ELSEVIER

Journal of Hydrology 178 (1996) 205–222

Journal of Hydrology

Isotopic imaging of surface water/groundwater interactions, Sacramento Valley, California

R.E. Criss[a,*], M.L. Davisson[b]

[a]*Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, USA*
[b]*Isotope Sciences Division L-231, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550, USA*

Received 16 August 1994; revision accepted 18 May 1995

Abstract

Groundwater isotope data across the Sacramento Valley, California establish two types of groundwater mining: (1) overdraft of ancient groundwater with limited recharge by surface waters, producing cones of depression; (2) ancient groundwater withdrawal followed by rapid recharge of irrigation water, reducing groundwater quality. The first type occurs in the Sacramento metropolitan area, where meteoric runoff is unnaturally high and 40 years of pumping have depressed water levels to 25 m below sea-level, inducing recharge from losing reaches of the Sacramento and American rivers. Lateral migration rates are quantified by the binary mixing between river water ($\delta^{18}O = -10.8$) and natural groundwater ($\delta^{18}O = -7.0$). The second type of mining occurs in agricultural regions to the west, where ^{14}C ages indicate that irrigation waters constitute more than 80% of modern recharge. This recharge has several characteristics of evaporated irrigation water, including: (1) high $\delta^{18}O$ values (to > -6.0) that define closed contour patterns; (2) elevated NO_3 concentrations (to 100 ppm); (3) low ^{14}C ages of less than 500 years.

Stable isotope contours, augmented by ^{14}C data, provide dynamic recharge patterns in this profoundly disturbed, giant alluvial aquifer. On a large scale (> 100 km^2), the lateral permeabilities of alluvial aquifers are essentially isotropic, whereas on a smaller scale (< 25 km^2), anisotropy is evident and isotope values can be geographically complex and seasonally transient. Groundwater flow patterns implied by the isotope data can differ substantially from steady-state models based on head measurements.

---

[*] Corresponding author.

1. Introduction

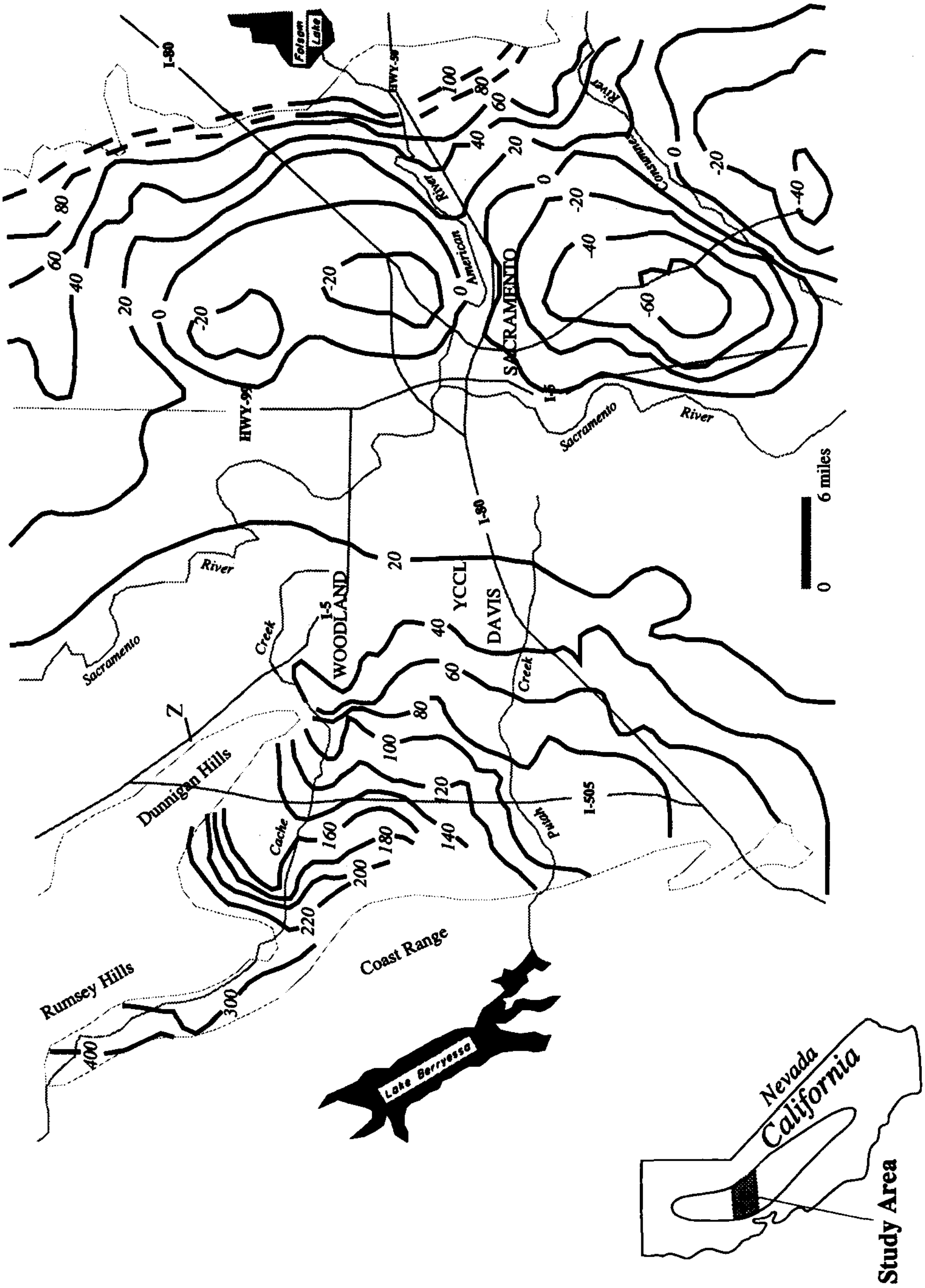
Groundwater provides one-half of the drinking water needs in the United States. In California alone, more than 15 million acre-feet of groundwater is pumped per year, an amount that supplies 46% of domestic water consumption and 39% of agricultural irrigation in the state (Spieker, 1984). Associated with extensive groundwater use are several deleterious consequences whose severity increases over time, including depression 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 for resource evaluation. To characterize and quantify regional transient effects in groundwater successfully using only hydrogeologic methods requires careful definition of aquifers and their permeabilities, multiple wells completed at various depths, time-series analysis of piezometric surfaces, and discharge monitoring. In most cases these data are difficult and expensive to obtain. Furthermore, the semiconfining, discontinuous fluvial sediments of the type discussed in this report do not lend themselves to simple lateral correlation in available well logs, and are generally not amenable to aquifer separation. This character limits the utility of water level measurements in monitoring and discerning the effects of groundwater recharge, discharge, and degradation.

