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California GAMA Special Study: Importance of River Water Recharge to Selected Groundwater Basins

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Final Report for the California State Water Resources Control Board

GAMA Special Studies Task 15.3: *Characterization of basin-scale recharge using Geotracker GAMA noble gas data*

Auspices Statement

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GAMA: AMBIENT GROUNDWATER MONITORING & ASSESSMENT PROGRAM SPECIAL STUDY

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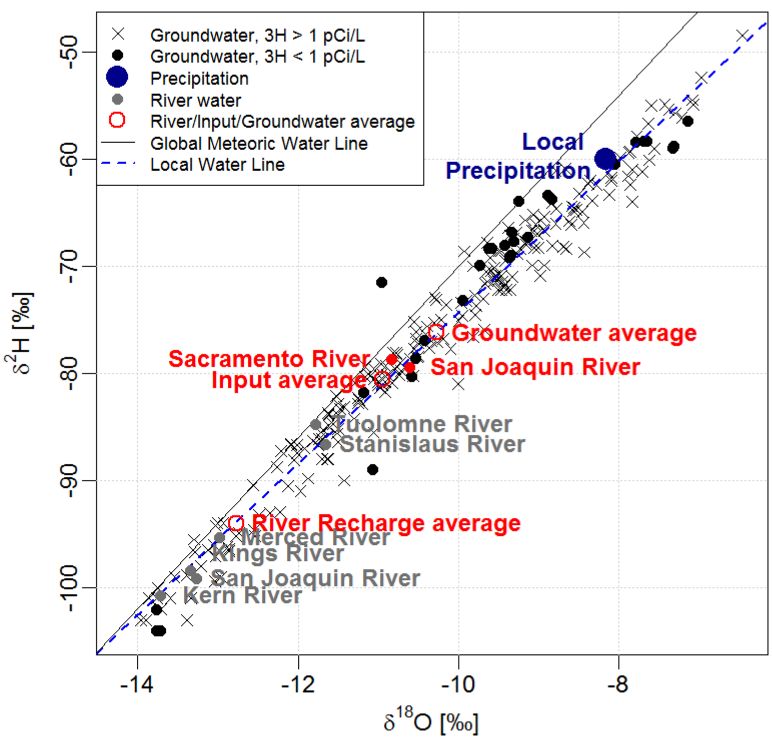

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Key Points

- River recharge represents 63%, 86% and 46% of modern groundwater in the Mojave Desert, Owens Valley, and San Joaquin Valley, respectively. In pre-modern groundwater, river recharge represents a lower fraction: 36%, 46%, and 24% respectively.

- The importance of river water recharge in the San Joaquin valley has nearly doubled and is likely the result of a total increase of recharge of 40%, caused by river water irrigation return flows. This emphasizes the importance of recharge of river water via irrigation for renewal of groundwater resources.

- Mountain front recharge and local precipitation contribute to recharge of desert groundwater basins in part as the result of geological features focusing scarce precipitation promoting infiltration.

- River water recharges groundwater systems under lower temperatures and with larger water table fluctuations than local precipitation recharge.

- Surface storage is limited in time and volume, as evidenced by cold river recharge temperatures resulting from fast recharge, compared to the large capacity for subsurface storage. Groundwater banking of seasonal surface water flows therefore appears to be a natural and promising method for increasing the resilience of water supply systems.

- The distinct isotopic and noble gas signatures of river water recharge, compared to local precipitation recharge, reflecting the source and mechanism of recharge, are valuable constraints for numerical flow models.

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Table of Contents

Abbreviations

	Abbreviations of Organizations and Study Units
CLUB	Central Desert Low Use Basin (USGS GAMA PB Study Unit)
DWR	California Department of Water Resources
GAMA	Groundwater Ambient Monitoring and Assessment program
GNIP	Global Network of Isotopes in Precipitation
GNIR	Global Network of Isotopes in Rivers
IAEA	International Atomic Energy Agency
LLNL	Lawrence Livermore National Laboratory
MOJO	Mojave River (USGS GAMA PB Study Unit)
PB	Priority Basin project
PRISM	PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu
USGS	United States Geological Survey

	Abbreviations of Recharge Sources and Mechanisms
IWR	Indian Wells Recharge
LR	Local Recharge
LPR	Local Precipitation Recharge
MAR	Managed Aquifer Recharge
MRR	Mojave River Recharge
MFR	Mountain Front Recharge
ORR	Owens River Recharge
RWR	River Water Recharge

	Abbreviations of Concepts, Variables and Units
GMWL	Global Meteoric Water Line, defined as $\delta^2H = 8.0 \times \delta^{18}O + 10$ ‰
LWL	Local Water Line. Regression line fitted through δ^2H and $\delta^{18}O$ data
MAAT	Mean Annual Air Temperature
NGRT	Noble Gas Recharge Temperature
km^2	1 square kilometer = 0.39 square mile
msl	Mean Sea Level
pCi/L	pico-Curies per liter water. For tritium, 3.2 pCi/L = 1 TU
pmC	percent modern carbon. ^{14}C activity, referenced to $^{14}C/^{12}C$ ratio in the atmosphere in 1950, expressed as percentage.
Ra	atmospheric helium-3 to helium-4 isotope ratio, 1.384×10^{-6}
TU	Tritium Unit, equals a tritium to hydrogen ratio of 10^{-18}
$\delta^{18}O$	oxygen-18 to oxygen-16 isotope ratio of water sample, referenced against the Vienna Standard Mean Ocean Water (VSMOW), in ‰. $\delta^{18}O = [\,(^{18}O/^{16}O)_{sample} / (^{18}O/^{16}O)_{VSMOW} - 1] \times 1000$ ‰
δ^2H	hydrogen-2 (deuterium) to hydrogen-1 isotope ratio of water sample, referenced against the Vienna Standard Mean Ocean Water (VSMOW), in ‰. $\delta^2H = [\,(^2H/^1H)_{sample} / (^2H/^1H)_{VSMOW} - 1] \times 1000$ ‰
ΔNe	Measure of noble gas excess air component. $\Delta Ne = [Ne_{sample} / Ne_{equilibrium} - 1\,] \times 100$ %

1 Introduction

The demand for fresh water in the US for domestic use, agriculture, industry and energy production, 1.2 billion cubic meters in 2010 (Maupin et al., 2014), is met by withdrawals from groundwater (25%) and surface water (75%). California relies on groundwater for 40% of its fresh water demands and on surface water for the remaining 60%. 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 complex of dams, aqueducts and reservoirs. Higher future temperatures will exacerbate the summer dry season and droughts, and reliance on groundwater will increase. Local precipitation and groundwater recharge fall short of groundwater pumping in many areas and overdraft of groundwater resources has led to declining groundwater levels, land subsidence, and seawater intrusion.

The Mediterranean climate and the proximity to high elevation mountain ranges with higher precipitation rates have naturally resulted in recharge of groundwater reservoirs by river water. This natural connection between the surface water and groundwater systems is impacted by anthropogenic alteration of the water system:

- Surface water diversions: The immediate effect on downstream users and habitats is clearly understood, whereas the impact of reduced surface water recharge on groundwater resources is extremely difficult to quantify.
- Groundwater pumping: Water table decline 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.
- Irrigation using surface water: Focused recharge along the river bank is diverted for irrigation, leading to increased areal recharge away from the river. The net effect depends on irrigation efficiency and changes in evapotranspiration rates.
- Artificial recharge: Directly increases surface water recharge to groundwater system.

Identifying the sources of recharge in a groundwater basin is important to interpreting water quality data and to managing water supply. The sources and mechanisms of recharge, whether through natural processes, irrigation return flow or Managed Aquifer Recharge (MAR), will not only affect water quality, but will also affect stable isotopic and noble gas signatures in the recharging water.

We studied the importance of river water recharge to groundwater in three large, contrasting, study areas in southern California: the Mojave Desert (35,000 km^2, population 300,000), Owens Valley (4,000 km^2, population 20,000) and 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 study the sources, mechanisms and time scales of groundwater recharge.

The concentrations of dissolved noble gases, referenced against well-established solubility vs. temperature curves, are 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. Recharge temperatures are known to vary considerably in mountainous regions (Manning and Solomon, 2003) but are expected to reflect the mean annual air temperature. Noble gas recharge temperatures have been applied in studies of paleoclimate. 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., 1995, 1992).

Fractionation of stable isotopes of the water molecule is dependent upon the temperature of condensation. Lower $\delta^{18}O$ and $\delta^{2}H$ signatures 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. The distinct noble gas and isotopic signatures that result from these physiographic gradients are excellent tools to trace the source, mechanism and time scale of recharge in California.

