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**Preliminary Report on the Stable Isotope Imaging
and Characterization of Surface and Ground Water
Resources in the Southern Sacramento Valley**

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**PRELIMINARY REPORT ON THE STABLE ISOTOPE IMAGING AND
CHARACTERIZATION OF SURFACE AND GROUND WATER
RESOURCES IN THE SOUTHERN SACRAMENTO VALLEY**

by

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ABSTRACT

Groundwater "mining" occurs in the southern Sacramento Valley by two different mechanisms. The usual type, overdrafting of groundwater and associated deflation of the water table, occurs in the urbanized areas on the east side of the Sacramento River. We define a new type of groundwater "mining", that entails withdrawal of ancient pristine groundwater, producing temporary depressions that are replaced shortly afterward by irrigation water. This withdrawal and replacement activity is accompanied by water quality degradation and occurs in the agriculturally intensive areas on the west side of the Sacramento River.

Stable isotope imaging of the groundwater in the southern Sacramento Valley, augmented by ^{14}C analyses, reveals that on the east side of the River the groundwater recharge is principally derived from modern surface water from the Sacramento and American rivers, which have $\delta^{18}\text{O} \sim -10.6\text{‰}$ and $\sim 100\%$ modern carbon. These river waters are migrating into the large cones of depression formed by overdrafting and are slowly replacing Pleistocene-Holocene water with $\delta^{18}\text{O} = -7.0\text{‰}$ and ^{14}C apparent ages of 9000-16,000 ka, that occurred naturally in the groundwater aquifer.

More complex stable isotope patterns occur on the west side of the Sacramento River and contrast with the regular, eastward sloping water table. Groundwaters in the Davis area that recharged directly from meteoric events have uniform $\delta^{18}\text{O}$ values of -7.5‰ and ^{14}C apparent ages of 3000-4000 ka, and would be expected to dominate much of the shallow groundwater in this region. However, such waters are now prevalent only in hilly terrane such as the lowlands of the eastern Coast Range, the Dunnigan Hills, and parts of the Plainfield ridge, where intensive irrigation has not occurred. In intensively irrigated areas, much of the natural meteoric groundwater is being replaced by groundwaters that have high $\delta^{18}\text{O}$ values ($\sim -6.0\text{‰}$), elevated nitrate concentrations (up to 44 ppm), and low ^{14}C ages of <500 years, all being characteristics that indicate incorporation of agricultural irrigation water that has been enriched by evaporation and subsequently recharged into the

groundwater aquifer. This latter water type threatens the long-term groundwater resource for Yolo county, and may have serious short-term consequences for certain municipalities. For instance, although groundwater levels in the City of Davis exhibit no net decrease with time and groundwater production is considered a "safe yield", progressive degradation of the groundwater quality is evidenced by secular increases in NO_3 accompanied by enriched $\delta^{18}\text{O}$ values and young ^{14}C ages.

Even higher ^{18}O groundwaters (-5.5‰) occur in large regions ($25\text{-}35\text{ mi}^2$) on the west side of the Sacramento River. One such area seems to be related to the long-term use (>100 years) and subsequent recharge of Cache Creek water that is diverted for flood irrigation. High ^{18}O groundwater is also found in the Zamora area in the floodplain regions of the Sacramento River. The latter groundwater, on the other hand, seems to represent ancient (apparent ages of $5000\text{-}7000\text{ ka}$), highly evaporated, flood plain waters that naturally recharged the aquifer. The City of Woodland is also surrounded by a large area of uniform, high ^{18}O groundwater, and may represent a mixture of old evaporated water and young agricultural water that both evolved from parent Cache Creek waters.

INTRODUCTION

Groundwater provides one-half of the drinking water needs in the United States. In California alone, greater than 15 million acre-feet of groundwater is pumped per year, an amount that accounts for 46% of domestic use and 39% of agricultural irrigation in the state (Spieker, 1984, p. 147). Associated with extensive groundwater use are several deleterious consequences whose severity increases over time, including deflation of water levels, soil salinization, ground subsidence, and water quality degradation. All of the latter interfere with the prudent use of this essential resource on a "sustainable" basis.

To combat these problems new and accurate information on the origin, age, source, and migration paths of groundwater is needed. Isotopic methods provide a well-tested but curiously underutilized means of gathering this information. Conclusions drawn from

isotopic studies are based on a completely independent set of assumptions than those used in traditional hydrogeologic assessments or computer models, and in many cases (e.g., Mazor, 1991) are demonstrably superior.

This paper provides a new $^{18}\text{O}/^{16}\text{O}$, D/H, and ^{14}C characterization of meteoric, surface, and groundwater resources of the southern Sacramento Valley, together with a detailed map of ^{18}O variations and a preliminary interpretation. A new classification of major groundwater bodies in this region is provided, permitting the sources of drinking water in the municipalities of Sacramento, Woodland, and Davis to be accurately defined. Possible locations of ancient, buried stream channels are delineated for further testing. The process of groundwater quality degradation elucidated by Davisson and Criss (1993), notably the mixing of contaminated irrigation water with pristine groundwater, is strongly supported by new ^{14}C apparent ages which show that the pristine component is thousands of years old. In short, these isotopic insights revolutionize current concepts about the nature of Sacramento Valley groundwater and have far-reaching consequences for the goal of its "sustainable" use.

