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Report on Isotope Tracer Investigations in the Forebay of the Orange County Groundwater Basin: Fiscal Years 1996 and 1997

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March 26, 1999

Lawrence Livermore National Laboratory

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Final Report

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EXECUTIVE SUMMARY

During fiscal years 1996 and 1997, groundwater in the Forebay of Orange County, California was measured for tritium (^3H), helium-3 (^3He), and oxygen-18 ($\delta^{18}O$) in an initial effort to determine groundwater flowpaths, ages and the extent of mixing. In general, the ^3H-^3He ages map preferred groundwater flowpaths and provide mean aquifer residence times. In particular, groundwater recharge originating from Anaheim Lake, Kraemer Basin, and Miller Basin follow southwestward to westward flowpaths. Flow rates were calculated using groundwater ages measured in wells along two distinct flow lines defined sequentially along wells 1) AMD-9 level 1, AM-10, AM-9, and AM-14, and 2) AMD-9 level 1, AM-7, AM-8, and SCWC-PLJ2. The groundwater age along the first flow line increases in age from 0 to 2 years, suggesting a linear flow rate up to 16.5 ft/day, and an average hydraulic conductivity of ~1000 ft/day. Groundwater age along the second flow line increases from 0 to 3 years and suggests a linear flow rate up to 8.0 ft/day and an average hydraulic conductivity of ~500 ft/day. However, close inspection of 1994 Colorado River recharge recorded in $\delta^{18}O$ time-series data collected at well SCWC-PLJ2 suggests that linear flow velocities may be as great as 140 ft/day. The $\delta^{18}O$ time-series data, as well as noble gas concentrations, indicate that groundwater mixing with Santa Ana River (SAR) water originating up gradient may be significant, which causes apparent increases in ^3H-^3He ages.

Fast groundwater flowpaths originating from the SAR and its adjacent recharge basins (e.g. Warner Basin) cannot be clearly defined due to minimum sampling locations. However, based on the $\delta^{18}O$ measurements, almost all the groundwater sampled in the YLWD production wells and the deep production wells A-42, A-43, and A-44 originated from SAR recharge. Therefore, general linear velocities from the SAR to these wells are between 800 to 1300 ft/yr, suggesting average hydraulic conductivities of 80 to 130 ft/day.

Groundwater ^3H-^3He ages vary from 1 to >10 years old in wells completed adjacent to the SAR channel. A measurable age of 1 year was even determined on the shallow (50 feet) monitoring well HG-1. These data suggest that deep groundwater flow of older age parallels the SAR channel and mixes with young shallow groundwater, creating mixed groundwater with apparently older ages. Two other lines of evidence support this hypothesis: Firstly, time-series $\delta^{18}O$ measurements in wells HG-1 and YLWD-11 have similar variations over an 18-month period, but are offset in time approximately 120 days. The magnitude of change in YLWD-11 furthermore is dampened by mixing, which is consistent with its older ^3H-^3He age of 4 years. Secondly, groundwater ages adjacent to the SAR downstream, where the gradient is steeper, are ~10 years old in shallow levels of monitoring wells SAR-6 and SAR-7. These wells correlate with the occurrence of a fault that offsets water table levels by several feet and shallowing of

basement rocks. The fault may cause deeper, older groundwater to flow upward toward shallower levels.

Using the $\delta^{18}O$ value of Colorado River water as a tracer, a recharge experiment in Anaheim Lake was implemented during this study period. It was found that travel times of Anaheim Lake water to wells AMD-9 level 1, A-27, A-28, and ABS-2 were less than 1 month. Groundwater from AMD-9 level 1 and A-27 were ~100% Anaheim Lake water, while groundwater in A-28 and ABS-2 were ~50% Anaheim Lake water. In the latter two wells, groundwater is likely diluted with SAR water recharged upgradient and is consistent with older ^{3}H-^{3}He ages for these wells. In addition, the tracer data provides direct evidence that TOC levels decreased 50% from Anaheim Lake to production well A-27.

Recommendations for further investigations include 1) introduction of a sulfur-hexafluoride tracer into the SAR stream and adjacent recharge basins in order to quantify transit times and dilution of SAR water to nearby wells, 2) introduction of xenon isotope tracers into Anaheim Lake, Kraemer Basin, and Miller Basin to determine the extent of their individual connection to various aquifer zones downgradient and the velocity of groundwater flow, and 3) measurement of $\delta^{18}O$ and ^{3}H-^{3}He ages in wells west of Highway 57 in order to map the preferred flowpaths and flow rates from the recharge area to production areas further west.

INTRODUCTION

Increasing water demands for agricultural and urban use throughout the western United States combined with drought-aggravated shortages has heightened interest in groundwater storage and waste-water reuse. For example, the Orange County Water District (OCWD) for years has developed and applied advanced treatment technology to waste water and injected it into a subsurface seawater barrier project (e.g. see Wesner, 1992; Hudson et al., 1995). OCWD continues to seek alternatives to imported water purchases by increasing water reuse practices and maximizing local water sources. In particular, OCWD seeks to transport and recharge recycled water into surface spreading facilities located in the Forebay region of Orange County (Fig. 1). OCWD currently recharges a total of ~250,000 acre-ft annually derived from the Santa Ana River (SAR), the Colorado River, and northern California to supplement drinking water demands on the groundwater basin. More can be recharged in this area, especially if recycled water can be made available. Proposed California state regulations, however, require that groundwater recharged by recycled sources must reside in the subsurface 6 to 12 months before subsequent use depending on local conditions. Treatment and blending requirements are also affected by whether an unsaturated zone exists in the case of infiltration basins used for recycled water recharge.

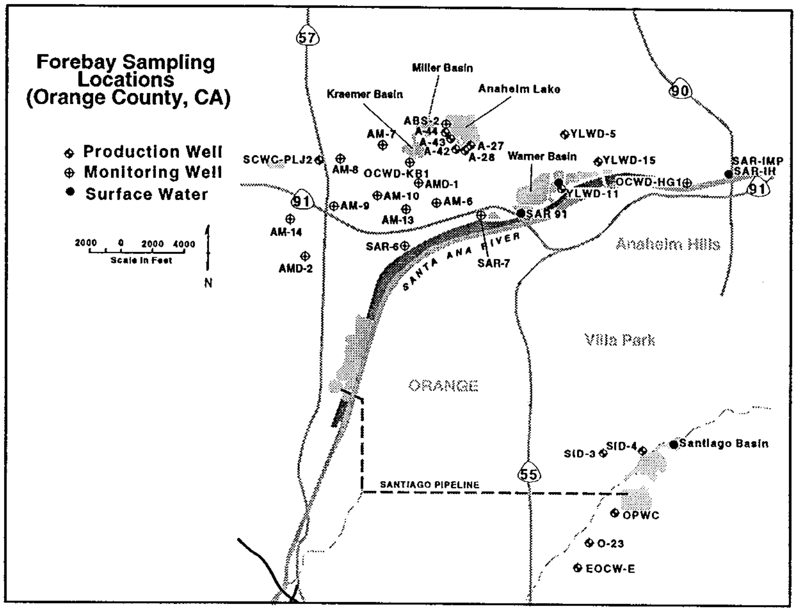

Figure. 1. Location of Santa Ana River, recharge basins, and wells.

In many cases, current hydrogeologic investigative tools (i.e. drilling, pump tests, and computer modeling) are costly and unable to provide the detail needed to demonstrate this level of regulatory compliance. Since one important requirement of the proposed regulations is the groundwater residence time, OCWD has contracted with the Lawrence Livermore National Laboratory (LLNL) to directly measure groundwater ages using isotope hydrology methods. In particular, LLNL is tasked to define with isotopic analysis the flow paths, flow rates, and mixing of groundwater recharged into the Forebay region. The goal of this research is to 1) improve the understanding of the Forebay area hydrogeology and the impact of existing recharge operations, 2) provide quantitative information in which to evaluate a proposed recycled water recharge project in light of the proposed regulatory criteria, including impacts on the basin and production wells, and 3) use this information in developing future monitoring programs. The research is being completed in two phases. The first phase measured in groundwater the existing abundances of oxygen-18 ($\delta^{18}O$), deuterium (δD), tritium (^{3}H), the helium-3 (^{3}He) resulting from ^{3}H decay, and the dissolved noble gases. The intent was to define 1) the general recharge sources and recharge characteristics (temperature, dissolved air, etc.) of groundwater samples using the $\delta^{18}O$, δD, and dissolved noble gas concentrations, and 2) age date the groundwater within one year using the ^{3}H and ^{3}He measurements. The goal of the first phase was to better understand the details of groundwater flow in the Forebay.

