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LLNL-JRNL-735797

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July 27, 2017

Environmental Research Letters

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Importance of River Water Recharge to the San Joaquin Valley Groundwater System

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Key Points:

- River water recharge represents 47±4% of modern groundwater in the San Joaquin Valley, but only 26±4% of pre-modern groundwater.
- River water recharges groundwater systems at lower temperatures and with larger water table fluctuations than local precipitation recharge.
- Groundwater banking of seasonal river flows appears to be a promising method for increasing the resilience of water supply systems.

Abstract

Groundwater is not a sustainable resource, unless abstraction is balanced by recharge. Identifying the sources of recharge in a groundwater basin is critical for sustainable groundwater management. We studied the importance of river water recharge to groundwater in the southeastern San Joaquin Valley (24,000 km^2, population 4 million). We combined dissolved noble gas concentrations, stable isotopes, tritium and carbon-14 analyses to analyze the sources, mechanisms and time scales of groundwater recharge. Area-representative groundwater sampling and numerical model input data enabled a stable isotope mass balance and quantitative estimates of river and local recharge.

River recharge, identified by a lighter stable isotope signature, represents 47±4% of modern groundwater in the San Joaquin Valley (recharged after 1950), but only 26±4% of pre-modern groundwater (recharged before 1950). This implies that the importance of river water recharge in the San Joaquin valley has nearly doubled and is likely the result of a 40% increase in total recharge, caused by river water irrigation return flows and increased stream depletion and river recharge due to groundwater pumping. Compared to the large and long-duration capacity for water storage in the subsurface, storage of water in rivers is limited in time and volume, as evidenced by cold river recharge temperatures resulting from fast infiltration and recharge. Groundwater banking of seasonal surface water flows and expansion of managed aquifer recharge practices therefore appear to be a natural and promising method for increasing the resilience of the San Joaquin Valley water supply system.

1 Introduction

Globally, 43% of the demand for irrigation water is met by groundwater, leading to groundwater exploitation at rates above groundwater recharge [Siebert et al., 2010]. In the US, the demand for fresh water, 1.2 billion cubic meters for domestic use, agriculture, industry and energy production combined in 2010 [Maupin et al., 2014], is met by withdrawals from groundwater (25%) and surface water (75%). California relies on groundwater for 38% of its fresh water demands during average precipitation years [http://www.water.ca.gov/groundwater/]. Local precipitation and groundwater recharge fall short of groundwater pumping in many areas and overdraft of groundwater resources has led to declining groundwater levels and land subsidence [Faunt et al., 2016]. Managed aquifer recharge (MAR) is deployed to counteract water level declines in parts of the San Joaquin Valley, particularly along the Kern and Kings River systems [*Gamon et al.*, 2016]. Surface water satisfies the remaining 60% of water demand. In California, where the source of most major stream flows is snowmelt from the Sierra Nevada, the availability of surface water during the growing season is limited, despite an extensive and complex system of dams, aqueducts and reservoirs.

Anthropogenic warming has increased the probability of the co-occurring temperature and precipitation conditions that have historically led to drought in California [Diffenbaugh et al., 2015] and exacerbated Sierra Nevada snowpack loss significantly during the 2012-2015 drought [Berg and Hall, 2017]. Higher future temperatures will exacerbate the summer dry season and droughts, and reliance on groundwater will increase [Meixner et al., 2016]. Groundwater levels in the Central Valley have tended to decline in response to drought

conditions [Wang et al., 2016] and are expected to decline more severely under future climate [Hanson et al., 2012].

The California Central Valley has a Mediterranean climate and about 85% of the precipitation falls from November to April. The rivers that drain the Sierra Nevada mountains to the west have naturally resulted in recharge of Central Valley groundwater reservoirs by river water during spring and summer snowmelt. This natural connection between the surface water and groundwater systems is intensified by anthropogenic alteration of the water system, such as surface water diversions, groundwater pumping, surface water irrigation and artificial recharge, impacting the natural hydrological system in a number of ways. The immediate effect of surface water diversions on downstream users and habitats is clearly understood, whereas the impact of reduced surface water recharge (due to reduced direct river recharge and reduced seasonal flooding) on groundwater resources is extremely difficult to quantify. If focused recharge along the river bank is diverted for irrigation, this will lead to increased areal recharge away from the river. The net effect depends on irrigation efficiency and changes in evapotranspiration rates. Water table decline due to groundwater pumping can create or enhance the conditions for surface water recharge to groundwater systems. The indirect effects of decreased surface water flow by groundwater pumping induced recharge are also difficult to quantify.

Evaluating the sustainability of meeting the demand for water from groundwater resources requires a detailed understanding of groundwater recharge sources and processes. A predevelopment water budget for the entire Central Valley [Faunt, 2009] estimated an annual recharge of 1.8 km^3 from precipitation (75%) and 0.6 km^3 from river recharge (25%). The average water budget years 1962-2003 of the Central Valley groundwater model included 3.2 km^3 (20%) river recharge and 13.2 km^3 (80%) recharge from surface processes including irrigation return flow and diffuse recharge of precipitation. Diffuse recharge of precipitation in the basin has been estimated at 11% [Meixner et al., 2016]. Neither estimate directly quantifies the importance of river water as a source of recharge to the groundwater system.

Observable geochemical and isotopic markers add important information to model results regarding sources and mechanisms of recharge, and can be used by water managers to assess sustainability. The physiographic gradients across California result in distinct noble gas and isotopic signatures that are excellent tools to trace the source, mechanism and time scale of recharge. We studied the importance of river water recharge to groundwater in the southeastern San Joaquin Valley (24,000 km2, population 4 million). Our estimates of the importance of river water as a source of recharge are compared for modern groundwater (recharged after 1950) and pre-modern groundwater (recharged before 1950) to evaluate changes in recharge patterns over the last century.

2 Study Area, Methods, Data and Analysis

2.1 Study Area

The study area comprises the southeastern portion of the San Joaquin Valley (SJV), specifically the following four study units of the California State Water Board Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin project [Belitz et al., 2010]: Central Eastside SJV, Madera-Chowchilla, Southeast SJV and Kern. The study area is 360 km long and 40-100 km wide. Land cover is predominantly agricultural, producing the majority of

crops grown in California. Mean annual temperatures vary from 14 °C to 18 °C, and January and July monthly mean temperatures are 8 °C and 27 °C on average across the study area.