FIELD AND ANALYTICAL METHODS

Rain waters were collected during storm events with small containers that were either emptied during or immediately after a rain event, or were designed to prevent evaporation. Most of the rain waters were collected during the 1990-1991 rainy season (Table 1); half of those were obtained from three simultaneously deployed remote samplers, one of which was in the Rumsey Hills (elevation ~1200'), another was ~3 miles east of Lake Berryessa, and the last was in the City of Davis. The remote samplers comprised a 500 ml Nalgene bottle with a 4" funnel placed through a hole in the cap and sealed with silica cement. An ~0.5" diameter hollow plastic ball was used as a stop valve inside the funnel, that buoyantly rose to allow any collected rain water to drain into the bottle, then automatically reseated in the bottom of the funnel and formed an effective seal. Laboratory tests (one

month @ 30% humidity) showed no evaporative effects on water collected in the sampler. The remote samplers were emptied either approximately once a month or when the prevailing rains filled them up. In a few cases, the bottles had overfilled and the volume measurement was lost, but evaporative effects were negligible because those samples were collected shortly after the overfilling. Most samples collected from the remote samplers represent a combination of different storm events, or accumulated precipitation over several days.

All groundwater samples were collected from actively pumped wells used for domestic and irrigation purposes; these data are used in Figures 4 through 6 and will be tabulated in a forthcoming report. The surface waters were collected from flowing rivers, streams and canals (Table 2). Most samples were collected at large irrigation wells used for flood, furrow, and sprinkler irrigation, that have average depths of approximately 300 feet below the surface. Bottles were filled at discharge points that represented a high volume flux (500 to >2000 gpm) of groundwater produced by 75-100 horsepower industrial pumps. Pumps for these wells typically pump continuously anywhere from several hours to several weeks. Domestic wells were sampled mostly in municipalities where each well was pumped long enough to empty the standing water in the well bores (1-5 mins; most depths = ~100-600 feet below the surface) and bottles were filled at water quality sampling taps placed along the discharge pipes within a few feet from the pumps. Only in the case of the City of Woodland were samples collected downstream of any chlorination input. The chemical character (NaClO_4) and rate of chlorine introduction posed no realistic potential for contamination of the water samples.

Either 15 or 30 ml stable isotope sample bottles were rinsed once and then filled, leaving a small head space at top, and capped with an air-tight seal that prevented evaporation. Each sample was analyzed for its $\delta^{18}\text{O}$ value and some for their δD value, by respectively using the CO_2 equilibration (Epstein and Mayeda, 1953) or the zinc-reduction methods (Coleman et al., 1982), followed by analysis on an isotope ratio mass

spectrometer at the Geology Department at the University of California, Davis. All oxygen and hydrogen isotope analyses are reported in the usual δ notation relative to the SMOW standard, where $\delta = (R/R_{\text{smow}} - 1)1000$, R represents either the $^{18}\text{O}/^{16}\text{O}$ or the D/H ratio of the sample, and R_{smow} is either the $^{18}\text{O}/^{16}\text{O}$ or the D/H ratio of SMOW (Standard Mean Ocean Water; Craig, 1961a).

The ^{14}C sample bottles (125, 250, or 500 ml) were flushed ~30 seconds to one minute, after which approximately 4 drops of concentrated HgCl_2 were added to the sample to kill all biological activity in the water, and the bottle was capped with an air-tight seal. The inorganic carbon was extracted from the sample by vacuum-line acid stripping of the water using 100% phosphoric acid to acidify the sample to a $\text{pH} < 1$. All the dissolved inorganic carbon is converted to CO_2 whose liberation from the water was further facilitated by an ultra pure nitrogen carrier gas. The CO_2 was cryogenically trapped and separated from the water. The CO_2 was then reduced to graphite on a separate vacuum line using a cobalt catalyst and hydrogen gas at a 570°C reaction temperature, and then the ^{14}C concentrations were determined with the 10 MeV accelerator mass spectrometer at Lawrence Livermore National Lab. The ^{14}C results are reported as a percentages of modern ^{14}C relative to a NBS OX-1 standard that represents pre-nuclear testing atmospheric CO_2 ^{14}C abundance. Apparent ages are calculated using a half-life of 5730 years (Walker et al., 1989).

RESULTS AND DISCUSSION

Isotopic Characterization of Meteoric Waters

The $\delta^{18}\text{O}$ values in meteoric waters in the southern Sacramento Valley vary from -2.3 to -13.5‰ and conform well with the Global Meteoric Water Line (MWL) of Craig (1961b; Table 1).

Figure 1. Stable isotope distribution of rain water collected in the southwestern Sacramento Valley, 1989-1991.

The most depleted and the most enriched rain samples tend to plot to the right of the MWL, and given that these types of rain waters are from low precipitation events, significant evaporation has probably occurred. Samples with $\delta^{18}\text{O}$ values between -6.0 and -9.0 show strong adherence to the MWL as expected for large volume storm events. The volumetric average of this precipitation is approximately -7.5‰ (Davisson et al., 1993a), identical to the average value to the west in the well-studied Geysers Geothermal Field (Gunderson, 1989) and similar to values that occur throughout the Coast Range province (White et al., 1973; Peters, 1993). Rayleigh effects in storm tracks cause a net eastward depletion in the ^{18}O abundance of the water vapor in this region, resulting in $\delta^{18}\text{O}$ values as low as -15.0‰ (Ingraham and Taylor, 1991), and in cases produce even lower $\delta^{18}\text{O}$ values in the upper elevations of the Sierra Nevada. Meteoric waters impounded in lakes and reservoirs or in flowing rivers and streams become enriched in both ^{18}O and deuterium

when they undergo evaporation (Table 1), largely due to the lower vapor pressures of HDO and H_2^{18}O relative to that of H_2^{16}O .

