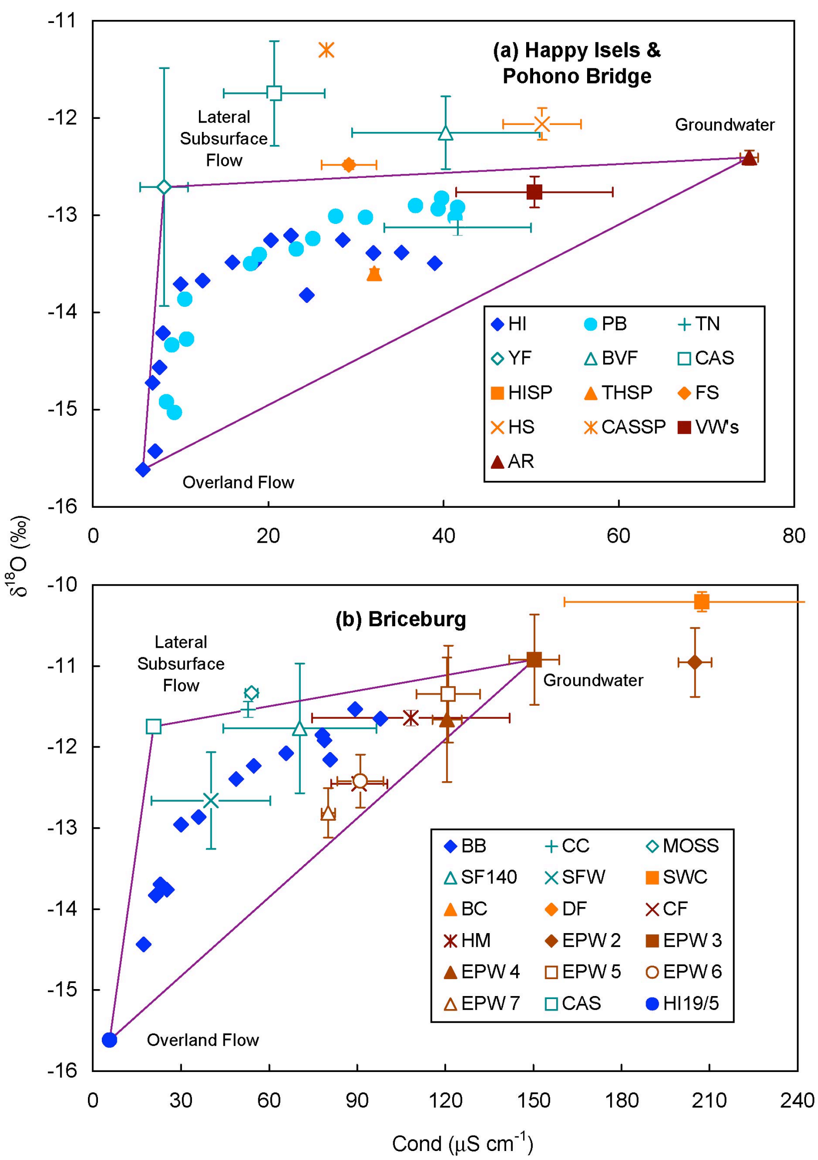

Figure 6 Mixing diagrams using conductance and $\delta^{18}O$ for (a) Happy Isles and Pohono Bridge and (b) Briceburg, with potential end-members shown by median values

One end-member appeared to lie near the lower corner of the streamflow sample cluster with lower conductance and $\delta^{18}O$ values, which matches the chemical and isotopic signature of snowmelt that makes up overland flow. Overland flow is defined in this report as an end-member that is generated directly from snowmelt and rainfall events and delivered via land surfaces, including, but not limited to infiltration-excess overland flow, saturation overland flow, laminar overland flow, and gully flows directly derived from snowpack and rain storms. These flows are event water (water that is directly from snowmelt or rainwater occurring at the time) *per se* with very short travel times (several hours to days). It is, however, problematic to parameterize overland flow using $\delta^{18}O$ values from snow. The $\delta^{18}O$ values in snow collected at Badger Pass, Gin Flat and Ostrander varied significantly, with a mean of -13.5‰ and 1σ standard deviation of 2.4‰ (Figure 5). The mean $\delta^{18}O$ value in those snowpits was 2.2‰ higher than that in the streamflow sample collected at the peak flow on May 19, 2006 at Happy Isles. Given that the peak streamflow was primarily derived from snowmelt (see next section), this result is counter-intuitive. Snowmelt may have more enriched stable isotopes than snow due to snow sublimation [*Earman et al.*, 2006]. Even if sublimation is not significant, snowmelt also becomes progressively more enriched in stable isotopes due to isotopic fractionation caused by phase change from solid ice (snow) to liquid water (snowmelt) [*Taylor et al.*, 2002]. The only explanation for more depleted $\delta^{18}O$ in streamflow than in snow is that snowmelt occurred around May 19, 2006 was primarily from areas with much higher elevations than where the snowpits were excavated. Stable isotopes usually become more depleted with an increase in elevation [*Kendall and McDonnell*, 1998]. The mean $\delta^{18}O$ value of these snowpits was therefore not representative of the $\delta^{18}O$ signature for overland flow. However, variability of $\delta^{18}O$ values between snow and snowmelt and in snowmelt from different elevation zones was usually muted in the peak streamflow [*Cooper*, 1998]. Thus, it seems reasonable to use $\delta^{18}O$ value in this peak streamflow sample to characterize overland flow. Conductance in this peak streamflow sample was 5.7 $\mu S\ cm^{-1}$, also very close to the mean conductance of snow (6.6 $\mu S\ cm^{-1}$; Figure 5).

The second end-member appeared to be near the upper right corner of the cluster with higher conductance and $\delta^{18}O$ values, which are characteristics of ground water. This end-member was characterized by conductance and $\delta^{18}O$ in the Valley wells for Happy Isles and Pohono Bridge and in the El Portal wells for Briceburg. Data from a single well were actually used instead of the mean or median values of all wells to obtain a triangle that bounds all of streamflow samples. For clarification, in this report, ground water is synonymous with mountain-block recharge.