[FIGURE 1]

Average precipitation over the study area is 248 mm/yr, varying from 143 in the south to 522 mm/yr in the north (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004), totaling to 6.0 km^3/yr. Nine major rivers (Stanislaus, Tuolumne, Merced, Fresno, San Joaquin, Kings, Kaweah, Tule, Kern) drain the Sierra Nevada, which runs along the eastern side of the San Joaquin Valley (Figure 1). Under pre-development conditions, these rivers fed a widespread wetland and lake [Moore et al., 1990]. At present, all rivers are dammed and discharge is diverted for agricultural irrigation and public water supply. Annual volumetric river inputs into the study area domain were estimated by Faunt [Faunt, 2009]. Nine river input locations within the study area were identified which introduce a total of 9.2 km^3/yr. The direct contribution of each of the rivers to the water budget varies from 1%-2% (Fresno River, Tule River) to 22%-25% (Tuolumne River and Kings River). The State Water Project (SWP), operated by the California Department of Water Resources, transfers water from the Sacramento-San Joaquin Delta in the north, along the length of the San Joaquin Valley to major urban areas in Southern California. The State Water Project also supplies 1.2 km^3/yr to the San Joaquin Valley [California DWR, 2015], almost entirely to Kern County Water Agency (1.0 km3/yr). The Central Valley Project (CVP), operated by the US Bureau of Reclamation, transfers water from the Sacramento-San Joaquin Delta to the west side of the San Joaquin Valley, through the Delta-Mendota Canal and the San Luis Canal. This water is delivered to agricultural land outside the study area and not considered here. The CVP also operates the Madera Canal and the Friant-Kern Canal, redistributing water from the San Joaquin River along the eastern side of the San Joaquin Valley. The redistribution affects the spatial delivery of San Joaquin river water, but not the net contribution of the San Joaquin to the study area. River water is the largest of the three sources of water to the study area (56%), followed by local precipitation (37%) and the State Water Project (7%).

2.2 Noble Gases

The concentrations of dissolved noble gases, referenced against well-established solubility vs. temperature curves, provide a robust estimate of the temperature at which recharge took place. Recharging groundwater typically equilibrates at the mean annual air temperature within the vadose zone [*Cey et al.*, 2009]. Recharge temperatures are known to vary considerably in mountainous regions [*Manning and Solomon*, 2003; *Segal et al.*, 2014; *Singleton and Moran*, 2010] but are expected to reflect the mean annual air temperature, although a number of studies have found differences between mean annual air temperatures and noble gas recharge temperatures [*Cey et al.*, 2008; 2009; *Hall et al.*, 2005; *Manning et al.*, 2015]. Groundwater recharged during the cooler Pleistocene epoch is identified and typified by a difference of about 5° C [*Aeschbach-Hertig et al.*, 2002; *Andrews and Lee*, 1979; *Clark et al.*, 1997; *Stute et al.*, 1992; *Stute et al.*, 1995]. Excess air is a proxy for water table fluctuations during recharge [*Ingram et al.*, 2007]. In addition, managed aquifer recharge operations leave a distinguishable fingerprint in dissolved noble gas concentrations [*Cey et al.*, 2008] with a larger excess air

component. Groundwater recharge temperatures and excess air concentrations were derived from the dissolved concentrations of all atmospheric noble gases (He, Ne, Ar, Kr and Xe) using the Unfractionated Air (UA) model [*Visser et al.*, 2016a]. Excess air is expressed as ΔNe, defined as:

$$\Delta\mathrm{Ne} = \left(\frac{\mathrm{Ne}_{sample}}{\mathrm{Ne}_{equilibrium}} - 1\right) \times 100\% \qquad \text{[Eq. 1]}$$

where $\mathrm{Ne}_{samples}$ and $\mathrm{Ne}_{equilibrium}$ are the concentrations of neon in the sample and in equilibrium with the atmosphere at the elevation and estimated recharge temperature.

The ranges of phreatic water table fluctuations under which groundwater had recharged were derived from the excess air concentrations under the assumption of complete bubble dissolution as the formation mechanism for excess air. The depth of the water above the trapped bubbles (D_w) that acts to dissolve the trapped gas is [*Ingram et al.*, 2007]:

$$D_w = \frac{(P-e)(q-1)}{(\rho g)} \qquad \text{[Eq. 2]}$$

where P is the atmospheric pressure, e is the saturation water vapor pressure, ρ is the density of water and g is the gravitational acceleration. The parameter q is the total pressure required to dissolve the trapped gas and can be calculated from the excess air concentration:

$$q = \sum_i \left[x_i\left(1 + A_e \frac{x_i}{C_{eq,i}}\right)\right] \qquad \text{[Eq. 3]}$$

where x_i is the fraction of gas i in the atmosphere, A_e is the concentration of dry air initially trapped in the saturated zone ($A_e = \Delta\mathrm{Ne}/100\% \times \mathrm{Ne}_{equilibrium}/x_{\mathrm{Ne}}$), and $C_{eq,i}$ is the equilibrium concentration of gas i ($C_{eq,\mathrm{Ne}} = \mathrm{Ne}_{equilibrium}$). For example, at 20°C, ΔNe = 100% corresponds to water table fluctuations of 5.9 meters.

2.3 Stable Isotopes

Global analyses of stable isotopes of hydrogen (^{2}H) and oxygen (^{18}O) have shown that groundwater recharge ratios (recharge/precipitation) are higher in winter in arid and temperate climates [*Jasechko et al.*, 2014] while tropical groundwater recharge is dominated by wet season and intensive rainfall [*Scott and Richard*, 2015]. Fractionation of stable isotopes of the water molecule is dependent upon the temperature of condensation [*Dansgaard*, 1964].

Oxygen isotope δ^{18}O values and deuterium isotope δ^2H values are defined and presented in standard notation:

$$\delta = (R_{sample} / R_{standard} - 1) \times 1000 \qquad \text{[Eq. 4]}$$

where R_{sample} and $R_{standard}$ are the $^{18}O/^{16}O$ ratios or $^2H/^1H$ for the sample and standard. All δ^{18}O and δ^2H data are reported in per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW). The deuterium excess is defined as:

$$d = \delta^2H - 8 \times \delta^{18}O \qquad \text{[Eq. 5]}$$

Isotopically lighter δ^{18}O and δ^2H signatures (depleted in the heavier isotopes) are observed for water that precipitates at lower temperature. In California, mean annual air temperature (MAAT) and stable isotope ratios are strongly affected by the physiographic

gradient from the Pacific Ocean maritime climate (relatively warm and constant temperatures) to the Sierra Nevada (cold temperatures with wider fluctuations). The 'continental effect', whereby water vapor becomes isotopically lighter as it moves inland because the heavier isotope rains out, also controls the stable isotope pattern in precipitation in California [*Ingraham and Taylor*, 1991].