The second phase proposes to measure abundances of artificial tracers intentionally introduced into recharging groundwater from surface spreading basins and in the SAR channel. The goals here are 1) to quantify groundwater ages (i.e. travel times) from zero to one year, and 2) to quantify the amount of dilution that occurs during groundwater flow. In particular, isotopically enriched xenon gases can be used as artificial tracers in the spreading basins. For the initial experiment of second phase work, however, Colorado River water was introduced into Anaheim Lake as a tracer since its $\delta^{18}O$ value is much lower than SAR water (Williams, 1994; Davisson et al., 1996a). For tracing groundwater recharged directly from the Santa Ana River, sulfur-hexafluoride (SF_6) can be used as an artificial tracer. This report includes all results from the first phase of research and the initial results from the Colorado River water recharged from Anaheim Lake. The remainder of the second phase of research will be incorporated in future reports.

INVESTIGATIVE APPROACH

General

In 1995 and 1996, LLNL demonstrated in a feasibility study that the ^{3}H-^{3}He dating method could provide age constraints of ±1 year in Forebay groundwater at OCWD (Davisson et al., 1996a). This research also showed that the δD and $\delta^{18}O$ values for this groundwater were variable over space and time, reflecting different recharge pulses. Although the ^{3}H-^{3}He age resolution is adequate for the general hydrogeologic modeling efforts, it was not accurate enough to answer the regulatory question of 0-1 year residence times in the aquifer. Therefore, artificial tracers needed to be introduced into the groundwater system in order to determine younger, more accurate ages. In order to develop an artificial tracer experiment it was necessary to develop a groundwater sampling plan. This plan required that we know when to collect groundwater at which wells in order to quantify the tracer movement and concentration without employing an impractical sampling frequency. This sampling plan was best facilitated by further determination of ^{3}H-^{3}He groundwater ages in the Forebay, and a time-series analysis of $\delta^{18}O$ values. The ages provided a geographical framework in which preferred flowpaths and their flowrates could be determined. The young groundwaters exhibited change in their $\delta^{18}O$ values that, when monitored over time, further resolved groundwater residence times and served to validate the ^{3}H-^{3}He age determinations.

This report includes all the ^{3}H-^{3}He ages and $\delta^{18}O$ data determined for Forebay groundwater from March 1995 through October 1996 (see Table 1). In addition, on October 1, 1996 approximately 6000 acre-ft of Colorado River water was purchased and recharged through Anaheim Lake. The initial $\delta^{18}O$ data from this experiment are also included and discussed (see Table 2).

Stable Isotopes

The stable isotope ratio measurements of oxygen-18/oxygen-16 ($^{18}O/^{16}O$) and deuterium/hydrogen (D/H; deuterium is hydrogen-2) ratios in water were used in this study to identify changes in different water populations in the Forebay groundwater. The method for comparing the isotopic character of different waters lies in the use of a δD- $\delta^{18}O$ plot of the isotope ratios. The $^{18}O/^{16}O$ and D/H ratios are normalized to a recognized standard and the converted results are reported in δ notation (pronounced "del"), whereby

$$\delta D = \left(\frac{D/H}{D/H_{std}} - 1 \right) 1000$$

$$\delta^{18}O = \left(\frac{^{18}O/^{16}O}{^{18}O/^{16}O_{std}} - 1 \right) 1000$$

In this case, the $^{18}O/^{16}O_{std}$ and D/H_{std} are the isotopic ratios of the NBS-standard "Standard Mean Ocean Water" (SMOW). A δ value is a per mil (or parts per thousand) deviation from the standard. A plot of δD vs. $\delta^{18}O$ values provides a graphical means to distinguish various populations of data relating to different water masses of different origins (Fig. 2).

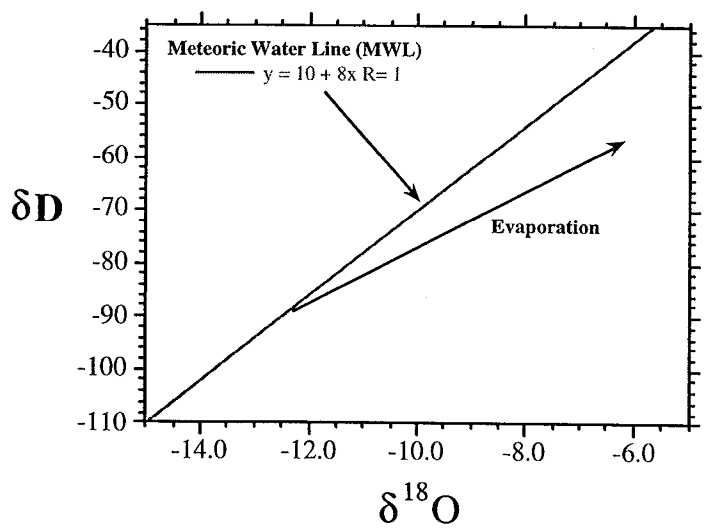

Figure 2. General δD- $\delta^{18}O$ plot showing the Meteoric Water Line (MWL) and the effects of evaporation on natural waters. The slope of the evaporation line can vary between 2 and 6 and depends on the ambient temperature and humidity. The MWL has a constant slope of 8 for global precipitation.

Also on this plot lies what is referred to as the Meteoric Water Line (MWL), a linear regression through the values of various unevaporated precipitation collected world-wide, which results in an equation of $\delta D = 8\ \delta^{18}O + 10$. An evaporated surface water lies to the right of the MWL along a straight line and progresses to the right with increasing evaporation. The proximity of a water's isotopic value relative to the MWL is proportional to the extent of evaporation or isotopic enrichment. Although this approach was used in the initial feasibility study, results from the subsequent work reported here only measured the $\delta^{18}O$ values, since differences between Colorado River (e.g. -11.5 per mil) and SAR waters (e.g. –7.5 ±1.0 per mil), as well as evaporative enrichment of SAR water can be easily distinguished from $\delta^{18}O$ alone. A water's isotopic values relative to the MWL have limited use in this present investigative phase.

Tritium-Helium-3 Age Dating

Attempts have been made in the past to date groundwater with the radioactive (unstable) hydrogen-3 isotope tritium (^{3}H; see Mazor, 1991 and references therein). Because of its radioactive half-life of 12.43 years, it is ideally a good chronometer for young (≤40 years) groundwater flow. Unfortunately from a dating standpoint, ^{3}H concentrations in precipitation have varied considerably over the past 30 years due to ^{3}H production from surface testing of thermonuclear weapons (Fig. 3).

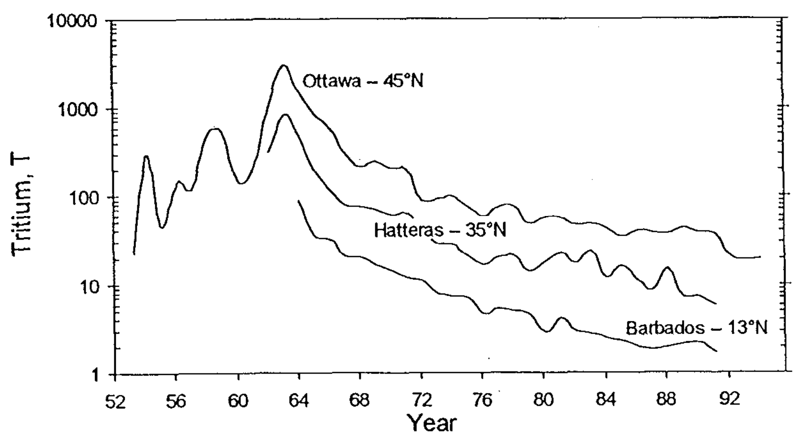

Figure 3. Changes in the ^{3}H concentration in precipitation have varied over an order of magnitude due to fallout of thermonuclear-produced tritium from surface testing.

Tritium measurements in groundwater 20 years ago were useful from the standpoint of tracing the "bomb-pulse" ^{3}H that had recharged into groundwater in the early 1960s and calculating the groundwater travel time based on the observed depth of the "bomb pulse". Today, however, much of the "bomb-pulse" is not well defined in groundwater due to ^{3}H decay and groundwater dispersion. Tritium measurements alone cannot be used for dating groundwater reliably because of the uncertainty in what the original ^{3}H concentration was at the time of recharge.