The third end-member is located above all streamflow samples on the upper left side, with conductance in between the former two end-members and $\delta^{18}O$ much more enriched than snowmelt. The characteristics of this end-member appeared to match the outflow of Yosemite Falls, Cascade Fall, Crane Creek, and Moss Creek. All of these streams except Yosemite Falls are perennial, and all originate from areas covered with soils. This end-member appears to be lateral subsurface flow, a flow component that is generated mainly from the interface of soil matrix and bedrock. Lateral subsurface flow occurs when infiltrating water encounters an abrupt decrease in hydraulic conductivity, typically as a result of a change in subsurface media (e.g., water flowing through alluvium encounters bedrock). The mean values of conductance and $\delta^{18}O$ in samples collected at Yosemite Falls were used to parameterize lateral subsurface flow for

Happy Isles and Pohono Bridge because they gave a triangle that bounded almost all of the streamflow samples. Outflow of Crane Creek may be used to characterize lateral subsurface flow for Briceburg. Due to missing samples before September at Crane Creek, however, samples from Cascade Falls were actually used to represent lateral subsurface flow below El Portal. Both streams are adjacent to each other, and have similar conductance and δ^{18}O values from August to October (Figure 5).

3.2. Determination of End-Member Contributions to Streamflow

Contributions of overland flow, lateral subsurface flow, and ground water were determined using the mixing diagrams described above and equations 1-8. The contribution of overland flow was on average 44% from May to November 2006 at Happy Isles, while the contributions of lateral subsurface flow and ground water were 40% and 16%, respectively. Overland flow accounted for more than 90% of the total streamflow in May and June, decreased rapidly to approximately 30% through early August, and then remained almost unchanged (Figure 7a). The proportion of lateral subsurface flow increased from nearly 0% to 60% from May to early August, remained relatively constant through early September, and then decreased to about 20% in early November (Figure 7b). The contribution of ground water was close to 0% from May to early August, but increased gradually until reaching over 40% in early November (Figure 7c). Compared with Happy Isles, the mean proportion of overland flow decreased by 14% at Pohono Bridge, while that of lateral subsurface flow and ground water increased by 4% and 10%, respectively. The temporal patterns of the proportion of contribution of these three end-members at Pohono Bridge were similar to Happy Isles (Figure 7). At Briceburg, the streamflow was comprised, on average, equally of overland flow, lateral subsurface flow and ground water from May to November. From May to early July, overland flow alone accounted for about 60%; from early August to early September, lateral subsurface flow was about 55%; from early September to November, groundwater contribution was 40%-60% (Figure 7).

The contributions of three end-members to streamflow were converted to flow rate by multiplying fractions (percentages divided by 100) by streamflow discharge. The discharge of overland flow and lateral subsurface flow was fitted to an exponential function from the time of peak streamflow on May 19 to November at Happy Isles, Pohono Bridge and Briceburg (Figure 8). The high regression coefficient of determination (R^2) for overland flow as a function of time was not expected and was probably dominated by a few samples, particularly during the snowmelt period. Nevertheless, this function reflects the decreasing trend of overland flow after peak flow. To aid in a description, the time scale was re-constructed for this analysis by using May 19 (day of peak flow) as day 0. For overland flow, the initial discharge (when $x = 0$, where x is date), which is an approximate measure of snow capacity at the maximum snowmelt, increased with increasing drainage area from Happy Isles to Briceburg. The decay constant, a factor describing how fast the decay of overland flow is over time, however, was almost the same for all three sites. This result is to be expected because this factor is controlled only by the surfacial conditions (e.g., roughness), which are probably not significantly different at higher elevations where overland flow primarily originates.

Without recharge, discharge from an unconfined aquifer decays over time [e.g., *Berne et al.*, 2005]. The decay of lateral subsurface flow follows this behavior. Initial discharge of lateral subsurface flow also increased with increasing drainage areas from Happy Isles to Briceburg. The decay constants decreased significantly (Figure 8), indicating that the sources for lateral subsurface flow had smaller capacity and also decayed faster at higher elevations. Soils are thinner and slopes are steeper at higher elevations than lower elevations in the Upper Merced River. It is worth noting that lateral subsurface flow at Happy Isles experienced two stages (indicated by HI_1 and HI_2 on Figure 8): increase with a growth function from May 19 to July 19, 2006 and decrease afterward. The contribution of lateral subsurface flow peaked on July 19, two months after the peak streamflow on May 19. This result suggests a mean travel time of two months for lateral subsurface flow in the drainage above Happy Isles. This phenomenon did not occur at Pohono Bridge and Briceburg because snow in lower elevations melted much earlier than higher elevations. A significant streamflow peak occurred on April 4 at Pohono Bridge and Briceburg, about two months earlier than the highest streamflow peak, but did not occur at Happy Isles (Figure 2). The higher contribution of lateral subsurface flow on May 19 at Pohono Bridge and Briceburg may be caused by earlier snowmelt in the lower elevations.