Isotopic Characterization of Surface Waters

The $\delta^{18}\text{O}$ values of surface waters given in Table 2 show that Putah Creek varies between -5.7 and -3.0. These samples were collected at different places and times, and have probably undergone substantial isotopic enrichment (Fig. 2). A sample collected in August 1993 just below the large Monticello Dam (constructed in 1957) had a $\delta^{18}\text{O}$ value of -4.7, indicating that significant evaporation occurred subsequent to its origination as meteoric precipitation in the Coast Range.

The $\delta^{18}\text{O}$ values of several samples of Cache Creek vary between -6.9 and +0.6. Compared to Putah Creek, Cache Creek has a considerable seasonal variation in its isotopic value. Part of this variation might be due to its dual source, notably from Clear Lake, a naturally damned source located approximately 30 miles to the northwest in the Coast Ranges, and from Indian Valley Reservoir (constructed ~1980) approximately 40 miles further to the north. Clear Lake probably provides much of the discharge, and we made a single $\delta^{18}\text{O}$ determination of -1.0 for a beach sample that shows a high degree of evaporation. Cache Creek water also experiences a much longer flow path and has a much larger catchment area below its impoundment structures than Putah Creek, resulting in a more isotopically variable signature that can vary by several per mil between the summer, when evaporation rates are high, and the winter, when significant storm events occur. On a graph of δD vs. $\delta^{18}\text{O}$, evaporation trends away from the MWL have slopes of ~ 5.0 (± 0.5), as exemplified on Figure 2 by the Putah and Cache Creek samples (also see Davisson and Criss, 1993).

Figure 2. Stable isotope values of Cache and Putah Creek collected 1990-1993. Note the regressed slope of ~ 5.0 for these evaporated samples, which contrasts with the slope of 8.0 for the MWL.

The $\delta^{18}O$ values of several samples of the Sacramento River and one sample from the American River vary comparatively little, ranging between -10.6 and -11.8, with the more depleted samples in our data set being from the Lake Shasta and Red Bluff areas of the northern Sacramento Valley. All these river water samples plot close to the MWL and are isotopically very distinct from typical meteoric and ground waters in the southern Sacramento Valley. The isotopically depleted nature of the river waters reflects their origination in high altitude regions to the north and east, especially in the Sierra Nevada, where greater isotopic depletion in rain water occurs due to orographic and rain-out effects (e.g. Ingraham and Taylor, 1991). Unpublished data of the US Geological Survey (W. Swain, written communication, 1992) indicate comparable values for the Sacramento River near Freeport

($-10.5 < \delta^{18}\text{O} < -11.2$; $-76 < \delta\text{D} < -82$), and further indicate that the values for the San Joaquin River near Stockton ($-9.7 < \delta^{18}\text{O} < -11.3$; $-74 < \delta\text{D} < -84$; omitting one sample) are very similar to those for the Sacramento River.

Isotopic Characterization of Groundwater Masses

Pristine Holocene Groundwaters - A very important resource of "pristine groundwaters" occurs at generally shallow depths (mostly 200 to 600') below the southern Sacramento Valley (see Davisson and Criss, 1993). These waters lie on or near the MWL at $\delta^{18}\text{O}$ values of about -7.5, and therefore are very similar to average meteoric precipitation in the general vicinity. The total dissolved contents (TDS) of these Ca-Mg- HCO_3 waters are moderate, generally ranging around 500 ppm. Nitrate contents are generally below 10 ppm. The ^{14}C apparent ages of bicarbonate in several samples range from 3 to 8 ka.

Pristine Pleistocene Groundwaters - Another type of "pristine groundwater" of the southern Sacramento Valley occurs at greater depths, mostly 750 to 1200' (see Davisson and Criss, 1993). These waters lie on or near the MWL at $\delta^{18}\text{O}$ values of about -8.0 to -9.4, and may represent meteoric precipitation that originated at high elevations of the Sierra Nevada and subsequently migrated under the valley, or might represent local precipitation that occurred under different climatic conditions than exist today. The total dissolved contents (TDS) of these waters are moderate, generally < 500 ppm, but these waters are of a sodium-bicarbonate type as would be expected from older, more geochemically evolved groundwaters. Nitrate contents are < 1 ppm. The ^{14}C apparent ages of bicarbonate in several samples range from 10 to 17 ka.

Formation Waters - Saline, geopressured formation waters emerge as perennial springs at high elevations (600-1500') along the western margin of the Sacramento Valley (Unruh et al., 1992; Davisson et al., 1993b, and in review), and also occur at depths of about 1500 to 3000'

below the southern Sacramento Valley in the Late Cretaceous and Early Tertiary geologic formations (Lico and Kharaka, 1983). These formation waters lie well to the right of the MWL, with high $\delta^{18}\text{O}$ values of +0.6 to +5.3. They appear to represent seawater that has undergone some isotopic exchange and Na for Ca cation exchange with the siliciclastic rocks, as well as some dilution with meteoric precipitation (Davisson et al., 1993b). The total dissolved contents (TDS) of these sodium chloride waters are high, typically between 15,000 and 28,000 ppm (Davisson et al., 1993b). The boron contents are very high (to 215 ppm), so the perennial springs could represent another source of the B in Sacramento Valley groundwaters in addition to Cache Creek sources (Evenson, 1985). The ^{14}C activity of these saline waters is generally very low or negligible, but where some activity is apparent, the water usually has encountered recent meteoric dilution.