Isotopic methods provide a well-tested but curiously under-utilized means for practical water management. Isotopic studies are based on a completely independent set of assumptions than those used in traditional hydrogeologic assessments, and provide a unique record of groundwater processes that commonly yields superior insight. Specifically, our isotopic data provide a dynamic visualization of the sources, migration and recharge processes of Sacramento Valley groundwaters that is much more complex than that which can be inferred from a map of hydrologic head.

This paper provides a new $^{18}O/^{16}O$, D/H, and ^{14}C characterization of meteoric, surface, and groundwater resources of the southern Sacramento Valley (Fig. 1), together with a detailed map and interpretation of the ^{18}O variations. This effort is facilitated by the large variations in the $^{18}O/^{16}O$ and D/H ratios that occur in the waters of the region. These variations provide the basis for a new classification of major groundwater bodies, allow for the determination of the sources and rates of groundwater recharge, provide a new and independent means to calculate rates of

Fig. 1. Contour map of groundwater levels (in feet above or below sea-level) across the southern Sacramento Valley. Light dotted line (approximately 350–400 ft) approximates the base of the topographic escarpment of the Coast Ranges and Dunnigan Hills on the west and the Sierran foothills on the east. The western valley is dominated by a regular, west to east gradient in hydrostatic head, whereas two prominent cones of depression have formed beneath the Sacramento metropolitan area. YCCL is the Yolo County Central Landfill, Z is Zamora. Data from the Department of Water Resources (1986).


Folsom Lake
I-80
HWY-99
100
80
60
40
20
0
-20
-40
-60
American River
Cosumnes River
SACRAMENTO
I-5
Sacramento River
6 miles
0
Sacramento River
Creek
I-5
WOODLAND
YCCL
DAVIS
Creek
I-80
N
Dunnigan Hills
Cache
Putah
I-505
100
120
140
160
180
200
220
300
400
Coast Range
Rumsey Hills
Lake Berryessa
Nevada
California
Study Area

groundwater migration, and permit the sources of drinking water in the municipalities of Sacramento, Woodland, and Davis to be accurately defined. 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 ages which show that the pristine component is thousands of years old. These isotopic insights have far-reaching consequences for attaining 'sustainable' use of groundwater, and elucidate processes that probably occur in large alluvial aquifers throughout the world.

2. Data and analytical methods

Groundwater samples were collected from actively pumped wells used for domestic, municipal, and agricultural purposes, and mostly represent large capacity irrigation wells that have average depths of approximately 100 m below the surface. The geology and hydrostratigraphy of the aquifers are discussed in detail by Thomasson et al. (1960), Olmsted and Davis (1961), Page (1986), and Davisson and Criss (1993). In general, the fluvial deposits are Pliocene to Recent in age, unconsolidated to weakly consolidated, and range from the surface to depths of 300–1000 m. The deposits have been separated into the underlying Plio-Pleistocene Tehama Formation and the overlying Pleistocene to Recent alluvium (Olmsted and Davis, 1961). Hydrostratigraphic units are poorly defined and groundwater yields can vary between less than 2 and 10 $m^3\ min^{-1}$.

Hydrogen and oxygen isotope analyses were made by, respectively, employing the standard CO_2 equilibration (Epstein and Mayeda, 1953) or the zinc-reduction techniques (Coleman et al., 1982), followed by analysis on an isotope ratio mass spectrometer. 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 $^{18}O/^{16}O$ or the D/H ratio of the sample, and R_{SMOW} is either the $^{18}O/^{16}O$ or the D/H ratio of Standard Mean Ocean Water (SMOW) (Craig, 1961a).

Samples for ^{14}C were collected in air-tight glass bottles that were flushed, filled, and then sterilized with approximately four drops of concentrated $HgCl_2$. The dissolved inorganic carbon (DIC) was acid stripped on a vacuum line (Davisson and Velsko, 1994; Rao and Killey, 1994; McNichol et al., 1994). The ^{14}C concentrations were determined by accelerator mass spectrometry at Lawrence Livermore National Laboratory, and are reported as percentages of modern ^{14}C (p.m.c.) relative to the NBS OX-1 (Stuiver and Polach, 1977). Apparent ages are calculated using a half-life of 5730 years (Walker et al., 1989). Subsequent corrections are applied to the ^{14}C apparent ages to account for incorporation of 'dead' carbon sources and generally follow the recommendations of Vogel (1967); the method is outlined in Davisson and Criss (1995).

Isotopic data for more than 500 samples used for this study are tabulated in companion reports by Davisson and Criss (1993) and Davisson et al. (1993, 1995). A summary of groundwater geochemical data can be found in Evenson (1985).

Table 1
Average characteristics of surface and ground water types in the southern Sacramento Valley

Type	$\delta^{18}O \pm SD$	Age	NO_3 (p.p.m.)	Slope[a]	TDS (p.p.m.)	Chemistry
Meteoric water	−7.5 ± 3.0	Modern	0	8.0	< 10	Fresh
Putah Creek	−4.0 ± 1.0	Modern	⩽ 5	5.0	250	Mg HCO_3
Cache Creek	~ −5.0 ± 3.0	Modern	< 1	5.0	450	Mg Ca HCO_3
Sacramento R.	−10.8 ± 0.2	Modern	< 1	8.0	200	Na Ca HCO_3
Ag Recharge	−6.0 ± 1.0	< 0.5 kyears	~ 50	2.5	1000	Mg HCO_3
Holocene GW	−7.5 ± 0.5	2.7–4 kyears	< 10	8.0	750	Mg HCO_3
Flood Plain GW	−5.0 ± 0.5	4–8 kyears	< 1	5.0	250	Mg Na HCO_3
Pleistocene GW	−8.7 ± 0.5	8–16 kyears	< 1	8.0	500	Na HCO_3
Formation water	+3.3 ± 1.5	Cretaceous	ND	3.5	23 000	Na Cl

[a] Slope refers to the trend on a graph of δD vs. $\delta^{18}O$.

3. Isotopic characterization of waters

3.1. Meteoric and surface waters

3.1.1. Rain waters

The characterization of local meteoric and surface waters is essential to the deduction of the source and character of shallow groundwater. This effort is facilitated by the large isotopic variations in waters of the southern Sacramento

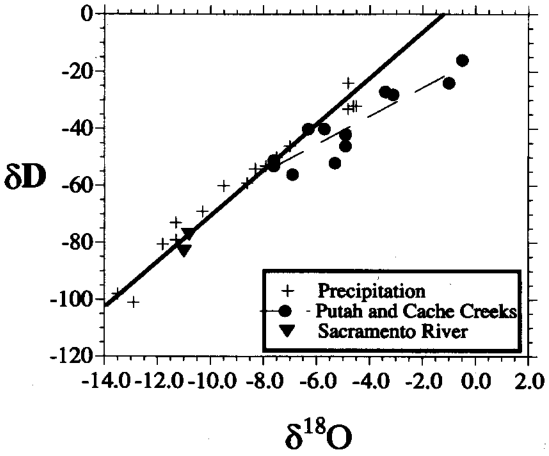


Fig. 2. Graph of δD vs. $\delta^{18}O$ values for rain and surface waters collected in the southwestern Sacramento Valley, 1989–1993. Rain samples lie along the global meteoric water line (heavy line) with a slope of 8.0. The $\delta^{18}O$ values of the Sacramento River (approximately −10.8) are lower than that of average local precipitation (approximately −7.5), owing to the river's alpine sources. Surface waters from Cache and Putah creeks have higher $\delta^{18}O$ values (to approximately 0) and lie along an evaporation trend (dashed line) with a slope of approximately 5.0. Data from Davisson et al. (1993).