2.4 Data Sources

The groundwater data for this study were collected within the framework of a number of studies funded by Lawrence Livermore National Laboratory (LLNL. n=54) [*Esser et al.*, 2006] or the State Water Boards Groundwater Ambient Monitoring and Assessment (GAMA) program, including California Aquifer Susceptibility (CAS, n=130) assessment studies [*Moran et al.*, 2004; *Wright et al.*, 2004], GAMA Special Studies [*Esser et al.*, 2009; *Singleton et al.*, 2010; *Visser et al.*, 2016b] and GAMA Priority Basin project studies (n=242) [*Belitz et al.*, 2010; *Burton and Belitz*, 2008; *Landon and Belitz*, 2008; *Shelton et al.*, 2008; *Shelton et al.*, 2009]. Samples were collected by LLNL or United States Geological Survey (USGS) staff and analyzed for dissolved noble gas concentrations at LLNL [*Ekwurzel*, 2004; *Visser et al.*, 2013]. Noble gas derived parameters (excess air, recharge temperature) were based on the Unfractionated Air (UA) model [*Visser et al.*, 2016a]. Samples were analyzed for tritium at LLNL [*Clarke et al.*, 1976; *Surano et al.*, 1992] and the USGS [*Thatcher et al.*, 1977], and for stable isotopes by LLNL or the USGS [*Kendall and Coplen*, 2001]. A subset of samples were analyzed for carbon-14 by the USGS [*Vogel*, 1967]. Calculated ^{14}C ages in this study are referred to as "uncorrected" because they have not been adjusted to consider exchanges with sedimentary sources of carbon [*Fontes and Garnier*, 1979]. Mapping noble gas and stable isotope patterns from the GAMA dataset [*Visser et al.*, 2016a] allows identification of non-naturally recharged groundwater (i.e. groundwater recharged from agricultural irrigation or from managed aquifer recharge (MAR)), on the basin scale [*Cey et al.*, 2008]. Stable isotope signatures of sources of recharge were compiled from a number of publications [*Coplen and Kendall*, 2000; *Ingraham and Taylor*, 1986; 1989; 1991; *Kendall and Coplen*, 2001; *Lechler and Niemi*, 2012] to establish the local precipitation end-member and "lapse rate" (change in stable isotope signature with elevation). Ingraham and Taylor [1991] studied the stable isotope composition of water across three longitudinal transects across California. The southernmost transect crosses this study area, from which two irrigation wells and five surface water samples were included in this study. A larger set (n=51) of stream water samples [*Lechler and Niemi*, 2012] were collected in the Tule and Kings River basins at elevations above 1000 m above msl. A set of shallow domestic well samples were collected in the foothills of Tulare County [*Singleton et al.*, 2010]. Quarterly samples are available for three major Sierra Nevada rivers (Merced, Kings and Kern) from the Global Network of Isotopes in Rivers (GNIR) collected and analyzed between 1984 and 1987 by the USGS [*Coplen and Kendall*, 2000; *Kendall and Coplen*, 2001]. Additional samples are available for Tuolumne, Stanislaus, San Joaquin Rivers [*Harms et al.*, 2016] and for the North and South Fork of the Kern River [*Lechler and Niemi*, 2012]. The San Joaquin River was sampled 14 times between 1984 and 1987 at Vernalis, at the northern edge of the study area, downstream from all of the rivers in the study area, except the Stanislaus [*Coplen and Kendall*, 2000; *Kendall and Coplen*, 2001].

2.5 Analysis

Four sources of water, distributed naturally or applied as irrigation, contribute to recharge in the San Joaquin Valley: Local Precipitation, River Water, State Water Project (imported from the Sacramento-San Joaquin Delta), and Pumped Groundwater.

Pumped groundwater is not considered in this analysis because it is not a net source of water to the groundwater budget. Irrigation return flow of pumped groundwater contributes to groundwater recharge at or near the location of groundwater extraction and as such it does not alter the spatial pattern of recharge sources. Recharge of locally pumped groundwater will affect how a shift in water sources propagates into the groundwater system, for example by diluting the effect of river water irrigation, but it is not considered as a distinct source of recharge in the analysis that follows.

Quantification of the importance of river water was based on a stable isotope budget for the groundwater in the study area. PRISM spatial precipitation data (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, version M2, July 2012) was compared with the California Central Valley groundwater model [*Faunt*, 2009] to calculate inflows of water into the San Joaquin Valley. River water inflow rates (km^3/yr) were combined with isotopic signatures of the rivers to calculate a mean (flow-weighted) river water signature. Mean stable isotope signatures of groundwater were compared to the mean river water signature and the local precipitation signature to calculate the relative importance of each source of water, assuming linear mixing between the two endmembers (river water and local precipitation). Limiting the analysis to Priority Basin samples, collected on representative aquifer areas [*Belitz et al.*, 2010], the proportion of groundwater from either local precipitation recharge (f_{LPR}) or river water recharge (f_{RWR}) can be calculated from the mean $\delta^{18}O$ and $\delta^{2}H$ signatures of Priority Basin groundwater samples ($\delta^{18}O_{GWmean}$, $\delta^{2}H_{GWmean}$), local precipitation recharge ($\delta^{18}O_{LPR}$, $\delta^{2}H_{LPR}$) and river water recharge ($\delta^{18}O_{RWR}$, $\delta^{2}H_{RWR}$), following equations 6 and 7 (with $\delta^{18}O$ as example):

$$f_{LPR} = (\delta^{18}O_{GWmean} - \delta^{18}O_{RWR}) / (\delta^{18}O_{LPR} - \delta^{18}O_{RWR}) \qquad \text{[Eq 6]}$$

$$f_{RWR} = (\delta^{18}O_{GWmean} - \delta^{18}O_{LPR}) / (\delta^{18}O_{RWR} - \delta^{18}O_{LPR}) = 1 - f_{LPR} \qquad \text{[Eq 7]}$$

To evaluate the uncertainty of the proportions of river water recharge and local precipitation recharge, the standard deviation of the groundwater mean and the endmember values was propagated.

The contribution of State Water Project water (contributing 7% of total water to the study area) is not-considered here because it is indistinguishable from either end-member by $\delta^{18}O$ or $\delta^{2}H$ and was not relevant for pre-modern groundwater recharge.

3 Results

3.1 Recharge Sources

The two major sources (river water and local precipitation) can be tracked through the San Joaquin Valley groundwater system by their distinct stable isotope signatures. The stable isotope signature of river water is highly depleted in heavier isotopes (resulting in more negative $\delta^{18}O$ and $\delta^{2}H$ values) as a result of the high elevation snowmelt dominated runoff in the source

areas of the rivers. The endmember signature of local precipitation recharge is approximated from three available literature sources of stable isotopes in streams and shallow groundwater (Figure 2), in the absence of available isotope signatures in local precipitation. We combined the data from Ingraham [1991], Lechler [2012] and Singleton [2010] reporting data from shallow wells and small streams, to calculate the slope of the topographic fractionation effect. In contrast to the large rivers discussed below, we assume that the capture area of these wells and streams is close to the sample elevation. We find that the slope of the topographic fractionation effect is -1.7±0.15 ‰ km^{-1} with an intercept at sea level of -8.2±0.23 ‰ for $\delta^{18}O$ and the slope of the topographic fractionation effect is -12±1.1 ‰ km^{-1} with an intercept at sea level of -60.0±1.7 ‰ for $\delta^{2}H$. This intercept is used as the signature of local precipitation in this study. The slope for $\delta^{18}O$ is similar to the one obtained by Rose et al. [*Rose et al.*, 1996] for spring recharge in Northern California (-2.1 ‰ km^{-1}) and smaller than the slopes obtained by Lechler [2012] for the Southern Sierras (-2.7 ‰ km^{-1} for precipitation, -3.1 ‰ km^{-1} for rivers) and by Dutton et al. [2005] for the entire US (-2.9 ‰ km^{-1} for precipitation, -4.2 ‰ km^{-1} for rivers). While the topographic effect is consistent across study areas, the variation in derived values for the slope illustrates local meteorological effects that play a role in isotopic fractionation of precipitation.