Agricultural and Natural Evaporated Waters - Two types of high ^{18}O groundwaters that have undergone substantial degrees of evaporation occur in the area. One is groundwater recharged by agricultural irrigation, derived either from diverted surface water or from pumped groundwater, that is applied to fields where it undergoes evaporation on the surface and, more importantly, in the vadose zone. In the southern Sacramento Valley, significant volumes of groundwater are inferred to have this origin based on the following characteristics: $\delta^{18}\text{O} \sim -6.0$; evaporation and mixing slopes of ~ 3 on a graph of δD vs. $\delta^{18}\text{O}$; unnaturally high levels of nitrate that generally range from 15 to 44 ppm; and young ^{14}C apparent ages of < 500 years. These characteristics arise because evaporation processes reduce the water volume while simultaneously increasing the salinities and enriching both the ^{18}O and D contents, and because cultivation and especially fertilizer application, including the direct addition of anhydrous ammonia to the water ("fertigation"), all increase the nitrate content of the water. Moreover, surface evaporation produces a slope of ~ 5 on a plot of δD vs. $\delta^{18}\text{O}$ values, whereas evaporation in the vadose zone typically produces a slope of ~ 3 (Barnes and Allison, 1983). The young ^{14}C

apparent ages are expected for waters that had recently communicated with surficial environments.

The second type of groundwater we have tentatively identified has a high $\delta^{18}\text{O}$ value that originated under natural evaporative conditions in the floodplains and former tule swamps of the Sacramento River. Such waters have undergone substantial degrees of evaporation, which produces isotopic enrichment but in this case along an expected slope of ~ 5 . Greatly elevated nitrate levels would not be expected, but the ^{14}C apparent ages could be quite old. We suggest that we have identified groundwaters of this type in the Zamora area, and on the eastern side of Davis, and possibly in Sacramento.

Regional Map of $\delta^{18}\text{O}$ Values of Groundwater

The significant variations in the $\delta^{18}\text{O}$ values of groundwater in the Sacramento Valley make it possible to employ a stable isotope "imaging" technique to delineate sources and movements of groundwater resources. In order to interpret the $\delta^{18}\text{O}$ contours, it is useful to first compare and contrast them to the regular, east-sloping gradient exhibited on a map of water tables (DWR, 1986; Fig. 3).

Figure 3. Contour map of groundwater levels (in feet relative to sea level) across the southern Sacramento Valley. Data from the Department of Water Resources (1986).

A traditional interpretation based on Figure 3 suggests that the pattern of subsurface flow in the western and central parts of this transect would be historically dominated by west to east transport of meteoric recharge derived from the Coast Ranges, and further north and northeast, by Cache Creek. The influence of Putah Creek is expected to be comparatively small. Further east, the Sacramento River might be expected to have a very substantial influence, although the gradient in the water levels is small immediately west of the river, so a precise interpretation is equivocal. Cones of depression at different scales produced by concentrated pumping during this century would be expected to have locally disturbed the inferred flow pattern of the shallow groundwater, as would surface diversions of Cache Creek irrigation water in the west central part of the transect, but the overall, west to east regional flow pattern would still be expected to dominate.

Figure 4. Contours are $\delta^{18}\text{O}$ isopleths of groundwaters derived from agricultural and municipal wells mostly during the spring of 1993.

Figure 4 shows the oxygen isotope variations in groundwaters across a broad transect from the edge of the Coast Range to the Sacramento River. The contours of the $\delta^{18}\text{O}$ values are very regular and, where augmented by ^{14}C determinations, yield spatial as well as temporal information of the character and origin of the groundwater. The $\delta^{18}\text{O}$ contours are striking and significantly contrast, in most areas, to the regular, east-sloping gradient exhibited on the map of water tables (Fig. 3). The isotope contours reflect that natural fluid sources are more complex than stated above, and even more importantly, that the human disturbance of the groundwater in many areas is profound. Remnants of the -7.5 per mil Coast Range meteoric recharge, which would dominate much of the area in the natural state, are mostly restricted to the foothills of the Coast Range, the Dunnigan Hills, and small parts of the Plainfield Ridge. This remnant pattern probably arises because these hilly areas are not intensely irrigated.

A high- ^{18}O tongue of groundwater is associated with a ~ 3-km wide zone along Putah Creek, most notable on its southern edge and its eastern extremity. Within this zone are groundwaters having the highest $\delta^{18}\text{O}$ values (≤ -5.0) observed in the entire transect, indicating that the parent waters at some time underwent a high degree of evaporation. Much of the infiltration of this highly evaporated water is probably related to Monticello Dam, which was constructed in 1957. The dam impounds ordinary meteoric water during winter storms, allows the waters to evaporate to high ^{18}O values as seen in Table 2, and steadily releases water to Putah Creek during the summertime, when the evaporation rates are high. Thus, the drainage down Putah Creek has an unnaturally high $\delta^{18}\text{O}$ value that contrasts with the pre-dam natural flow that was dominated by high winter flushing with low ^{18}O waters. Subsequent infiltration of the higher ^{18}O water into the shallow groundwater adjacent to the creek produces the higher ^{18}O patterns seen in figure 4. A very reasonable minimum transport rate of the high ^{18}O groundwater of ~100ft/year perpendicular to the creek can be calculated if it is assumed that the recharge of this high ^{18}O water postdates dam construction. Moreover, there has been long-term application of

ground and surface waters from Putah Creek to nearby orchards, especially near the town of Winters, that has caused a broadening of the high ^{18}O groundwater pattern in this area.