Valley, that permit the definition of several distinct mixing end-members (Table 1). Local meteoric waters have variable $\delta^{18}O$ values but conform well with the Global Meteoric Water Line (MWL; Fig. 2) of Craig (1961b). The volumetric average of this local precipitation ($\delta^{18}O = -7.5$‰; Davisson et al., 1993) is similar to values that occur throughout the Coast Range province (e.g. White et al., 1973; Gunderson, 1989; 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 much lower average $\delta^{18}O$ values (to less than −14.0‰) for precipitation in the upper elevations of the Sierra Nevada and the southern Cascades (Ingraham and Taylor, 1991; Rose et al., 1996).

3.1.2. Coast Range surface waters

The $\delta^{18}O$ values of Putah Creek (−5.7 to −3.0) and Cache Creek (−6.9 to +0.6) vary widely depending on the place and time of collection. The data indicate that substantial evaporative enrichment of the heavy isotope concentrations has occurred, which produces the distinctive kinetic slope of $\approx 5.0 \pm 0.5$ on Fig. 2. Part of this variation is due to the dual source of Cache Creek from Clear Lake, a large, shallow natural lake, and Indian Valley Reservoir.

3.1.3. Alpine runoff

Owing to their high-elevation sources in the Sierras and southern Cascades, the $\delta^{18}O$ values of the major rivers are highly depleted and distinctive from other water types in the southern Sacramento Valley. Thus the $\delta^{18}O$ values of several samples of the Sacramento River and one sample from the American River are low and uniform (−10.6 to −11.0), and plot close to the MWL. Unpublished data of the US Geological Survey (W. Swain, private communication, 1992) indicate comparable values for the Sacramento River near Freeport ($-10.5 > \delta^{18}O > -11.2$; $-76 > \delta D > -82$) and for the San Joaquin River south of Stockton ($-9.7 > \delta^{18}O > -11.3$; $-74 > \delta D > -84$; omitting one sample).

3.2. Shallow groundwaters

3.2.1. Pristine Holocene groundwaters

A very important resource of 'pristine groundwaters' occurs at generally shallow depths (mostly 60–200 m) below the southern Sacramento Valley (see Davisson and Criss, 1993). These waters lie on or near the MWL at $\delta^{18}O$ values of about −7.5, and therefore are very similar to average meteoric precipitation in this region. The total dissolved solids (TDS) of these magnesium bicarbonate waters are moderate, generally ranging from 500 to 1000 ppm. Nitrate contents are generally below 5 ppm. The ^{14}C ages of DIC in several samples range from 2.7 to 4 kyears.

3.2.2. Agricultural waters

Agricultural irrigation in the southern Sacramento Valley is derived either from diverted surface water or from pumped groundwater, and is applied to fields where it undergoes evaporation on the surface and in the vadose zone. We infer that significant groundwater volumes are primarily recharged by this source based on the following characteristics: (1) enriched $\delta^{18}O$ values of $-6.0 \pm 1‰$; (2) slopes of approximately 3 on a graph of δD vs. $\delta^{18}O$, representative of evaporation and mixing trends produced in the vadose zone (Barnes and Allison, 1983; Davisson and Criss, 1993); (3) unnaturally high levels of nitrate that generally range from 10 to 100 ppm; (4) young ^{14}C apparent ages of less than 500 years. These characteristics arise because evapotranspiration and evaporation processes reduce the volume while enriching both the ^{18}O and D contents. Moreover, cultivation and especially fertilizer application, including the direct addition of anhydrous ammonia to the water ('fertigation'), all increase the nitrate content of the water and correlate with the isotopic enrichment (Davisson and Criss, 1993). The young apparent ^{14}C ages are expected for waters that have recently communicated with surficial environments.

3.2.3. Holocene evaporated waters

In addition to the above, we have identified a type of evaporated, high ^{18}O groundwater that originated under natural conditions in the floodplains west of the Sacramento River. These waters have also undergone substantial isotopic enrichment, but in this case along the slope of approximately 5 that is expected for surface evaporation. Nitrate levels are near zero, and the ^{14}C ages are 4–8 kyears. Groundwater pockets of this type have been identified near Zamora and east of Davis.