In more recent years with the development of high-precision noble gas mass spectrometry, the decay product of ^{3}H, helium-3 (^{3}He), can be measured. The advantage to this lies in the dating equation which states

$$-17.9 \ x \ ln\left(\frac{^{3}H}{^{3}H_{0}}\right) = age$$

where ^{3}H is the concentration of the tritium at any given time and $^{3}H_{0}$ is the original tritium concentration at the time of recharge. Since the $^{3}H_{0}$ has a large uncertainty due to the spatially and temporally variable "bomb pulse" tritium, the resulting age calculation will have large uncertainties. By simultaneously measuring the ^{3}He that has resulted from the decay of the tritium (known as the tritiogenic ^{3}He or $^{3}He_{trit}$) we can reconstruct the $^{3}H_{0}$ by adding the tritiogenic $^{3}He_{trit}$ to ^{3}H and derive the initial concentration such that,

$$-17.9xln\left(\frac{^{3}H}{^{3}H+^{3}H_{trit}}\right) = age$$

Several components comprise the measured ^{3}He and they include:

$$^{3}He_{meas} = {^{3}He_{trit}} + {^{3}He_{equil}} + {^{3}He_{excess}} + {^{3}He_{rad}}$$

where ${}^{3}He_{meas}$ is the total ^{3}He analytically measured, ${}^{3}He_{equil}$ is the amount of ^{3}He dissolved in a non-turbulent surface water in equilibrium with the atmosphere, ${}^{3}He_{excess}$ is the amount of ^{3}He dissolved in water exceeding the equilibrium amount (a common phenomenon in groundwater due to excess dissolved air), and ${}^{3}He_{rad}$ is the amount of ^{3}He produced from radioactive decay of isotopes other than tritium. The latter species is very minor and totals only about 0.2% of the total ^{3}He.

Separating these different components of the ^{3}He requires additional measurements of the ^{4}He abundance which comprise:

$$ {}^{4}He_{meas} = {}^{4}He_{equil} + {}^{4}He_{excess} + {}^{4}He_{rad} $$

where the subscripts are the same as those for ^{3}He. In the case of ${}^{4}He_{rad}$, a product of uranium-thorium decay, the abundance can be significant where older waters are involved (e.g. >1000 years old).

The ${}^{3}He_{equil}$, ${}^{4}He_{equil}$, and ${}^{4}He_{rad}$ terms are either assumed or determined by other noble gas abundance measurements (see below), while the ${}^{3}He_{rad}$ term is assumed. The two unknowns left are the excess air terms and the tritiogenic ^{3}He, of which we can formulate two equations to solve for them.

The ${}^{4}He_{meas}/{}^{4}He_{equil}$ ratios provide a method for determining the excess air contribution to the sample, since a ratio >1.0 is created by incorporation of more dissolved helium than in equilibrium with the atmosphere, assuming an appreciable amount of ^{4}He has not accumulated from radioactive decay (see below). In this study, that assumption is essentially valid since most waters are expected to be young (<100 year old). This assumption has been validated with additional noble gas measurements. If radiogenic ^{4}He is a concern, though, the ${}^{3}He/{}^{4}He$ ratios can be calculated and compared to ratios expected in water at equilibrium concentrations. This comparison is important since if there is any appreciable radiogenic ^{4}He, then the ${}^{3}He/{}^{4}He$ ratio relative to equilibrium will be <1.0. This is due to the accumulation of ^{4}He from uranium-thorium decay. Where there are indications of radiogenic ^{4}He we can correct for it in the age calculations.

Noble Gas Abundances

The noble gases of helium, neon, argon, krypton, and xenon naturally occur at trace abundances in the atmosphere. They also dissolve in groundwater during recharge. Their dissolution is controlled by 1) equilibrium solubility and 2) incorporation of excess air. The solubility of the noble gases in non-turbulent, free-standing water is temperature dependent, with increasing solubility with decreasing temperature. This temperature dependency is most pronounced in the argon, krypton, and xenon concentration (Fig. 4).

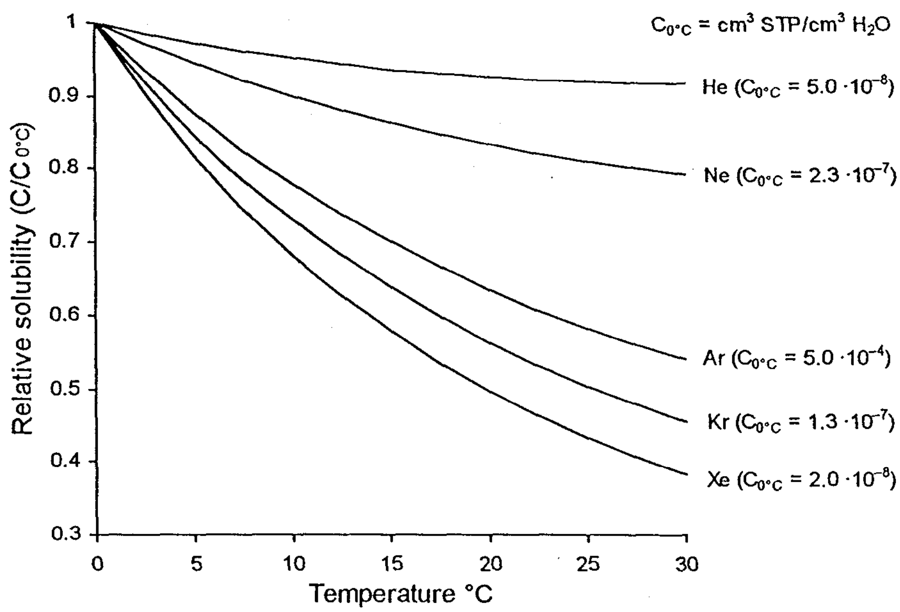

Fig. 4. Solubility of noble gases in water at various temperatures can be used to calculate groundwater recharge temperatures. See Mazor (1991) for examples and further discussion.

The curves in figure 4 provide a means to calibrate measured dissolved noble gas abundances in groundwater against its recharge temperature. During most groundwater recharge, the mean soil temperature dictates the equilibrium noble gas concentrations dissolved in recharging water, which in most regions is around 2°C greater than the mean annual air temperature (for example see Mazor, 1991). In the Forebay groundwater, recharge may be very rapid, and the equilibrium noble gas concentration may also be controlled by the air temperature at the time of recharge.

Dissolved noble gas abundances, other than helium, in groundwater that exceed an equilibrium amount results from dissolution of excess air. Incorporation of excess air into recharged groundwater is thought to occur when air in the vadose zone is trapped by a plug of recharge water and is transported to deep enough depths that it is dissolved. Groundwater recharged through a vadose zone likely has excess dissolved air. In almost all cases the composition of the excess air is the same as the atmosphere (Heaton et al., 1981). Therefore, the amount of noble gases dissolved in groundwater above the equilibrium amount is a simple arithmetic addition of each noble gas from the atmosphere. Therefore, the amount of each dissolved noble gas relative to each other within a single sample should reflect a single equilibrium solubility temperature at the time of groundwater recharge. The amount of excess air dissolved in a groundwater can also provide qualitative information about the type of groundwater recharge. For instance, high excess air content may suggest recharge by a periodic "piston" flow under vadose zone conditions. Little excess air may suggest recharge with a limited vadose zone such as in river or lake infiltration.

The remaining noble gas effect that requires some consideration is the build-up of radiogenic ^{4}He. There is a constant flux toward the ground surface of ^{4}He derived from radioactive decay of uranium and thorium in the Earth's crust that, given enough time, can accumulate in groundwater. Typically groundwater that is thousands of years old will have an appreciable amount of radiogenic ^{4}He, while young groundwater (<100 years old) has little or none except in special conditions such as close proximity to large-scale active faults.

To test for the presence of radiogenic ^{4}He, the other noble gas abundances must be measured and calibrated to a recharge temperature. With this recharge temperature, the ^{4}He content can be predicted based on equilibrium solubility. Any ^{4}He that is above this predicted amount can be attributed to radiogenic ^{4}He, and subsequently subtracted. This will provide a revised $^{3}He/^{4}He$

ratio that can be used for calculating the groundwater age. In almost all groundwater sampled and analyzed in the Forebay, the radiogenic ^{4}He is negligible. Only wells A-47 and F-AIRP sampled further downgradient had detectable radiogenic ^{4}He. In these cases, groundwater in the well was a mixture of young and old water (see Davisson et al., 1996a).

Field Sampling

Over 60 samples were collected and analyzed for δ^{18}O, ^{3}H-^{3}He ages, or noble gas concentrations from March 1995 through October 1996 (Table 1). Monthly samples for some wells were collected for time-series analysis. Some gaps exists in this sampling due to well failure or maintenance. Also, Anaheim Lake was empty periodically for routine cleanup.

Groundwater was sampled from either dedicated turbine pumps in domestic supply wells or with a portable submersible pump lowered on a boom truck into monitoring wells. Three well volumes were pumped before sampling. Westbay-type wells require no purging mechanism and groundwater was collected in evacuated stainless steel bailers. Noble gas samples were collected from Westbay wells with a modified sampling tool as discussed in detail below. Surface water samples were either a grab sample collected from the shore or collected with a peristaltic pump at different depths from a boat in the center of the spreading basins. SAR samples were collected along the shore at the Imperial Headgates except for storm samples, which were collected by the USGS at their sampling station below Prado Dam.