In addition, northeast of Davis a narrow northwest trending band of -7.5 groundwater is sandwiched between higher ^{18}O waters. In the -7.5 area groundwater is largely utilized for seasonal agricultural irrigation, whose production effects overlap with those by the City of Davis. On the eastern and southern sides of Davis, higher ^{18}O groundwater dominated by agricultural recharge waters appears to have migrated parallel to the hydrologic gradient beneath Davis. The -7.5 water on the northeast side has been ^{14}C dated at ~ 3 ka and represents the last remnant of "pristine" meteoric groundwater that exists at shallow levels in this area of intense irrigation. This lower ^{18}O zone may be related to deeper penetration depths of the wells and to gross changes in permeability of the shallow subsurface geologic deposits. Surface geologic investigation in this region (Helley, 1979) show that an interfingering relationship exists between fluvial deposits derived from the west and fine-grained flood deposits derived from the Sacramento River flood plain areas to the east. The low ^{18}O groundwaters may be temporally protected from recharging agricultural water due to more pervasive low-permeability layers that separate the zone of groundwater production from shallower zones where agricultural irrigation water infiltrates.

Two large zones of approximately -5.5 groundwaters occur in the western part of Fig. 4 as well as surrounding the City of Woodland. The western -5.5 zone comprises an area of approximately 25 mi^2 and resides in a region that, under natural conditions, would clearly be expected to be dominated by the -7.5‰ meteoric water. However, for probably >100 years, this area has utilized surface water derived from Cache Creek through a network of diversion canals for intense irrigation. The -5.5 groundwaters in this area are more enriched in ^{18}O than recharging agricultural waters observed near Davis and are probably related to the pervasive, long-term application of irrigation water diverted from Cache Creek. Two samples of canal water derived from Cache Creek collected in this area

(Table 2) had highly enriched $\delta^{18}\text{O}$ values of -3.2 and -2.4 per mil. Mass balance calculations for mixing of this surface water with the pristine meteoric water suggests that nearly half of the water residing in the -5.5 zone is derived from this canal water. This percentage is consistent with the observed mixing proportions in the Davis area between meteoric water and evaporated irrigation water from the same source. However, the isotopic uniformity of these high ^{18}O groundwaters is remarkable and unexpected at this scale.

A similar argument may be advanced for the 35 mi² zone of -5.5 groundwater that surrounds Woodland. The isotopic uniformity is again remarkable and unexpected, and may suggest a high dispersion rate facilitating mixing between groundwaters of disparate character. A more complex explanation of the source(s) may be necessary to explain the ^{18}O patterns for this area. In addition, since Woodland is proximal to both Cache Creek and the flood plain areas to the east, ancient natural surface water sources of the -5.5 water cannot be ruled out at this time.

Shallow groundwaters sampled from a nested piezometer in the Zamora area in the northern part of the map adjacent to the Sacramento River have $\delta^{18}\text{O}$ values between -5.0 and -6.0, along with an apparent ^{14}C age between 5000 and 8000 years. Deeper in this piezometer, the $\delta^{18}\text{O}$ value is -7.5 with approximately the same apparent ^{14}C age. The data suggest that the shallow subsurface in this area (~0-400') is recharged very slowly by evaporated floodplain waters. The deeper groundwaters, however, have a more characteristic meteoric water signature and a reasonable age for natural recharge (~8000 years). In addition, a groundwater sampled east of Woodland adjacent to the west side of the Sacramento River had a $\delta^{18}\text{O}$ value of -7.0 and an apparent ^{14}C age of ~6000 years, suggesting slow recharge of floodplain water. Given that the ^{18}O patterns in Figure 4 are complicated by the occurrence of the floodplain waters recharged into the groundwater, more data and field work is necessary. Geographic delineation of the general ages and

sources of groundwaters adjacent to the Sacramento River, and refined interpretation of their relationship to areas such as the City of Woodland will then be possible.

Municipal Groundwater Sources

Municipal groundwater pumping within the study area clearly causes the replacement of the pristine ancient groundwaters by younger surface waters that in many cases have lower quality. Surrounded by intensively irrigated agricultural land on the west-side of the Sacramento River, the Davis and Woodland areas have relatively uniform water table levels that lack any large coherent cones of depression. In contrast, in the City of Sacramento two 100 foot-deep, ~10 mile-wide cones of depression have developed north and south of the American River (Fig. 3).

Davis - Davis extracts groundwater from a system of 20 wells with perforation depths of 110 to 580 feet and includes at least two of the above mentioned major sources of water: 1) pristine, 3 ka groundwater representing centuries of meteoric recharge, and 2) a significant amount of agricultural irrigation water infiltrating back into the groundwater supply.

Groundwater pumping causes the progressive replacement of this pristine water predominantly by infiltrating agricultural flood irrigation water with an enriched $\delta^{18}\text{O}$ value of approximately ≥ -6.0 , young ^{14}C ages < 0.5 ka, and high NO_3 concentrations (to 44 ppm or higher). In some wells, as much as 50% of the discharge now represents the latter type of water. Thus, even though water table levels tend to recover over an annual cycle, the older component of groundwater is in effect being "mined", and thus the concept of "safe yield" no longer applies in these kind of cases.