2 Data

The data were collected within the framework of the State Water Boards Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin program. Samples were collected by USGS staff and analyzed for tritium and dissolved noble gas concentrations at LLNL, and for stable isotopes and carbon-14 by the USGS. Mapping noble gas and stable isotope patterns from the GAMA dataset allows identification of non-naturally recharged groundwater (i.e. groundwater recharged from agricultural irrigation or from MAR), on the basin scale.

3 Mojave Desert

3.1 Study Area

The Mojave Desert is a 35,000 km^2 arid area in southern California with cold winters (January mean temperature: 8 °C) and hot summer (July mean temperature: 28 °C). Precipitation is less than 200 mm annually. The Mojave Desert is bound in the south by the San Bernardino and San Gabriel mountains, where precipitation rates can exceed 1000 mm annually.

Rapid population growth and dependence on groundwater has led to significant declines in groundwater levels. The groundwater systems in the Mojave Desert have been the subject of a number of studies led by the USGS (Izbicki et al., 2000; Izbicki and Michel, 2004; Kulongoski et al., 2008, 2003), investigating groundwater flow through the regional Mojave River Groundwater basin and the local Mojave River Floodplain aquifer by means of stable isotopes of water, tritium, carbon-14 and helium-4 age tracers and numerical models. A paleoclimate study on a selected noble gas samples from a portion of the regional groundwater basin presented a temperature shift of 4 °C from the Pleistocene to the Holocene (Kulongoski et al., 2008).

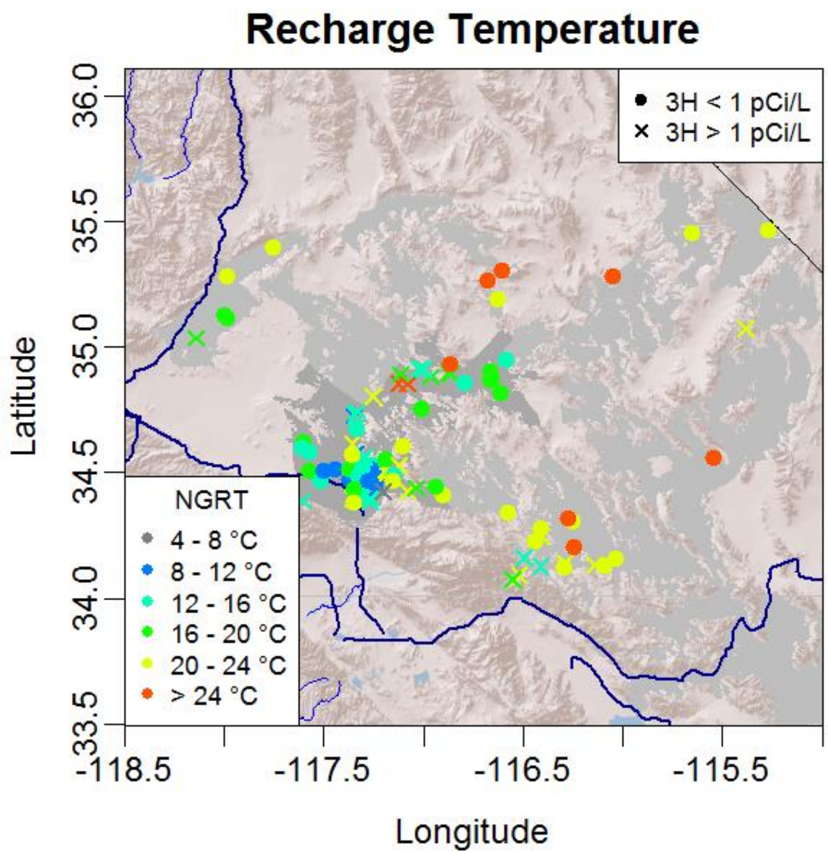
The study area was limited to the Mojave River (MOJO) and Central Desert Low Use Basin (CLUB) Priority Basin study units, as defined by the USGS.

3.2 Sources of recharge

Previous studies have identified the following sources of water that recharge the Mojave groundwater basins:

- Mojave River recharge
- Mountain front recharge
- Local recharge

The Mojave River originates at Cajon Pass, between the San Bernardino and San Gabriel Mountains. It does not flow perennially under present climate conditions and only discharges winter precipitation. It is estimated that the Mojave River recharges 0.054 km^3 annually to the Floodplain aquifer, which is typically 2.5 - 10 km wide and 60 m thick. Mountain front recharge is estimated to contribute 0.003 km^3 annually to the Regional aquifer, composed of alluvial fan and basin fill deposits of Pleistocene and Pliocene age that are up to 1000 m thick (Cox and Hillhouse, 2000). Small streams like Sheep Creek conduct snowmelt and winter stormflow from the San Bernardino and San Gabriel mountains down to the Desert where recharge is facilitated by the Oro Grande wash and Antelope wash (west of the Mojave River) and by Pipes wash (east of the San Bernardino Mountains in the Morongo groundwater basin). Direct infiltration of local precipitation is believed to be very limited under present climate conditions, but focused runoff from geological features may facilitate localized infiltration.



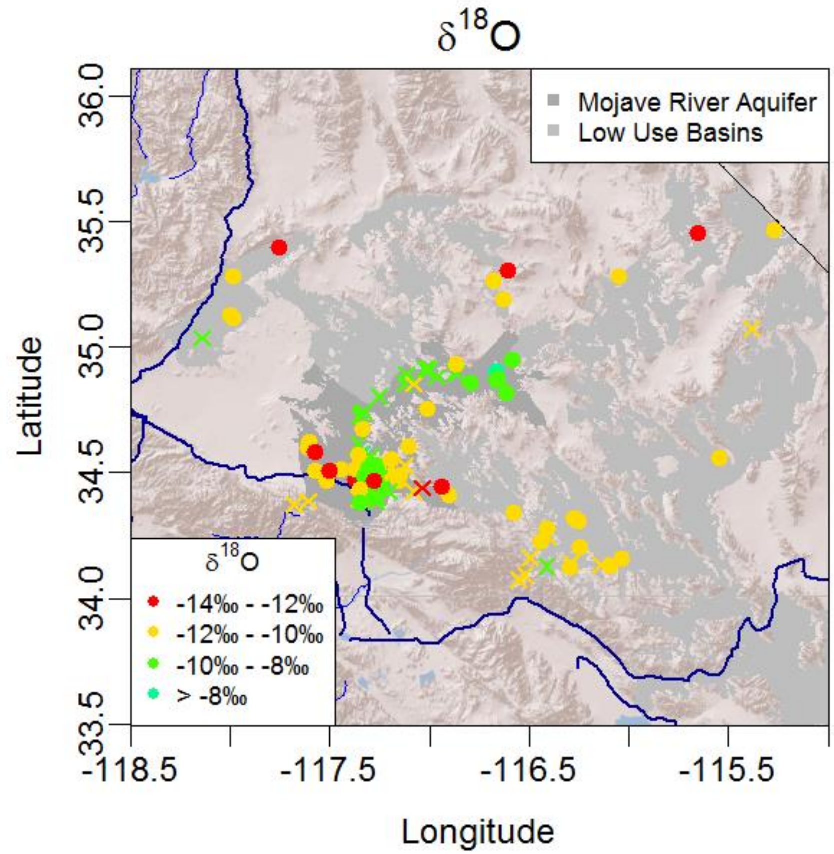


Figure 1: Map of Mojave Desert study area with noble gas recharge temperatures (left) and $\delta^{18}O$ values (right) within the Mojave River Aquifer (dark gray shading) and Low Use Basins (light gray shading).