Temperature, electrical conductivity (EC), pH, dissolved oxygen, and alkalinity were measured in the field when possible at the time of sampling. Commercial colorimetric kits were used for the dissolved oxygen (CHEMetrics CHEMets®) and titration kits for the alkalinity (CHEMetrics Titrets®).

Samples were collected for analysis of ^{18}O and ^{3}H in glass, air-tight sealed bottles. The noble gas sampling required a copper tube pinch-clamp assembly that sealed a water sample in a copper tube free of any gas bubbles. Details of the sampling procedures are provided in Appendix 1.

Westbay Wells

These monitoring wells are completed with a single casing with multiple perforations. A smaller diameter PVC sleeve sits inside this casing and each perforation interval is independently packed off between the annulus of the PVC sleeve and the casing. The inside of the sleeve has machined grooves and a single point ball-valve located at the middle of each perforation level. During sampling, a wireline tool with a train of evacuated bailers is guided down the hole. The tool has an electronically controlled lever that is deployed and is guided to the sampling point by the groove in the PVC sleeve. The tool also has an electronically controlled foot jack that when deployed connects a valve on the tool to the ball-valve of the casing which forms a sealed connection. The valve operates remotely and the water at that perforation level inside the packed off annulus fills the evacuated bailers.

Sampling for the ^{3}H-^{3}He age-dating required a minor modification of the sampling tool and procedures. The copper tube sample for noble gas analysis (see Appendix 2) must be filled free of atmospheric gases. The vacuum level used for the Westbay well bailers was not low enough to ensure reliable samples. Therefore, bailers were not used and, instead, a 4-foot length of copper tubing was vacuum fitted to the bottom end of the sampling tool. The lower end of the copper tubing was connected to a one-way valve and a flow restricting tube. When the tool was seated against the ball-valve of the PVC sleeve and the valve was opened, the water from the perforation interval filled the copper tube and slowly flowed out the bottom through the flow restrictor. This provided a mechanism to flush the copper tube and eliminate entrained air bubbles. The one-way valve prevented back flow of water already inside the PVC sleeve. The copper tube was flushed for several minutes and then the one-way valve was closed. The copper tube was brought to the surface and clamped between the wireline tool and the valve.

Earlier samples encountered problems of only partially filled tubes. A wider diameter flow restrictor and longer flushing times were used to correct this problem. As a matter of testing the reliability of the age-dating samples from the Westbay wells, repeat samples were collected in the course of a single day at one sampling level in one Westbay well. Results in Table 1 show that the reproducibility of the analyses is ~1%, consistent with reproducibility achieved from standard age-dating samples (i.e. Appendix 1).

Analytical Methods

Stable isotopes were measured with a standardized technique using the CO_2 equilibration method for the ^{18}O (Epstein and Mayeda, 1953). The extraction method results in purified CO_2 gas that was analyzed on a VG Prism isotope ratio mass spectrometer at LLNL.

Tritium is analyzed by the helium-accumulation method (Surano et al., 1992), where water samples are cryogenically degassed, sealed, and stored for 15-60 days to allow accumulation of ^3He from the tritium decay. The sample is subsequently degassed and the ^3He is isolated and quantified on a VG-5400 noble gas mass spectrometer.

The copper tubes for the dissolved noble gas measurements are vacuum fitted to an evacuated container. The copper cold seal formed during sampling is uncrimped and the water sample is released into the evacuated container where the water sample is subsequently degassed and the noble gases of interest are isolated and analyzed. The helium isotopes were analyzed on a VG-5400 noble gas mass spectrometer, while the remaining noble gases were analyzed on a Nuclide-6-60 noble gas mass spectrometer.

RESULTS

Time-series $\delta^{18}O$ samples of groundwater were collected from several locations that include surface water and groundwater (Table 1). These data were generated specifically to determine if any significant changes in the $\delta^{18}O$ of surface water in the Forebay were subsequently observed in nearby groundwater after the surface water was recharged. Linking the changes in $\delta^{18}O$ values of surface water recharge to groundwater may provide an upper limit on age, and in special cases tests the ^3H-^3He age.

Samples for the ^3H-^3He method were collected over the course of several months (Table 1). These results represent the mean residence times for groundwater in each particular well at the particular time of sampling. These data were generated specifically to determine the mean age to ±1 year, and from these ages determine the preferred flowpaths and flowrates. In addition, noble gas abundance measurements, performed as part of the ^3H-^3He age-dating method, independently provide general information on the recharge temperature and type of the groundwater recharge.

Surface Water $\delta^{18}O$ Data

The $\delta^{18}O$ values for the SAR samples varied a total of ~0.7 per mil over 550 days, ranging from -7.5 to -8.2 per mil (Fig. 5). The river showed a general decrease in its $\delta^{18}O$ over time, with only two significant increases in the spring and summer of 1996. The spring 1996 sample coincided with a high runoff flow. The frequency of sampling may not have been high enough to record all runoff events in the winter/spring of 1996, so other increases or decreases in $\delta^{18}O$ having short duration may have also occurred. This is illustrated in figure 14, which shows the variation in $\delta^{18}O$ values of the SAR below Prado Dam during two storm events in late 1996. Both storms show a rapid $\delta^{18}O$ increase of over 1.0 per mil with increasing flow. The $\delta^{18}O$ values are not coincident with discharge rate variations after the initial rise.

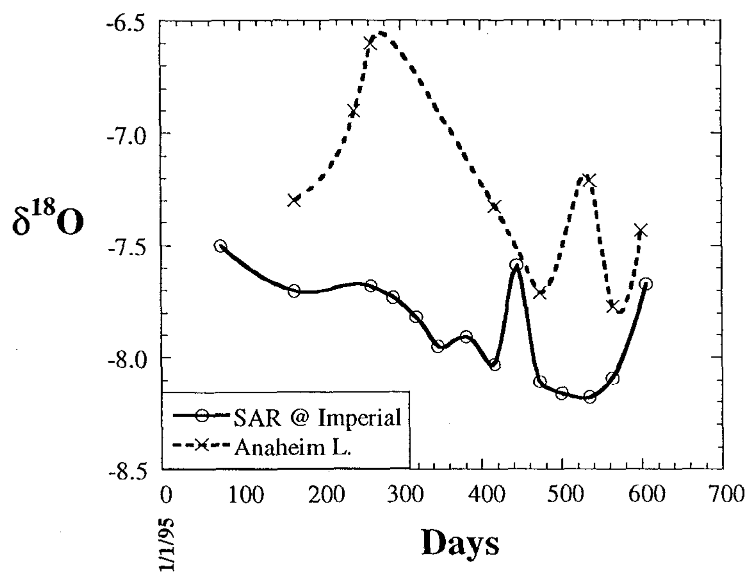

Fig. 5. The $\delta^{18}O$ of SAR shows a general decrease with time with two excursion to higher values during this investigation.

$\delta^{18}O$ in Anaheim Lake water was observed to vary over time more than SAR water. In particular, the $\delta^{18}O$ increased up to -6.6 per mil in summer/fall 1995. The average $\delta^{18}O$ value of Anaheim Lake was higher than the SAR during the study period (Fig. 5). Except when Colorado River water (lower $\delta^{18}O$) is diverted, Anaheim Lake water is derived exclusively from the SAR. The higher average $\delta^{18}O$ value and the large increases during summer months likely result from evaporative enrichment of the lake water. This is demonstrated in figure 6 which shows depth profiles of $\delta^{18}O$ in Anaheim Lake, Warner Basin, and Kraemer Basin collected in June, 1996. All of these basins are fed by SAR water. Even though each recharge pond has a similar depth, only Anaheim Lake has a distinctly higher $\delta^{18}O$ in the upper 10 feet. In summer, lakes typically develop a thermocline due to surface water warming (see Davisson and others, 1996b). If the residence time of water in the thermocline is long enough, significant evaporation and $\delta^{18}O$ enrichment can occur. Anaheim Lake water likely has a high enough residence time that it shows an evaporative enrichment in its $\delta^{18}O$ value above the thermocline. Kraemer Basin is known to percolate faster than Anaheim Lake (~3 ft/day vs ~1 ft/day), and evaporative enrichment of $\delta^{18}O$ may be limited. Warner Basin, however, is not a terminal basin and has continuous SAR water through-flow, therefore, the exact thermocline development and any evaporative enrichment of $\delta^{18}O$ may depend on season and SAR diversion operations. The data in figure 6 is not extensive enough to distinguish the occurrence and extent of evaporative enrichment.

