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Seasonal variation of high elevation groundwater recharge as indicator of climate response

Daniel C. Segal [a,*], Jean E. Moran [a], Ate Visser [b], Michael J. Singleton [b], Bradley K. Esser [b]

[a] California State University, East Bay, Hayward, CA, United States
[b] Lawrence Livermore National Laboratory, Livermore, CA, United States

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SUMMARY

High elevation groundwater basins in the western United States are facing changes in the amount and timing of snowmelt due to climate change. The objective of this study is to examine seasonal variability in a high elevation aquifer (Martis Valley Watershed near Truckee, CA) by analyzing (1) tritium and helium isotopes to determine groundwater sources and age, (2) dissolved noble gases to determine recharge temperatures and excess air concentrations. Recharge temperatures calculated at pressures corresponding to well head elevations are similar to mean annual air temperatures at lower elevations of the watershed, suggesting that most recharge is occurring at these elevations, after equilibrating in the vadose zone. The groundwater flow depth required to increase the water temperature from the recharge temperature to the discharge temperature was calculated for each well assuming a typical geothermal gradient. Groundwater samples contain large amounts of excess helium from terrigenic sources, including mantle helium and radiogenic helium. Terrigenic helium and tritium concentrations are used to determine the amount of mixing between the younger and older groundwater sources. Many of the wells sampled show a mix of groundwater ages ranging from >1000s of years old to groundwater with tritium concentrations that are in agreement with tritium in modern day precipitation. Higher seasonal variability found in wells with younger groundwater and shallower flow depths indicates that the recent recharge most vulnerable to climate impacts helps to supplement the older, less sustainable waters in the aquifer during periods of increased production.

1. Introduction

The western United States continues to rely heavily on groundwater to support population growth and agriculture making it critically important to understand how groundwater recharge will be impacted by predicted climate change (Green et al., 2011). Overall, regional groundwater recharge may increase or decrease as a result of higher predicted temperatures (Earman and Dettinger, 2007). However, groundwater recharge has been shown to be vulnerable to the effects of climate, especially in arid and semiarid regions (Aguilera and Murillo, 2009; Ajami et al., 2012; Barthel et al., 2009; Novicky et al., 2010). Alpine and subalpine groundwater basins in California may be particularly affected since they receive most of their groundwater recharge from seasonal snowpack melting. Even modest increases in temperature predicted by climate change have the potential to cause a greater proportion of precipitation in California to occur as rain, decrease the amount of snowpack in the Sierra Nevada, and shift the snowmelt hydrograph to an earlier and sharper peak (Earman and Dettinger, 2007). This will increase the likelihood of flooding events and likely cause a decrease in groundwater recharge of snowmelt, since there will be less total snowmelt and more snowmelt will leave the watershed as surface water. Climate change presents a challenge to managing the water supply, since it will have an effect on how much groundwater is recharging, where it is recharging, and by what mechanism recharge is occurring (Manning et al., 2012). One way of assessing the vulnerability of an aquifer system to relatively sudden shifts in recharge amount and location is to examine the degree of seasonal variability in the characteristics of the water mass produced at wells. Seasonal variability can include both natural and anthropogenic causes, such as variations in pumping rates and groundwater abstraction. By understanding current seasonal groundwater recharge conditions and residence times in high elevation basins where climate change is likely to affect precipitation and runoff, we can assess the vulnerability of mountain aquifers to climate change (Earman and Dettinger, 2007; Singleton and Moran, 2010).

* Corresponding author at: Chevron Energy Technology Company, San Ramon, CA, United States.
E-mail address: danielsegal@chevron.com (D.C. Segal).

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Dissolved noble gases and isotope analysis have the potential to add new and unique information to aid in assessing groundwater vulnerability to climate change. Noble gas concentrations are used to examine recharge conditions, including recharge temperatures (Aeschbach-Hertig et al., 2000; Stute et al., 1995a) and excess air concentrations (Ingram et al., 2007; Wilson and McNeill, 1997). Tritium and helium isotope measurements can be used to evaluate the apparent age of a groundwater sample that is less than 50 years old, if circumstances allow for quantification of the various helium components (Poreda et al., 1988; Schlosser et al., 1988; Takaoka and Mizutani, 1987).

Previous studies have used noble gases and other environmental tracers to examine the vulnerability of mountain alluvial aquifers to climate change. Singleton and Moran (2010) identified zones of very young groundwater and pointed out their sensitivity to changing recharge conditions that might result from short-term climate variations. Manning et al. (2012) observed a general trend of increasing groundwater age over the past 13 years and attributed this to declining recharge rates due to recent warming and declining snowpack. This study utilizes the novel approach of examining seasonal variations in groundwater age and recharge temperature to identify the most seasonally dynamic parts of an aquifer, which would presumably be the most susceptible to short-term climate variations. Specifically, we use tritium and helium isotopes and dissolved noble gases to examine seasonal variability in groundwater age and recharge source for samples collected from wells in the Martis Valley near Truckee, CA in the Sierra Nevada Mountains. We then use this information to address two key questions important for effective management of this and other mountain alluvial aquifers under changing climate conditions: (1) Will mountain aquifers with large storage capacity, like the Martis Valley, be well-buffered against short-term fluctuations in the availability of recharge? (2) What portion of recharge occurs through exposed fractured bedrock at the highest-elevations in the watershed where most of the snowpack resides, the recharge component most directly impacted by warming and declining snow amounts?