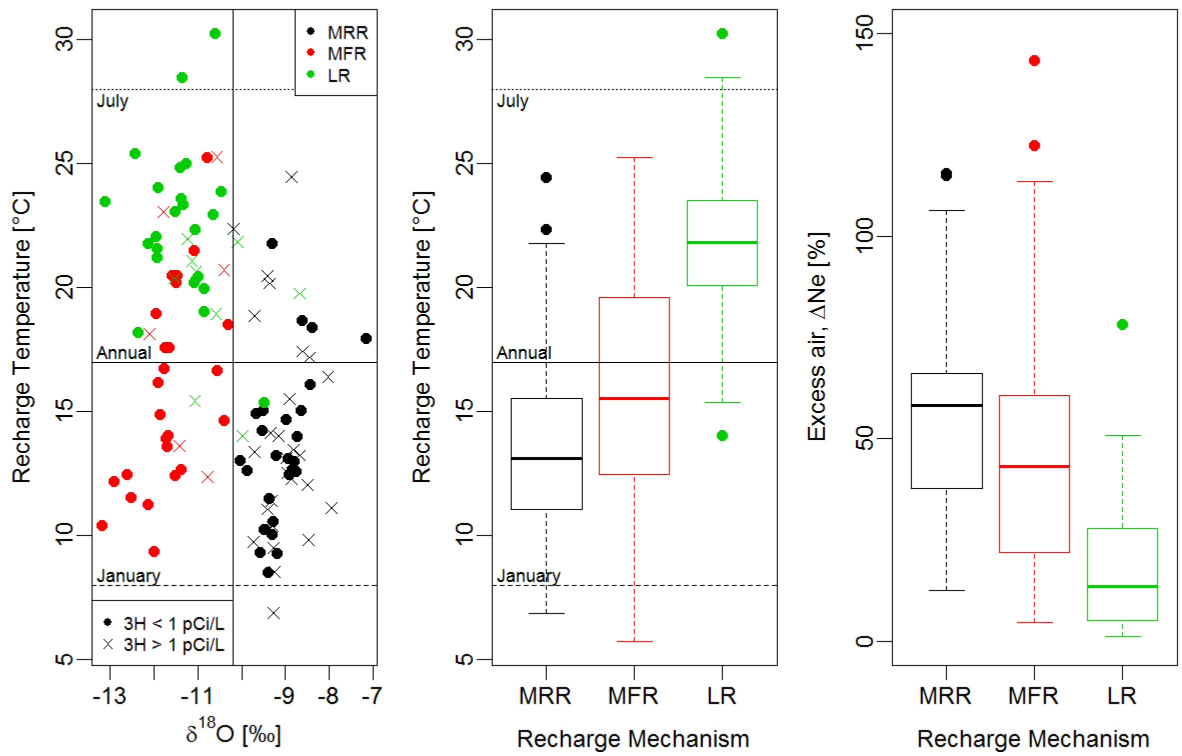


Figure 2: Noble gas recharge temperature and $\delta^{18}O$ of samples in Mojave River Recharge ($\delta^{18}O$ > -10.2‰ within the Mojave River aquifer), Mountain Front Recharge ($\delta^{18}O$ < -10.2‰ within the Mojave River aquifer, red) and Local Recharge (sampled in the Regional Aquifer, green) with mean temperatures at well locations for January, July and annual. Box-and-whisker plot of noble gas recharge temperature (middle) and excess air (right) for three identified recharge mechanisms.

The isotopic signature of Mojave River recharge is distinctly different from the other two sources. The elevation of the San Gabriel (3,000 m) and San Bernardino (3,500 m) mountains prevents isotopically heavy moisture from reaching the Mojave Desert, resulting in local precipitation that is significantly depleted in the heavier isotopes, ^{18}O and ^{2}H. Precipitation on the lower elevation (1,000 m) Cajon Pass that feeds the Mojave River does not undergo the isotopic depletion and is significantly less depleted. Izbicki showed that a $\delta^{18}O$ value of -10.2‰ distinguishes Mojave River water from isotopically lighter (more negative in $\delta^{18}O$) regional precipitation in the Mojave Desert.

The Mojave River signature is found along 85 km of the river bed leading to Barstow, and another 45 km beyond Barstow into the groundwater basin below the lower main stem.

The data were divided in three categories, representing the three recharge mechanisms. The Mojave River recharge (MRR, black) category contained samples within the Mojave River study unit (MOJO), with a $\delta^{18}O$ value of greater than -10.2 ‰. The Mountain Front recharge (MFR, red) contained MOJO samples with a $\delta^{18}O$ of less than -10.2 ‰. Samples collected in the Central Desert and Low Use Basin study units were categorized as Local recharge (LR, green).

3.3 Recharge Mechanisms

The Mojave River isotopic signature coincides with a distinct dissolved noble gas signature. Mojave River recharge wells (n=54) have a noble gas recharge temperature of 13.8±3.8 °C (mean ± standard deviation). The mean is significantly ($P<0.001$) cooler than the mean annual air temperature at the well locations by 3.5±3.5 °C. (The mean annual air temperature is 17.3±1.3°C at the selected well locations. (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004)) Mojave River recharge occurs in winter during snow melt and storm runoff, and noble gas concentrations are not equilibrated with the soil temperature (which typically matches the mean annual air temperature). A soil temperature study at the Oro Grande and Sheep Creek wash (Kulongoski et al., 2008) showed that streamflow infiltration of small streams can lower the soil temperature by 0 to 1.9 °C, but the effect is mostly limited to less than 1°C. Constant soil temperatures were observed below 15 m depth.

In addition to the temperature constraints on the recharge mechanism, the selected wells show a large excess air component, varying between ΔNe values of 12% and 115%, with a mean of 55%±26%. The higher excess air concentrations are evidence of recharge through an initially unsaturated zone, entrapping air while the water table rises several meters, in line with reports of flash floods occurring across an initially dry, incised riverbed. Because excess air is formed by the added pressure of the rising water table on entrapped bubbles, the amount of excess air is directly linked to water table fluctuations (Ingram et al., 2007). ΔNe values between 12% and 115% correspond to mean water table fluctuations between 0.7 and 6.6 meters. Water tables in the underlying aquifer have been reported between 6 m and 30 m below the riverbed (Lines, 1996), as well as water table fluctuations of up to 26.5 m.

The combination of low recharge temperatures and high excess air concentrations requires a specific set of conditions. Recharge must occur only in winter, when air and water temperatures are below the mean annual temperature. The riverbed is disconnected from the groundwater system, resulting in rapid increases in the water table. Recharge must occur rapidly, retaining the noble gas concentration pattern in equilibrium with the lower water temperatures, while infiltrating an unsaturated zone that is close to the mean annual temperature. Recharge must occur at high volumes and rates, preventing re-equilibration of noble gases across the water table during the rest of the year when the riverbed is dry. These conditions are met beneath the Mojave River, resulting in noble gas recharge temperatures that are significantly lower than the mean annual air temperature.

Observations of noble gas recharge temperatures below the mean annual temperature in samples that are not associated with the Mojave River are limited to the western portion of the regional Mojave River aquifer. Mountain front recharge is facilitated by the Sheep Creek fan, Victorville fan and the Oro Grande wash. The mean recharge temperature of the Mountain Front recharge category was 16.0±4.6 °C, close to the mean annual air temperature. The pattern of excess air in these samples is similar to that of the Mojave River recharge, varying from 3% to 143%, with a mean of 46±34%. Because recharge in this area is isotopically indistinguishable from local recharge across the Mojave Desert, noble gas signatures provide a valuable fingerprint to trace the extent of the mountain front recharge.

In contrast to the Mojave River and mountain front recharge, the remainder of the wells showed a noble gas recharge temperature of 21.7±3.4 °C, which is significantly ($P<0.001$) higher than the mean annual temperature at the well locations, by 3.8±2.9 °C. Noble gas recharge temperatures in excess of the mean annual temperature may be explained by a geothermal gradient across the thick unsaturated zone in large portions of the Mojave Desert (Manning et al., 2015). Excess air in these samples is significantly ($P<0.001$) lower than the Mojave River and mountain front recharge group, ranging from 1% to 78%, with a mean of 18±18%, corresponding to water table fluctuations of 1.3 m.

3.4 Time Scales of Recharge

Previous work on a small subset (n=10) of noble gas data attributed a 4°C shift in recharge concentrations to climate variability (Kulongoski et al., 2008). Tritium and carbon-14 activities in sampled wells demonstrate that all three mechanisms of recharge have been active since the Pleistocene and continue into the modern era. Samples with the Mojave River recharge signature are both pre-modern (^3H < 1 pCi/L, n=27) and modern (^3H > 1 pCi/L, n=27) in equal proportions. Higher recharge temperatures are more likely to occur in modern samples, possibly because of recharge after irrigation. Carbon-14 activities vary from 36 pmC (percent of modern carbon) to 113 pmC, dating the oldest sample back 16 thousand years. 78% of mountain front recharge samples (n=32) is pre-modern. Carbon-14 activities (available for 7 samples) vary from 1.9 pmC to 91pmC. While the few modern samples indicate that mountain front recharge is ongoing, this mechanism is mostly responsible for filling the Mojave River regional aquifer over pre-historic time scales. A similar proportion of samples showing the local desert signature contain tritium (9 out of 32). Carbon-14 activities vary from 4.2 pmC to 107 pmC. Modern groundwater with a local desert recharge signature is found in the northwest of the Mojave Desert (near the city of Mojave) and the southeast (near Yucca Valley and Pipes wash). One exception is a well in the east of the Mojave Desert, located in a local wash; evidence that recharge through a thick unsaturated zone is ongoing in the modern era, at select locations where geological features such as slot canyons or incised washes can focus limited precipitation to infiltrate the soil and recharge the groundwater system.