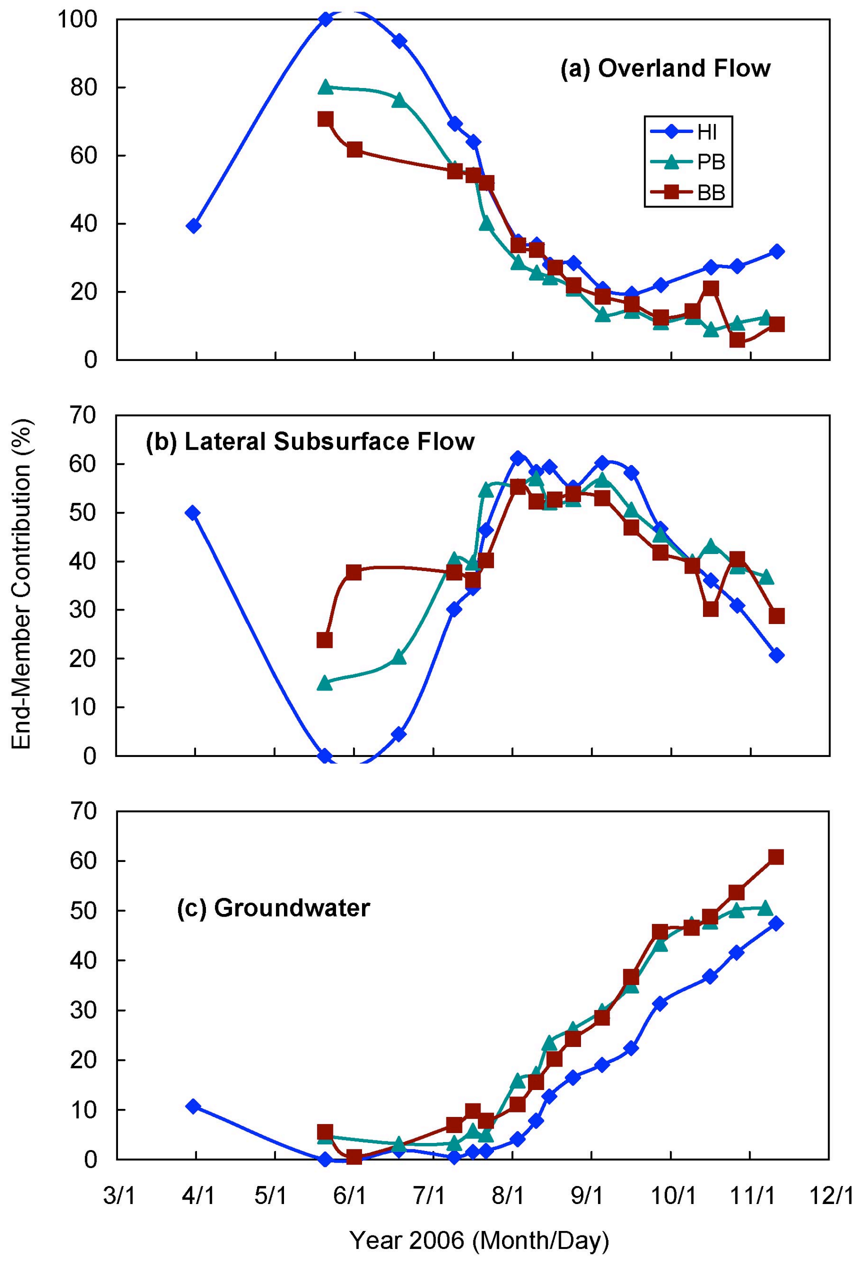

Figure 7 Percent contributions of end-members to streamflow in 2006 for (a) overland flow, (b) lateral subsurface flow, and (c) bedrock ground water

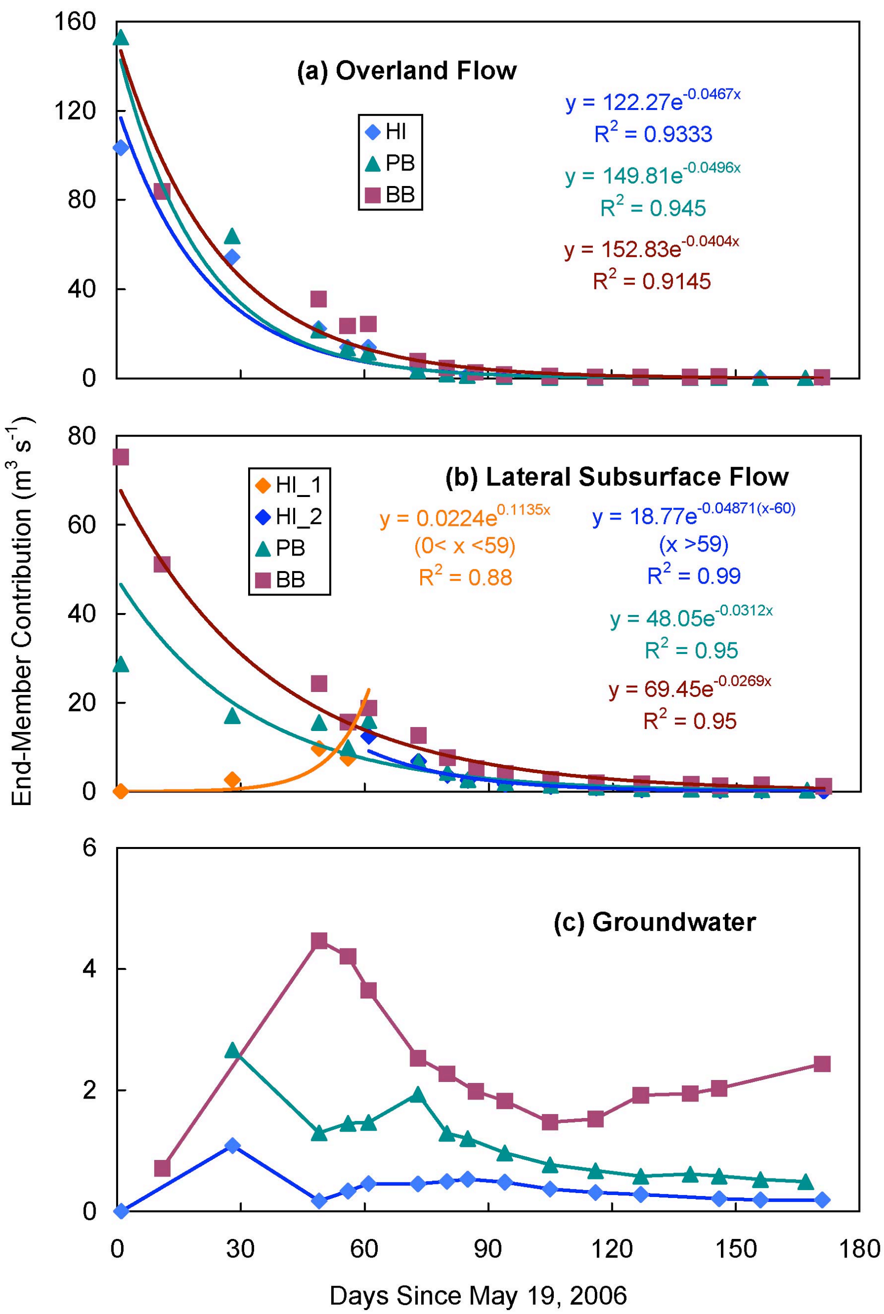

Figure 8 Contributions of end-members to streamflow in 2006, expressed as flow rate, for (a) overland flow, (b) lateral subsurface flow, and (c) ground water, with fitted exponential equation for overland flow and lateral subsurface flow