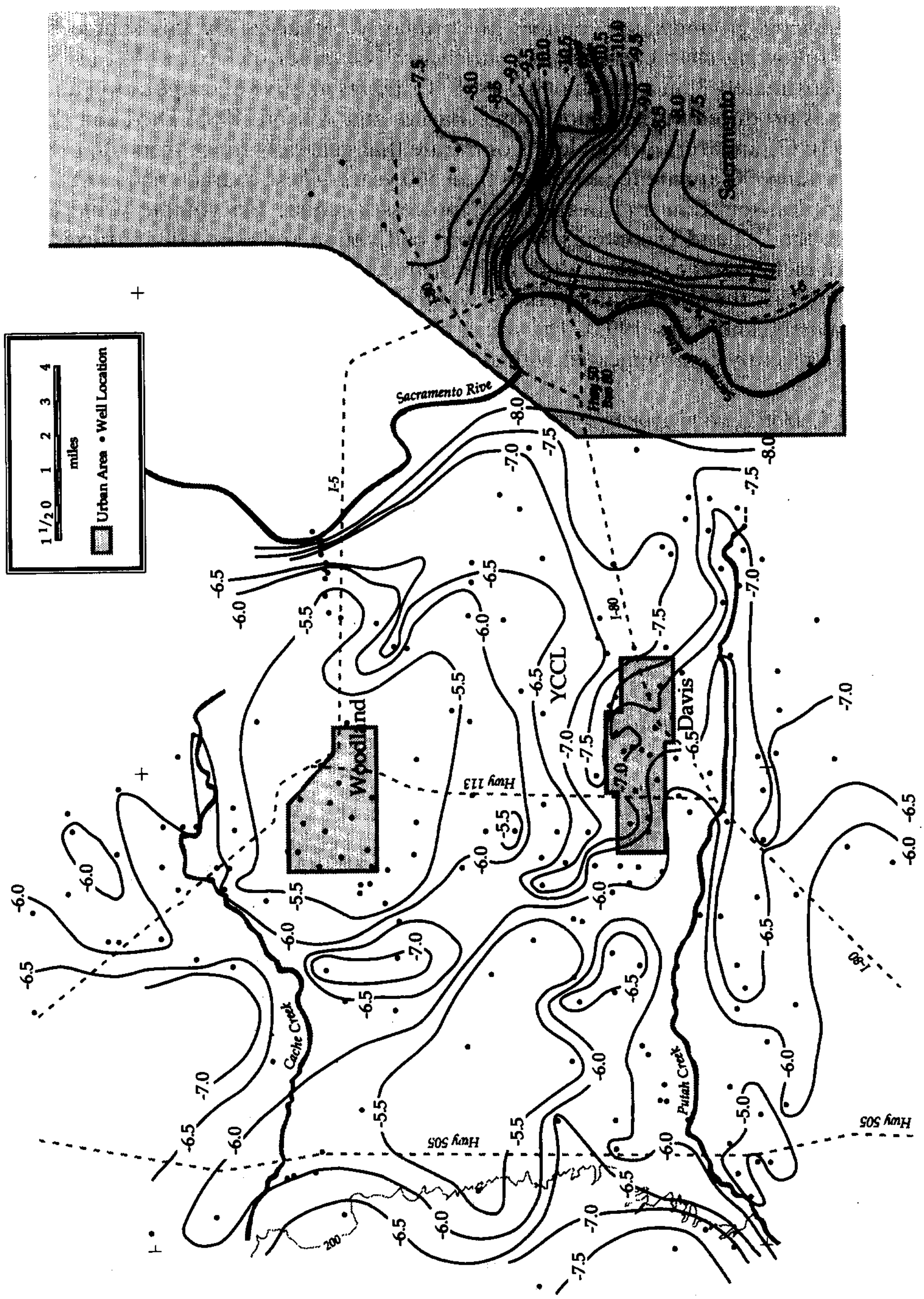
3.3. Deeper groundwaters

3.3.1. Pristine Pleistocene groundwaters

Ancient 'pristine' groundwaters also occur in the southern Sacramento Valley, but are not included on the $\delta^{18}O$ map (Fig. 3, below) because these groundwaters occur as isolated pockets ranging in depth from 115 to more than 300 m below the surface (Davisson and Criss, 1993). These low-salinity (< 500 ppm), low nitrate (< 1 ppm), sodium bicarbonate waters lie on or near the MWL at $\delta^{18}O$ values of about -7.8 to -9.4, and may represent local precipitation that occurred under different climatic conditions than exist today. The ^{14}C ages of bicarbonate in several samples range from 8 to 16 kyears, suggesting recharge during Pleistocene time.

3.3.2. Formation waters

Saline, geopressured formation waters underlie the potable groundwaters of the southern Sacramento Valley, and occur within Great Valley sequence marine rocks, generally at depths of more than 1 km (Lico and Kharaka, 1983). These waters also emerge as perennial springs along the western margin of the Sacramento Valley (Davisson et al., 1994). These saline (15 000–28 000 ppm TDS), boron rich (to 215 ppm) formation waters have high $\delta^{18}O$ values of $+0.6$ to $+5.3$ that lie well to the right of the MWL, and represent modified, Cretaceous to Tertiary-aged seawater (Davisson et al., 1994).


1 1/2 0 1 2 3 4
miles
Urban Area • Well Location
Sacramento
Sacramento River
I-5
I-80
Hwy 113
Hwy 505
Woodland
YCCL
Davis
Cache Creek
Putah Creek
200
-5.0
-5.5
-6.0
-6.5
-7.0
-7.5
-8.0
-8.5
-9.0
-9.5
-10.0
-10.5

4. Regional variations and mining of groundwaters

4.1. Water table map

A map of water table levels (Department of Water Resources, 1986; Fig. 1) exhibits a regular, east-sloping gradient on the west side of the Sacramento Valley. This overall pattern is clearly related to the east-sloping topographic gradient in this area, and is generally consistent with the expected eastward flow before human development of the resource. Starting in the early 1900s, groundwater pumping created local areas of groundwater overdraft. For example, an approximately 100 km^2 cone of depression (not shown) developed in the agricultural region just south of the Davis area. In the late 1950s, delivery of Putah Creek water from Lake Berryessa to this groundwater depression for agricultural use nearly restored the eastward-sloping water table gradient (Department of Water Resources, 1978). Similarly, Cache Creek water has been diverted for nearly 100 years to the western part of the study area. Also prominent are two pumping-induced cones of depression that extend well below sea-level in the Sacramento metropolitan area east of the Sacramento River (Fig. 1).

The water table measurements are a composite of various well completion depths and do not follow any hydrostratigraphic layering. At the scale of Fig. 1, the geographic extent of individual aquifers are expected to be small. In general, groundwater aquifers are semiconfined in this region (Thomasson et al., 1960; Olmsted and Davis, 1961), comprising deposits of low to moderate energy streams such as Putah and Cache Creeks. Grain size can vary from clay to gravel over distances shorter than typical well spacing, and hence, aquifer definition is limited (e.g. Mohr et al., 1992).

A standard interpretation of Fig. 1 would predict groundwater flow in the down-gradient direction, i.e. perpendicular to the contours, provided of course that the permeability is approximately isotropic, which is realistic for this clastic deposit at this scale (see below). Thus, in the western and central parts of Fig. 1, the inferred pattern of subsurface flow would be historically dominated by west to east transport of −7.5‰ meteoric recharge, derived from as far as the eastern edge of the Coast Ranges. Farther north and northeast, along Cache Creek, surface water recharge is likely in losing reaches of the stream. To the south, the influence of Putah Creek would be expected to be comparatively small, owing to its natural lower flow rates and ephemeral nature. Further east, the Sacramento River might be expected to have a very substantial influence near its western bank, although the small gradients west of the river prevent a precise interpretation. Cones of depression at different scales

Fig. 3. Map of $\delta^{18}O$ isopleths of groundwaters across the southern Sacramento Valley. Prominent features from west to east include: (1) low $\delta^{18}O$ values (−7.0 to −7.7) indicating meteoric recharge in the Dunnigan Hills and the Coast Range foothills (cf. 200′ topographic contour, dotted line); (2) closed, high ^{18}O contours (−5.5) encompassing two large areas around and southwest of Woodland, indicating Cache Creek recharge; (3) a prominent high ^{18}O tongue associated with Putah Creek; (4) a complex zone of mixing near Davis; (5) steep $\delta^{18}O$ gradients beneath the Sacramento metropolitan area that coincide with the prominent cones of depression in Fig. 1. Data from Davisson and Criss (1993) and Davisson et al. (1995).

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. Overall, a regional pattern dominated by west to east flow of −7.5‰ meteoric waters would be expected in much of this area. East of the river, radial inflow into the two large cones of depression beneath the Sacramento urban area would be expected, subsequent of course to the origination of the depressions.