3.5 Discussion

The most surprising result is the discovery of noble gas signatures corresponding to recharge temperatures that are significantly lower than the local mean annual temperature by 3.5°C. Rapid, high volume, focused recharge is necessary to maintain both the temperature and the noble gas signature in the groundwater after infiltration through a thick unsaturated zone experiencing large water table fluctuations. Previous model studies showed very limited (<2°C) impacts of cold water infiltration on soil temperatures. This is evidence that groundwater recharge in desert environments is most likely to occur only where limited precipitation is focused by geological features.

4 Owens Valley

4.1 Study Area

Owens Valley is a 250 km long, less than 20 km wide, arid valley bound by the Sierra Nevada on the west and by the White Mountains and Inyo Mountains on the east. The climate is arid (less than 140 mm precipitation) being on the leeward side of the Sierra Nevada, with cold winters (January: 5.4 °C) and hot summer (July: 26.9 °C). The Owens River drains the eastern slopes of the Sierra Nevada north of Bishop (elevation 1270 m above msl), flowing 100 km south into former Owens Lake (elevation 1085 m above msl). Since 1913, most water is diverted in the Los Angeles Aqueduct, about halfway between Big Pine and Independence. Owens River was dammed in 1941, for additional storage for the LA Aqueduct and flood control, forming Crowley Lake, 40 km northwest of Bishop. Owens River is the major source of recharge to the valley groundwater basin. Smaller creeks draining the eastern slopes south of Bishop also contribute to groundwater recharge. In the Pleistocene, Owens Lake drained further south into China Lake and Searles Lake, and eventually east into Manly Lake, now known as Death Valley. The Owens Valley Priority Basin study area includes the groundwater basin from north of Bishop to Owens Lake. The Indian Wells study area encompasses the aquifers below former China Lake.

4.2 Recharge Sources

Owens River drains the leeward side of the highest section of the Sierra Nevada mountain range, the crest elevation exceeding 3000 m above msl. Precipitation moving across the crest is highly depleted in ^{18}O. Groundwater in Owens Valley has $\delta^{18}O$ values between -17.6 ‰ and -13.9 ‰, mostly below -15 ‰. The Indian Wells study area is located east of the southern edge of the Sierra Nevada, where the crest is below 2000 m above msl, resulting in precipitation that is less depleted in ^{18}O. $\delta^{18}O$ in groundwater samples in this area varies from -13.7 ‰ to -11.2 ‰, mostly higher than -13 ‰. The two sources of recharge, Owens River Recharge (ORR) and Indian Wells Recharge (IWR) can be distinguished based on the $\delta^{18}O$ values, with -13.8 ‰ being the cutoff.

Stable isotopes, collected quarterly between September 1984 and June 1986 (Coplen and Kendall, 2000; Kendall and Coplen, 2001) (data retrieved from the IAEA Global Network of Isotopes in Rivers) vary between -15.9 ‰ and -14.1 ‰, along an evaporation trend line with a slope of 5.3, shallower than the slope of 8 for the global meteoric water line (GMWL). The trend line intercepts the GMWL at (-17 ‰, -125 ‰). Most pre-modern ORR groundwater samples fall along this trend, between the intercept with the GMWL and the lowest (June) Owens River sample. The evaporation signal in Owens River is likely the result of evaporation from Crowley Lake.

The stable isotope signature of Indian Wells recharge is similar to the Mojave Desert local recharge signature, significantly offset from the GMWL.

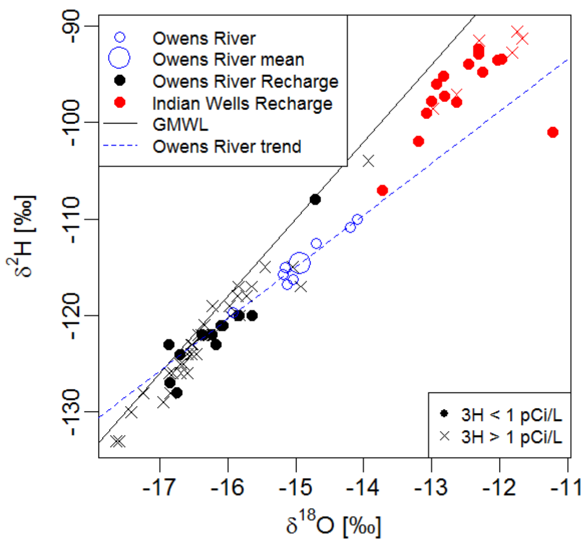


Figure 3: Stable isotope plot of Owens River samples (blue), Owens River Recharge (black) and Indian Wells Recharge (red).

4.3 Recharge Mechanisms

The noble gas recharge temperature of ORR is 13.4 °C ± 3.1 °C, significantly below the mean annual air temperature ($P < 0.025$, one-sided Student's t-Test) at the well locations by 0.9 °C ± 3.2 °C. Excess air varies between 0% and 106% (ΔNe), corresponding to water table fluctuations of up to 6 m. These water table fluctuations are lower than Mojave River recharge and similar to Mojave mountain front recharge. Mountain front recharge may play a significant role south of Bishop and above Crowley Lake.

Wells with modern ages in the ORR area (with more than 64 pmC, see Recharge Time Scales) show significantly lower ($P < 0.001$) noble gas recharge temperatures than pre-modern wells (less than 64 pmC) and are located in areas with irrigated agriculture in Owens Valley. Excess air is also higher in modern groundwater samples (not significant, $P=0.08$), suggesting flood irrigation.

Indian Wells recharge temperatures are 21.5°C ± 4.8 °C, significantly higher ($P < 0.001$) than the annual mean (by 3.6 °C ± 4.7 °C). ΔNe varies across a similar range (0%-117%) with a mean of 23% ± 28%, corresponding to water level fluctuations of 1.3 m. Comparing with the Mojave Desert local recharge, the water table fluctuations are higher than expected, although the observed difference between the mean recharge temperature and the mean annual air temperature is similar.