A simple 2-D groundwater flow model can be derived based on the following assumptions: 1) the natural groundwater flow originates as rain water along a 15 mile strip that is one foot wide and 1000 feet deep that extends west of Davis, 2) average porosity of the aquifer is 30%, 3) the linear velocity of the groundwater in the upper 50 ft of the aquifer

is ~100 ft/yr based on stable isotope patterns adjacent to Putah Creek and Sacramento River and suggested flow rates from Mohr et al. (1992), 4) linear velocities of groundwater at 400 ft and 1000 ft below Davis are respectively 20 ft/yr and 8 ft/yr based on the apparent ^{14}C ages. Given these conditions, a suggested total groundwater flux of ~55 gal/ft²-yr occurs a vertical, north-south trending plane below Davis. The average annual precipitation in the Davis area is 1.4 ft, or 17 inches, and therefore, the total rain on average along the 15 mile strip is ~11 gal/ft²-yr or a total rain fall of ~850,000 gal/yr. Given a groundwater flow rate of ~55 gal/ft²-yr, this suggests that only ~6% of the total yearly rainfall (0.7 gal/ft²-yr) is recharged into the groundwater aquifer under natural conditions, and the remaining precipitation (~800,000 gal/yr) is lost due to runoff, evaporation, and evapotranspiration.

Superimposed on this natural groundwater flow is groundwater pumping and application of irrigation water. In California on average, ~3.6 feet of water is applied per year to irrigated fields, of which approximately 30% is recharged into the groundwater (Snyder et al., 1986). Assuming that 75% of the surface is irrigated along the 15 miles strip west of Davis, at 3.6 ft/yr on average, an estimated 6 gal/ft²-yr is recharged annually into the groundwater, representing nearly 10 times more water than is infiltration of rainfall. Since the water table along the 15 mile strip maintains a constant elevation over an annual cycle, then the total groundwater pumped along the cross-section would be the total irrigation recharge, or 6 gal/ft²-yr. This amount is ~0.2% of the total groundwater stored within the 1000 foot deep cross-section, suggesting that the complete turn-over cycle of the resource is ~500 years. Most groundwater production, though, occurs in the upper 500 feet, and the turn over rate is probably much faster, as indicated by the disturbed ^{18}O patterns in Fig. 4, where the gross effects of long-term pumping and irrigation water recharge is clearly evident. By far the recharging agricultural waters maintain most of the uniform water table levels on the west side of the Sacramento River over time, but cause progressive groundwater degradation, as exemplified by the non-linear secular increase in

average nitrate concentrations in the Davis municipal well waters, which have increased from <10 ppm in 1960 to 18 ppm today.

An additional source of recharge to the groundwater supply in the Davis area appears to be derived from the east. This source has an average $\delta^{18}\text{O}$ value around -7.0 and plots to the right of the meteoric water line on a δD - $\delta^{18}\text{O}$ plot. This water tends to have Cl and SO_4 levels that are approximately a factor of 5 higher than the pristine meteoric groundwaters. Most likely, given their evaporative stable isotope signatures, the -7.0 groundwater represents flood plain water that recharged in the overbank areas on the western side of the Sacramento River. Extensive evaporation may have elevated their Cl and SO_4 concentrations (Davisson and Criss, 1993). Additional ^{14}C dating of these waters is needed.

As mentioned above, a deep, low ^{18}O groundwater resides at depths between 700 to 1400' below the surface. One well operated by the City of Davis produces at this level, as do the domestic wells at the University of California, Davis. These groundwaters are Pleistocene in age and appear to form a wedge-shape mass that tapers to the west (Davisson and Criss, 1993). The water may originate from Sierran-type sources, particularly from high-elevation regions with depleted meteoric water, and the groundwater may reside in an intermediate-scale or regional-scale flow regime. On the other hand, it is reasonable to suggest that the groundwater originated under different climatic conditions during the Pleistocene, that imparted a more depleted stable isotope signature. Lower average temperatures, or alternatively a different origin of storm systems that caused more rainout of cloud masses than occurs today, could explain this difference.

Sacramento - Groundwaters under Sacramento have large oxygen isotope variations ($\sim 4.0\text{‰}$), as seen in a contour map of $\delta^{18}\text{O}$ values (Fig. 4). The variations closely correlate with the large cones of depression in the water table that occur to the north and south of the American River (see Fig. 3). This relation is shown on a graph of $\delta^{18}\text{O}$

values versus the static water levels in each well (Fig. 5). The general trend of the data indicate that the groundwater samples associated with shallower water tables are isotopically depleted. This low ^{18}O component clearly originates from the Sacramento and American Rivers, which both have $\delta^{18}\text{O}$ values of approximately -10.6 and modern ^{14}C abundances. In contrast, the deeper water tables associate with groundwater having a $\delta^{18}\text{O}$ value around -7.0. This higher ^{18}O groundwater has apparent ages between ~9000 and 16,000 years old and may represent slowly recharged meteoric or floodplain waters.

The four labeled points in Figure 5 indicate well identification numbers (top number) and calculated ^{14}C ages (bottom number). Note that the groundwaters with the lower $\delta^{18}\text{O}$ values have very young ages, consistent with a large River water component, while those with higher $\delta^{18}\text{O}$ values have much older apparent ages. Other waters are mixtures of these sources in varying proportions. Groundwater from well 41 is Pleistocene in age even though its total drill depth is less than 300 feet.

Figure 5. Water table level vs. $\delta^{18}\text{O}$ value of groundwater with well numbers (top) and ^{14}C ages (bottom) for four wells.

In addition, Figure 6 shows a relation between the minimum perforation depths versus the $\delta^{18}\text{O}$ value of the groundwater for these Sacramento wells. This plot also indicates that the deeper the intake level of the well, the higher the $\delta^{18}\text{O}$ value and older the apparent age of the groundwater. These relationships suggest that the pumping of groundwater north and south of the American River and the consequent lowering of the water table is drawing water from the Sacramento and American Rivers into the groundwater supply. Moreover, river water probably represents the majority of the modern groundwater recharge beneath Sacramento.