4.2. Regional map of $\delta^{18}O$ values of groundwater

A contour map of $\delta^{18}O$ values of shallow groundwater delineates the sources and recharge characteristics of the alluvial aquifer in the Sacramento Valley (Fig. 3). The $\delta^{18}O$ contours are strikingly regular and tend to form closed patterns that significantly contrast, in most areas, with the regular, east-sloping gradient exhibited by the water table map (Fig. 1).

The intricate isotopic patterns of Fig. 3 demonstrate that fluid sources and migration pathways are complex, and even more importantly, that the human disturbance of the groundwater in many areas is profound. Groundwater derived from −7.5‰ meteoric recharge, which would under natural conditions be expected to dominate most of the region, is mostly restricted to the foothills of the Coast Range and the Dunnigan Hills which are not intensely irrigated. Another belt of remnant, −7.5‰ groundwater occurs in the flat agricultural area northeast of Davis, sandwiched between higher ^{18}O waters (Fig. 3). Small-scale isotopic gradients in this latter area may be related to anisotropic permeabilities, related to interfingering fluvial and fine-grained flood plain deposits in the shallow subsurface (Helley, 1979; Davisson and Criss, 1993).

The dominant features of the western part of Fig. 3 are the large, 50–100 km^2 zones of high $\delta^{18}O$ (> -5.5) groundwaters. The closed $\delta^{18}O$ contours delineating these zones mostly outline areas where intense water mining has induced the recharge of high-^{18}O agricultural waters. For example, for nearly 100 years, most of these areas have utilized surface water derived from Cache Creek through a network of diversion canals for flood irrigation. Samples of these canal waters have highly enriched $\delta^{18}O$ values (to −2.4; Davisson et al., 1993), and additional evaporative enrichment will occur after field application.

Simple mixing calculations indicate that nearly half of the groundwater now pumped from these closed, high-^{18}O zones is derived from recycled irrigation water. The uniform $\delta^{18}O$ value of −5.5 for the groundwater in the two largest zones results because Cache Creek provided most of the recharge in both ancient and modern times. This is further clarified by the identification of an ancient source of evaporated, high-^{18}O groundwater in the floodplain regions adjacent to the Sacramento River, for example, near Zamora. This complexity requires that additional data are used to make definitive mixing calculations. Both the ^{14}C data and the NO_3 concentrations (Table 1) support our conclusion that agricultural recharge now dominates groundwater recharge in the western half of Fig. 3. In general, the uniform distribution of −5.5 groundwater is related to recharge by stand-

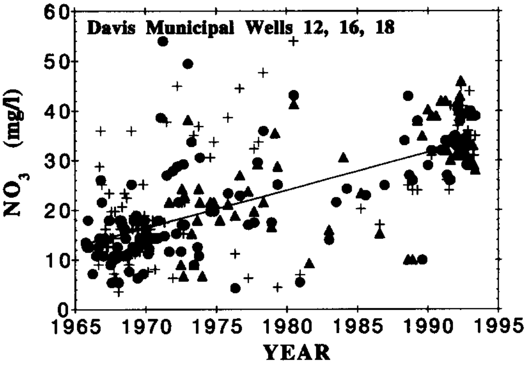


Fig. 4. Secular increase of nitrate concentrations in municipal wells 12 (solid dots), 16 (+s) and 18 (solid triangles) of the City of Davis. The nitrate levels in these wells are increasing at an average of 0.75 ppm per year, and are approaching the maximum concentration level of 45 ppm for drinking water. Data provided by the Davis Public Works Department.

ing water subjected to surface evaporation, which occurs at large geographic scales in natural flood plains as well as in flood irrigated areas where surface water is applied.

For small cities such as Davis and Woodland that are surrounded by intensively irrigated agricultural land, the replacement of pumped pristine groundwaters by recharging agricultural waters generally maintains annual water levels but results in a progressive deterioration in quality. Fig. 4 establishes the progressive nitrate contamination that accompanies this recharge process, and now impacts numerous municipalities in the Central Valley (e.g. Davisson and Criss, 1995). Fig. 5 establishes the modern age of this high nitrate component in the city wells of Davis and Woodland. As much as 50% of the water currently discharged by some municipal wells represents recharged irrigation water.

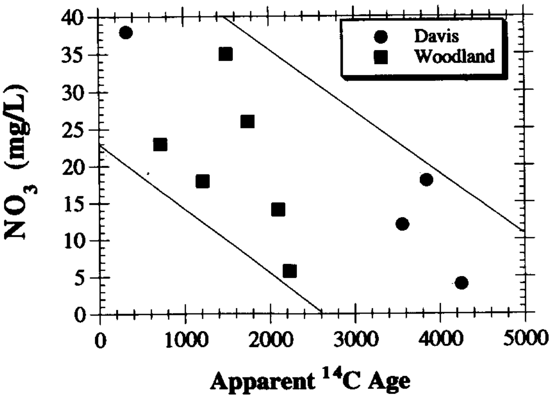


Fig. 5. Graph of NO_3 concentrations vs. apparent ^{14}C ages of Woodland and Davis municipal groundwater. The young, high NO_3 component represents irrigation water that mixes with ancient (> 3 kyears), low NO_3 groundwater. Data from Davisson et al. (1995).

A different consequence of groundwater mining occurs in the Sacramento metropolitan area. Flood irrigation in the surrounding region is scarce, and meteoric runoff is high owing to urbanization, making surface recharge in developed areas negligible. Consequently, in response to municipal pumping, two 30 m deep, 8–16 km wide cones of depression have developed north and south of the American River (Fig. 1). These depressions have induced the lateral recharge of modern, low-^{18}O waters from the Sacramento and American rivers, producing the striking contour pattern on Fig. 3. In this clearcut case, the maps of water tables and $\delta^{18}O$ values provide congruent information.

4.3. Permeability characteristics

Isotopic maps provide a new and independent means to quantify the permeability characteristics of groundwater basins. In several areas we have been able to use isotopic patterns to determine lateral rates of groundwater flow in the Sacramento Valley. That is, the average linear velocity may be simply estimated from the length scale of an isotopic anomaly provided that the time required for its development is known. A lateral hydraulic conductivity K may then be readily determined from Darcy's equation, rewritten as follows

$$K = (L/T)\phi/\nabla h$$

where L and T are the length and time-scales of the isotopic anomaly, ϕ is the porosity, and ∇h is the hydraulic gradient. An excellent example is provided by the City of Sacramento, where 40 years of urban pumping adjacent to the Sacramento and American rivers has induced flow over a lateral distance of 3–5 km (Fig. 3). The average linear velocity is evidently close to 100 m year^{-1}, equivalent to a darcy velocity of about 30 m year^{-1} at 30% porosity, over an area of approximately 300 km^2. Given the hydraulic gradient of approximately 0.003 m m^{-1} (Fig. 1), Darcy's law may be used to readily calculate a hydraulic conductivity of 0.03 cm s^{-1}, roughly equivalent to a permeability of 30 darcys. This is a very plausible value for this sand to gravel aquifer, and in general this permeability is uniformly distributed at this scale, given the regularity of the $\delta^{18}O$ contours adjacent to the rivers.