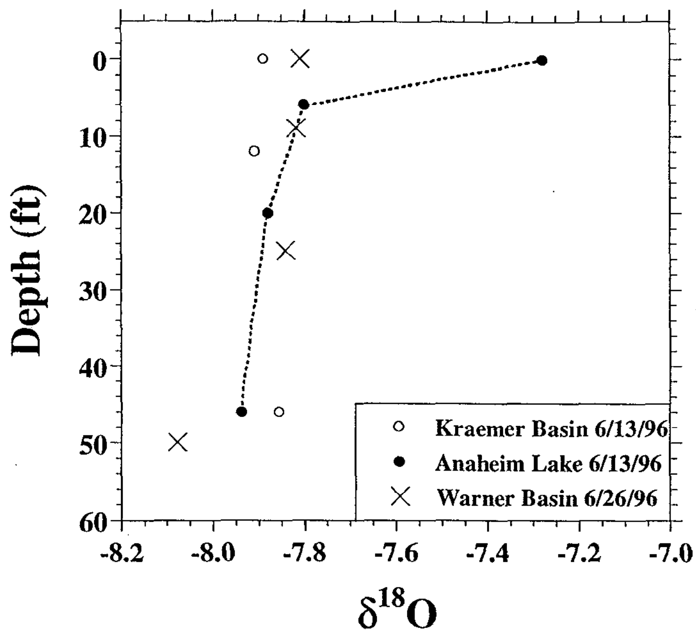

Fig. 6. Summer thermoclines are common in the upper 10-20 feet of lakes and are typically associated with increases in $\delta^{18}O$ due to evaporation. Only Anaheim Lake shows a $\delta^{18}O$ enrichment effect, while in Kraemer residence times may be shorter. Warner Basin is more complex due to through-flow, and more data is required to determine if $\delta^{18}O$ enrichment occurs.

Groundwater

Groundwater recharge has been divided into those wells adjacent to or just down gradient of the SAR, and those adjacent to or down gradient of Anaheim Lake. Other wells are also included which are located outside areas influenced by these recharge sources (i.e. F-AIRP, A-47, and SCWC-PBF4).

Wells Adjacent to the SAR - Wells of this type, which have isotopic measurements completed on them, include HG-1, YLWD-5, YLWD-11, YLWD-15, SAR-6, and SAR-7 (Table 1). The $\delta^{18}O$ values from these well waters ranged from -7.3 to -8.5 per mil. This is the same general range in $\delta^{18}O$ values of the SAR observed during the study period.

Time series $\delta^{18}O$ data collected from HG-1 and YLWD-11 record much of this variation (Fig. 7), starting in March of 1995 and continuing through the summer of 1996. HG-1 and YLWD-11 had the same $\delta^{18}O$ value (-8.0 per mil) at the beginning of sample collection, which was lower than the SAR at this same time (-7.7 per mil). The $\delta^{18}O$ value of HG-1 increased over 0.5 per mil within the next 100 days, maintained this value through late 1995, and then oscillated from -7.3 to -8.3 per mil through the summer of 1996. YLWD-11 showed a similar oscillating trend, but lagged HG-1 by ~120 days, and the magnitude of its variation was smaller. Meanwhile, the SAR only showed a general decrease in $\delta^{18}O$ during this time with only two excursions to higher values in the spring and summer of 1996. These two excursions were not reflected in the data collected from HG-1 and YLWD-11. The variation in $\delta^{18}O$ in HG-1 and YLWD-11 are independent of changes in the $\delta^{18}O$ of SAR during the monitoring period.

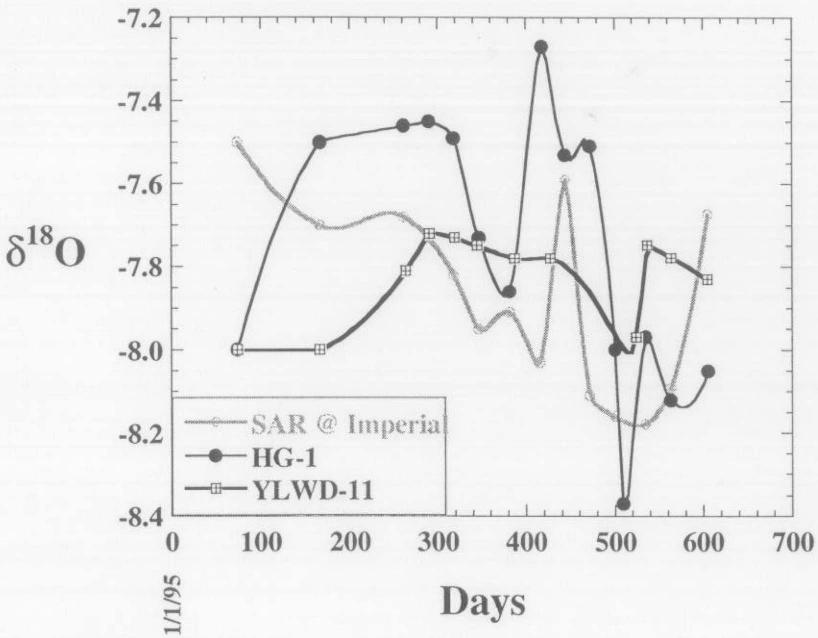

Fig. 7. The $\delta^{18}O$ variation in HG-1 and YLWD-11 are similar, but offset by ~120 days, while they are different than the variation for SAR.

Groundwater was collected from YLWD-5 on only two occasions (both had the same value) and from YLWD-15 only once (Table 1). Their $\delta^{18}O$ values are consistent with an SAR recharge source. The Westbay monitoring well SAR-6 was also measured only once, and SAR-

7 was measured twice (Table 1). No variation of $\delta^{18}O$ in SAR-7 water was observed between these two sample sets. The depth profiles with respect to $\delta^{18}O$ in SAR-6 and SAR-7, however, showed that the upper 800 feet of groundwater had $\delta^{18}O$ values consistent with observed SAR values, but that below 800 feet the values are ~0.5 per mil lower (Fig. 8). The 800 foot depth in this area is the approximate depth to bedrock characterized by consolidated marine sediments (see Herndon, 1992).

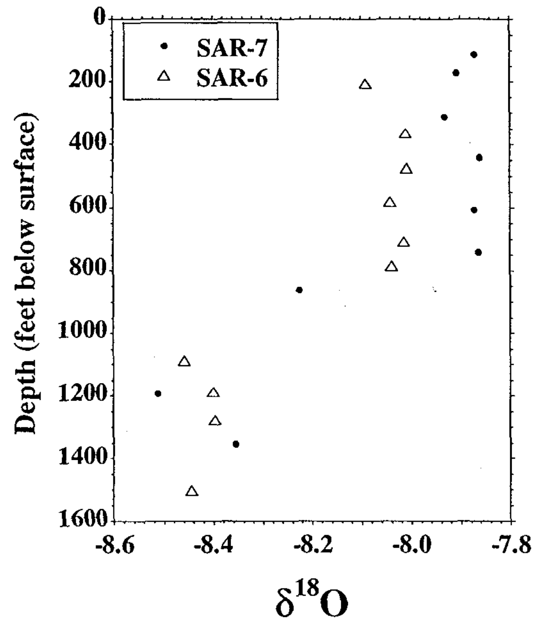

Fig. 8. Above 800 ft, the $\delta^{18}O$ of groundwater in these wells is similar to modern SAR, while deeper groundwater is significantly lower. The 800 ft depth approximately corresponds to top of bedrock.

Groundwater ages in wells adjacent to the SAR vary from <1 year to 15 years (Table 1). HG-1 lies approximately 50 feet from the shore of SAR, and is approximately 50 feet in depth, but has a mean age of ≥1 year, even though groundwater elevations in HG-1 respond quickly to river height (Tim Sovich, personal communication). Likewise, YLWD-11 lies in close proximity to SAR and its off-channel spreading basins and has a perforated depth ranging from 115-514 feet below the surface. Its mean groundwater age, however, is 4 years. Groundwater from YLWD-5 is over half a mile from the SAR (believed to be its recharge source) and ranges in perforated depth from 90-340 feet below the surface. It had a mean age of 11 years. YLWD-15 is within 1,000 feet of the SAR and had a mean age of <1 year. Its perforated interval is unknown.

Groundwater ages from SAR-6 and SAR-7 were between 7 and 15 years. The shallowest samples were the second level of SAR-6 at ~350 feet and the fourth level of SAR-7 at ~410 feet. Mean groundwater ages measured at each of these levels are 10 years old. The groundwater ages increase with depth in SAR-6. Ages in SAR-7 decreased with depth in upper levels, but increased at deeper levels. The oldest age in SAR-7 was actually the fourth level.

