Preliminary Report on the Groundwater Isotope Study in the Brentwood Region

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Executive Summary

Under contract with the City of Brentwood and auxiliary support by the East Contra Costa Irrigation District (ECCID), a preliminary research assessment of the groundwater resources beneath the Brentwood region is complete. The research was performed by an isotope geochemistry approach rather than traditional hydrogeological methods. The isotope approach is inexpensive relative to the traditional methods and has been used here mostly as a tracer that details the source, migration paths, and migration rates of existing groundwater supplies. In addition, the isotope results provide a quantitative framework in which to answer questions important to Brentwood including:

- 1) What is the long-term and short-term sustainability of the groundwater resources relative to current urban growth projections?
- 2) How can the good water quality be maximized in groundwater wells under short and long-term groundwater use schemes?
- 3) What underground areas exist within the Brentwood region that indicate untapped groundwater supplies that may provide plentiful, good quality water?

This preliminary report focuses only on the first question. The second and third questions will be addressed in the final report to be completed by January 1, 1995. Furthermore, the conclusions in this preliminary report of how much groundwater is available for use will be incorporated into the Groundwater Management Plan currently being developed by the ECCID in conjunction with the City of Brentwood.

Results of this preliminary report include the following:

- The amount of groundwater that can be pumped from the ground without depleting the resource is between 300 and 1800 acre-ft per year for a population of ~70,000 people. This quantity of groundwater represents only 2 to 14% of the water needed to meet the annual domestic demand.
- Poor water quality, in particular the high nitrate concentrations, is a result of agricultural irrigation and fertilizer application historically practiced in this area. In the long-term (≥ 10 years), much of the 300 to 1800 acre-ft of available groundwater will probably have excessive nitrate concentrations and water treatment will be necessary.
- Simple model results indicate that the current groundwater use rate by the City of Brentwood exceeds the yearly supply by about 3 times. These overdraft rates can probably be maintained only in the short-term before nitrate contamination appears.
- Most of the groundwater recharged during the past ~80 years has been agricultural irrigation water. Retirement of agricultural land will eliminate most of the groundwater recharge, and therefore, the available groundwater supply will decrease as urban growth increases. Urbanized growth of the City of Brentwood will be predominantly in the recharge areas of the groundwater basin. Therefore, the 300 acre-ft per year water supply is probably more realistic than the 1800 acre-ft per year.

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Introduction

The groundwater resources of the Brentwood region are being evaluated with quantitative isotope measurements under a research agreement with the Nuclear Chemistry Division of Lawrence Livermore National Laboratory. This preliminary report is a promised deliverable to the City of Brentwood and the East Contra Costa Irrigation District (ECCID) that briefly outlines current field and laboratory results and preliminary groundwater resource projections. This report also provides an additional research component for the AB 3030 Groundwater Management Plan under development by the respective agencies. This report is intended to be brief and all details of the research history, methods, and detailed interpretations and recommendations, etc. will be left for the final report scheduled to be completed by January 1, 1995.

This groundwater study incorporates the entire geographic area of the ECCID, which includes the City of Brentwood. This report refers to this area as the "Brentwood region". Also in this report, the term groundwater "yield" refers to a safe yield. Safe yield is defined as the groundwater pumped at a rate that does not create a permanent groundwater deficit. Groundwater pumped beyond the safe yield is referred to as "overdraft".

Preliminary Results

Field data - Well waters were analyzed in the field for their electrical conductivity, temperature, pH, alkalinity, dissolved oxygen (DO), and nitrate (NO_3) concentration. Standard electronic devices were used for conductivity, temperature, and pH, while NO_3 and DO were completed with commercial color indicator techniques and alkalinity by commercial field titration kits. Only the NO_3 concentrations will be discussed in this report. NO_3 concentrations have an analytical uncertainty of $\pm 20\%$. The NO_3 measurements provide a general survey of the NO_3 variability throughout the Brentwood region. The field NO_3 measurements do not constitute EPA certified results. Groundwater samples have been collected for standard mineral analysis that will include qualified EPA laboratory results of NO_3 concentrations.

The NO_3 concentrations have a significant impact on the groundwater quality in this region. Field concentrations of NO_3 range from 0 to ~ 100 mg/L as nitrate, and approximately 40% of all wells measured exceed the EPA primary drinking water standard set at 45 mg/L. It is assumed that pre-anthropogenic NO_3 concentrations are < 5 mg/L for this region. The NO_3 concentrations show a regular distribution in map view and cross-section view in the Brentwood region (Fig. 1a and 1b), with the highest concentrations observed in groundwater along a broad zone stretching from the northwest

to the southeast of the City of Brentwood. In cross-section the NO_3 concentration approaches 100 mg/L at shallow depths (<100 ft below surface), but decreases with increasing depth. In three wells north, east and south of the City of Brentwood, groundwater has non-zero NO_3 values greater than 250 ft below the surface. The western side of the Brentwood region has the deepest penetration of high NO_3 groundwater. On average, the depth of 50 mg/L NO_3 groundwater is between 100 and 150 ft below the surface.