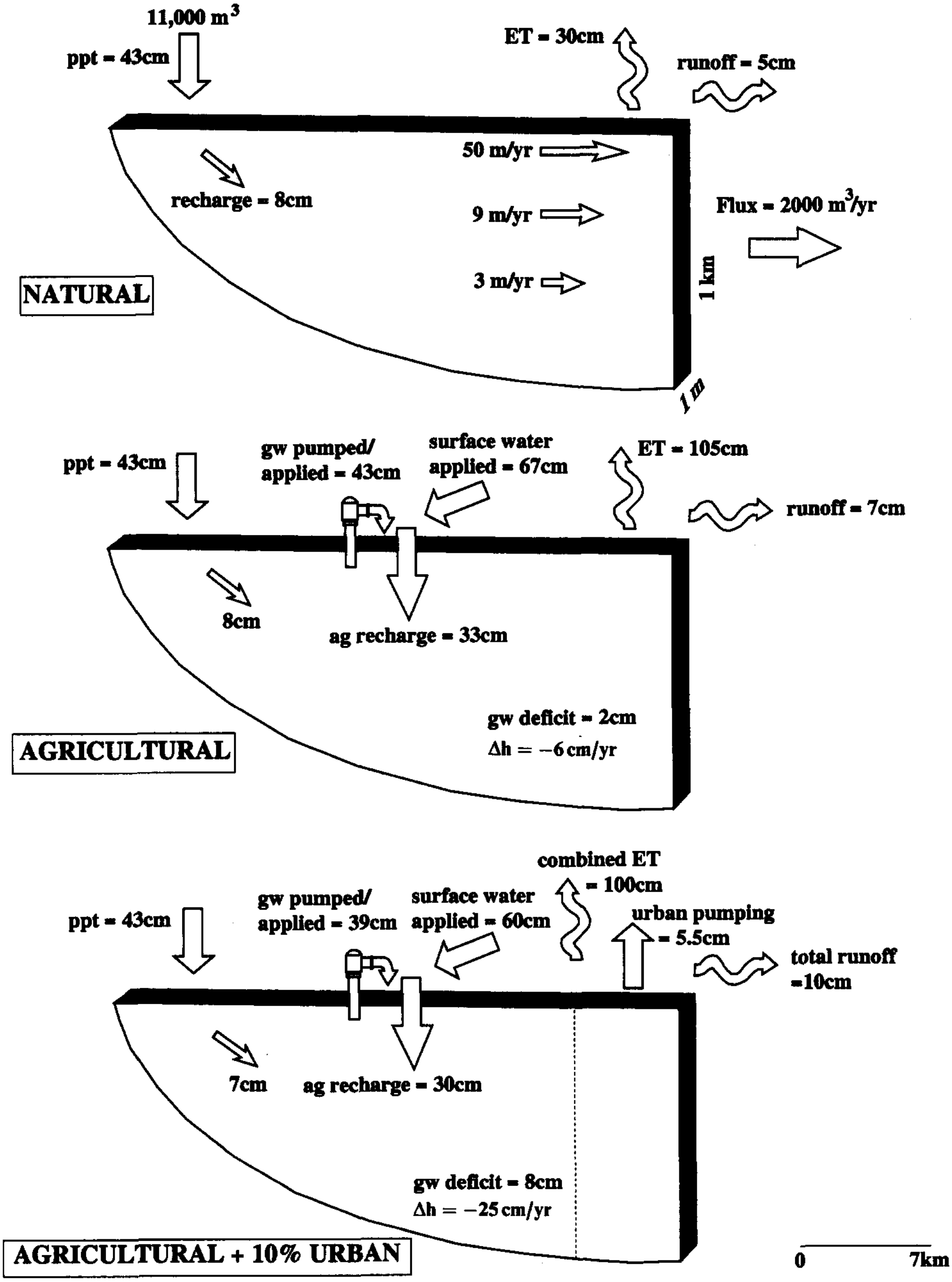
An example on a somewhat smaller scale is provided by the zone adjacent to Putah Creek. Following the 1957 construction of Monticello Dam, Putah Creek flow has changed from high intermittent discharge of winter precipitation to rather steady discharge of evaporated water that has been impounded in Lake Berryessa. Over this intervening approximately 35 year interval, this high ^{18}O water has migrated approximately 2 km perpendicular to the creek, representing an average linear groundwater flow rate of about 60 m year^{-1}. Although water table levels in this area vary seasonally (Davisson and Criss, 1993), available information indicates an average hydraulic gradient comparable with that in the Sacramento area, so computed permeabilities would be similar. However, on this approximately 50 km^2 scale, some channelization of flow is evident in the isotopic contours (Fig. 3), and 30% variations in flow rates and computed permeabilities are realized.

Last, beneath the approximately 5 km^2 Yolo County Central Landfill (Fig. 3), intense pumping has become necessary to maintain adequate separation of refuse from the water table. This pumping has reversed the original gradient and induced the infiltration of several distinctive water types, which in channelized zones migrated over distances as great as 2 km in a 20 year period (see Mohr et al., 1992). The observed migration rate in these broad channels is therefore approximately 100 m $year^{-1}$. Given the measured hydrologic gradient of approximately 0.002 m m^{-1}, a hydraulic conductivity of 0.05 cm s^{-1} or a permeability of 50 darcys is calculated. This is a plausible value for a stream channel.

The above data provide unique insight about the scale dependence of permeability and of permeability anisotropy. On the regional scale (> 100 km^2), the regularity of the $\delta^{18}O$ contours suggests that the horizontal permeability is indeed approximately isotropic in this alluvial basin. On an intermediate scale ($\approx$ 25 km^2), as within the City of Davis, preferred channelways of flow were identified by Davisson and Criss (1993). On the smaller, approximately 5 km^2 scale of the Yolo County Central Landfill, the isotopic patterns are quite irregular, channels with higher permeabilities than the regional average are present, and effects of anisotropy are consequently important. This results because the scale of these stream channels and other irregularities is much smaller than the scale of this giant alluvial basin.