The discharge of ground water was almost constant from August to November 2006 at Happy Isles and Pohono Bridge, and also did not vary significantly at Briceburg (Figure 8c). The discharge increased with increasing drainage areas. Streamflow at Briceburg received more than twice the groundwater discharge than streamflow at Happy Isles. The discharge of ground water was highest during and right after the snowmelt period at Briceburg.

3.3. Residence Times of Ground Water

Tritium concentrations varied slightly from stream water to springs (Figure 9a). The tritium value of stream water at Happy Isles and El Captain Bridge was 4.1 TU, 0.4 TU lower than that in snow collected in early April 2006 at Gin Flat. The tritium value in stream water decreased to 3.7 and 3.3 TU at downstream stations at Pohono Bridge and Briceburg, respectively, on July 31, 2006. The tritium values were lower in springs than in stream water, with 2.7 TU at both Happy Isles Spring and Fern Spring. Surprisingly, the tritium values did not vary significantly in various groundwater samples collected in November 2006 (Figure 9b). The mean tritium value was 3.6 TU for all groundwater samples with 1σ standard deviation of only 0.15 TU. The decrease in tritium value downstream in the Merced River may be caused by an increase in groundwater contribution, consistent with the results of the mixing models above.

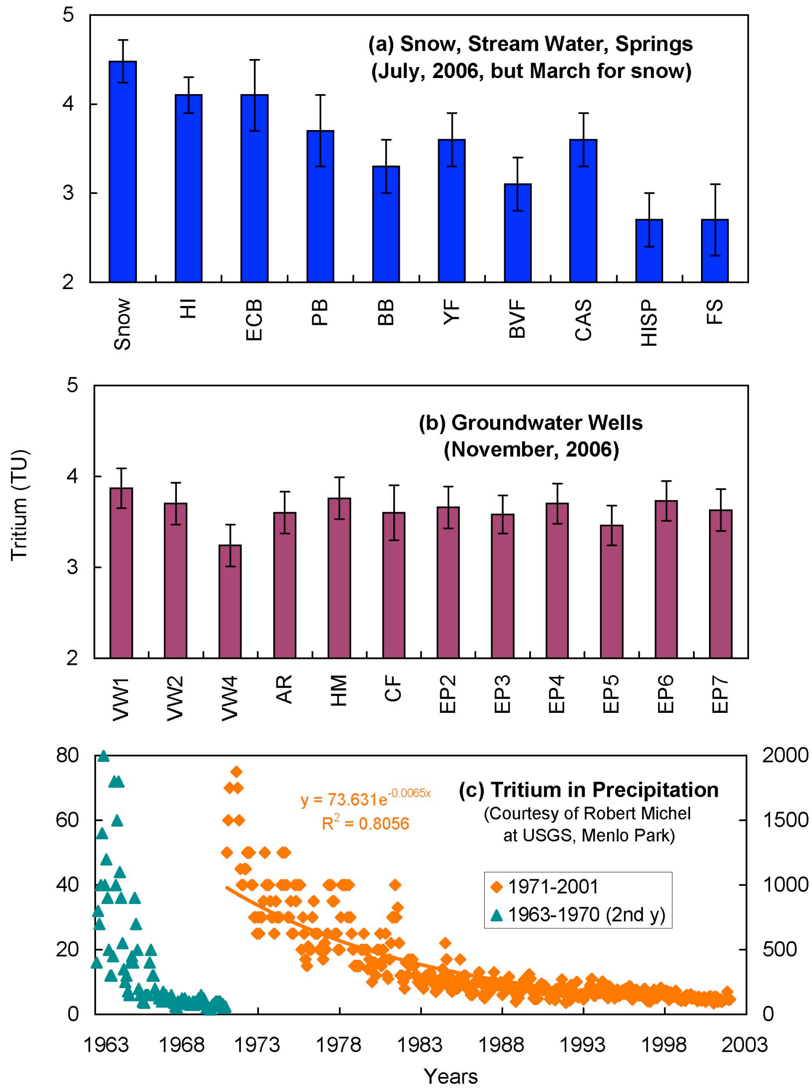

Figure 9 Tritium concentrations in (a) snow, stream water, and spring samples, (b) groundwater samples (error bars represent analytical uncertainty from the lab), and (c) historical

precipitation in Sierra Nevada based on data from Robert Michel at USGS, Menlo Park, CA. Values are separated into two periods (1963 to 1970 and 1971 to 2001) due to their significant difference in tritium values

Due to intensive thermonuclear tests in the early 1960s, tritium values in precipitation peaked in 1963 in the Sierra Nevada (Figure 9c). After then, tritium in precipitation decreased gradually and became relatively invariant through 2000 and 2001 (the last 24 months in Figure 9c). The tritium concentrations in precipitation from 2002 to 2006 are not available, but should be close to those in 2000 and 2001. After groundwater recharge, tritium decays naturally with a half life of approximately 12.43 years. Using equation 9, decay-corrected tritium values were estimated assuming that recharge from historical precipitation (meteoric water) occurred in given years still circulates in the current hydrologic system (Table 1). If the recharge of meteoric water occurred before the intensive nuclear tests, its decay-corrected tritium value would be very low, e.g., 0.1 TU for 1940 meteoric water and 1.1 TU for 1955 meteoric water. If meteoric water from 1963 is decay-corrected, its 2006 tritium value would be 182 TU. Interestingly, the decay-corrected tritium values for meteoric water from after 1980 would remain a similar level between 3 and 4 TU, with the lowest value for 1985. This results from the concatenation of natural decay and the gradual decrease of tritium in precipitation due to the halt of nuclear tests in the United States.