Isotope Data - Groundwater was sampled for the stable isotopes of oxygen-18 (hereafter: ^{18}O) and deuterium (hereafter: D), and for radiocarbon (carbon-14, hereafter: ^{14}C). The terminology, systematic behavior, and the utility of these isotopes in groundwater resource evaluation are discussed in the Appendix. The ^{18}O concentrations in the groundwater are measured as ratios of $^{18}\text{O}/^{16}\text{O}$. These ratios are then normalize to a standard (seawater) and reported in a δ notation (pronounced "del"), where $\delta^{18}\text{O}$ is the concentration as parts per thousand or per mil (symbol used here is "‰"). The deuterium analyses are in progress and will not be discussed.

The $\delta^{18}\text{O}$ values of the groundwater sampled in the Brentwood region indicate two sources of groundwater originating as 1) pristine groundwater recharged by local rain water, 2) and agricultural irrigation water that has recharged for the past ~80 years. Local rain water has an average $\delta^{18}\text{O}$ value between -6.5 to -7.0‰, and these type of groundwaters are observed at the western edge of the Brentwood region as well as down-gradient on the eastern edge (Fig. 2a and 2b). In addition, these groundwater types are observed at deeper depths in the basin, typically >250 ft below the surface. Agricultural irrigation water is predominantly imported in this region from a San Joaquin River source that originates as Sierra Nevada precipitation. The $\delta^{18}\text{O}$ value of precipitation in the Sierra Nevada is more negative than the local rain water in the Brentwood region due to orographic rain-out effects that deplete the storm tracks of ^{18}O and deuterium (Ingraham and Taylor, 1991). Earlier isotope results from Phase I of this study showed that the canal water pumped from Indian Slough by the ECCID was around -9.2‰, and with associated evaporation effects, the recharged agricultural irrigation water was between -8.5 and -9.2‰. As can be seen in Figs 2a and 2b, these lower $\delta^{18}\text{O}$ values predominate over much of the Brentwood region, and like the NO_3 concentrations, they have a mean penetration depth between 100 and 150 ft below the surface. An excellent correlation exists between the measured NO_3 concentration and the $\delta^{18}\text{O}$ value of the groundwater (Fig. 3), showing that the recharged agricultural water is the source of the high NO_3 in the groundwater supply.

The ^{14}C analyses are still in progress. Available measurements indicate that pristine groundwater in the alluvial aquifers of the Brentwood region range up to 4000 years old in apparent age, where a single measurement of groundwater in the marine sandstone of the western hills is 8400 years old. The latter age may be due to the lower porosity and permeability of the marine sandstone that is also reflected in poor groundwater yields from wells completed in this rock type. Recharged agricultural irrigation water in the Brentwood region typically has ^{14}C ages that are modern, further supporting their recent introduction into the groundwater aquifers.

Groundwater Flow - The water table under the Brentwood region shows a regular slope to the east and northeast with about a 70 ft change in elevation over an approximately 5 mile distance. This regular slope in the water table appears constant from the 1930's to 1980's (Historical Water Table Maps, ECCID). From the water table slope, groundwater is inferred to flow generally from west to east

Groundwater flow can be inferred from the contoured $\delta^{18}\text{O}$ values in the Brentwood region. Agricultural irrigation water has penetrated the deepest in the western side of the area, defined by a broad zone that parallels the hilly regions on the western edge. In the northeast part of the region and the eastern edge of the study area, the agricultural irrigation recharge is not well defined and local rain water $\delta^{18}\text{O}$ values are observed instead at relatively shallow depths (~150 ft below the surface). The northeastern part of the Brentwood region historically has had poor subsurface drainage and is currently lined with tile drains. This has limited the vertical penetration of recharged agricultural irrigation water. Similar conditions also probably exist east of the study area.