4.4. Conceptual model of transient flow

The isotopic data may be combined with annual rates of rainfall, evaporation, irrigation and pumping, and urban pumping in order to produce a simple flux and transport model on an east–west transect from the Coast Range foothills to the Yolo Bypass between Davis and Sacramento (Fig. 6). This model ignores heterogeneity in the groundwater flow system, but rather compares modern recharge rates with natural recharge rates inferred from ^{14}C ages. A good estimate for recharge in the natural state (Fig. 6, top) can be gained from the average annual precipitation at Davis of 43 cm (17"), plus the information that the ^{14}C ages of the groundwater vary from modern at the surface, to approximately 2.7 kyears at 180 m, to approximately 8.7 kyears at 600 m beneath Davis. Assuming an average aquifer porosity of 30%, and an average flow path of 25 km for this basin, one can readily calculate that the effective linear velocity is approximately 9 m $year^{-1}$ at 180 m depth and approximately 3 m $year^{-1}$ at 600 m depth. Given the hydraulic conductivities calculated above, under natural hydraulic gradients a shallow groundwater transport rate of 50 m $year^{-1}$ is calculated, so about approximately 2000 m^3 $year^{-1}$ of water would have passed through a vertical plane beneath Davis that is 1 m wide. Rainfall on a 25 km long, 1 m wide horizontal strip would total 11 000 m^3, so our isotopic estimate for meteoric recharge to the groundwater aquifer under natural conditions is approximately 20% of precipitation, or about 8 cm $year^{-1}$. It should be noted that these fluxes represent maximum rates since preferential recharge is assumed on the western boundary of the study area. For the case of vertical recharge, the ^{14}C ages indicate that only 5% of the annual precipitation is recharged in the natural setting. An average 10% annual recharge may be more realistic, but for the model we have chosen the faster recharge


11,000 m³
ppt = 43cm
ET = 30cm
runoff = 5cm
50 m/yr
recharge = 8cm
9 m/yr
Flux = 2000 m³/yr
3 m/yr
1 km
NATURAL
1 m
ppt = 43cm
gw pumped/ applied = 43cm
surface water applied = 67cm
ET = 105cm
runoff = 7cm
8cm
ag recharge = 33cm
gw deficit = 2cm
Δh = −6 cm/yr
AGRICULTURAL
combined ET = 100cm
gw pumped/ applied = 39cm
surface water applied = 60cm
urban pumping = 5.5cm
ppt = 43cm
total runoff =10cm
7cm
ag recharge = 30cm
gw deficit = 8cm
Δh = −25 cm/yr
AGRICULTURAL + 10% URBAN
0
7km

rate since mechanisms of natural groundwater discharge from this region are not well understood at this time.

It is more difficult but nevertheless informative to consider the more complicated water flux situation today. Available information on the inputs and losses includes the following: (1) the average annual precipitation at Davis is 43 cm (17"); (2) average irrigation in California is 110 cm (43"), of which 39% is derived on average from groundwater (Snyder et al., 1986; Spieker, 1984); 3) approximately 30% of irrigation, here representing 33 cm, is recharged into the ground (Snyder et al., 1986); (4) annual pan evaporation near Davis is 173 cm (68.3"; Thomasson et al., 1960), but probably only approximately 2/3 of this can effectively be lost in evapotranspiration because this region has a natural net water deficit; (5) runoff is low; (6) municipal groundwater pumping in Davis and Woodland is approximately 55 cm; i.e. 1.8 acre-feet per urban acre, but these urban areas constitute less than 10% of the total area under consideration. Thus, excluding the urban areas (Fig. 6, middle), water sources that include rainfall (43 cm), groundwater irrigation (43 cm), and surface water irrigation (67 cm) total 153 cm year^{-1}. Of this, approximately 20 % of the rainfall and 30% of the irrigation water recharge the groundwater aquifer system, totaling approximately 41 cm year^{-1}. The evapotranspiration of 105 cm year^{-1} makes up most of the difference, a figure that is very close to our estimate of 2/3 of the observed pan evaporation. Note that 43 cm of groundwater is withdrawn in this model, yet only 41 cm is recharged. The slight deficit of approximately 2 cm year^{-1} indicates very slow but progressive deflation of the water table, approximately as observed.

If an urban pumping zone that covers 10% of the east–west transect is added, then a 10% reduction of agricultural surface and groundwater application is realized, and the combined agricultural recharge is reduced to 30 cm (Fig. 6, bottom). Subsequently, the urban area will withdraw 5.5 cm year^{-1} from the groundwater with negligible recharge, and associated increased runoff. This result increases the groundwater deficit to approximately 8 cm year^{-1}, and will be reflected in an approximately 25 cm year^{-1} water table deflation. Such localized urban pumping will inevitably produce local cones of depression that are recharged by several radial directions, as is now occurring in Davis and in the Sacramento metropolitan area.

5. Summary

Oxygen and hydrogen isotopes provide powerful natural tracers, intrinsic to the water molecule, to identify, delineate, and characterize the fluxes of 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

Fig. 6. Groundwater flux models across the southern Sacramento Valley, comparing the natural condition with modified systems. Agricultural or agricultural plus urban activities have greatly increased recharge rates over the natural levels, yet have produced net groundwater deficits and reduced water quality in this region. See text.

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. In the hope of exploiting these characteristics to distinguish different water bodies and sources, we initiated a systematic isotopic investigation of groundwater across the southern Sacramento Valley in the spring of 1993.

West of the Sacramento River, groundwater levels maintain a near natural hydrologic gradient that generally parallels the topography, even though thousands of acre-feet of groundwater are pumped from this region every year. However, the isotopic analyses show that recharge to this region is no longer dominated by meteoric precipitation, but rather by agricultural irrigation water that is undergoing large-scale mixing with the pristine natural groundwater sources. Remnants of the 'pristine' meteoric recharge mostly occur in hilly terrain, but also in an approximately 20 km^2 zone to the east and northeast of Davis. The ^{14}C analyses show that these high-quality meteoric groundwaters are ancient, with ages of 2.7 kyears or more. In contrast, the groundwater end-member derived from agricultural irrigation is highly enriched in ^{18}O relative to the pristine meteoric values, and has apparent ^{14}C ages of less than 500 years. This much younger age, the enriched $\delta^{18}O$ signature, and the associated elevated nitrate concentrations all indicate that the end-member represents recently recharged irrigation water. Progressive groundwater degradation is indicated by increasing proportions of this latter end-member, and during the last 20 years, by sizable increases in nitrate levels of municipal wells in Davis and Woodland. We argue that this replacement process effectively constitutes overdraft and 'mining' of the ancient groundwater.

Striking cones of depression beneath the City of Sacramento extend to depths greater than 30 m 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 is 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 $\delta^{18}O$ groundwater is ancient, ranging from 9 to 16 kyears, whereas the low $\delta^{18}O$ groundwater is essentially modern. These data quantify that the ancient groundwater is also effectively being 'mined' on the eastern side of the Sacramento Valley, in this case with deflating water levels but not with rapid degradation of quality.

In short, isotopic data provide a dynamic visualization of the sources, migration and recharge processes of groundwaters. These data also provide a new means of estimating the velocities of groundwater flow, from which hydraulic conductivities may be calculated.

Acknowledgments

We thank Karla R. Campbell for indispensable help in the laboratory, and for performing most of the $^{18}O/^{16}O$ analyses. Laboratory assistance was also rendered by

Mark Smith and Mike Davis. We thank James Gibboney, Euhla Taber, Alex Vasquez, Eric Senter, and Toccey Dudley of the Department of Water Resources Central District, and Rob Beggs of West-Yoste Associates, for discussion and providing many of the samples. The cooperation of the Public Works Departments of Sacramento, Davis, and Woodland, the UC Davis Physical Plant, and numerous ranchers and private residents is appreciated. George Davis and David Maidment provided helpful critical comments. This research was supported by Water Resources Center grant W-795 and by NSF-EAR 9204993, and part of this work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract number W-7405-Eng-48.