Table 1. Tritium values in historical precipitation and decay-corrected values in 2006 given that the recharge from historical precipitation in given years still circulates in the current hydrological system (calculation based on data from Robert Michel at USGS, Menlo Park, CA)

The tritium value in ground water at present represents an average tritium value for a mixture of meteoric water from many years in the past. Travel times of groundwater recharge follows an approximate power-law distribution [*Kirchner et al.*, 2000], implying that groundwater recharge from a particular year in the past initially decreases significantly but persists many years with low and slowly decreasing flow rate. Based on this principle, it is determined that the sampled ground water did not contain a significant amount of meteoric water from 1963; otherwise, the tritium value in ground water at present would be much higher than 4 TU. To illustrate this, a simple example is presented. Assume that ground water was composed of 2% meteoric water from 1963 (contribution of tritium concentration then would be 182×2% = 3.6 TU) and 98% meteoric water from 1964 to 2005 with a mean decay-corrected value 3 TU (contribution 3×98% = 2.9 TU). The tritium value in ground water would be 6.7 TU (3.6 plus 2.9). This example is very conservative because the decay-corrected tritium value was much higher than 3 TU for precipitation occurred from 1964 to 1980 (see Table 1 for more details). Similarly, the sampled ground water may not contain a significant amount of meteoric water from before 1963 since the tritium values in groundwater samples were very close to decay-corrected tritium values in precipitation after 1975 (Table 1). It appears that groundwater samples collected from wells are primarily a mixture of meteoric water recharged after 1970. Spring recharge at Happy Isles Spring and Fern Spring, with lower tritium values than the well samples, may date back to 1985, with mean residence times shorter than groundwater samples collected from wells.

3.4. Impact of Climate Warming on Baseflow

The long-term record of streamflow was separated into two periods for trend analysis: before 1975, and after 1975. Mean global temperature has steadily increased since about 1975 [*IPCC*, 2007]. Historical simulations of streamflow in the Merced River yielded stationary climate and hydrologic variations through the first part of the 20th century until about 1975 [*Dettinger et al.*, 2004]. The trend of baseflow since 1975 is thus of particular interest in this study. Annual precipitation was greater than 1,000 mm in seven of nine years from 1975 to 1983 at YNP. This relatively wet period was not included in the analysis to eliminate trend bias.

The mean annual discharge at Happy Isles in the Upper Merced River did not show an obvious trend from 1916 to 1974, but there was a slight, statistically insignificant, increase from 1984 to 2005 ($p = 0.3$) (Figure 10). The mean discharge for baseflow from August to October did not change from 1984 to 2005. The mean discharge for baseflow in October, however, significantly decreased from 1984 to 2005 ($p < 0.05$).

The trend of minimum daily discharge in October was also analyzed for Happy Isles and Pohono Bridge in the Merced River (Figure 11). The minimum daily discharge in October was usually the lowest daily discharge for the entire year. Since 1984, the minimum daily discharge in October has decreased slightly at both Happy Isles and Pohono Bridge. However, the decline was only significant at Happy Isles ($p < 0.05$).

Trends in precipitation were analyzed using data from 1984 to 2004 or 2005 (data available at http://www.wrcc.dri.edu). All weather stations within or near YNP were selected, yielding stations at a range of elevations (Figure 1). There was no significant trend observed for annual averages, nor for the August-October period. Apparently, precipitation amount during the August-October period was not the controlling factor responsible for the baseflow decline at Happy Isles.