[FIGURE 2]

The endmember signature of river water recharge was also obtained from a number of sources. Stable isotope data from major rivers are plotted at the mean watershed elevation of each river [*Goulden and Bales*, 2014; *Lechler and Niemi*, 2012]. Samples from the Merced and the Kings River were collected at 1224 m and 899 m elevation (Table 1) and only represent the higher elevations of these watersheds. These major rivers are not captured by the previously established trend line based on smaller streams and well data. The source area of the major rivers appears to be higher in elevation than the average river basin elevation. This discrepancy is caused by higher precipitation rates at higher elevations and higher evapotranspiration rates at lower elevations, resulting in disproportional high runoff generation between 2500 m and 3000 m above msl [*Goulden et al.*, 2012]. To predict the river signature, a regression line was fitted through the river data and the signature at sea level ($\delta^{18}O$ = -8.2 ‰; $\delta^{2}H$ = 60.0 ‰) and a slope of -2.4±0.1 ‰ km^{-1} was obtained for $\delta^{18}O$ and -17±0.9 ‰ km^{-1} was obtained for $\delta^{2}H$. The source signature of the nine rivers delivering water to the study area was estimated using this trend (Table 1). Predicted $\delta^{18}O$ values vary from -13.6 ‰ (Kings River) to -10.0 ‰ (Tule River). The standard deviation of the residuals (trend – observed) was 0.54 ‰ for $\delta^{18}O$ and 4.4 ‰ for $\delta^{2}H$. The flow weighted average river signature was -12.7±0.2‰ for $\delta^{18}O$ and -93.4±1.8 ‰ for $\delta^{2}H$. The State Water Project signature was assumed to be similar to that of the Sacramento River, -10.8±0.2 ‰ [*Coplen and Kendall*, 2000; *Kendall and Coplen*, 2001]. The combination of river water and local precipitation in flow weighted proportions results in an average input signature of -10.9±0.1 ‰ for all recharge sources.

[FIGURE 3]

All groundwater data plot along a local water line (LWL) with a slope of 7.1±0.08 (R^2 = 0.97, p-value < 0.001), intercepting the global meteoric water line (GMWL) at -14.6 ‰ $\delta^{18}O$ (Figure 3). Samples resembling river water plot closer to the GMWL and samples similar to local precipitation have a more negative deuterium excess. The local precipitation recharge endmember plots close to the LWL, indicating that it effectively captures effects of land surface evaporation on the groundwater recharge signature. The San Joaquin River at Vernalis drains the San Joaquin Valley, mixing the inputs from local precipitation and the Tuolumne, Merced, Fresno and San Joaquin Rivers (Figure 4). The Kings, Kaweah, Tule and Kern Rivers recharge depleted the groundwater basin under normal conditions and only flow towards the San Joaquin in extremely wet years. The stable isotope signature of the San Joaquin River at Vernalis, (-10.6±0.2 ‰ for $\delta^{18}O$, -79.4±1.3 ‰ for $\delta^{2}H$) is close to the weighted total input signature of the entire San Joaquin Valley (-10.9±0.2 ‰ for $\delta^{18}O$, -80.1±1.2 ‰ for $\delta^{2}H$), but significantly different from the River Water signature (-12.4‰ for $\delta^{18}O$, for the Tuolumne, Merced, Fresno and San Joaquin alone) or the Local Precipitation signature (-8.2±0.2‰). The mean $\delta^{18}O$ signature of all groundwater data is -10.2±0.1 ‰, 0.7±0.2 ‰ closer to the local precipitation signature than the total inflow average.

[TABLE 1]

The lowest $\delta^{18}O$ values are found in groundwater downstream of the Kings and Kern rivers – the rivers with the highest elevation headwaters (Figure 4, right). A plume with the signature of Kings River water extends west across the entire study area. The Kern River signature is found around the city of Bakersfield, where unlined canals recharge city wells and deliver water to farms outside the city. Even smaller rivers like the Kaweah and the Tule appear to create a plume of river water with low $\delta^{18}O$ in the groundwater system. The local precipitation signature is found in groundwater on the eastern side of the study area, in the foothills, between the Merced and San Joaquin Rivers and between the Kaweah and Kern Rivers, above irrigation canals and away from a natural river recharge source.

[FIGURE 4]

3.2 Recharge Mechanisms

Recharge from major rivers (Kings, Kern) is associated with noble gas recharge temperatures of less than 14 °C. Especially low recharge temperatures (< 12 °C) are found along the Kern River near Bakersfield. Even smaller rivers like the Kaweah and Tule appear to recharge locally to the groundwater system under cooler conditions.

The correlation between $\delta^{18}O$ and the noble gas recharge temperature is significant ($P<0.001$, $R^2=0.21$) with a trend of 0.73 °C per 1 ‰ change in $\delta^{18}O$ (Figure 5). Three recharge mechanisms were identified based on noble gas results, with sources distinguished by the $\delta^{18}O$ of the sampled groundwater: (1) River Water Recharge (n=116 , $\delta^{18}O$ < -12 ‰), (2) Mixed Source Recharge (n=237, -12 ‰ ≤ $\delta^{18}O$ ≤ -9 ‰) and (3) Local Precipitation Recharge (n=73, $\delta^{18}O$ > -9

‰). The cutoff for River Water Recharge (-12 ‰) was selected because it includes the mean values for all rivers, other than Tule and Fresno, which have little flow. The cutoff for Local Precipitation Recharge (-9 ‰) was selected at a similar distance (0.8 ‰) from the LPR mean value. River Water Recharge has a mean recharge temperature of 14.7 °C ± 3.0 °C, which is significantly cooler than the mean annual temperature at the well locations by 2.9 °C ($P < 0.001$). River water recharge shows a large range of excess air concentrations, with ΔNe ranging from less than zero (indicating degassing) to over 200%. Estimates of water table fluctuations, based on the interquartile range of ΔNe values (23%-83%), are on the order of 1.3 m to 4.8 m. The mean ΔNe for river recharge is significantly higher (by more than 6%) than other recharge groups ($P < 0.01$).

The mean noble gas recharge temperature of local precipitation recharge is 18.7 °C ± 2.9 °C, significantly ($P < 0.001$) higher than the mean annual temperature at the well locations by 1.4 °C. The excess air ΔNe in local precipitation recharge also varies from zero to over 200%, but the interquartile range is limited from 17% to 41%, corresponding to water table fluctuations of 1 m to 2.4 m.

[FIGURE 5]

3.3 Recharge Time Scales

Both modern ($^{3}H > 1$ pCi/L, recharged after 1950) and pre-modern ($^{3}H < 1$ pCi/L, recharged before 1950) groundwater samples are present in each recharge mechanism group. The proportion of pre-modern wells in the entire data set is 9%, but pre-modern samples at 6% are under-represented in the River Water Recharge group, and at 16% are over-represented in the Local Precipitation Recharge group.