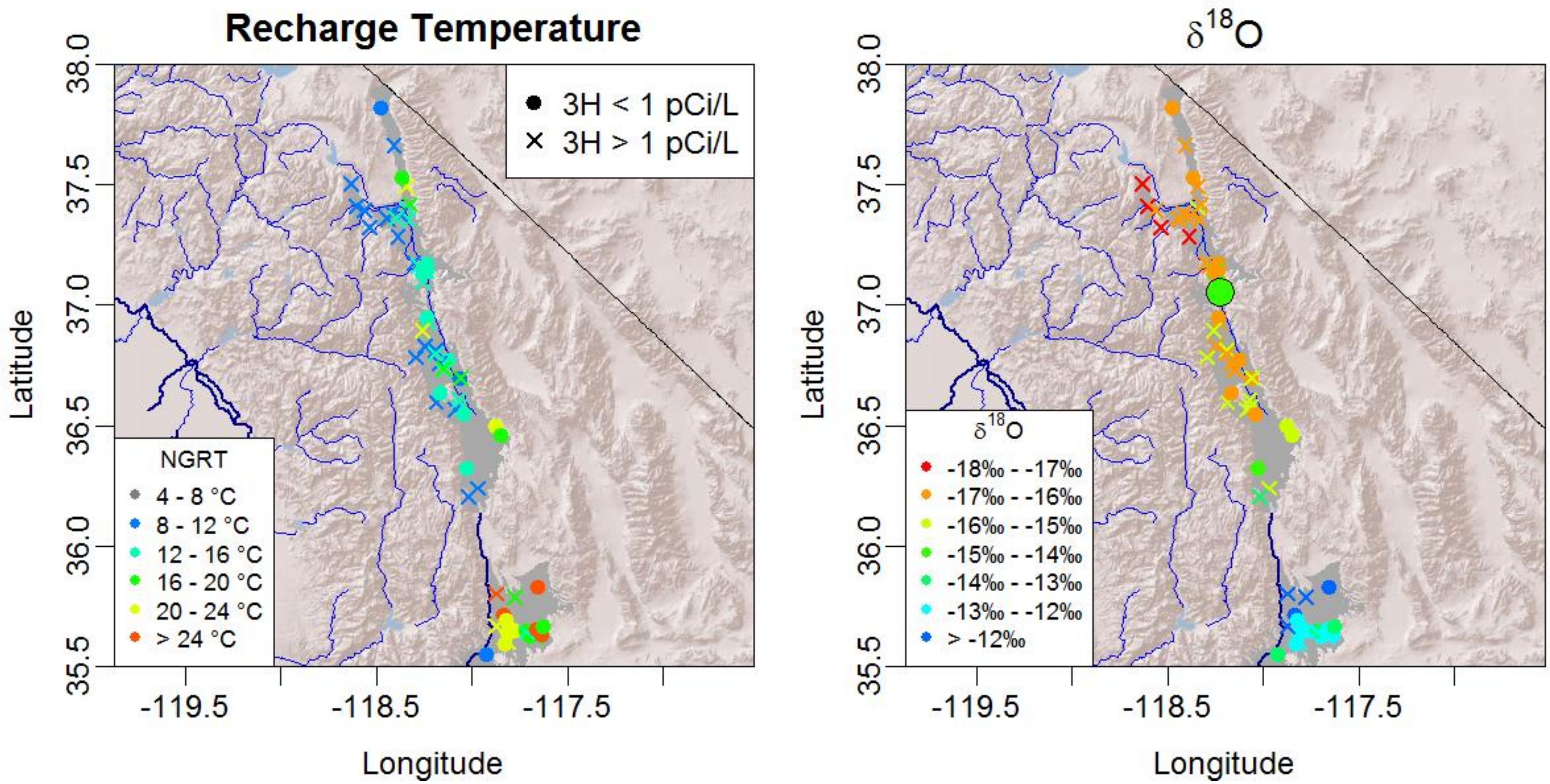


Figure 4: Map of Owens Valley study area with noble gas recharge temperatures (left) and $\delta^{18}O$ values (right) within the Owens Valley and Indian Wells aquifers. Green symbol shows location and mean isotopic signature of Owens River.

4.4 Recharge Time Scales

Tritium and carbon-14 activities confirm that both recharge mechanisms have been active in both the Pleistocene and Holocene, continuing into the modern era (since 1950). The majority (15/21) of Indian Wells groundwater samples are pre-modern (tritium less than 1 pCi/L), with carbon-14 activities ranging from 3 pmC to 93 pmC. In contrast, the majority of samples exhibiting Owens River recharge are modern (38/51) with a similar range in carbon-14 activities. The highest carbon-14 activity in pre-modern samples is 64 pmC for both study areas, while most modern samples have an activity above 64 pmC. 64 pmC appears to be the initial activity of carbon-14 at the water table before the onset of the nuclear age. The presence of terrigenic helium in modern samples is an indication of mixing with older groundwater. Volcanic activity and associated magmatic fluids in both study areas preclude the use of terrigenic helium as a reliable chronometer. The helium isotope ratio of the terrigenic component varies between 0.015 Ra (typical of radiogenic helium) and 1.5 Ra. (An isotope ratio of 1.5 Ra corresponds to a mixture of 80% radiogenic helium and 20 % mantle helium.)

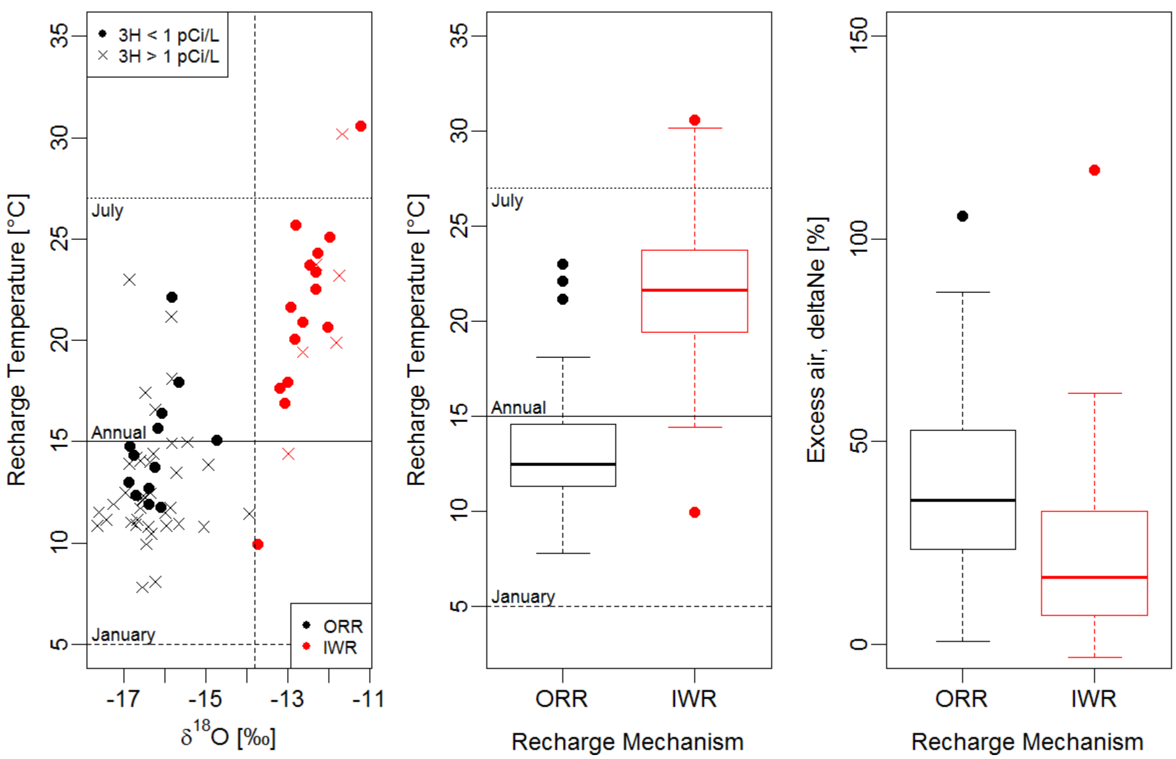


Figure 5: Noble gas recharge temperature and δ^{18}O of samples in Owens River Recharge (δ^{18}O < -13.8‰ within the Owens River aquifer) and Indian Wells Recharge (δ^{18}O > -13.8‰ within the Indian Wells aquifer, red), with mean air temperatures at well locations for January, July and

annual. Box-and-whisker plot of noble gas recharge temperature (middle) and excess air (right) for two identified recharge mechanisms.

4.5 Discussion

Two neighboring study areas in Owens Valley have distinctly different recharge sources, mechanisms and time scales, based on stable isotopes, noble gas derived parameters and age tracers. Indian Wells groundwater has excess air and noble gas recharge temperatures similar to local recharge in the Mojave Desert. Excess air and temperature differences with the annual mean in the Owens River groundwater are similar to river and mountain front recharge in the Mojave Desert, but the contrast with local recharge is smaller than in the Mojave Desert.

5 San Joaquin Valley

5.1 Study Area

The study area comprises of four GAMA PB study units within the south eastern portion of the San Joaquin Valley: Central Eastside SJV, Madera-Chowchilla, Southeast SJV and Kern. The study area is 360 long and 40-100 km wide. Precipitation in the study area varies from 140 mm to 520 mm in the foothills. 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. Nine major rivers (Stanislaus, Tuolumne, Merced, Fresno, San Joaquin, Kings, Kaweah, Tule, Kern) drain the Sierra Nevada, east of the San Joaquin Valley. Under pre-development conditions, these rivers fed a widespread wetland and lake. At present, all rivers are dammed and discharge is diverted for agricultural irrigation and water supply. Population of the San Joaquin valley counts four million. Land cover is predominantly agricultural, producing the majority of crops grown in California.

5.2 Recharge Sources

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
- Pumped Groundwater

Pumped groundwater is locally recharged and 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. Evapotranspiration losses affect the net flux of water available for recharge. Here we assume evapotranspiration affects both local precipitation and river water equally. Average precipitation over the study area is 248 mm/yr, varying from 143 to 522 mm/yr (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004), totaling to 6.0 km^3/yr. River inputs into the study area domain were estimated by Faunt (2009). Nine river input locations within the study area were selected which introduce a total of 9.2 km^3/yr. The direct contribution of each of the rivers varies from 1%-2% (Fresno River, Tule River) to 22%-25% (Tuolumne River and Kings River). The State Water Project supplies 1.2 km^3/yr to the San Joaquin Valley (California DWR, 2015), almost entirely to Kern County Water Agency (1.0 km^3/yr). Of the three sources, river water is the largest (56%) followed by local precipitation (37%) and the State Water Project (7%).