References

Barnes, C.J. and Allison, G.B., 1983. The distribution of deuterium and ^{18}O in dry soils, 1. Theory. J. Hydrol., 60: 141–156.

Coleman, M.L., Sheperd, T.J., Durham, J.J., Rouse, J.E. and Moore, G.R., 1982. Reduction of water with zinc for hydrogen isotope analysis. Anal. Chem., 54: 993–995.

Craig, H., 1961a. Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. Science, 133: 1833–1834.

Craig, H., 1961b. Isotopic variations in meteoric waters. Science, 133: 1702–1703.

Davisson, M.L. and Criss, R.E. 1993. Stable isotope imaging of a dynamic groundwater system in the southwestern Sacramento Valley, California, USA. J. Hydrol., 144: 213–246.

Davisson, M.L. and Criss, R.E., 1995. Stable isotope and groundwater flow dynamics of agricultural irrigation recharge into groundwater resources of the Central Valley, California. In: Int. Symp. on Isotopes in Water Resources Management, Vienna, 20–24 March 1995. International Atomic Energy Agency, IAEA-SM-336/14, 12 pp.

Davisson, M.L. and Velsko, C.A., 1994. Rapid extraction of dissolved inorganic carbon from small volumes of natural waters for ^{14}C determination by accelerator mass spectrometry. UCRL-JC-119176, Lawrence Livermore National Laboratory, Livermore, CA, 17 pp.

Davisson, M.L., Criss, R.E. and Campbell, K.R., 1993. Preliminary report on the stable isotope imaging and characterization of surface and ground water resources in the southern Sacramento Valley. UCRL-ID-115393, Lawrence Livermore National Laboratory, Livermore, CA.

Davisson, M.L., Presser, T.S. and Criss, R.E., 1994. Geochemistry of tectonically expelled fluids from the northern Coast Ranges, Rumsey Hills, California. Geochim. Cosmochim. Acta, 58: 1687–1699.

Davisson, M.L., Criss, R.E. and Campbell, K.R., 1995. Compilation of data for isotope mapping of groundwater in the Central Valley of California. UCRL-ID-120321, Lawrence Livermore National Laboratory, Livermore, CA, 12 pp.

Department of Water Resources, 1978. Evaluation of groundwater resources: Sacramento Valley. Bull. 118-6, Department of Water Resources, Sacramento, CA, 136 pp.

Department of Water Resources, 1986. Elevation of Water in Wells, Spring 1986, Sacramento Valley and Redding Basin. Prepared by the Central District and Northern District, Department of Water Resources, Sacramento, CA.

Epstein, S. and Mayeda, T.K., 1953. Variation of O^{18} content of waters from natural sources. Geochim. Cosmochim. Acta, 4: 213–224.

Evenson, K.P., 1985. Chemical quality of groundwater in Yolo and Solano counties, California. US Geol. Surv., Water Resour. Invest. 84-4244.

Gunderson, R.P., 1989. Distribution of oxygen isotopes and non-condensable gas in steam at the Geysers. Geotherm. Resour. Council Trans., 13: 449–454.

Helley, E.J., 1979. Preliminary geologic map of Cenozoic deposits of the Davis Quadrangle, California. U.S., Geol. Surv., Open-File Rep. 79-583.

Ingraham, N.L. and Taylor, B.E., 1991. Light stable isotope systematics of large-scale hydrologic regimes in California and Nevada. Water Resour. Res., 27: 77–90.

Lico, M.S. and Kharaka, Y., 1983. Subsurface pressure and temperature distributions in Sacramento Basin, California. In: R.L. Herster and D.E. Hallinger (Editors), Selected Papers of the Pacific Section, May 1983 Annual Meeting, Sacramento, CA. Am. Assoc. Pet. Geol., Los Angeles, CA, pp. 57–75.

McNichol, A.P., Jones, G.A., Hutton, D.L., Gagnon, A.R. and Key, R.M., 1994. The rapid preparation of seawater ΣCO_2 for radiocarbon analysis at the National Ocean Sciences AMS Facility. Radiocarbon, 36: 237–246.

Mohr, T.K.G., Davisson, M.L., Criss, R.E. and Fogg, G.E., 1992. Small scale application of stable isotopes ^{18}O and deuterium to delineate migration pathways at a Class III landfill site. Proc. Sixth Natl. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, Las Vegas, NV, 9–13 May 1992. National Ground Water Association, pp. 231–244.

Olmsted, F.H. and Davis, G.H., 1961. Geologic features and groundwater storage capacity of the Sacramento Valley California. US Geol. Surv., Water-Supply Pap. 1497.

Page, R.W., 1986. Geology of the fresh groundwater basin of the Central Valley, California, with texture maps and sections. US Geol. Surv., Prof. Pap. 1401-C.

Peters, E.K., 1993. D-^{18}O enriched waters of the Coast Range Mountains, northern California: Connate and ore-forming fluids. Geochim. Cosmochim. Acta, 57: 1093–1104.

Rao, R.R. and Killey, R.W.D., 1994. Quantitative separation and determination of inorganic and organic forms of total carbon and radiocarbon in natural waters and application at a radioactive waste management site. Radiochim. Acta, 65: 63–74.

Rose, T.P., Davisson, M.L. and Criss, R.E., 1996. Isotope hydrology of voluminous cold springs in fractured rock from an active volcanic region, northeastern California. J. Hydrol., in press.

Snyder, R.L., Hanson, B.R. and Coppack, R., 1986. How farmers irrigate in California. Leaflet 21414, Cooperative Extension University of California, Division of Agriculture and Natural Resources, Leaflet 21414, 4 pp.

Spieker, A.M., 1984. California groundwater resources. US Geol. Surv., Water-Supply Pap. 2275, pp. 147–152.

Stuiver, M. and Polach, H., 1977. Reporting of ^{14}C data. Radiocarbon, 19: 355–363.

Thomasson, H.G., Olmsted, F.H. and LaRoux, E.F., 1960. Geology, water resources and usable groundwater storage capacity of part of Solano County, California. US Geol. Surv., Water-Supply Pap. 1464.

Vogel, J.C., 1967. Investigation of groundwater flow with radiocarbon. In: Isotopes in Hydrology. International Atomic Energy Agency, Vienna, pp. 355–369.

Walker, F.W., Parrington, J.R. and Feiner, F., 1989. Nuclides and Isotopes. General Electric Co. Nuclear Energy Operations, San Jose, CA.

White, D.E., Barnes, I. and O'Neil, J.R., 1973. Thermal and mineral waters of non-meteoric origin, California Coast Ranges. Geol. Soc. Am. Bull., 84: 547–560.