Carbon-14 (^{14}C) activities in mixed source and local precipitation groups range from fossil (0.7 percent modern carbon, pmC) to nuclear (129 pmC). The highest carbon-14 activities in pre-modern groundwater range from 68 pmC (local precipitation) to 82 pmC (mixed source). Equilibration with carbonate minerals in the unsaturated zone is likely the cause of the low initial carbon-14 activities [*Fontes and Garnier*, 1979].

Carbon-14 in modern river water recharge ranges from 63 pmC to 116 pmC. The 7 pre-modern river recharge samples ($^{3}H < 1$ pCi/L) have no carbon-14 data. Considering samples with both tritium and carbon-14 data (n=102), 58 are modern ($^{3}H > 1$ pCi/L, $^{14}C > 80$ pmC), 15 are pre-modern ($^{3}H < 1$ pCi/L, $^{14}C < 80$ pmC). 28 samples are a mixture of modern and pre-modern water ($^{3}H > 1$ pCi/L, $^{14}C < 80$ pmC), with tritium concentrations as high as 23 pCi/L in samples with less than 50 pmC.

3.4 Proportions of River Water and Local Precipitation Recharge

Based on the mean stable isotope signatures (Table 2) of all Priority Basin groundwater samples in the study area ($\delta^{18}O_{GWmean} = -10.2 \pm 0.1$ ‰, $\delta^{2}H_{GWmean} = -75.3 \pm 0.8$ ‰) and the endmembers for Local Precipitation Recharge ($\delta^{18}O_{LPR} = -8.2 \pm 0.2$ ‰, $\delta^{2}H_{LPR} = -60.0 \pm 1.7$ ‰),)

and River Water Recharge ($\delta^{18}O_{RWR}$ = -12.7±0.2 ‰, $\delta^{2}H_{RWR}$ = -93.5±1.8 ‰), we find that 55±4% of groundwater in the study area originates from local precipitation [Eq 6, average of $\delta^{18}O$ and $\delta^{2}H$ estimates] and 45±4% originates from river water [Eq 7]. Estimates of recharge proportions based on either isotope ($\delta^{18}O$ or $\delta^{2}H$) differ by 2% (Table 2) and agree within the propagated uncertainty (4%). To evaluate how these proportions have changed over time, the same calculations were performed on all Priority Basin samples containing less than 1 pCi/L tritium. These samples have recharged before 1950 and represent pre-modern groundwater. We find that the proportion of Local Precipitation Recharge is 74±7% versus 26±7% River Water Recharge in pre-modern groundwater (samples with less than 1 pCi/L tritium) (Table 2). Limiting the calculation to modern groundwater (samples with more than 1 pCi/L tritium), we find that the proportions (47±4% LPR v. 53±4% RWR) are similar to the proportions in the entire Priority Basin data set.

[TABLE 2]

Discussion

The two major sources of water to the San Joaquin Valley groundwater system (river water and local precipitation) can be tracked by their distinct stable isotope signatures. The stable isotope signature of local precipitation in the San Joaquin Valley was derived from multiple studies and estimated at -8.2±0.2 ‰ for $\delta^{18}O$ and -60±1.7 ‰ for $\delta^{2}H$. Stable isotope signatures of the nine major rivers in the San Joaquin Valley were established and the weighted mean river water signature is estimated at -12.7±0.2‰ for $\delta^{18}O$ and -93.4±1.8 ‰ for $\delta^{2}H$. The variation in groundwater (-14 ‰ to -7 ‰) spans the entire range of both source signatures and the spatial distribution of isotopic signatures in wells shows clear patterns that reveal recharge sources. In contrast, the stable isotope signature of the San Joaquin River at Vernalis, close to the weighted input signature of all sources of water to the San Joaquin Valley, is the result of the man-made hydrologic system of the San Joaquin valley, mixing the northern rivers, agricultural return flow from State Water Project and other irrigation sources, and local precipitation. Diversions of the rivers naturally entering the southern San Joaquin valley can cause the river to run dry in the valley floor during summer.

The interconnections between the groundwater and surface water systems, impacted by agricultural diversions, result in an isotopic signature that is similar to complete mixing between the two sources, with a slight preference for discharging local precipitation over river water. Despite this mixing at the outflow, clear patterns of each recharge source are observed in the groundwater system. The two sources also show distinct patterns of recharge conditions, as illustrated by noble gas recharge temperatures and excess air components. Further detailed studies could quantify the local recharge rates for specific stretches of riverbed [*Massmann et al.*, 2009]. The extensive alluvial fans and unconfined conditions present at the eastern edge of the valley allow rapid infiltration and transport of irrigation return flow, spring runoff and floodwaters [*Fogg et al.*, 1998]. The patterns in $\delta^{18}O$ in wells near individual major perennial rivers, reflecting recharge of river water, have been discussed in several GAMA reports [*Moran et al.*, 2003; 2004; *Singleton et al.*, 2015].

The spatial patterns of recharge source signatures correlate with the noble gas recharge temperatures, pointing to distinctly different recharge mechanisms, i.e., aerial recharge of local

precipitation in the foothills and away from perennial streams, and recharge of cold runoff in the areas directly influenced by perennial streams. Recharge of local precipitation in the San Joaquin valley occurs with limited water table fluctuations at temperatures above the annual mean. These patterns of local precipitation recharge, higher recharge temperatures and less water table fluctuations, have not changed between pre-modern and modern time periods. Noble gas recharge temperatures above the mean annual air temperature have previously been observed in the northern part of the Central Valley and ascribed to the geothermal gradient in a thick unsaturated zone [*Manning et al.*, 2015]. Noble gas signatures of mixed source recharge are in between river water recharge and local precipitation recharge in every respect. Mixed source signatures are either the result of mixing of water sources within the groundwater system or during pumping, or, less likely, application of river water for irrigation in areas where local precipitation recharge is still a significant source. Recharge of river water occurs below mean annual temperatures with larger water table fluctuations than other recharge mechanisms. Noble gas recharge temperatures below the mean annual air temperature are the result of rapid, preferential recharge of cold snowmelt during the cooler spring season [*Hall et al.*, 2005]. The cold signature and high excess air indicating fast recharge over short time scales are evidence that surface storage in rivers is limited in time and volume, consistent with global estimates of river water ages [*Jasechko et al.*, 2016] and that infiltration takes place fast enough to preserve a recharge temperature lower than the mean annual air temperature.

The choice of the Unfractionated Air (UA) model may have introduced a bias towards colder estimated recharge temperatures when compared with Closed Equilibrium (CE) or Partial Re-equilibration (PR) models. Previous studies [*Cey et al.*, 2008; *Visser et al.*, 2014] found that the UA model tends to predict lower recharge temperatures, up to 2 °C, compared to CE or PR models. While it is possible to infer from interpretation of the whole array of noble gases which excess air model is statistically most probable, it is difficult to evaluate which model is most appropriate in each case, given the range of recharge conditions in the study area (rapid recharge from surface water vs. diffuse slower recharge). In any case, the differences in noble gas recharge temperatures between the river water recharge and local precipitation recharge are much larger than the potential bias and the observed patterns can be attributed to actual differences in recharge mechanism.