The broad, low $\delta^{18}\text{O}$ zone of recharged irrigation water that is pervasive at depth (Fig. 2a and 2b) on the western side of the Brentwood region indicate that this area is where groundwater principally has recharged, as would be inferred from the groundwater table maps. The recharged irrigation water flows east as best indicated by the penetration of the low $\delta^{18}\text{O}$ water (-9.0‰; Fig. 2a) into the eastern side of the Brentwood region. This low $\delta^{18}\text{O}$ zone creates an isotope mixing pattern with the higher $\delta^{18}\text{O}$ groundwater observed along the eastern edge of the study area (Fig 2a). In the northeastern part of the Brentwood region, though, the eastward flow of low $\delta^{18}\text{O}$ irrigation water is not well defined. This either suggests that groundwater aquifers are 1) not connected between the northern and northeastern parts of this region, or 2) irrigation water has flowed eastward into aquifers deeper than have been presently sampled. In general, though, the

groundwater principally recharges on the western and northwestern side of the region, and flows towards the east as would be inferred from the water table maps.

Water Resources

The following discussion will address a regional-scale mass balance model for the groundwater resources of the Brentwood region. Six general components comprise the mass balance model: 1) agricultural irrigation water recharge, 2) recharge from local precipitation, 3) recharge from stream loss, 4) agricultural pumping, 5) domestic pumping, and 6) groundwater underflow that leaves the Brentwood region by easterly flow. The first three components represent groundwater that annually enters groundwater storage. The latter three components consist of groundwater that is annually removed from storage. The sum of the latter three components subtracted from the sum of the first three components is the total change in storage of the groundwater basin. For the Brentwood region the change in storage is essentially zero as indicated by the uniform water table levels in wells across the region over at least 50 years (Historical Water Table Maps, ECCID). The groundwater flow (component #6 above) is the most important part of the mass balance model since this represents groundwater available for consumption. The groundwater flow (component #6) can be calculated such that,

$$\text{Groundwater Flow} = \text{Total Recharge} - \text{Total Pumped}$$

where the total recharge is the sum of components 1-3, and the total pumped is the sum of components 4 and 5. Listed below are the quantities of groundwater in each component calculated from available data spanning the past 77 years, and a discussion of their derivation follows.

Groundwater Balance: in acre-ft over 77 years (1917-1994).

Component	Maximum	Minimum	Mean
Ag Recharge	694,000	694,000	694,000
Rain Recharge	261,800	130,900	196,350
Stream Recharge	83,600	0	41,800
Ag Pumping	288,700	288,700	288,700
Domestic Pumping	73,540	73,540	73,540
Groundwater Flow	677,160	462,660	569,910

Agricultural Recharge - The ECCID has extensive historical records on the amount of water annually diverted and delivered for irrigation dating from 1917 to 1972 (Fig. 4). Irrigation water records from 1950 to 1972 specify the total water delivery as 1) surface water diverted at Indian Slough and 2) groundwater pumped into the delivery canals. In addition, the total water lost from canal seepage was measured and typically averaged around 7%. Irrigation water records from 1917 to 1949 were measured only as the total water diverted at Indian Slough and lacked groundwater pumpage and seepage loss data. It is not clear how much groundwater was pumped before 1950 but estimates are provided below. The total agricultural irrigation water before 1950 was calculated by subtracting a 7% water loss by seepage from the diversion quantities at Indian Slough, but no groundwater inputs were added.

The data distribution in Fig. 4 shows a regular increase in irrigation water deliveries over time. Extrapolation of the trend beyond 1972 would suggest a linear increase in agricultural irrigation water applied above the 1972 quantity. For the purposes of this report, though, a more conservative estimate is used instead, since irrigation water distribution over the entire ECCID in 1972 was nearly 100% of the available acreage during this period, and any increased application beyond 1972 is unlikely. Assuming that the delivery of annual agricultural irrigation water approaches a steady-state amount subsequent to 1972, a total of ~37,550 acre-ft per year is calculated. Therefore, the steady state quantity of 37,550 acre-ft per year is used as the amount applied to the land annually between the years 1972 and 1994. Also in Fig. 4, the total water delivered from 1930 to 1944 does show somewhat of a decreasing trend and may be related to increasing groundwater inputs that are not included in the data. More work is needed to resolve this small effect.

When the irrigation water delivered is integrated over 77 years, the total is 2,313,230 acre-ft that was applied over $\leq 17,000$ acres. This amount is equivalent to an average of 1.8 ft per year applied for irrigation per acre, and is about one-half the current average (3.6 ft per year) in California (Snyder, et al., 1986). The 1.8 ft per year assumes that 100% of the 17,000 acres was irrigated over the 77 years and ignores fallow land and areas where high water consumptive crops such as fruits were grown. For the mass balance model it is assumed that the irrigation water efficiency on average is 70%, and 30% of the total irrigation water applied is recharged to the groundwater basin. This results in 694,000 acre-ft of total groundwater recharge over 77 years.