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 (^{18}O and ^{2}H) as a result of the high elevation, snowmelt dominated runoff in the source areas of the rivers. The local precipitation signature is not characterized by any precipitation collection stations and is therefore approximated from available literature sources. Ingraham and Taylor (1991) collected three longitudinal transects across California. The southernmost transect crosses this study area, from which two irrigation wells and five surface water samples were relevant. A larger set (n=51) of stream water samples were collected in the Tule and Kings River basins at elevations above 1000 m above msl, and constrain the slope of the topographic fractionation effect to between -2.1 ‰/km and -3.1 ‰/km. Extrapolation to sea level results in an unrealistic value of -5.9 ‰. A better approximation of the groundwater recharge signature is a set of domestic well samples collected in the foothills of Tulare County (Singleton et al., 2011). Wells above 200 m show an elevation gradient of -2.3 ‰/km and extrapolate down to -7.5 to -8.0 ‰ at sea level. Combining these sources, selecting samples within the study area of transect 3, surface water samples from small area catchments (< 10 km^2) and domestic wells above 200 m, a trend of -1.7 ‰/km is derived, with the intercept at sea level at -8.16 ‰ which was used as the signature of local precipitation in this study. The slope is similar to the one obtained by Rose et al. (1996) for spring recharge in Northern California (-2.1 ‰/km) and smaller than the slopes obtained by Lechler and Niemi (2011) for the Southern Sierras (-2.7 ‰/km for precipitation, -3.1 ‰/km for rivers) and by Dutton et al. (2005) for the entire US (-2.9 ‰/km for precipitation, -4.2 ‰/km for rivers). The obtained slope does not need to capture the precipitation signature, as we are interested in the signature of recharging groundwater, which may have been subject to evaporation at the land surface.

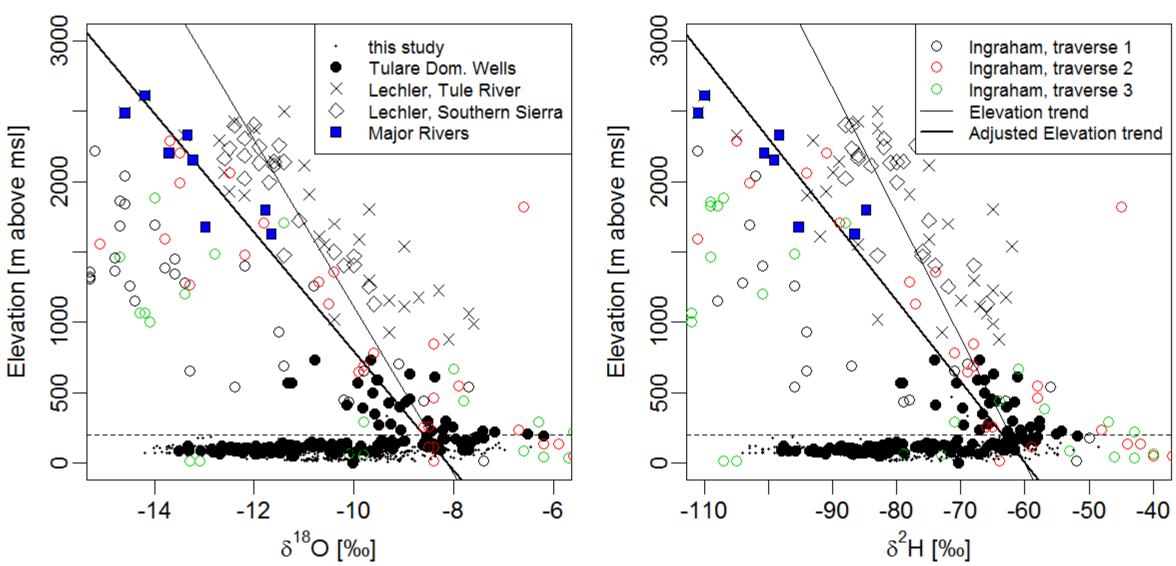


Figure 6: Vertical profile of δ^{18}O (left) and δ^{2}H (right) show an elevation trend of -1.7 ‰/km (δ^{18}O), which was adjusted to -2.35 ‰/km to align with the signatures of major rivers.

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, 2011). These rivers, plotted at the average elevation of the river capture area (Goulden et al., 2012; Lechler and Niemi, 2011) are not captured by the trend line. 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 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, the slope was adjusted to -2.35 ‰/km. By using the adjusted trend, the source signature of seven of the nine rivers delivering water to the study area was estimated (Table 1). (Catchment elevation was not available for the two smallest rivers.) Predicted δ^{18}O values vary from -13.4 ‰ (Kings River) to -11.7 ‰ (Stanislaus) with a flow weighted average δ^{18}O of -12.5 ‰. The State Water Project signature was assumed to be similar to that of the Sacramento River, -10.8 ‰ (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 ‰.

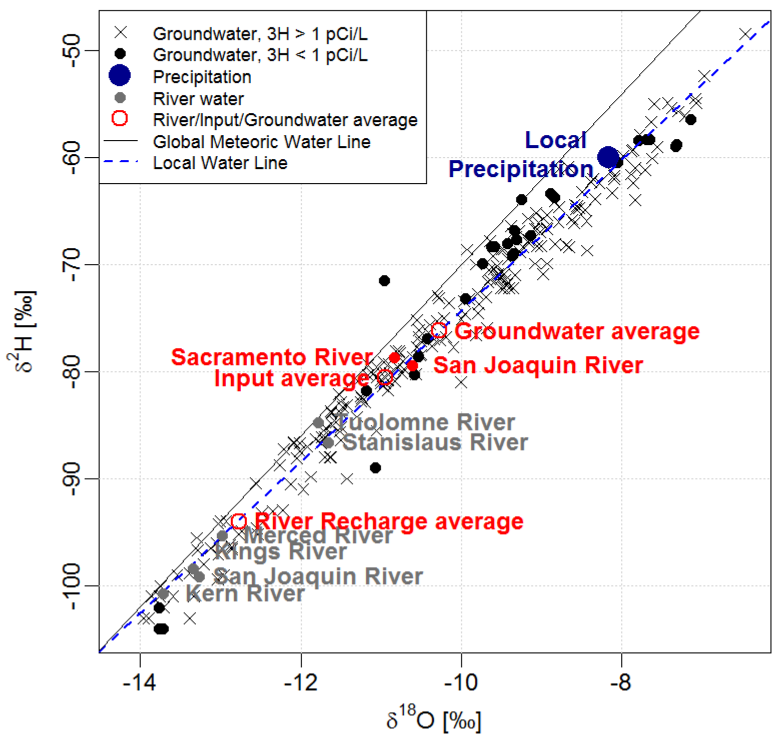


Figure 7: Stable isotope plot of San Joaquin Valley groundwater data, with the GMWL (black) and LWL (dashed blue) and estimated signatures of local precipitation recharge (blue), observed major rivers (gray), and the flow weighted average input and output signatures (red).

All groundwater data plot along a local water line (LWL) with a slope of 7.1, intercepting the global meteoric water line (GMWL) at -14.6 ‰. Samples resembling river water plot closer to the GMWL and samples similar to local precipitation have a smaller deuterium excess. The local precipitation recharge signature plots close to the LWL, indicating that it effectively captures effects of land surface evaporation on the groundwater recharge signature.

The San Joaquin River was sampled 14 times between 1984 and 1987 at Vernalis (Figure 8), at the northern edge of the study area. The mean δ^{18}O signature (-10.6 ‰) is close to the weighted total input signature (-10.9 ‰) and the Sacramento River (-10.8 ‰), but different from the river input signature (-12.8 ‰). Diversions of the rivers naturally entering the southern San Joaquin valley cause the river to run dry in the valley floor. The Vernalis signature is the result of the man-made hydrology of the San Joaquin valley, mixing the northern rivers, agricultural return flow from State Water Project and local precipitation. The mean signature of all groundwater data is -10.2 ‰, 0.7 ‰ closer to the local precipitation signature than the total inflow average. 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.

Table 1: Contributions and stable isotope signature of sources of recharge in the San Joaquin Valley.

Source	Elevation	$\delta^{18}O$ [‰]		Inflow	Proportion	
	m	observed	trend	[km^3/a]	of rivers	of total
Stanislaus	1628	-11.7	-12.0	1.3	15%	
Tuolumne	1801	-11.8	-12.4	2.1	22%	
Merced	1677	-13.0	-12.1	1.2	13%	
Fresno				0.1	1%	
San Joaquin	2155	-13.2	-13.2	0.6	6%	
Kings	2332	-13.3	-13.6	2.3	25%	
Kaweah	1845		-12.5	0.6	6%	
Tule				0.2	2%	
Kern	2204	-13.7	-13.3	0.9	10%	
Rivers		**-12.7**	**-12.8**	**9.2**	100%	**56%**
Local Precipitation		**-8.2**	**-8.2**	**6.0**		**37%**
State Water Project		**-10.8**	**-10.8**	**1.2**		**7%**
Total Inflow		**-10.9**	**-10.9**	**16.4**		**100%**

The lowest $\delta^{18}O$ values are found in groundwater downstream of the Kings and Kern rivers – the rivers with the highest elevation headwaters. A plume of Kings River water extends west across the entire study area. The Kern River signature is found around the city of Bakersfield. Even smaller rivers like the Kaweah and the Tule appear to leave a plume of depleted water in the groundwater system. The extensive alluvial fans and unconfined conditions present at the eastern edge of the valley allow rapid infiltration and transport of spring runoff and floodwaters. Losing conditions created by pumping adjacent to rivers leads to this flow pattern in modern times.