Groundwater recharge temperatures calculated from the noble gas abundances ranged from 8 to 27°C (Table 1). Repeat samples on HG-1 ranged between 19 and 27°C, while single determinations on YLWD-5, YLWD-11, and YLWD-15 fell between 13 and 17°C. In all analyses HG-1 had a very low excess dissolved air content (<0.1%), while the YLWD wells all show excess contents of ~1.0%, or within the range of natural groundwater. The lowest recharge temperatures were calculated for two Westbay wells (SAR-7/7 and AMD-1/8). Air temperatures of 7°C are not unreasonable for this region, but most temperature measurements of SAR water typically range between 11 and 28°C.

Wells Downgradient of Anaheim Lake - Wells in this area include AMD-9, A-27, A-28, ABS-2, AM-7, AM-9, AM-10, AM-14, OCWD-KB1, and SCWC-PLJ2 (Table 1). Wells A-42, A-43, and A-44 are also located adjacent to Anaheim Lake, but the lake's influence on these wells is not well understood. In particular, these wells are screened within and below a low-permeability sedimentary deposit at approximately 400 feet below the surface (Table 1). Determining the extent to which transport of Anaheim Lake water across this low-permeability zone occurs is one of the central questions regarding these particular water supply wells. Wells A-27, A-28, and ABS-2 are located adjacent to Anaheim Lake, but have perforation levels completed across or above the low-permeability zone. Anaheim Lake recharge to these wells is anticipated, but exact quantities and travel times need to be better understood. Monitoring well AMD-9 was completed in the summer of 1996 and has perforation levels completed above (levels 1 and 2) and below (levels 3 and 4) the low-permeability zone. The remaining wells are located down gradient of Anaheim Lake, but have perforation levels in permeable strata that are believed to have lateral continuity with shallow aquifer layers below Anaheim Lake.

Time series $\delta^{18}O$ data were generated from spring 1995 to fall 1996 for wells A-27 and SCWC-PLJ2 (Figs. 9a and 9b). Earlier repeat analyses of these two wells (see Davisson et al., 1996a) revealed that the $\delta^{18}O$ value changed significantly over a relatively short period of time; therefore they were selected to be long-term monitoring points. Starting in March, 1995, well A-27 increased in $\delta^{18}O$ from -8.3 to -6.9 per mil over approximately 300 days. In general, this variation was similar to variations in $\delta^{18}O$ of Anaheim Lake water during this same period. After 300 days, Anaheim Lake was emptied of water for approximately 100 days. During this period A-27 showed a significant decrease in $\delta^{18}O$ to -7.7 per mil. This likely represents an isotopic value of a recharge source upgradient of A-27, which is consistent with an SAR water signature.

Well SCWC-PLJ2 initially had a $\delta^{18}O$ value of -10.5 per mil, but steadily increased to approximately -7.7 per mil in about 400 days. The initial $\delta^{18}O$ indicated a significant mixture of Colorado River water (see Davisson et al., 1996a). Therefore, $\delta^{18}O$ values record a transition from Colorado River to SAR during this period. The total time required for this change was ~18 months.

Time-series analysis on deep wells A-42 and A-43 showed that no measurable variation in $\delta^{18}O$ occurred during the period of observation (Fig. 9c). The $\delta^{18}O$ values for A-42 and A-43 were similar to values observed in the YLWD wells (~-8.0 per mil). A repeat analysis on deep well A-44, however, showed a 0.4 per mil increase within an ~2 month period (see Table 1 and Fig. 13). This shift is significant enough to indicate a small change in the recharge source.

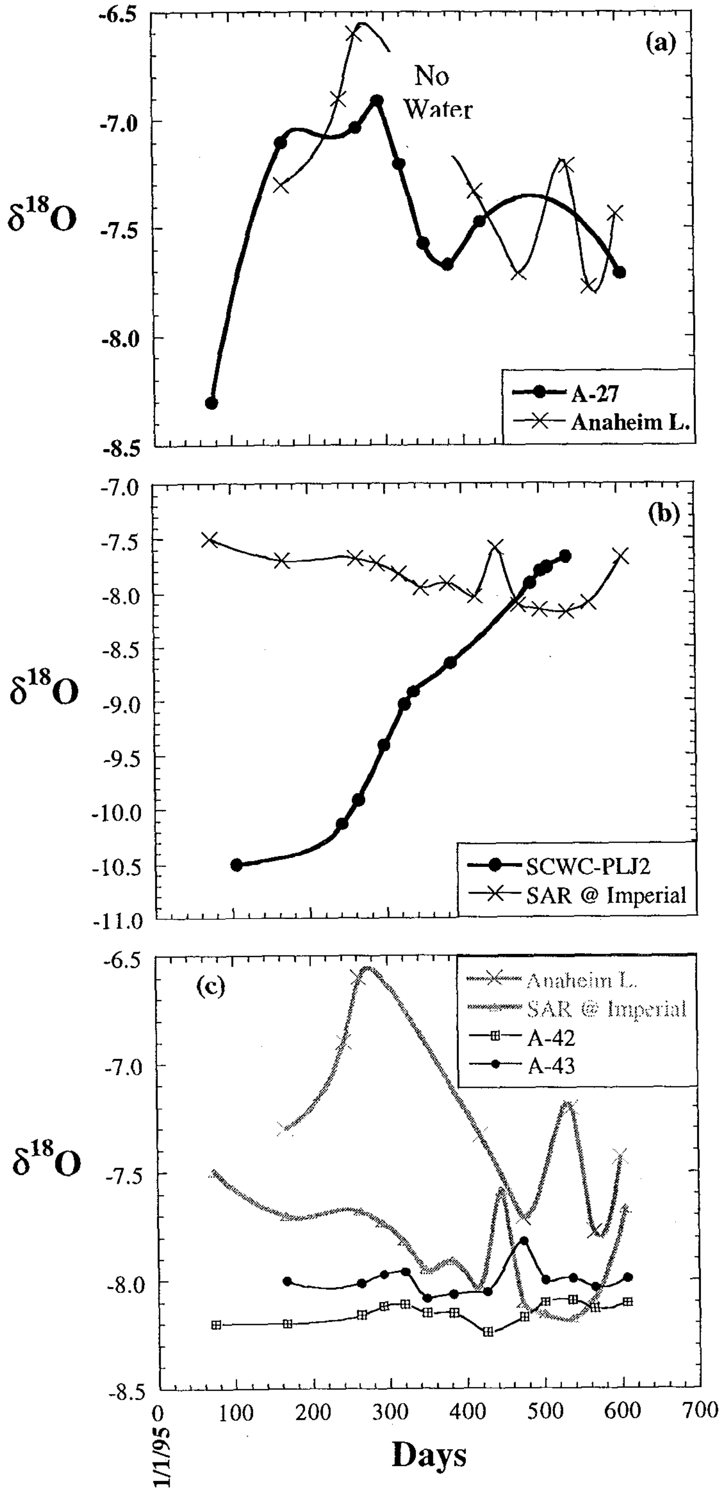

Fig. 9. Time series data for a) A-27 showed close similarity to Anaheim Lake, while b) SCWC-PLJ2 showed a transition from Colorado River to SAR, and c) A-42 and A-43 showed no variation.

Depth-specific samples were collected for A-42, A-43, and A-44 in February, 1997 by inserting a sampling tube down the well casing while the pump was running (Fig. 10). Assuming that all flow from the perforations into the casing was upward, then each sample represents an integration of groundwater at its respective sampling depth plus flow from deeper depths. The $\delta^{18}O$ variation in wells A-42 and A-43 are less than 0.4 per mil, while in well A-44 the variation is 1.0 per mil, ranging from -8.9 per mil at the bottom to -7.9 per mil at the top. Analyses of $\delta^{18}O$ were also completed on composite flows from each of these wells collected from pump discharge. In the case of wells A-42 and A-43, the composite samples were approximate averages of the $\delta^{18}O$ at the different depths, while the composite $\delta^{18}O$ of well A-44 was most similar to the shallowest level.