The total agricultural water recharged over the 17,000 acres is equivalent to approximately 41 ft of applied water at the surface or 136 ft of aquifer volume, assuming

a 30% porosity. This total depth of groundwater recharged by agricultural irrigation (136 ft) is essentially the approximate average depth of irrigation recharge observed in the $\delta^{18}\text{O}$ values and NO_3 concentrations. The comparison is a quantitative validation of the agricultural recharge component of the model.

Rain Recharge - No data records of this component have been compiled to date, and quantities are only estimated. Based on quantitative data from the southern Sacramento Valley, where surface geologic deposits and precipitation rates are very similar to the Brentwood region, approximately 10-20% of the precipitation is recharged annually into the groundwater basin (Davisson et al., 1994). These same rates are applied to the Brentwood region assuming an average precipitation rate of 12 inches per year (Chuck Hamilton, personal communication). Calculations of the total recharge from rain are given as a maximum (20%) and a minimum (10%) in the table above and has a mean of 196,350 acre-ft over 77 years. Any precipitation recharged above the 20% annual level is probably unrealistic. Mixing groundwater from higher precipitation recharge rates with the recharging agricultural water would increase the resulting $\delta^{18}\text{O}$ to values greater than those observed. Completion of the deuterium analyses will help test this assumption.

Stream Recharge - Marsh Creek is the only surface water that could contribute appreciable recharge to this area. Flow data are not available at this time, but annual average flow is estimated at 5 cubic feet per second. Assuming at most 30% of this water is lost as groundwater, a total of 83,600 acre-ft could be recharged. Qualitative observations of Marsh Creek, though, indicate no significant losses occur and recharge could be essentially zero. The stable isotope data of the groundwater do not indicate any definable source directly from Marsh Creek.

Agricultural Pumping - This component comprises all water derived from groundwater pumping by the ECCID. The ECCID has thorough records on total groundwater pumped between 1950 and 1972. The groundwater was pumped for two reasons: 1) to augment irrigation supplies in the canals, and 2) to provide drainage to areas with high water tables that are lined by tile drains in the northeastern part of the Brentwood region. Typically, 30-50% of the total groundwater pumped by the ECCID was for enhancement of drainage, and that water was always disposed of outside the Brentwood region. Total groundwater pumped between 1950 and 1972 generally decreased between ~6000 to 4500 acre-ft (Fig. 5). Because detailed data are not available subsequent to 1972, annual groundwater extractions from 1972-1994 are estimated at 4500 acre-ft per year. Annual

extractions prior to 1950 are less clear. Large capacity pumps only became routinely accessible during the early 1930's (Thomasson et al., 1960). Therefore, for convenience, the rate estimated for groundwater pumped by ECCID from 1935-1950 is 4500 acre-ft/yr. This amount may change as more information becomes available. The total groundwater pumped from the Brentwood region by the ECCID over the 77 years is calculated at 288,700 acre-ft. No maximum or minimum values have been calculated for this component at this time.

Agricultural pumping from privately owned wells was probably insignificant during the 77 years. Most water used for irrigation was available at affordable rates from the ECCID.

Domestic Pumping - Groundwater pumped by individual well owners and the municipalities of Brentwood and Knightsen can be estimated from general population figures available at the ECCID. Better population data may exist elsewhere but has not been compiled to date. The ECCID records indicate that between 1950 and 1961 the population was close to 5000. Between 1962 and 1968 the population was 6000. The population is reported as 8000 in 1968, and for this report, that figure has been extended through 1985. A population of 10,000 is used from 1986 to 1994. Between 1917 and 1950, where no records are available at this time, the population is estimated at 2500. It is assumed that the per capita daily water use is 164 gals (City of Brentwood-CCWD, 1990) and is similar to municipalities like the City of Davis where 3.7 billion gals are consumed annually by ~50,000 people (Davisson and Criss, 1993). Summing up the groundwater pumped for domestic consumption over the 77 years using the population figures provided above, a total of 73,540 acre-ft is calculated. No uncertainty is derived for this value at this time, but the total groundwater pumped for domestic use is a small percentage of the total mass balance.