A large range of noble gas recharge temperatures ($\sigma = 3.1$°C) is observed in modern samples (recharged after 1950, defined as having tritium activities >1 pCi/L) due to variations in recharge and irrigation practices, compared to the smaller range ($\sigma = 0.9$ °C) observed in pre-modern river recharge (recharged before 1950, defined by tritium activities <1 pCi/L). Mixing and dispersion does not explain the limited range in pre-modern groundwater because these processes would also result in less depleted $\delta^{18}O$ values. Recharge in pre-modern floodplains was likely slower than recharge on cultivated fields, allowing water to reach thermal equilibrium with the surroundings at temperatures closer to the mean annual air temperature. The extensive irrigation with river water also impacts air temperatures through the irrigation cooling effect [*Kueppers et al.*, 2007], the height of the planetary boundary layer [*Gilbert et al.*, 2017] and precipitation patterns [*Yang et al.*, 2017].

Both river water recharge and local precipitation recharge have been active in the San Joaquin Valley since the pre-modern era, although their relative importance has shifted in recent decades. Tritium-free samples with a river water signature are clear evidence that recharge of river water occurred before large scale irrigation practices commenced in the Central Valley. A

lower proportion of River Water Recharge is found in pre-modern samples than in modern samples. Both natural and anthropogenic factors can be contributing to these differences. Naturally, river water recharge is limited to the river floodplain whereas local precipitation recharge is distributed across the study area. River Water Recharge to the groundwater system will likely flow along and underneath the river bed and discharge after a shorter flow path accumulating less travel time. Anthropogenic factors include large scale, intensive groundwater pumping and widespread, year-round irrigation. Groundwater pumping can increase the recharge rate of naturally losing rivers by creating a steeper gradient, extended time periods of losing conditions, and a larger unsaturated volume for river recharge to occur, thereby increasing the river water proportion in modern groundwater. Diversions of river water for irrigation across agricultural land has increased the rate and extent of river water recharge and increased the river water component in modern groundwater. Local precipitation recharge is more likely to travel longer flow paths to discharge locations, accumulating longer travel times. Fossil (Pleistocene) groundwater has mostly recharged as local precipitation because flow paths from the foothills to the discharge areas near the valley center are naturally longer[*Izbicki et al.*, 2000]. Mixtures of modern and fossil groundwater, representing 28% of all samples, are vulnerable to modern contamination [*Jasechko et al.*, 2017] but recharge rates and sustainability are difficult to determine. The age ranges found in groundwater – decades to millennia [*Jasechko et al.*, 2017] – reflect the large capacity of subsurface storage to buffer inter-annual variability and drought. Pleistocene groundwater in the San Joaquin Valley recharged mostly as local precipitation, while river water recharge naturally followed shorter flow paths.

The map of stable isotope signatures (Figure 4) illustrates that the groundwater of the southeastern San Joaquin valley shows a complex pattern of variable sources: local precipitation, rivers with distinct signatures and in some areas imported water. To estimate, for each of the sampled wells, the proportions of local precipitation and river water recharge would require estimating isotope signatures of nearby (spatially variable) precipitation and nearby (spatially variable) river water sources, with associated uncertainties. These complexities were not intended to be focus of this study. Instead, to evaluate the importance of either source on the scale of the San Joaquin Valley, we have derived mean signatures for local precipitation and river water inputs as endmembers and evaluated the mean groundwater signature with respect to these endmembers. This does not imply that the mean groundwater signature is the result of mixing of all endmembers. The method is in essence a basin wide accounting of the isotopic composition of groundwater, supported by the water budget of the study area. The result is an attribution of sources that contribute to the San Joaquin groundwater basin as a whole.

Local precipitation comprises 55±4% of modern groundwater in the San Joaquin Valley. While it is still the majority of recharge in modern groundwater, it is no longer the dominant form of recharge as it was to pre-modern groundwater (74%). The pre-modern ratio between precipitation recharge (74±7%) and river recharge (26±7%) agrees with the pre-development water budget estimates of recharge from precipitation (referred to as “Central Valley Surface Processes” in Faunt) (75%) and surface water losses to groundwater (25%) for the entire Central Valley [*Faunt*, 2009].

Estimates of the proportion of river recharge based on isotopic evidence presented in this study confirm that rivers draining mountain ranges, also referred to as mountain front recharge or mountain system recharge are an important component in the water balance of highly productive agricultural regions like the Central Valley [*Meixner et al.*, 2016]. The global estimate that

groundwater meets 43% of irrigation water demand [*Siebert et al.*, 2010] does not take into consideration the source of recharge to groundwater systems, which is critically important in evaluating sustainability.

Considering the change in the proportion of river water in pre-modern samples (26±4%) to that in modern samples (47±4%), the importance of river water has nearly doubled. Irrigation return flow with re-distributed river water likely caused the increase of river water recharge. If the rate of local precipitation recharge has remained constant, the decrease in the proportion of local precipitation recharge from 74±7% to 53±4% requires an additional 2.4 km^3/yr of river water recharge to increase the total net recharge rate by 40%. In effect, the transport of water via the river system to discharge areas (wetlands, an inland lake, and the Pacific Ocean) is slowed down as a greater proportion of river water resides in the subsurface for extended time periods.

Conclusions

The importance of river water recharge to San Joaquin Valley groundwater has nearly doubled due to enhanced river water recharge through managed aquifer recharge and more significantly, through irrigation return flows. At present, river water recharge is an important mechanism of groundwater replenishment. While river water recharge has increased, it has not been able to keep up with increased discharge by pumping, resulting in overdraft and significant, long-term groundwater level declines [*Scanlon et al.*, 2012]. This highlights the importance of Sierra Nevada rivers to meet the demand for water in California and for irrigation in the Central Valley in particular. Loss of snowpack in the Sierra Nevada [*Fengpeng et al.*, 2016] under future climate scenarios and earlier snowmelt prior to peak evapotranspiration demand by agricultural crops, necessitate a larger capacity for managed aquifer recharge and conjunctive use [*Scanlon et al.*, 2016] such as groundwater banking on agricultural lands [*Kocis and Dahlke*, 2017; *O'Geen et al.*, 2015].

Acknowledgments

AV, JEM, MJS and BKE designed the study, AV conducted the analyses; all authors contributed to interpretation of results, and writing the paper. The authors thank Ken Belitz and Miranda Fram for collaboration on the Priority Basin project and Erik Oerter for insightful comments to the manuscript. Funding for the study was provided by the California State Water Boards as part of the Groundwater Ambient Monitoring and Assessment Special Studies project. The authors declare no competing financial interests. The data used in this study is available for download at http://geotracker.waterboards.ca.gov/gama/datadownload. Prepared by LLNL under Contract DE-AC52-07NA27344, with funding from LDRD project 15-ERD-042. LLNL-JRNL-735797