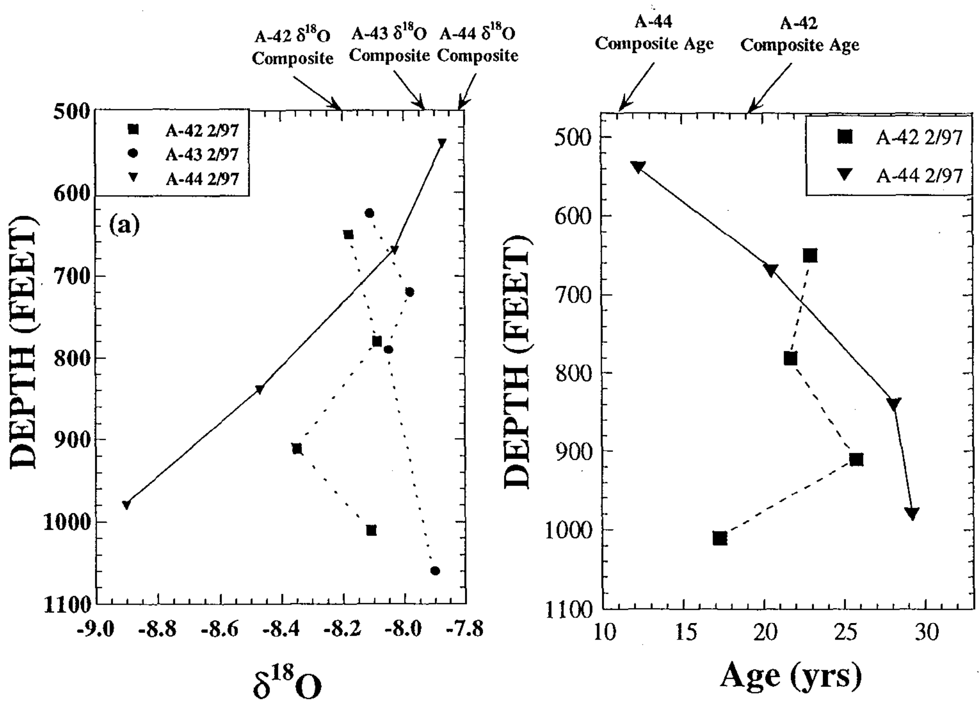

Fig. 10. Depth-specific data reveal that the ^{3}H-^{3}He ages and $\delta^{18}O$ values in A-42 and A-43 are not dramatically different, while well A-44 shows a systematic increase in $\delta^{18}O$ and a corresponding decrease in age with decreasing depth.

The ^3H-^3He ages in the depth-specific samples vary from 12 to 29 years old (Fig. 10). Samples from well A-43 were not collected successfully and were compromised by air. The ages in well A-42 showed a narrow range with the youngest actually occurring at the deepest depth, while ages in well A-44 showed a systematic increase with depth. It should be noted that these results are consistent with flowmeter surveys of these wells. The flowmeter surveys indicated that in A-44, a larger percentage of the water was produced from the shallow perforation interval compared to A-42 and A-43. In A-42, the upper zone (430-660 bgs) produced 31 percent of discharge; in A-43, the upper zone (530-620 bgs) produced 32 percent of the discharge; in A-44, the upper zone (450-660 bgs) produced 67 percent of the total discharge (West, 1997).

Repeat analyses were made on other wells during the study period and include AM-7, AM-9, ABS-2, and OCWD-KB1 (see Table 1). Wells AM-9 and ABS-2 showed a change from a mixture of Colorado River to SAR water similar to SCWC-PLJ2, while wells AM-7 and OCWD-KB1 had an increase in $\delta^{18}O$ similar to A-27, suggesting recharge from recharge basins.

Other wells had only single $\delta^{18}O$ measurements and include AM-10, which was dominated by Colorado River water in the spring of 1995; AM-14, which is downgradient of AM-10, but did not have a Colorado River signature in summer of 1996; and AMD-9, which mostly reflected a SAR $\delta^{18}O$ signature but varied slightly with depth (Table 1).

Mean ^3H-^3He ages are plotted next to their sampling locations (Fig. 11) and range from <1 to 18 years. Wells adjacent to Anaheim Lake exhibited this entire age range. For example, wells A-27 and AMD-9 level 1 had near-zero ages, while wells of comparable depths like ABS-2 and A-28 had ages 5 and 3 years, respectively. In contrast, the deep wells A-42, A-43, and A-44, which are perforated below a low permeability layer, have mean ages of 18, 12, and 11 years, respectively. The increased age with depth below Anaheim Lake is also defined by depth-specific ages in AMD-9, which are near-zero at the upper level, 3 years old at the second level, and 25 years old at the fourth level.

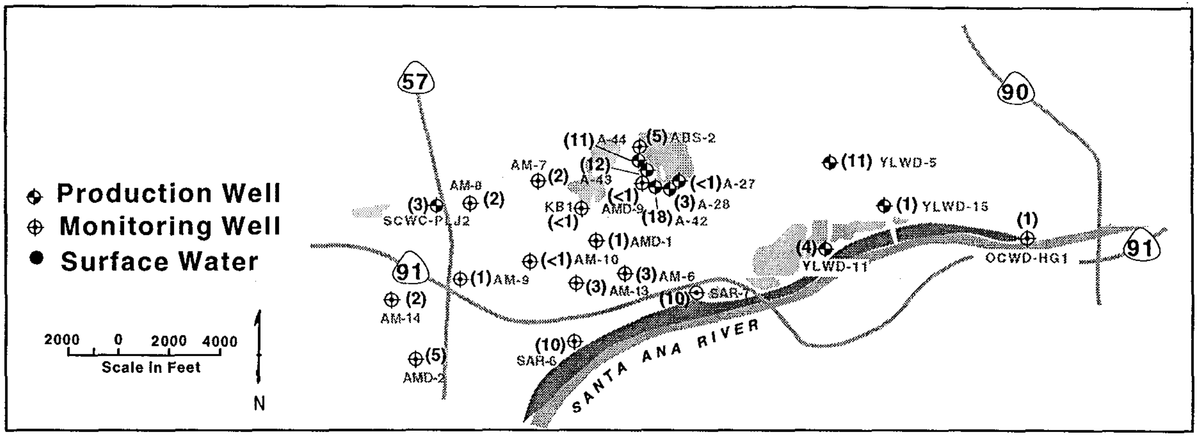

Fig. 11. Mean groundwater ages plotted next to their sampling sites indicate areas of preferred, more rapid flow downgradient of Anaheim Lake, Kraemer Basin, and Miller Basin.

Younger groundwater ages that occurred downgradient of Anaheim Lake fell along a line defined by wells AM-10, AM-9, and AM-14, which sequentially had ages 0, 1, and 2 years. Likewise, groundwaters along a line defined by wells AM-7, AM-8, and SCWC-PLJ2 showed mean ages sequentially of 2, 2, and 3 years. The remaining well in this group, OCWD-KB1, is located at shallow depths adjacent to Kraemer Basin and had a near-zero ^{3}H-^{3}He age.

The recharge temperature and excess dissolved air had a general inverse relationship for most groundwater samples in the Forebay (Fig 12a and 12b). For example, wells located along a potential groundwater flow path from Anaheim Lake west to well SCWC-PLJ2 showed that the recharge temperature and dissolved excess air content were co-variable. Multiple analyses of well A-27, which is located closest to the recharge point, showed a ~20°C variation in its recharge temperature. This variation is consistent with the annual surface water temperature variation of Anaheim Lake, which is similar to the variation in SAR water (e.g. 11-28°C), but probably tend to be higher in the summer. The variation in the excess air of A-27 suggests that unsaturated conditions are periodically encountered during recharge, particularly at times of cooler temperatures. A similar pattern is formed for groundwater along a flowpath from

Anaheim Lake towards well AM-14 (Fig. 12b). Here a similar variation in recharge temperature and the same general dissolved excess air contents were observed.

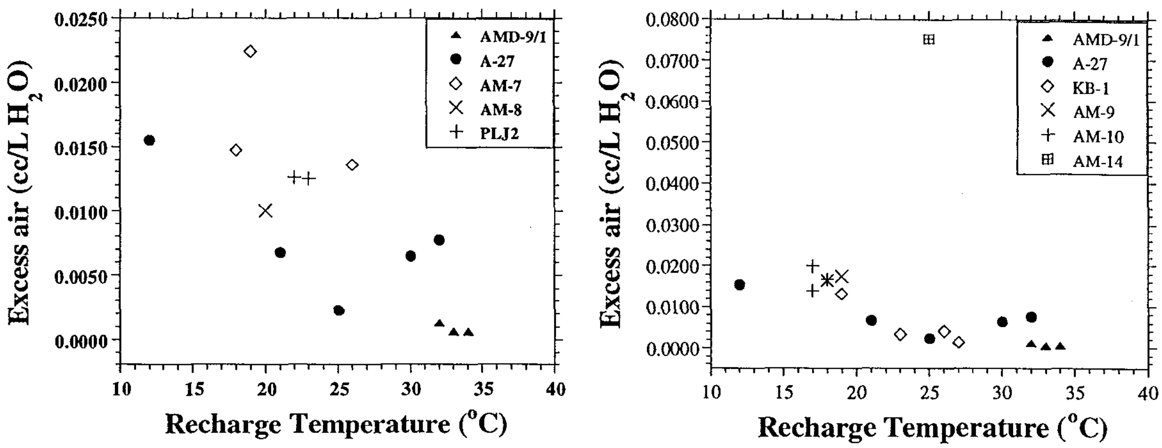

Fig. 12ab. The noble gas recharge temperature and excess air content are quite variable in wells adjacent to recharge points, but are more homogenous in wells further downgradient.