Groundwater Flow - As stated above, the difference between the recharge and the discharge is the groundwater flow and is calculated at a mean value of 569,910 acre-ft. This groundwater represents flow that must leave the Brentwood region in order to create aquifer volume for the groundwater recharged over the past 77 years. The groundwater flow also represents a total amount of groundwater that was not used for consumption, but is theoretically available as a water resource. The total groundwater flow represented as an annual supply over the 17,000 acre region is calculated at 279 acre-ft/mi² per yr. For a projected population of ~70,000 in the year 2020 (City of Brentwood-CCWD, 1990), it is estimated ~12 square miles will be developed. Simply multiplying the 279

acre-ft/mi²-yr by the 12 mi², results in a groundwater yield of 3344 acre-ft per year over the developed area. This yield falls in the 2000-4000 acre-ft per year range estimated by Henneman (1990). This groundwater yield, though, does not account for groundwater recharge loss due to agricultural land retirement and urban development, and actual yields will be much less as discussed below. It is also assumed in this simple model that the aquifer below the Brentwood region is homogeneous and isotropic. Real aquifer conditions are heterogeneous and actual yields may vary depending on location within the Brentwood region. Safe yield values presented are considered more or less averages.

Projected Groundwater Yields - The mean projected groundwater yield calculated above represents an average yield over the 77 year data history. But when the influence of the change in land use practice on the groundwater mass balance is taken into account, a different yield scenario is projected. The most significant modern recharge source to the groundwater basin is the applied irrigation water as indicated by the stable isotope and NO₃ data. This recharge component represents 67-84% of the total estimated recharge over the past 77 years. Retiring agricultural land removes this recharge source. Likewise, suburban or urban development of retired agricultural land further results in a reduction of available recharge areas for precipitation due to increase land coverage of pavement and water efficient plants such as grass. It is estimated that the urbanization of agricultural land causes over a 90% reduction in groundwater recharge. The increase in urban and suburbanization will have a major impact on the groundwater availability.

A simple model can be developed to quantify the change in groundwater yield per square mile as land is converted to urban uses, and follows such that

$$\frac{R}{mi^2} = \frac{0.74 ft(acres_{ag}) + 0.05 ft(acres_{urb}) - 0.50 ft(acres_{drained} - acres_{drainedlost})}{26.6 mi^2}$$

where R is the total annual recharge in acre-ft/mi²-yr (equivalent to available yield), $acres_{ag}$ is the total acres irrigated for agriculture, $acres_{urb}$ is the total acres converted to suburban or urban use, $acres_{drained}$ is the total acres drained by tile drains in the eastern part of the Brentwood region, and 0.05 ft is equivalent to 5% of annual precipitation that is the estimated recharge in an urban setting. Precipitation recharge in the agricultural areas is estimated at 20% of annual precipitation (i.e. 1.0ft of total rain @ 20%=0.2 ft. This is added to ag recharge @ 0.54 ft for a total of 0.74 ft). The sum of $acres_{ag}$ and $acres_{urb}$ always equals 17,000 acres. Figure 6 indicates the change in groundwater yield per square mile per year as the projected population increases. The population increase

was calculated by assuming 8.8 people per acre in an urban development scheme. Lines (a) and (b) were calculated with the above equation and indicates that approximately 3 acre-ft/mi² per year of groundwater is lost for every 1000 person increase in population. The inflection point in the trend is where urbanization begins to encroach on the agricultural areas underlain by tile drains. At a projected population of ~70,000 people, Fig. 6 suggests that 150 acre-ft/mi² per year will be available for groundwater consumption at a safe yield. This is equivalent to 1800 acre-ft per year over a 12 mi² area and ~14% of the total water demand from a population of 70,000.

Line (c) in Fig. 6 was calculated using a similar equation as above but one that only considers a total acreage of 8000 acres and ignores groundwater contribution from the outlying regions. The 8000 acres is equivalent to the total land urbanized for a projected ~70,000 person population. The results show that at this 8000 acre scale the safe yield per mi² for a small population is greater than for a small population at the 17,000 acre scale. The loss of available yield for the 8000 acre scale, though, is approximately 6 acre-ft per 1000 people increase in population. This is twice the rate as the larger scale. At a ~70,000 person population, the available safe yield at the 8000 acre scale is ~25 acre-ft/mi²-yr or 313 acre-ft per year for the entire 8000 acres. This is equivalent to ~2% of the total water demand for a population of 70,000.

The 1800 acre-ft per year estimate for groundwater yield assumes that all the groundwater recharged by agriculture can be captured for domestic groundwater pumping. The 313 acre-ft per year yield assumes that no agricultural recharge can be captured by domestic pumping. Therefore, 1800 acre-ft per year is an upper limit of safe yield and 313 acre-ft per year is a lower limit for a population of 70,000. According to this simple model, the City of Brentwood currently is using ~3 times more groundwater than the average safe yield. If the population reaches 70,000 within the next ~25 years, the city must decrease their groundwater consumption by 92% by this time in order to meet a safe yield.