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Figures

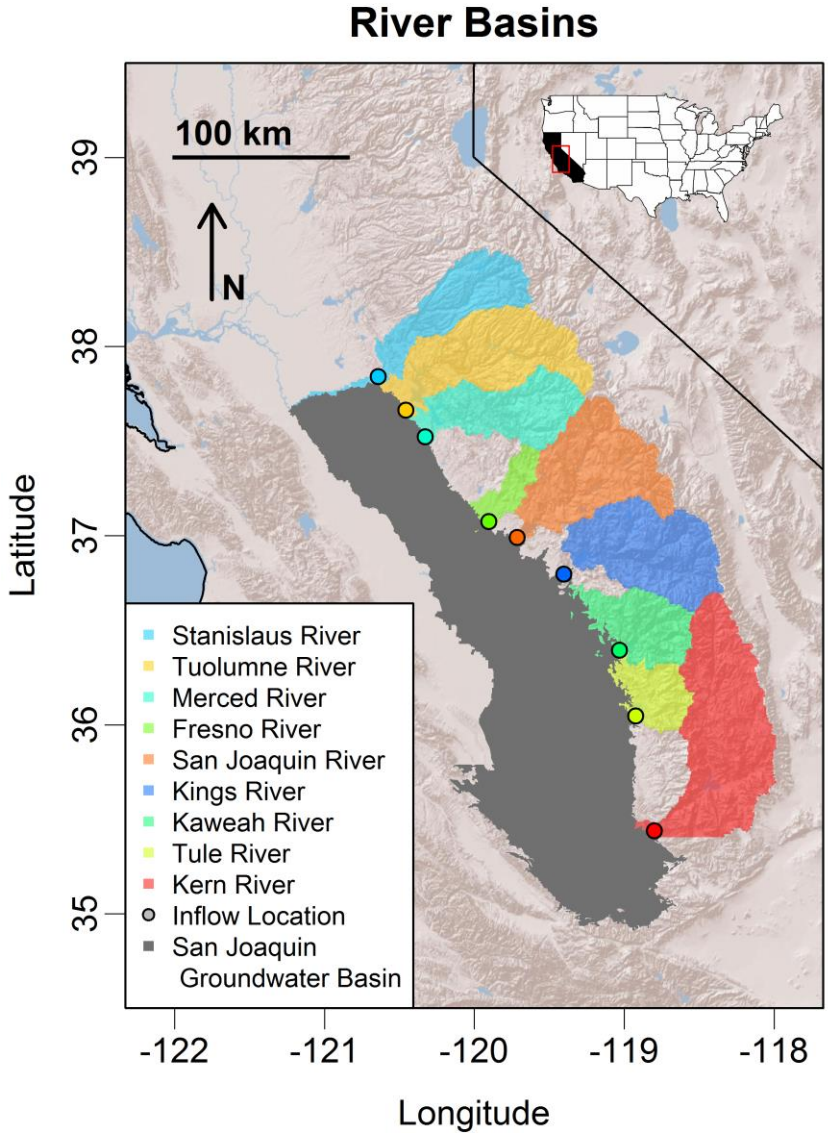

Figure 1: Nine river basins (shaded colors) draining the Sierra Nevada flow into the San Joaquin Valley groundwater basin (shaded grey). Inflow locations identified with filled points. Inset map shows location of study area and California in the continental US.

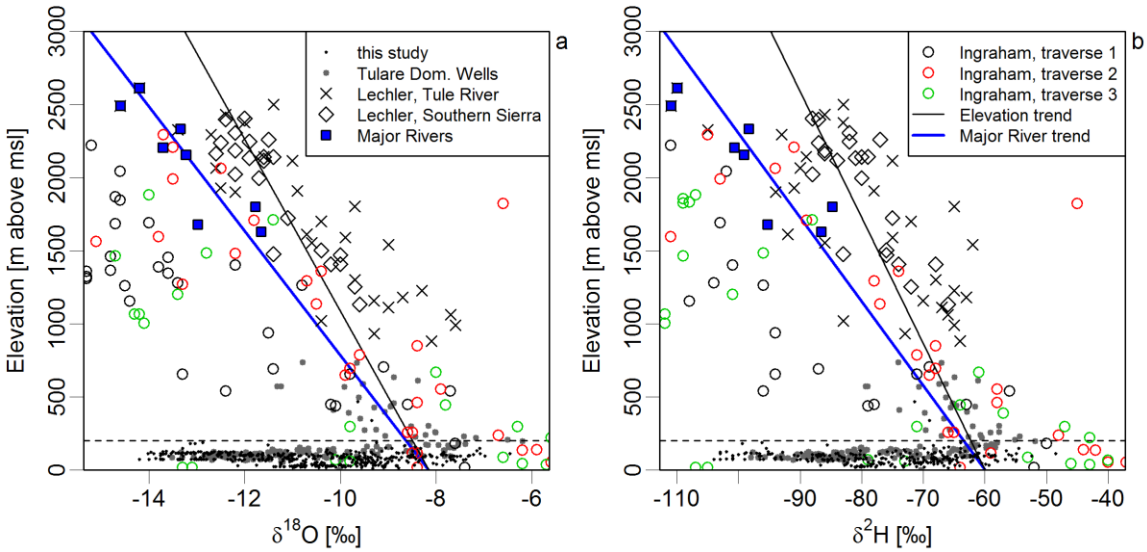

Figure 2: Vertical profile of $\delta^{18}O$ (a) and $\delta^{2}H$ (b) values in small streams and shallow groundwater (see text for references to data sources) show an elevation trend of -1.7±0.1 ‰ km-1 ($\delta^{18}O$) and -12±1.1 ‰ km-1 ($\delta^{2}H$). Major Rivers (blue filled square symbols) show a trend of -2.4±0.1 ‰ km-1 ($\delta^{18}O$) and -17±0.9 ‰ km-1 ($\delta^{2}H$).

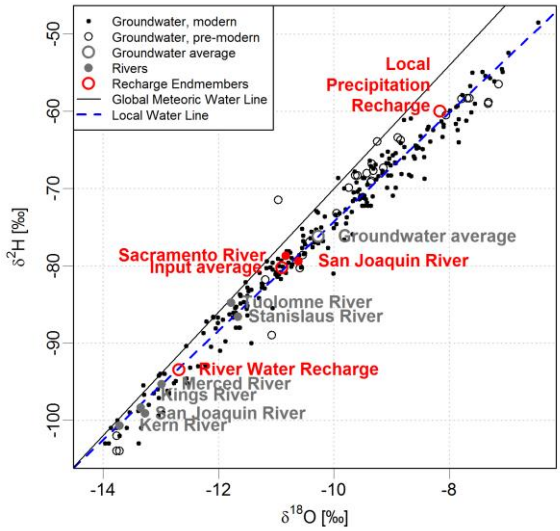

Figure 3: Stable isotope plot of San Joaquin Valley groundwater data, with the global meteoric water line (GMWL, black) and local meteoric water line (LWL, dashed blue) and observed major rivers (gray symbols), and the flow weighted average input and output signatures (red).