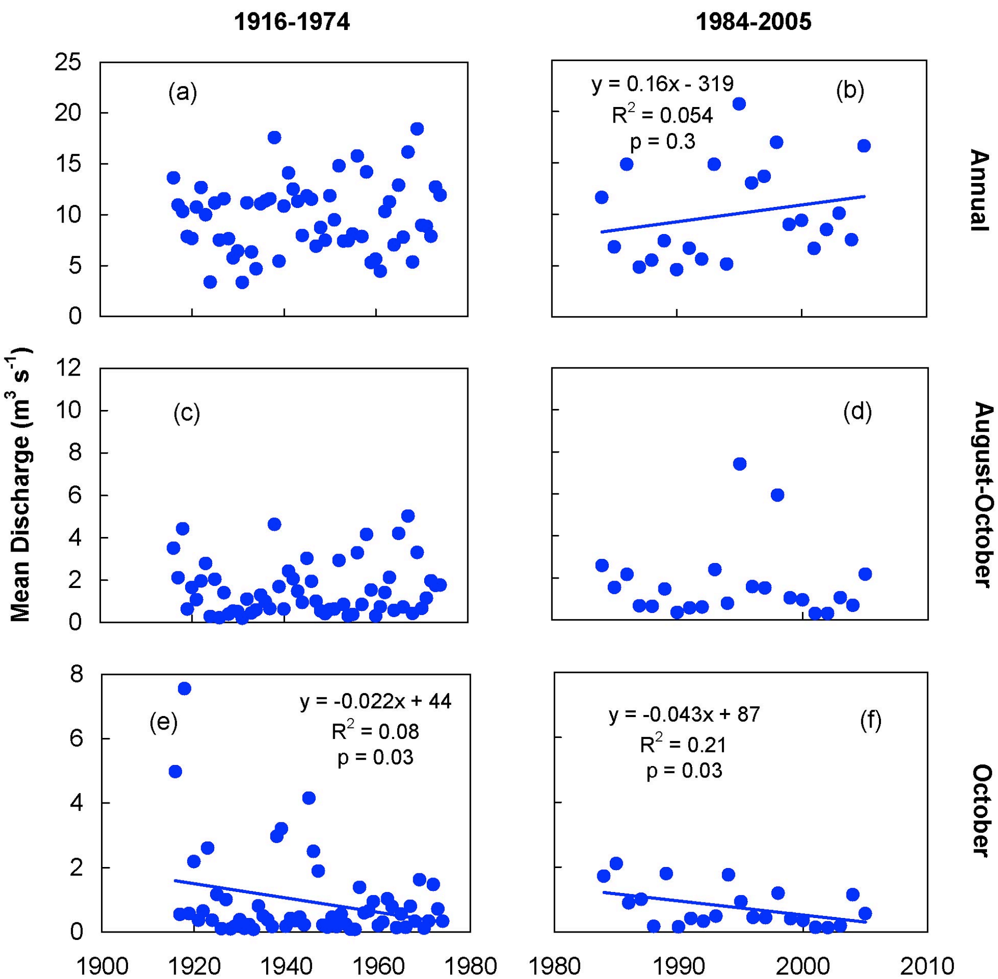

Figure 10 Trend of streamflow discharge at Happy Isles from 1916 to 1974 and from 1984 to 2005 (a) and (b) at annual basis, (c) and (d) for the August-October period, and (e) and (f) for October

The decline in snow water equivalent (SWE) and earlier onset of snowmelt in spring may be the major factors contributing to the decline of baseflow over time at Happy Isles. Observations over the last half-century have demonstrated that, across a broad region of mountainous western North America, spring snow accumulation has declined (e.g., *Mote et al*., 2005), and snowmelt has come earlier in the year (e.g., *Steward et al*., 2005). In the Sierra Nevada, onset of snowmelt has come 1-4 weeks earlier over the past 30 years [e.g., *Cayan et al*., 2001]. The decay functions of overland flow and lateral subsurface flow were used, as an example, to evaluate effects of earlier onset of snowmelt on their contributions to streamflow under the same snow condition (e.g., same SWE) and no precipitation events after the peak streamflow.

Under those constraints, the contributions of overland flow and lateral subsurface flow to streamflow were controlled by the timing of snowmelt. If snow started melting 15 days earlier, for example, overland flow and lateral subsurface flow on day 1 would be the same as on day 15 under this scenario. Following this principle, the reduction of overland flow and lateral subsurface flow was calculated for October, 2006 given that snowmelt started 1 to 15 days earlier and the value was normalized using percentage difference that occurred each day (Figure 13). If snow started melting 15 days earlier, the contribution of overland flow to streamflow would be reduced by about 50% in October, 2006 at all three locations. The decrease was similar for all three locations, indicating that snowmelt at this time was mainly from higher elevations above Happy Isles, which is realistic. Lateral subsurface flow would also be reduced about 50% at Happy Isles and about 30% at Pohono Bridge and Briceburg. Lateral subsurface flow is more sensitive to the change in snowmelt timing at higher elevations than lower elevations. The decline of baseflow at lower elevations was not significant in the past decades, but may become more important in the future if the earlier onset of snowmelt continues in the region. Note, however, that this calculation was based on ideal conditions outlined above. In reality, any precipitation events occurring after the peak streamflow and any change in SWE in May could change the situation very much. This research team recommends additional studies for 3-5 years, so that a variety of different snow years could be used to do this simulation.

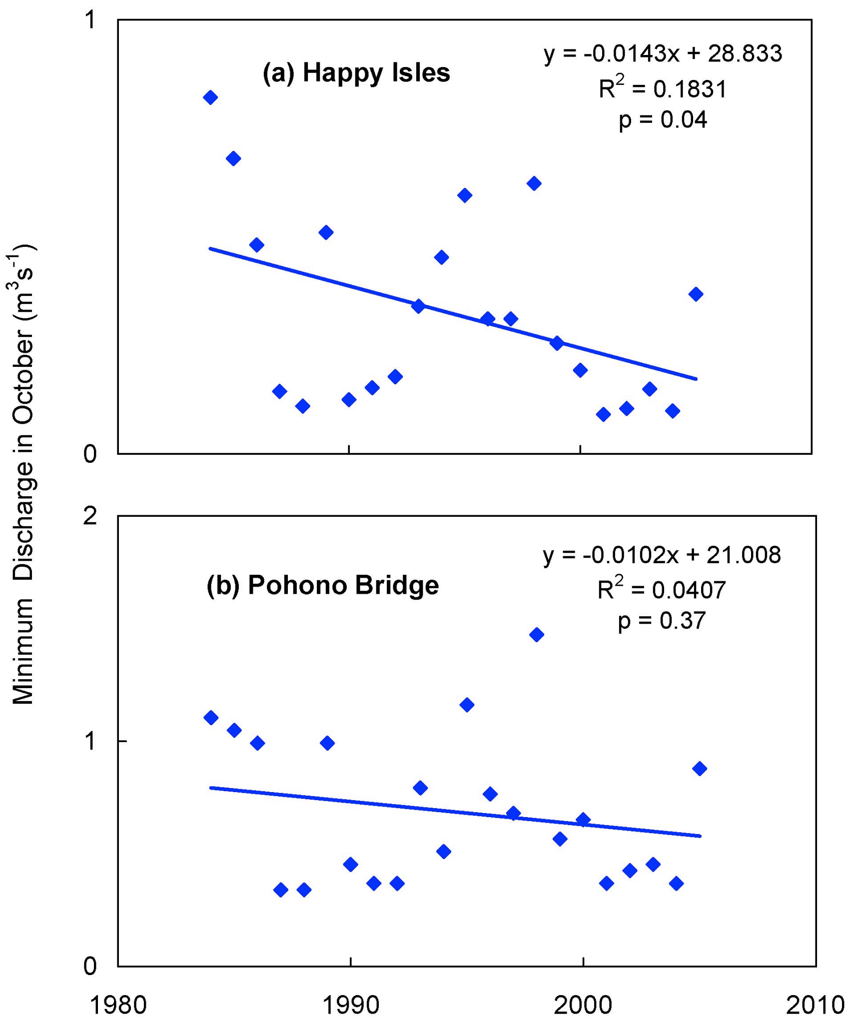

Figure 11 Trend of minimum daily discharge in October from 1984 to 2005 at (a) Happy Isles and (b) Pohono Bridge