Figure 6. Minimum well perforation depth vs. $\delta^{18}\text{O}$ value of groundwater

The City of Sacramento also operates a groundwater pumping system known as the Ranney Collector, a mechanism whereby pumping on horizontal, perforated pipes 150 feet directly below the bed of the Sacramento River withdraws groundwater for domestic use. Stable isotope and ^{14}C analyses of this groundwater indicates that the water is 100% Sacramento River water (-10.5‰) with an abnormally high ^{14}C abundance of 111% modern, representative of thermonuclear bomb-pulse fallout from above-ground testing during the early 1960's. Modern Sacramento River water has a ^{14}C abundance of 104% of modern. Age estimates of the Ranney Collector water vary between 10 and 30 years old based on this ^{14}C signature. These results suggest that the vertical groundwater flow rates down to 150' below the Sacramento River are between 5 and 15 ft/yr. Similar vertical flow rates exist in the Davis aquifer (Davisson and Criss, 1993). It is interesting to note from

the stable isotope map that the total horizontal extent of Sacramento and American River migration south and north into the cones of groundwater depression is between 1 and 2 miles. Assuming steady groundwater pumping over the past 50 years, river water migrates horizontally 100 to 200 ft/yr. This suggests that the difference between the vertical transport rates beneath the Sacramento River and the horizontal transport rates adjacent to the river is 1-2 orders of magnitude. This result is consistent with laboratory measurements and field examples from pump tests on horizontally stratified material (Domenico and Schwartz, 1990).

Woodland - Municipal and agricultural wells within and peripheral to Woodland have extremely uniform $\delta^{18}\text{O}$ values of -5.1 to -5.4 . This uniform mass of groundwater is at least 35 mi² in geographic extent. The perforation depths of wells in Woodland are comparable to those in Davis, ranging from depths between 150-600 feet below the surface. The aquifer beneath Woodland is lithologically heterogeneous comprising clays to gravels. Nitrate levels in the groundwater range between ~5 and 35 ppm nitrate, and average about 20 ppm, suggesting anthropogenic contributions of nitrogen dissolved in the groundwater.

In general, groundwater and aquifer characteristics in the City of Woodland are very similar to those in the City of Davis, yet the stable isotope signature of the groundwater is strikingly different and far more uniform. The Woodland groundwaters all plot significantly to the right of the Meteoric Water Line on a δD - $\delta^{18}\text{O}$ plot, indicating an evaporated source. The higher $\delta^{18}\text{O}$ value for Woodland waters might originate in part from natural flood plain waters that preferentially recharged this area, but given the unusually high nitrate levels in some wells, a modern agricultural component probably also contributes to the groundwater mass. Given the mass balance arguments presented above on the relative proportions of annual groundwater recharge derived from agricultural water and rain water, a significant component of irrigation water would be expected in the shallow groundwater in Woodland. In addition, much of the modern recharge to the Woodland groundwater system may be through the subsurface discharge of Cache Creek.

Several ^{14}C analyses on the Woodland groundwater are in progress and will help differentiate young recharge from ancient recharge in the Woodland groundwater, and may also help explain the remarkable uniformity of the $\delta^{18}\text{O}$ values.

SUMMARY

Oxygen and hydrogen isotopes provide powerful natural tracers, intrinsic to the water molecule, to identify and delineate different masses of ground and surface waters. These data may also be used to quantify groundwater origins and subsequent histories, including subsurface movements, particularly when augmented by ^{14}C analyses. Moreover, deuterium and ^{18}O contents progressively and systematically increase when a body of water is subjected to evaporation, permitting meteoric sources to be distinguished from evaporated waters that form in floodplains or irrigated fields.

A regional isotopic investigation of groundwater in the southern Sacramento Valley began in the spring of 1993. On the west side of the Sacramento River, groundwater levels maintain a near natural hydrologic gradient that generally parallels the topography, even though hundreds of thousands of acre-feet of groundwater are pumped from this region every year. Analyses show that recharge of agricultural irrigation water affects over 100 square miles and that groundwater recycling is pervasive. For instance, groundwater 4 miles to the west, south and northwest of Davis is highly enriched in ^{18}O relative to pristine meteoric values. In contrast, an ~8 square mile zone to the east and northeast of Davis has groundwaters with near meteoric values. Comparison of ^{14}C analyses shows that the latter, near-meteoric groundwater has apparent ages ~4000 years, whereas the groundwater with the enriched $\delta^{18}\text{O}$ value has an apparent age of <500 years. This much younger age and enriched $\delta^{18}\text{O}$ signature indicate that recently recharged irrigation water is utilized from these zones. The enriched $\delta^{18}\text{O}$ values also correspond to an enriched nitrate concentration. The progressive groundwater degradation is mostly evident during the last

20 years as indicated by near-linear increases in nitrate levels within the City of Davis municipal wells.

Striking cones of depression beneath the City of Sacramento exceed depths greater than 100 feet below the surface and have developed on both sides of the American River. The stable isotope variations are dramatic and uniformly follow the water table levels. High ^{18}O groundwaters occur near the centers of the cones, and low ^{18}O groundwaters largely derived from the Sacramento and American Rivers occur near the edges of the cones where the water table levels are highest. These data clearly indicate that the municipal pumping causes surface water from the rivers to be the dominant recharge component to the groundwater system. In addition, the ^{14}C apparent ages of the groundwater indicate that the high $\delta^{18}\text{O}$ groundwater is ancient, ranging from 9000 to 16,000 years old, whereas the low $\delta^{18}\text{O}$ groundwater is essentially modern.