The lower limit safe yield is more realistic than the higher one. This is due to the fact that currently the City of Brentwood overlies parts of the recharge area to the groundwater basin. The growth plan for Brentwood stretches into the northwestern part of the basin where more recharge areas occur. Most importantly, Brentwood will be upgradient of most of the agricultural irrigation in the proposed Ag core, and in order to capture groundwater flow from irrigation recharge, domestic pumping would have to reverse the regional groundwater flow towards the west. This would require large regional drawdowns (≥50 ft)

With urban growth, the City of Brentwood seeks to augment 20% of its total water demand with groundwater (City of Brentwood-CCWD, 1990), an amount equivalent to ~3000 acre-ft/yr over the next 25 years. If this quantity were to be used from the groundwater basin, then a groundwater overdraft would result. This would result in an regional average deflation of the current water table level to ≤ 25 ft of the current elevation over 25 years.

Lastly, any long-term use of the current groundwater for domestic consumption must incorporate clean up costs of the dissolved nitrates. Although not all groundwater exceeds the EPA drinking water limits for NO_3 , the projected growth areas for Brentwood overlie some of the highest dissolved NO_3 groundwater (Fig. 1a). Under current conditions, the higher nitrate concentrations occur in shallower groundwater. Any cones of depressions developed during groundwater pumping can enhance the downward flow of the higher NO_3 groundwater, accelerating the degradation of the potable groundwater surrounding the well (Davisson and Criss, 1993). Projected rates of these occurrences will be incorporated in the final report.

Conclusion

The dissolved NO_3 concentrations in the groundwater under the Brentwood region present a regional-scale groundwater quality problem. Areas currently targeted for urban development are underlain by groundwater with some of the highest concentrations of dissolved NO_3 . Long-term planning of groundwater utilization should incorporate projected treatment costs.

The stable isotope results map out the extent of irrigation water recharge over the past ~80 years and quantitatively validate the major recharge component for the mass balance model.

The estimated groundwater safe yields for the Brentwood region are between 313 to 1800 acre-ft/year for a population of ~70,000 over a ~12 square mile area. Although the higher safe yield could occur under ideal recharge conditions in the Brentwood region, this is not likely because urbanization is proceeding within groundwater recharge zones and is upgradient from the groundwater recharge generated by irrigation in the planned Ag core to the east. Therefore, the lower safe yield limit may be more realistic. Any capturing of groundwater from the Ag core would require a regional-scale reversal of current groundwater flow directions accomplished possibly through large regional drawdowns (≥ 50 feet). Modest adjustments of the projected yields may be included in the final report.

Figure Captions

Figure 1a. Contour of dissolved nitrate concentrations in wells sampled for the isotope study. Analyses are performed with field color indicator strips and are not certified EPA results.

Figure 1b. Cross-section along the flow path (A-A') and orthogonal to the flow path (B-B'). Nitrates have penetrated to greater depths on the western side of the Brentwood area. The highest concentrations are observed in the shallowest groundwater.

Figure 2a. Contoured $\delta^{18}\text{O}$ values of well waters sampled for the isotope study. Values more negative than -7.0‰ represent mixing of agricultural irrigation water that originated from Sierra Nevada sources. Groundwater between -7.0 and -6.5‰ represent pristine groundwater recharged by local rain. Note that the areas with the most irrigation water recharge are essentially the same as the high NO_3 areas of Fig. 1a.

Figure 2b. Cross-section view along the same lines as Fig. 1b. Note that the agricultural recharge water has a similar distribution as the higher NO_3 water. The average vertical penetration of irrigation water is between 100-150 ft below the surface.

Figure 3. The measured NO_3 concentration of the groundwater compared to their $\delta^{18}\text{O}$ values show that both result from agricultural irrigation water recharge.

Figure 4. The applied irrigation water over time shows a near linear increase over time. A conservative steady-state quantity was derived, though, for the mass balance model at 37,550 acre-ft/yr and used for the years 1973-1994.

Figure 5. The record of groundwater pumped by the ECCID shows that an approximate 25% decrease occurred between 1950 and 1972. Extrapolation of groundwater pumped from 1935 to 1949 and 1973-1994 yielded an estimate of 4500 acre-ft/yr.

Figure 6. Simple model showing the decrease in recharge available for sustaining a safe yield. An estimated 92% decrease in recharge occurs when urban growth eliminates irrigation recharge and reduces recharge from precipitation. For the model the total acreage remains the same and a one-for-one replacement of agricultural land for urban land occurs as the population grows. Lines (a) and (b) are modeled for the total 17,000 acres in the Brentwood region, although only approximately half of this land is slated for urban development. Line (c) is modeled just for the ~8000 acres slated for urban development and ignores contributions from outlying regions.