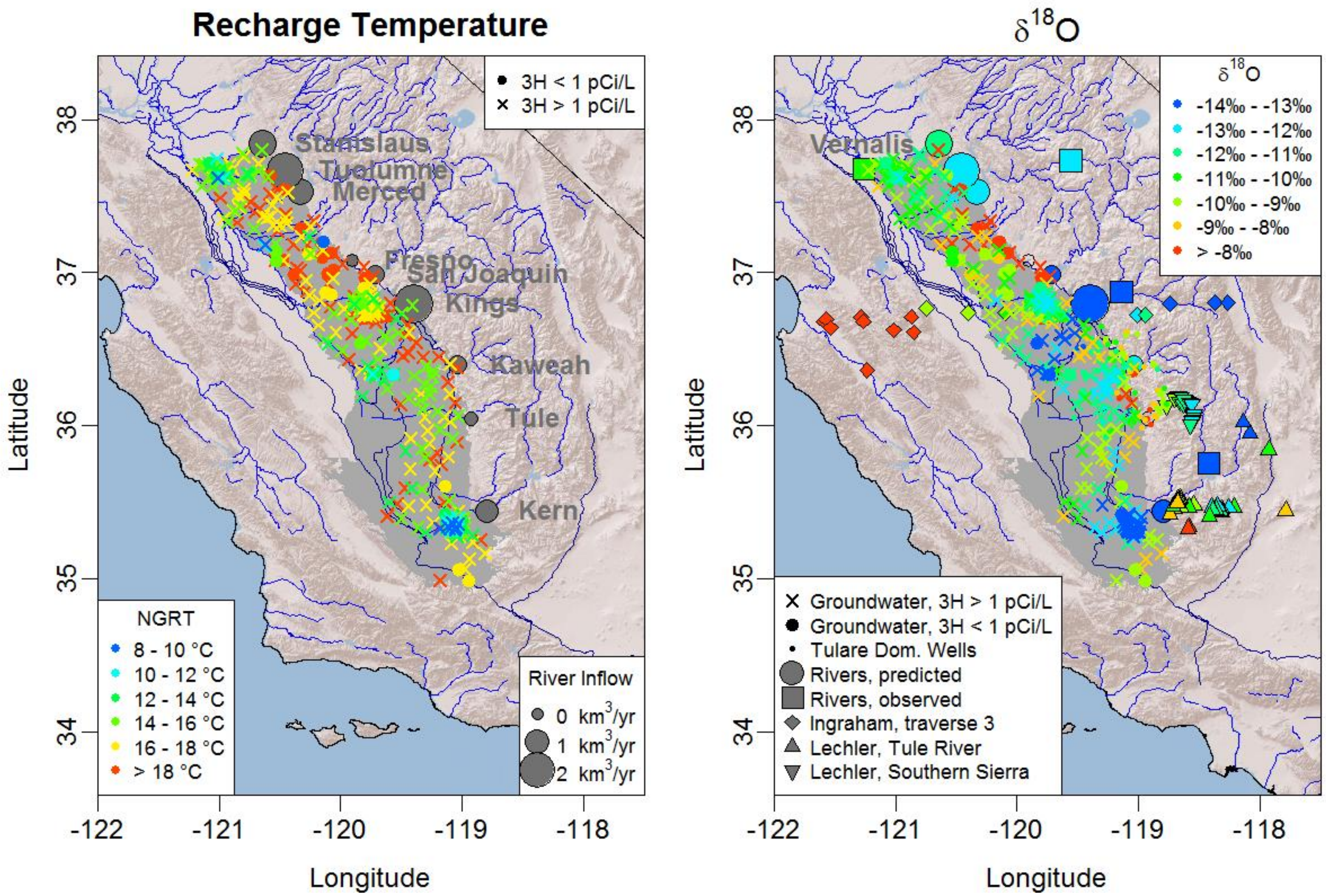


Figure 8: Map of the San Joaquin Valley study area (shaded gray) with noble gas recharge temperatures (left) and δ^{18}O (right) of groundwater (this study and Tulare domestic wells) and surface water. River symbol size reflects river discharge or valley inflow rate.

The local precipitation signature is found in groundwater on the east 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. The patterns of source signature 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.

5.3 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 ($P<0.001$, $R^2=0.21$) and a trend of 0.73 °C per 1 ‰ change in $\delta^{18}O$ is found. Three recharge mechanisms were distinguished based on the $\delta^{18}O$ of the sampled groundwater:

- River Water Recharge (n=116):$\delta^{18}O$ < -12 ‰
- Mixed Source Recharge (n=237): -12 ‰ ≤ $\delta^{18}O$ ≤ -9 ‰
- Local Precipitation (n=73): $\delta^{18}O$ > -9 ‰.

River water recharge has a mean recharge temperature of 14.7 °C ± 3.0 °C, which is significantly ($P < 0.001$) cooler than the mean annual temperature at the well locations by 2.9 °C ± 3.1 °C. This difference in temperature is similar to the cooling effect observed for the Mojave River system, and is the result of preferential recharge of cold snow melt during the cooler spring season. A large range of noble gas recharge temperatures is observed in modern samples (σ = 3.1°C) due to variations in recharge and irrigation practices, compared to the pre-modern river recharge (σ = 0.9 °C). Mixing and dispersion does not explain the limited range because it would also result in less depleted $\delta^{18}O$ values. Recharge in pre-modern floodplains was likely slower, allowing water to reach thermal equilibrium with the surroundings at temperatures closer to the mean annual air temperature.

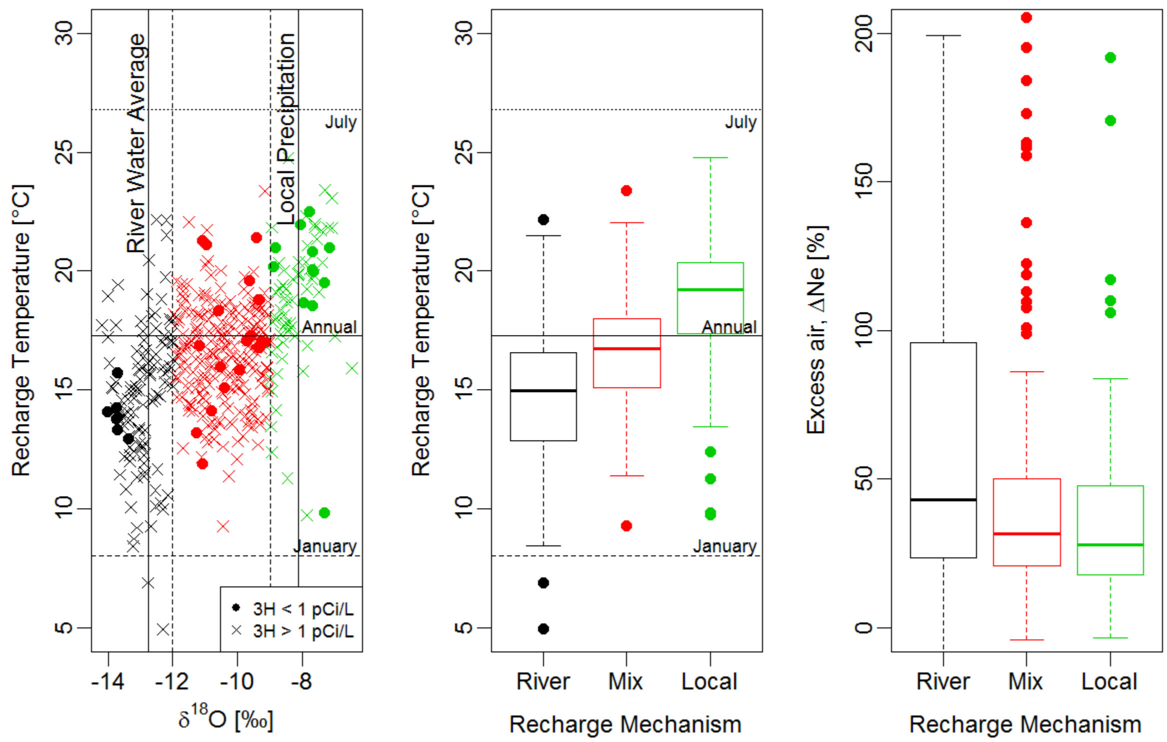


Figure 9: Noble gas recharge temperature and δ^{18}O of samples in San Joaquin study area. Vertical lines show estimated input signatures of rivers and local precipitation; vertical dashed lines (-12 ‰, -9 ‰) show cutoff between River Water, Mixed Source and Local Precipitation Recharge. Horizontal lines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