Our data quantify that the ancient groundwater is effectively being "mined" on the eastern side of the Sacramento Valley, manifested by the large cones of depression. The ancient groundwater is also being "mined" on the west side of the Sacramento River, but is indicated by decreasing groundwater quality from recharging agricultural waters and not by declining water tables. In both cases, many of the changes in the groundwater character due to production are not reversible, and therefore, the term "safe yield" is not applicable.

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TABLE 1: Meteoric Waters

DATE	$\delta^{18}\text{O}$	δD	REMARKS
9/28/89	-8.0	-	Davis
10/23/89	-4.5	-32	Davis
11/25/89	-4.6	-32	Davis
1/12/90	-8.6	-59	Davis
1/13/90	-4.8	-33	Davis
1/14/90	-11.3	-73	Davis
2/3/90	-9.3	-	Davis
2/16/90	-6.2	-	Davis
2/17/90	-5.5	-	Davis
3/4/90	-6.8	-	Davis
4/22/90	-6.4	-	Davis
5/27/90	-11.4	-	Davis
9/22/90	-2.6	-	Apple Ln., Davis
10/18/90	-4.3	-	UC Davis/Phys. Geol. Bldg.
11/25/90	-6.3	-	Apple Ln., Davis
12/10/90	-2.3	-	Morning, Apple Ln., Davis
12/10/90	-3.9	-	1:15pm, Apple Ln., Davis
12/10/90	-6.7	-	2:15pm, Apple Ln., Davis
4/23/93	-3.1	-	UC Davis-Freeborn Hall
11/6/90	-5.0	-	*Rain Gauge-Rumsey Hills
11/27/90	-8.0	-	*Rain Gauge-Rumsey Hills
12/27/90	-13.5	-98	*Rain Gauge-Rumsey Hills
1/20/91	-10.3	-69	*Rain Gauge-Rumsey Hills
2/16/91	-7.9	-53	*Rain Gauge-Rumsey Hills
3/3/91	-9.5	-60	*Rain Gauge-Rumsey Hills
12/14/90	-12.9	-101	*Rain Gauge-east of Berryessa
1/17/91	-11.3	-79	*Rain Gauge-east of Berryessa
2/16/91	-7.0	-46	*Rain Gauge-east of Berryessa
3/3/91	-8.3	-54	*Rain Gauge-east of Berryessa
11/19/90	-6.6	-	*Rain Gauge-Davis (?ml)
1/19/91	-9.8	-	*Rain Gauge-Davis (70ml)
2/10/91	-7.5	-50	*Rain Gauge-Davis (420ml)
3/3/91	-8.2	-	*Rain Gauge-Davis (450ml)
3/12/91	-4.8	-24	*Rain Gauge-Davis (425ml)
3/24/91	-10.0	-	*Rain Gauge-Davis (550ml)
3/29/91	-11.8	-80.5	*Rain Gauge-Davis (325ml)

*Indicates samples are combined storm events.

TABLE 2: Surface Waters

DATE	$\delta^{18}\text{O}$	δD	REMARKS
9/22/89	-1.0	-24	Clear Lake @ beach
10/13/90	-3.0	-	Putah Creek-Rd 95A
10/13/90	-3.4	-27	Putah Creek-below Dam
8/6/91	-3.1	-28	Putah Creek (D&C, 93)
3/8/91	-5.7	-40	Putah Creek (D&C, 93)
7/9/93	-4.4	-	Putah Creek @ Davis
8/10/93	-4.7	-	Putah Creek-below dam
8/15/93	-4.0	-	Putah Creek @ Davis
5/2/90	-5.3	-52	Cache Creek @ Rumsey
5/2/90	-4.9	-46	Cache Creek @ Guinda
5/29/90	-6.9	-56	Cache Creek @ Guinda
11/6/90	-4.9	-42	Cache Creek @ Guinda
11/6/90	-4.7	-	Cache Creek @ Capay Dam
2/16/91	-5.0	-	Cache Creek @ Guinda
3/3/91	-6.3	-40	Cache Creek @ Guinda
8/6/91	-0.5	-16	Cache Creek @ Guinda
9/26/91	0.0	-	Cache Creek @ canyon
7/17/93	-2.4	-	Cache Creek @ Guinda
8/15/93	0.6	-	Cache Creek @ Rd 102
4/26/93	-11.0	-	American River-Howe Ave.
6/5/92	-10.8	-77	Sacramento R: I-5 bridge near airport
1/5/91	-11.0	-83	Sacramento R-Tower Bridge (D&C, 93)
8/13/91	-10.8	-	Sacramento R-Tower Bridge
3/16/93	-10.6	-	Sacramento R-Miller Park
2/15/91	-11.7	-	Sacramento R-Red Bluff
6/16/91	-11.5	-	Sacramento R-Red Bluff Lake
7/31/91	-11.8	-	Sacramento R-Red Bluff
2/15/91	-11.4	-	Lake Shasta(McCloud R arm)
8/15/91	-4.8	-	Willow Slough-Yolo Co. Landfill
4/29/93	-3.2	-	Yolo Co. irr.canal (CS-18)
4/25/93	-3.7	-	Solano Co irr canal (Curry Rd.)
7/10/93	-2.4	-	Canal Water
9/22/89	0.2	-	Grizzley Spring
9/22/89	5.8	-	Wilbur Springs
5/8/90	-7.6	-53	Spr., Meyer's Flat-Capay Valley
1/91	-7.9	-	Spr., Meyer's Flat-Capay Valley
2/21/91	-7.6	-51	Bird Spr. Dunnigan Hills
2/21/91	-7.8	-	Willow Spr. Dunnigan Hills
2/21/91	-7.6	-51	Spr., Oat Valley-Dunnigan Hills

DATE

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