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Appendix

Stable Isotopes.- A water molecule is made from two hydrogen atoms and one oxygen atom. We use natural isotopes of these atoms to trace water in the hydrologic cycle. Isotopes is a name for different types of atoms of the same element characterized by different number of neutrons in its nucleus. The element of oxygen is made of 3 different kinds of atoms or isotopes. The most abundant (99.8%) is oxygen-16 (^{16}O). The second-most abundant (0.2%) is oxygen-18 (^{18}O). The least abundant (0.04%) is oxygen-17, but because it is so rare, we can ignore it for hydrologic studies. Likewise, the element hydrogen also has three different kinds of isotopes. Hydrogen (H) is the most abundant (99.9%). Deuterium (D) is the second-most abundant (0.01%). Tritium (^3H) is the least abundant and is radioactive. Tritium has hydrologic applications but is not part of this proposal.

We are concerned with the relative abundance of ^{18}O and deuterium in different phases of the hydrologic cycle, i.e. liquid water, water vapor, and ice. All water in the hydrologic cycle originates from the ocean. For the most part, the liquid water in the ocean has a uniform ^{18}O and deuterium abundance throughout the world. Water in clouds (water vapor), rain, and ice have ^{18}O and deuterium abundances that differ from ocean water. This difference arises because natural chemical laws force more ^{18}O and deuterium to stay in one phase over another. In fact, the more solid the water phase the more ^{18}O and deuterium is incorporated in the water molecules, i.e. ice has more ^{18}O and deuterium than water, and water has more ^{18}O and deuterium than clouds. The absolute amount of ^{18}O and deuterium in any one phase depends on temperature only. Therefore, rain and snow near the polar regions of the earth have less ^{18}O and deuterium than rain water in the tropical or equatorial regions. This simple law allows us to trace the origin of a water sample by measuring its absolute ^{18}O and deuterium abundance.

All ^{18}O and deuterium measurements are normalized to ocean water abundances. This allows us to compare the ^{18}O and deuterium abundance in a hydrologic sample to its parent water. The normalization of the ^{18}O and deuterium is accomplished by comparing the $^{18}\text{O}/^{16}\text{O}$ ratio and the D/H ratio to the same ratios of ocean water such that,

$$\delta = \left(\frac{^{18}\text{O}/^{16}\text{O}_{rw}}{^{18}\text{O}/^{16}\text{O}_{SMOW}} - 1 \right) 1000 \quad \text{and} \quad \delta = \left(\frac{D/H_{rw}}{D/H_{SMOW}} - 1 \right) 1000$$

where $^{18}\text{O}/^{16}\text{O}_{rw}$ and D/H_{rw} are the isotopic ratios of a rain water, and $^{18}\text{O}/^{16}\text{O}_{SMOW}$ and D/H_{SMOW} are the isotopic ratios of an ocean water standard or Standard Mean Ocean Water. The δ symbol is pronounced "del" and normalized data are referred to as $\delta^{18}\text{O}$ and δD . We also refer to the $\delta^{18}\text{O}$ and δD values as a "per mil" (‰, or parts per thousand). Notice that if you normalize the SMOW standard against itself, then its $\delta^{18}\text{O}$ and δD values are both 0‰. This is the value of ocean water. Since ^{18}O and deuterium tend to stay in the more solid phase, almost all rain produced on land from clouds have $\delta^{18}\text{O}$ and δD values less than zero. For instance, rain waters on the western side of the Central Valley of California have, on average throughout the winter, $\delta^{18}\text{O}$ values approximately between -7.0 and -8.0‰, and δD values approximately between -46 and -54‰, as shown by our previous work (Davisson and Criss, 1993). These rain water "signatures" retain their values as they recharge into the groundwater beneath the surface.

Surface waters that evaporate lose water by releasing water vapor to the atmosphere. We can exploit the isotopic effects of ^{18}O and deuterium in evaporating waters. Because more ^{18}O and deuterium stay in the liquid phase than the vapor phase, evaporating waters, such as lakes, reservoirs, irrigation water, etc., will over time increase their ^{18}O and deuterium abundances, and hence increase their $\delta^{18}\text{O}$ and δD values. This "enrichment" of the $\delta^{18}\text{O}$ and δD values allows us to distinguish water that has a rain water isotopic value from a water with an evaporated isotopic value. This allows us to distinguish groundwaters that are recharge principally from winter rain storms from those recharged from evaporated water sources, such as agricultural irrigation water, reservoir water, or even Delta water.