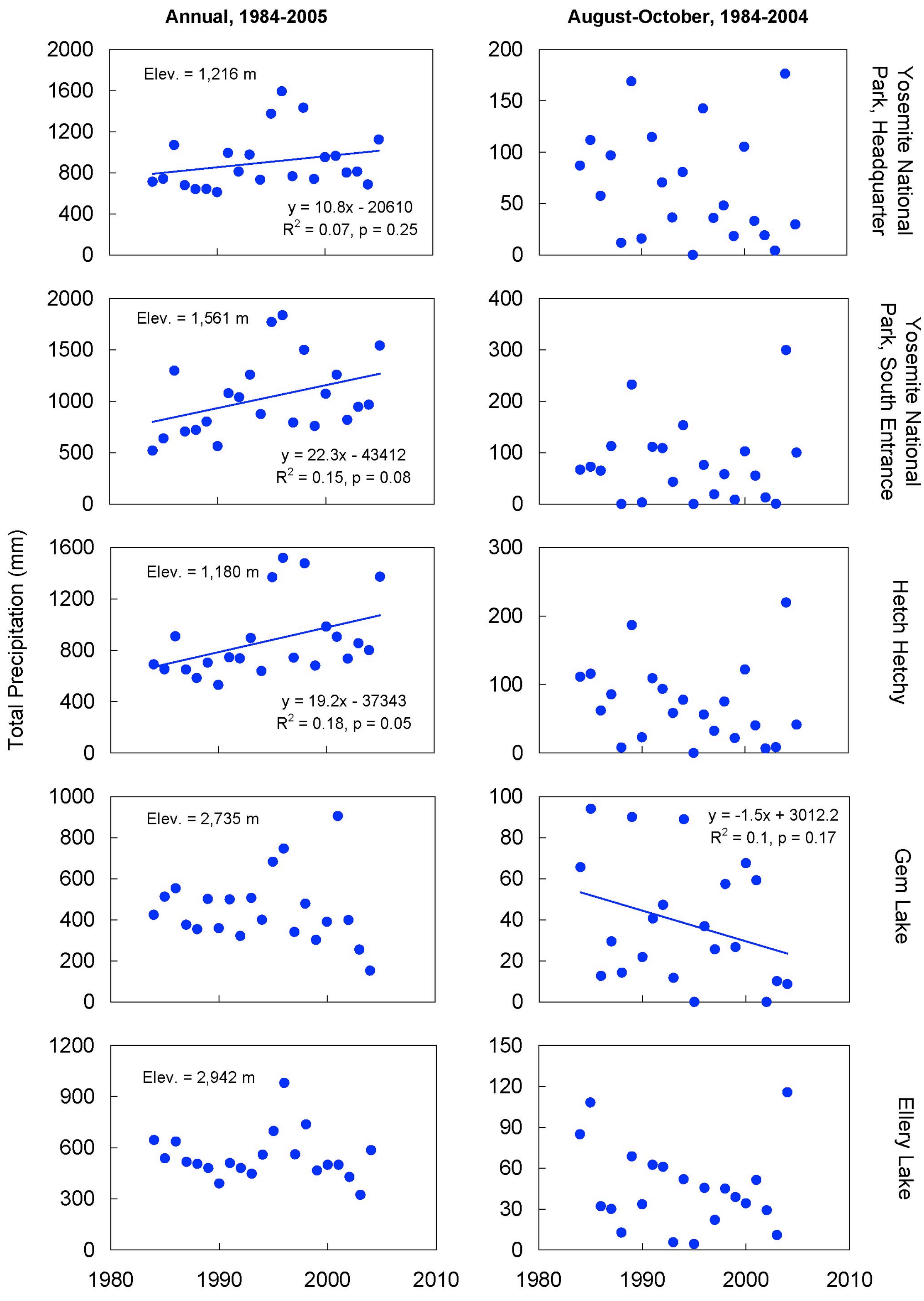

Figure 12 Trend of precipitation for annual and September-October totals at Yosemite National Headquarter, Yosemite National Park South Entrance, Hetch Hetchy, Gem Lake and Ellery Lake