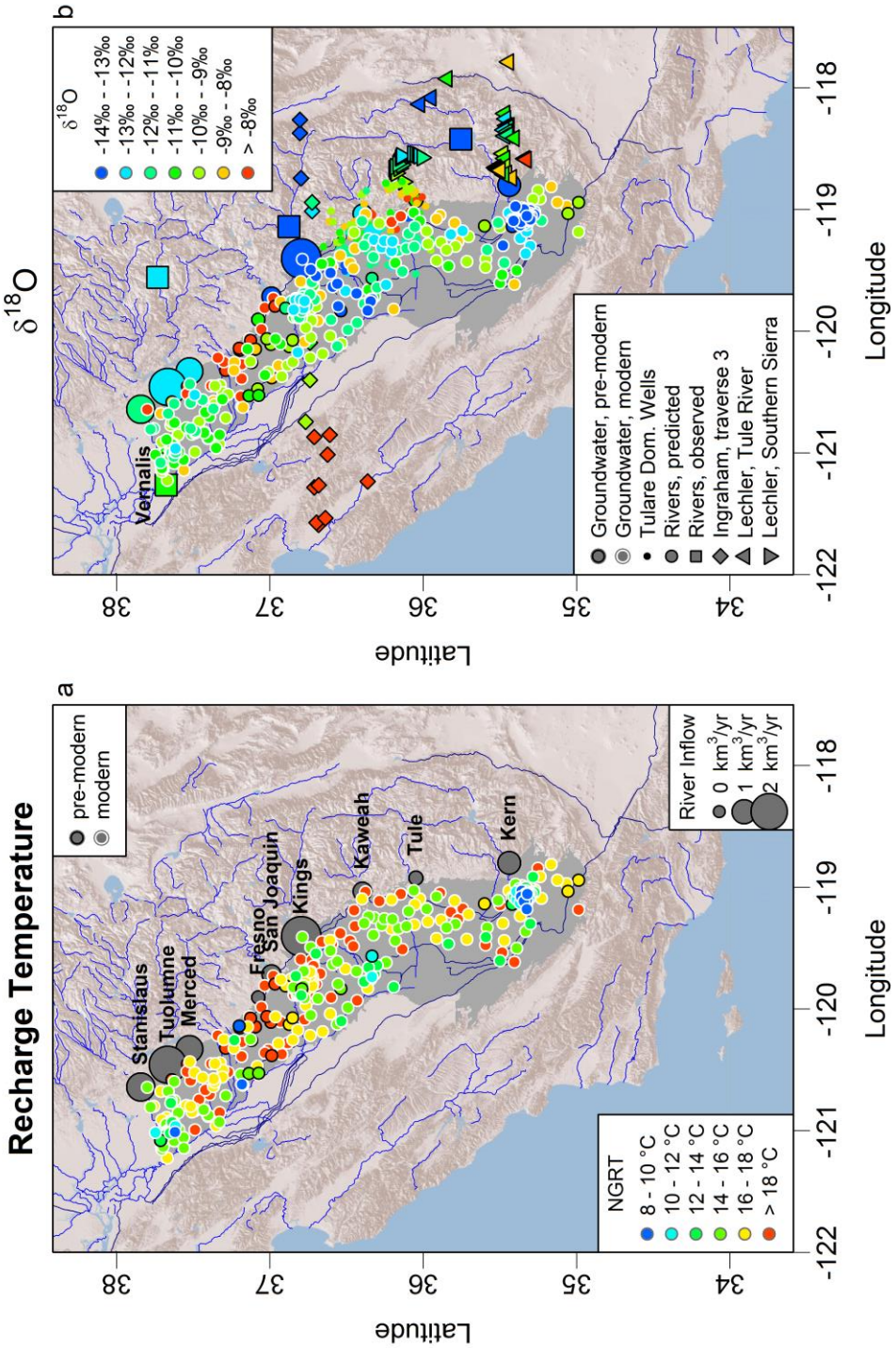

Figure 4: Map of the San Joaquin Valley study area (shaded gray) with noble gas recharge temperatures (a) and $\delta^{18}O$ (b) of groundwater (this study and Tulare domestic wells) and surface water ($\delta^{18}O$ only). River symbol size reflects river discharge or valley inflow rate. Modern groundwater samples have a white border; pre-modern groundwater samples have a black border. See text for references to $\delta^{18}O$ data sources.

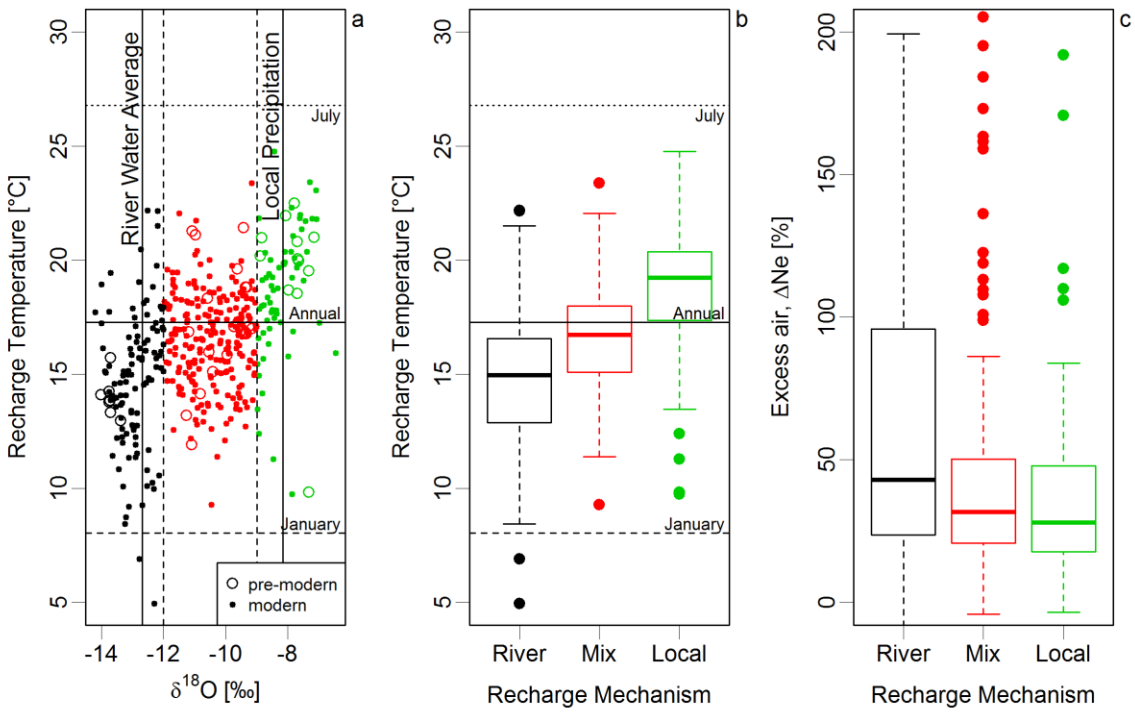

Figure 5: Noble gas recharge temperature and $\delta^{18}O$ of samples in San Joaquin study area (a). Vertical lines show estimated input signatures of rivers and local precipitation; vertical dashed lines (at $\delta^{18}O$ = -12 ‰ and $\delta^{18}O$ = -9 ‰) show cutoff between River Water, Mixed Source and Local Precipitation Recharge. Horizontal lines show mean temperatures at well locations for January, July and annual. Box-and-whisker plot of noble gas recharge temperature (b) and excess air (c) for three identified recharge mechanisms.