In addition, water that has been imported from Sierra Nevada sources, such as the San Joaquin River, will have lower $\delta^{18}\text{O}$ and δD values than the locally derived groundwater (i.e. rain water or evaporated surface water). Snow and rain that falls in the Sierra Nevada has less ^{18}O and deuterium than rain water in the Valley because of the orographic effects from increased elevation (lower temperatures) and distance from the ocean.

Carbon-14—The natural element of carbon is made up of three different kinds of atoms. The most abundant (99%) is carbon-12 (^{12}C). The second most abundant (1%) is carbon-13 (^{13}C). A very small amount of carbon atoms are carbon-14 (written as " ^{14}C " or "radiocarbon"), which unlike the other two is not stable and is constantly decaying to the element nitrogen. At the same time, though, new ^{14}C atoms are being made in the upper atmosphere by high-energy particles colliding with other atoms. The rate of ^{14}C

production in the upper atmosphere is matched by the rate at which ^{14}C converts to nitrogen.

Once the ^{14}C atom is made, it typically is incorporated into a CO_2 molecule. That CO_2 molecule will be circulated down near the surface of the earth where plants can utilize it in their biological processes. Plants also expel excess CO_2 through their roots. This excess CO_2 respired through their roots will also have the same tiny amount of ^{14}C atoms as the atmosphere. When it rains, water will percolate through the soil, and dissolve the CO_2 the plant has respired from its roots. The dissolved CO_2 becomes HCO_3 in the water and will be carried down into a groundwater aquifer. Once the HCO_3 is in the aquifer, it can't communicate with the atmosphere above and so the ^{14}C atoms in the HCO_3 molecules are stuck in the aquifer. At this point, all the ^{14}C atoms in the HCO_3 molecules of the groundwater begin to decay to nitrogen, but can't be replenished by new ^{14}C atoms. Therefore, the total ^{14}C content of the groundwater decreases with time. The rate at which ^{14}C decays has been experimentally determined by previous scientific researchers. The best way to understand the rate is by using the term *half-life*. This term is defined as the time it takes for half of the ^{14}C atoms to convert to nitrogen. That half-life is 5730 years. For example, if we had 100 ^{14}C atoms and we isolated them and let them decay, we could recount them 5730 years later and find that only 50 atoms are left. We can use this same principle to determine the age of the groundwater.

The ^{14}C atom has an unstable nucleus and decays by emission of beta particles. This converts the ^{14}C atom to a stable nitrogen atom. The rate at which the ^{14}C decays is always the same. Therefore, the ratio of ^{14}C atoms in a material measured at any given time to the initial amount in a sample is proportional to time such that:

$$\frac{^{14}\text{C}}{^{14}\text{C}_i} = e^{-\lambda t}$$

where ^{14}C is the amount of ^{14}C in a material at any given time, $^{14}\text{C}_i$ is the initial amount, t is time, and λ is the proportionality constant. This $^{14}\text{C}/^{14}\text{C}_i$ ratio is known as the *fraction of modern carbon*. In the natural environment the $^{14}\text{C}_i$ is constant over time. Therefore, the fraction of modern carbon will always be ≤ 1.0 . When thermonuclear above-ground testing began in the early 1950's, an unnatural amount of ^{14}C was injected into the atmosphere. If some material has incorporated this unnaturally high ^{14}C level, then its fraction of modern carbon is > 1.0 . For natural samples, we always consider the $^{14}\text{C}_i$ to be equal to the pre-nuclear testing atmospheric levels.

The traditional methods of measuring the amount of ^{14}C in a material is by beta counting, or counting up the number of beta particles emitted from the sample. As the ^{14}C atoms decay, the number of ^{14}C atoms can be calculated from the number of beta counts. Therefore, the ratio in the above equation can be represented by a ^{14}C activity (beta activity) or A/A_i

New methods involving the use of the Accelerator Mass Spectrometer at Lawrence Livermore Lab, provide a means to separate ^{14}C atoms from the more abundant ^{12}C atoms by actually counting the ^{14}C atoms in a sample. This gives us a relative amount of ^{14}C atoms to total carbon in a sample. We can then compare that relative amount of ^{14}C to the pre-nuclear test levels and derive a fraction of modern carbon. To calculate an age we just solve for t in the above equation. The advantages to this new method is that only a small water sample is needed (one-hundredth the size of the traditional techniques) and the analyses are ten-times faster.

Figure 1a.

V.E. = 12 X

Figure 1b.

Figure 2a.

V.E. = 12 x

Figure 2b.

Figure 3

Figure 4

Figure 5

Figure 6