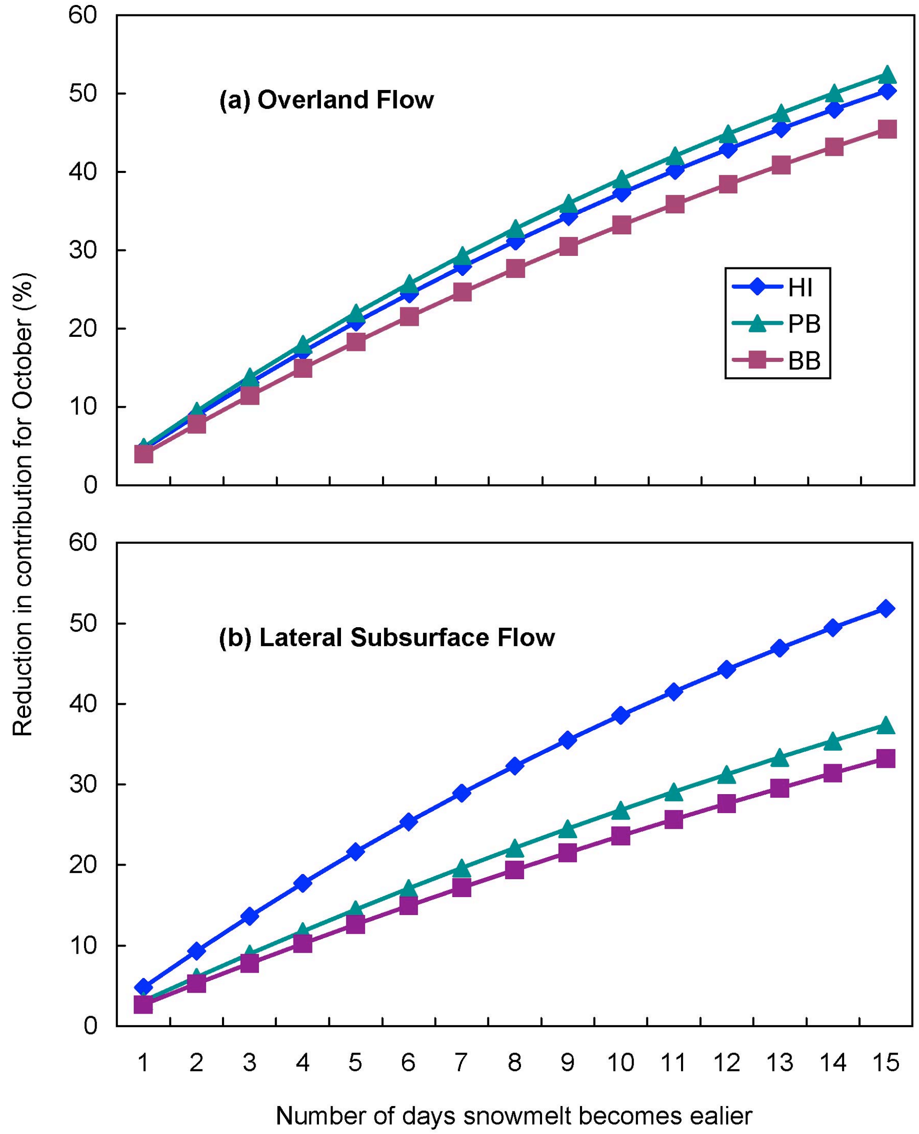

Figure 13 Reduction of (a) overland flow and (b) lateral subsurface flow in October normalized by the difference that occurred each day if snowmelt had been 15 days earlier.

4.0. Conclusions

Baseflow was primarily controlled by mountain-block recharge, lateral subsurface flow, and overland flow from August to October, 2006 in the Upper Merced River, showing a strong linkage between surface water and groundwater processes. The contribution of mountain-block recharge increased from 10-20% of the total streamflow discharge in August to over 50% in October. The contribution of mountain-block recharge also increased with increasing drainage areas, as expressed by flow rate, 0.2-0.5 $m^3 s^{-1}$ at Happy Isles, 0.5-1.2 $m^3 s^{-1}$ at Pohono Bridge and 1.5-2.5 $m^3 s^{-1}$ at Briceburg. An increase in groundwater withdrawal in the mountains and foothills would reduce discharge of mountain-block recharge to the Upper Merced River. Lateral subsurface flow dominated baseflow in August and September 2006 and accounted for more than 50% of the total streamflow. Overland flow primarily occurred at higher elevations above

Happy Isles and accounted for less than 30% of the total streamflow. The discharge (flow rate) of lateral subsurface flow and overland flow decreased gradually over time and were described using an exponential function. The timing of their contributions to the river was controlled by the snow quantity and timing of snowmelt. The response of lateral subsurface flow to snowmelt lagged two months behind the peak snowmelt, indicating that the mean travel time was about two months. Baseflow in October has been significantly declining since 1984 at Happy Isles in the Upper Merced River. The research team hypothesizes that this decreasing trend is a response to the decrease in spring time SWE and earlier onset of snowmelt occurring in the Sierra Nevada. Lateral subsurface flow is more sensitive to the change in snowmelt timing at higher elevations than lower elevations. If the decline of SWE and the earlier onset of snowmelt continue as a result of climate change in the region, the decline in baseflow may expand to all autumn months and across the entire Sierra Nevada.

5.0. Recommendations

This study demonstrated that it is efficient and cost-effective to use natural tracers to understand the processes that control streamflow generation in mountains and develop a conceptual understanding of how climate change may affect mountain water resources. To develop an operational model to predict low-flow hydrology and evaluate the impact of low-frequency droughts on hydroelectricity generation, ecosystems, and water supplies, two continuation research projects are recommended: (i) extend and validate the conceptual understanding of streamflow generation developed by this study using data from multiple years with different climates and different river systems and (ii) develop a physically based, spatially distributed hydrologic model based on the conceptual understanding of streamflow generation to predict low-flow hydrology. These projects would require funding for 3-5 years at 0.5-1 million dollars each.

6.0. Benefits to California

The results of this study are of interest to broader communities, stakeholders and policymakers. The results can aid decision making regarding California's water resources, ecosystem management, electricity generation, irrigation and aquatic resources. This research led to a better understanding of the relationship between the water cycle and climate change in the Sierra, and will benefit the reservoir managers in their day-to-day operational decisions. It also will benefit the Federal Energy Regulatory Commission and the California Department of Water Resources and provides information relevant to decisions on the dam re-licensing and hydroelectricity strategies. Furthermore, information about the change in groundwater contribution to baseflow is critical for ecosystem managers to monitor stream temperature to protect salmon and steelhead.

7.0. Sampling Location Acronyms

Municipal locations (may also serve as sampling sites):

- YNP – Yosemite National Park
- EP – El Portal
- BB – Briceburg

Sampling sites along main stream of the Merced River:

- HI – Happy Isles
- ECB – El Captain Bridge
- PB – Pohono Bridge

Sampling sites at water falls and tributaries:

- YF – Yosemite Falls
- BVF – Bridalveil Falls
- CAS – Cascade Falls
- TN – Teneya Creek
- CC – Crane Creek
- SF140 – South Fork Merced River at Highway 140
- SFW – South Fork at Wawona
- SWC – Sweetwater Creek
- BC – Beer Creek

Sampling sites at springs:

- FS – Fern Spring
- HISP – Happy Isles Spring
- THSP – Trail Head Spring
- CASSP – Cascade Spring
- HS – Harding Spring
- DF – Drinking Fountain

Sampled groundwater wells:

- AR – Arch Rock Well
- HM – Hodgon Meadow Well
- CF – Crane Flat Well
- VW's – Valley Wells (VW1, VW2, and VW4)
- EPW's – El Portal Wells (EPW2 to 7)

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