2. Methods

2.1. Study site

Martis Valley, in the Sierra Nevada, has been identified as a region likely to face water shortages in the future (Coats, 2010) and was selected to study how climate change is impacting groundwater supply. Martis Valley, at over 1800 m above sea level, is unique for a high elevation basin, since there are 14 production wells producing large volumes (1.15×10^7 m^3/year) of groundwater from various locations and depths in the aquifer (Fig. 1). Martis Valley's economy is largely sustained by tourism (Dean Ruyan Associates, 2013) and groundwater is the exclusive source for providing drinking water to the town of Truckee and the surrounding region, irrigation for golf courses in summer and for creating artificial snow at ski resorts in winter. Despite heavy reliance upon and development of groundwater resources, relatively little is known about the groundwater system.

Martis Valley is a structural basin north of Lake Tahoe in the Walker Lane Belt shear zone, a transitional zone between the Sierra Nevada Mountains and the Basin and Range Geomorphic Provinces (Brown and Caldwell, 2013). The lowest terrace in the valley floor is at 1737 m elevation. Mountains rise dramatically to the south including the 2665 m elevation Martis Peak. The Martis Valley groundwater basin lies between the Sierra Nevada crest in the west and the Carson Range to the east. Extensional Basin and Range-style normal faulting, as well as Walker Lane Belt associated strike-slip faulting formed this structural valley during the Pliocene and early Pleistocene as the Sierra Nevada uplifted about 1524 m relative to the graben. Most structural development has occurred during the last five million years and active faulting continues to this day. Four major glacial events shaped the topography of Martis Valley during the Pleistocene. Glacial moraines and outwash plain sediments from the Tahoe and Tioga glaciations fill much of the Martis Valley basin (Fram et al., 2009).

The Martis Valley watershed occupies an area of 147.6 km^2 in Nevada and Placer counties. The Truckee River flows SW to NE across Martis Valley and is controlled upstream by a dam at the edge of Lake Tahoe. Flows in the Truckee River are managed by the Truckee River Operating agreement (Coulter et al., 2009). The groundwater bearing units in Martis Valley are up to 300 m thick and are comprised of interlayered Miocene to late Pleistocene volcanic and sedimentary deposits. Low-permeability Miocene volcanic rocks form the base of the water bearing units. Basin-fill volcanic units include andesite lava, tuff, and breccia. Sediments originating from the volcanic and volcaniclastic units surrounding Martis Valley comprise the glacial, lacustrine, and fluvial sedimentary deposits. These sedimentary deposits provide the most groundwater storage and best opportunity for extraction. These units also include relatively impermeable laterally extensive clay and silt layers (California Department of Water Resources, 2006). Roughly half of the surface of Martis Valley is covered in glacial outwash sediments that are up to 46 m thick. The basin depocenter, where sediments are up to 300 m thick, is located to the south of the Truckee River near the middle of the watershed area. The basin's stratigraphy is divided into lower and upper aquifer systems. The lower aquifer system is found in the Truckee formation while the upper aquifer system consists of the shallower glacial and alluvium deposits. These units are thought to have limited interconnectivity, with the Lousetown volcanic units acting as a barrier to flow. Some wells were historically artesian in southern Martis Valley, indicating confined conditions over some portion of the aquifer system. These wells are also situated near faults, which are interpreted as barriers to groundwater flow (Brown and Caldwell, 2013). Thermal springs are found in this region, adjacent to the recently-mapped Polaris Fault (Hunter et al., 2011).

Annual groundwater levels have remained relatively constant from 1990 through 2000 with seasonal water level variations often exceeding 3 m. The water level elevation is controlled by the hydrogeologic units' complex stratigraphy, topography, and groundwater flow barriers. In general, hydraulic gradients determined from groundwater elevations indicate that groundwater flow in the basin is toward the Truckee River (California Department of Water Resources, 2006; Hydro-Search, 1995). Groundwater storage for Martis Valley Basin has been estimated at 5.97×10^8 m^3 with an average specific yield of 0.05. Annual groundwater recharge is estimated at 2.9×10^7 m^3 (0.20 m) from precipitation, including snowmelt, and 2.9×10^6 m^3 (0.02 m) from artificial recharge at a wastewater treatment facility east of Truckee. Urban extraction of groundwater is estimated at 8.71×10^6 m^3 (0.06 m) per year, with an additional 1.57×10^6 m^3 (0.01 m) extracted to irrigate golf courses. Mountain-block recharge and subsurface outflow are estimated at 6.6×10^6 m^3 (0.04 m) and 2.2×10^7 m^3 (0.15 m) per year, respectively (Nimbus Engineers, 2001). Desert Research Institute's Martis Valley integrated groundwater, surface water, and climate change model (Huntington et al., 2013) provides a more recent groundwater recharge estimate of 4.0×10^7–4.3×10^7 m^3/year (0.27–0.30 m/year), consisting of the sum of shallow infiltrated water that discharges to the Truckee River and its tributaries plus deep percolation to aquifers tapped by water supply wells. While current annual groundwater extraction is only about 30% of groundwater recharge, future scenarios predict higher demand and potentially lower recharge.