River water recharge shows a large range of excess air concentrations, with Δ Ne ranging from less than zero (indicating degassing) to over 200%. Water table fluctuations, based on the interquartile range (23%-83%) are on the order of 1.3 m to 4.8 m. The mean Δ Ne is significantly higher by more than 6% than other recharge groups ($P < 0.01$). In summary, river recharge occurs below mean annual temperatures with larger water table fluctuations than other recharge mechanisms.
The 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 ± 2.9 °C. This temperature difference is smaller than the Mojave and Owens local recharge differences, possibly due to factors linked to shallower water tables and soil temperature cooling by vegetation transpiration.
The excess air Δ Ne 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. In summary, recharge of local precipitation in the San Joaquin valley occurs with limited water table fluctuations at temperatures above the annual mean.

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 application of river water for irrigation in areas where local precipitation recharge is still a significant source.

5.4 Recharge Time Scales

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. Both modern (3H > 1 pCi/L) and pre-modern 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 represent only 6% of the river water recharge group, and 16% of the local precipitation recharge group. 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. For local precipitation recharge to reach a discharge location, it needs to travel longer flow paths, accumulating larger travel times. River water that has recharged the groundwater system will likely discharge again closer to where it recharged, after a relatively short flow path, and will accumulate less travel time. River incision naturally creates the opportunity for groundwater discharge, rather than recharge. Anthropogenic factors include groundwater pumping and irrigation. Groundwater pumping can increase the recharge rate of naturally loosing rivers by creating a larger gradient and unsaturated volume for river recharge to occur. Irrigation of river water across agricultural land has overwhelmed local precipitation recharge and filled in the modern slice of groundwater with river water.

Carbon-14 activities in mixed source and local precipitation groups range from fossil (0.7 pmC) to nuclear (129 pmC). The higher carbon-14 activity in pre-modern groundwater is 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). 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. Flow paths along rivers tend to be shorter (Izbicki et al., 2000).

Carbon-14 in modern river water recharge ranges from 63 pmC to 116 pmC. (7 pre-modern samples have no carbon-14 data.) Considering samples with both tritium and carbon-14 data (n=102), 58 are modern (tritium > 1 pCi/L, carbon-14 > 80 pmC), 15 are pre-modern (< 1 pCi/L, < 80 pmC). 28 are a mixture of modern and pre-modern water, with tritium concentrations as high as 23 pCi/L in samples with less than 50 pmC. These mixtures of modern and pre-modern groundwater have a limited component of old water, the age range of which cannot be determined.

5.5 Discussion

Limiting the analysis to Priority Basin samples, collected on representative aquifer areas, the proportion of groundwater from either local precipitation recharge (f_{LPR}) or river water recharge (f_{RWR}) can be calculated:

$$f_{LPR} = (\delta^{18}O_{GWmean} - \delta^{18}O_{RWR}) / (\delta^{18}O_{LPR} - \delta^{18}O_{RWR})$$

$$f_{RWR} = (\delta^{18}O_{GWmean} - \delta^{18}O_{LPR}) / (\delta^{18}O_{RWR} - \delta^{18}O_{LPR}) = 1 - f_{LPR}$$

57% of groundwater in the study area originates from local precipitation and 43% originates from river water (Table 2). Limiting the calculation to pre-modern groundwater (samples with less than 1 pCi/L tritium) the proportion of local precipitation is 76%. Local precipitation recharge flows over longer distances and over longer travel times through the groundwater system to reach a discharge point. River water recharge does not appear to follow long flow paths leading to groundwater age of more than two thousand years at the discharge point (assuming an initial carbon-14 value of 80 pmC).

Local precipitation recharge is still the majority of recharge at present (it composes 54% of groundwater but only contributes 40% to the yearly inflow), but it is no longer the dominant mechanism of recharge as it was in pre-modern groundwater (76%).Considering the change in the proportion of river water in pre-modern samples (24%) to that in modern samples (46%), the importance of river water has nearly doubled. Irrigation with re-distributed river water likely caused the increase of the river water recharge proportion. If the rate of local precipitation recharge has remained constant and the proportion of local precipitation recharge decreased from 76% to 54%, the net recharge rate need to have increased by 40% (2.4 km^3/yr). In the extreme scenario that all river water (9.2 km^3/yr) is applied as irrigation in the San Joaquin valley, irrigation losses recharging groundwater (irrigation return flow) are at least 26% of the water applied, or more if less river water is used for irrigation.

Table 2: Isotopic signatures of selected data subsets and calculated proportions of River Water Recharge and Local Precipitation Recharge

Data Selection	$\delta^{18}O$ mean	Proportion River Water Recharge $(\delta^{18}O_{GWmean} - \delta^{18}O_{LPR}) / (\delta^{18}O_{RWR} - \delta^{18}O_{LPR})$	Proportion Local Precipitation Recharge $(\delta^{18}O_{GWmean} - \delta^{18}O_{RWR}) / (\delta^{18}O_{LPR} - \delta^{18}O_{RWR})$
Priority Basin samples	-10.15 ‰	43%	57%
- Pre-modern samples	-9.25 ‰	24%	76%
- Modern samples	-10.26 ‰	46%	54%
San Joaquin at Vernalis	-10.60 ‰	53%	47%
River Water Recharge Signature	-12.80 ‰	0%	100%
Local Precipitation Recharge Signature	-8.20 ‰	100%	0%
Average Input Signature	-10.90 ‰	59%	41%

Local precipitation recharge represents a larger proportion of outflow of the San Joaquin River at Vernalis (47%) than of total inputs into the study area (41%). 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, 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).

Local recharge occurs at higher temperatures with less water table fluctuations and these patterns have not changed between pre-modern and modern period. Pleistocene groundwater in the San Joaquin Valley recharged as local precipitation, while river water naturally occurs along shorter flow paths. The fraction of local precipitation in groundwater decreased from 76% in pre-modern samples to 54% in modern groundwater. An increase of 40% in net recharge is made up of irrigation return flow (of applied river water). The proportion of river water recharge increased from 24% in pre-modern samples to 46% in modern groundwater. The importance of river water has nearly doubled due to enhanced river water recharge through managed aquifer recharge and irrigation return flows. At present, river water recharge is an important mechanism of groundwater replenishment. The extensive irrigation with river water also impacts regional climate and air temperatures through the irrigation cooling effect (Kueppers et al., 2007). While river water recharge has increased, is has not been able to keep up with increased discharge by pumping, resulting in overdraft and groundwater level declines (Scanlon et al., 2012).

6 Conclusions

River recharge contributes 63% of modern pumped groundwater in the Mojave Desert, 86% of modern water pumped in Owens Valley, and 46% of San Joaquin Valley modern groundwater. In pre-modern groundwater, river recharge represents 36%, 46%, and 24% respectively. The nearly doubling of the importance of river water recharge in the San Joaquin valley is accompanied by a total increase of recharge of 40% caused by river water irrigation return flows. Similar increases in proportion of river water in pumped groundwater in desert environments stresses the importance of river water recharge for renewal of groundwater resources. Nevertheless, even in desert environments, mountain front recharge and local precipitation contribute to recharge of groundwater basins as the result of geological features focusing scarce precipitation promoting infiltration.

River water recharges groundwater systems under lower temperatures and with larger water table fluctuations than local precipitation recharge. The cold signature and high excess air indicating fast recharge over short time scales are evidence that surface storage is limited in time and volume. The large age ranges found in groundwater reflect the large capacity for subsurface storage. Groundwater banking of seasonal surface water flows appears a natural and promising method for increasing the resilience of water supply systems.

The large variations in noble gas recharge temperatures pose a challenge for paleoclimate reconstruction in environments where both recharge mechanisms (river water recharge and local precipitation recharge) have been active, requiring careful selection of sampling sites (Kulongoski et al., 2008). The distinct isotopic and noble gas signatures of river water recharge, compared to local precipitation recharge, reflecting the source and timescale of recharge, are valuable data to constrain numerical flow models (Izbicki et al., 2000).

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