Colorado River Recharge Experiment

On October 1, 1996 Colorado River water was diverted into Anaheim Lake for use as a $\delta^{18}O$ tracer in the groundwater system. The goal of this tracer experiment was to understand travel times from zero to one year and the amount of dilution with other groundwater sources at each well. SAR water in Anaheim Lake before October 1 was entirely drained before the Colorado River water was introduced. The Colorado River water flowed into Anaheim Lake at an average flow rate of ~100 cfs, and a total of ~6000 acre-ft was purchased and diverted over ~50 days. The lake level never exceeded ~25 feet in depth.

Wells A-27, A-28, AMD-9, ABS-2, A-42, A-43, and A-44 (see Table 2) were measured for $\delta^{18}O$ several times in the first week, and then weekly thereafter. The first 120 days of experimental data are reported. As the Colorado River migrates away from the Anaheim Lake area, these monitoring points will be abandoned for others downgradient. The $\delta^{18}O$ value of Colorado River water was determined in Anaheim Lake on two separate days in several locations. Little variation was observed in the Colorado River water while it resided in the lake, remaining between -11.1 and -11.3 per mil. Before arrival of Colorado River water, the initial $\delta^{18}O$ value of wells A-27, A-28, and AMD-9/1 were between -7.2 and -7.5, reflecting a slightly ^{18}O-enriched SAR water source. The $\delta^{18}O$ values of the remaining wells were slightly lower, ranging between -7.5 and -8.1 per mil.

Wells AMD-9 level 1 and A-27 responded similarly to the Colorado River recharge pulse (Fig. 13a). In approximately 15 days from the start of Colorado River diversion, the $\delta^{18}O$ value of these well waters began to decrease. Within 30 days, their $\delta^{18}O$ values comprised nearly 100% Colorado River water. Approximately 30 days later the $\delta^{18}O$ value began to rise, and within another 30 days it had returned to an SAR water signature. Therefore, for these two wells, the arrival time of the tracer pulse was ~15 days, the turnover time was 30 days, the dilution was nearly zero, and the duration of the tracer was ~90 days.

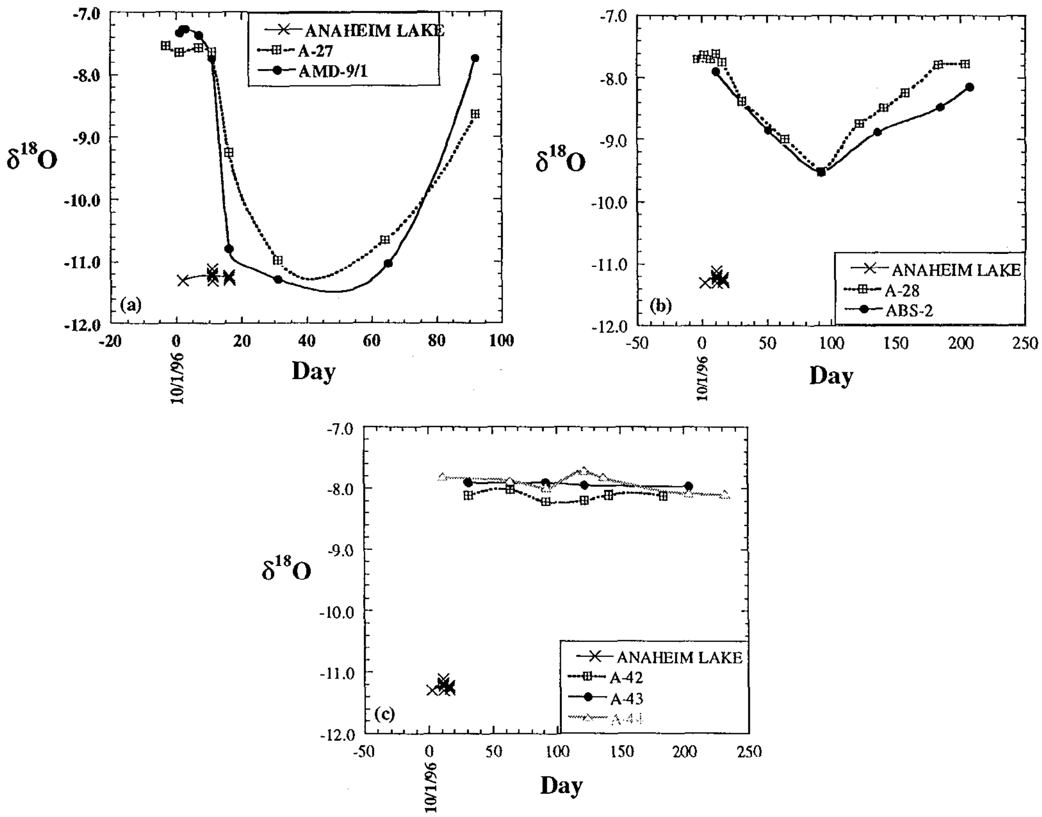

Fig. 13. a) 100% of Colorado River recharge from Anaheim Lake arrived in ~15 days in AMD-9 level 1 and A-27. Arrival times were approximately the same, but ~50% diluted in b) A-28 and ABS-2. c) The $\delta^{18}O$ data for deeper wells indicate no Colorado River tracer during this period.

Water quality analyses were collected for the Colorado River water in Anaheim Lake during the recharge period and also for AMD-9 level 1 and A-27 when the water was nearly 100% Colorado River water (Table 3). The higher EC levels in these well waters also reflect nearly 100% Colorado River. The total organic carbon (TOC) concentration in Colorado River water in Anaheim Lake was measured at 3.0 mg/L. The TOC was ~2.1 mg/L in AMD-9/1 and only 1.5 mg/L in A-27. This is strong quantifiable evidence that 50% TOC removal occurred during recharge through Anaheim Lake for groundwater produced at well A-27.

Table 3: Water quality data collected during Colorado River recharge experiment

	Anaheim Lake10/2/96	AMD-9/1 10/16/96	A-27 10/31/96
pH (field)	8.2	7.2	8.0
Temp. °C	23.0	26.7	25.6
EC µS	1050	1040	1050
Alk. mg/L CaCO3	118	125	136
Diss. Oxygen mg/L		0.1	
NO3-N mg/L	<0.1	0.31	0.40
SO4 mg/L	265	260	256
Cl mg/L	94.6	86.0	84.8
As µg/L	5.0		5.7
B mg/L	0.16	0.20	0.17
TOC mg/L	3.04	2.09	1.50

The arrival of Colorado River water in wells A-28 and ABS-2 also behaved similarly to each other (Fig. 13b). The $\delta^{18}O$ in these wells also began to decrease after ~15 days, however, the change was much slower than in wells AMD-9 level 1 and A-27. A-28 and ABS-2 did not reach a minimum $\delta^{18}O$ value until after ~70 days. The minimum $\delta^{18}O$ value they reached was only a ~50% mixture of Colorado River water. The subsequent increase in $\delta^{18}O$ in these wells also was slower, and they returned to an SAR-source signature after ~150 days. Therefore, for these wells, the arrival time of the tracer was ~15 days, the turnover time was ~60 days, the dilution was ~50%, and the total duration of the tracer was ~120 days.

The remaining wells, A-42, A-43, and A-44 all showed no variation in their $\delta^{18}O$ during the period of this initial monitoring (Fig. 13c). From the perspective of the $\delta^{18}O$ measurements, where analytical uncertainty is ±0.1 per mil, this suggests that Colorado River water was not observed in these well waters within the first 120 days. This statement is accurate for Colorado River contribution of ≥10% within a mixed groundwater. Therefore, for example, if 5% of the groundwater in these wells was Colorado River, the change in the $\delta^{18}O$ of the well water would be too small to cause a significant variation in the $\delta^{18}O$ value.

DISCUSSION

Groundwater Flowpaths

In the Forebay area groundwater flowpaths can be defined by conventional hydrogeologic methods, which combine groundwater gradients with general permeability of subsurface geologic material. In general, groundwater elevations measured in monitoring wells decrease ~160 feet from east to west across the Forebay. Groundwater flow directions are theoretically orthogonal to the lines of equal groundwater elevation. For example, based on the November 1996 water table contours, groundwater recharge should follow a flowpath that originates at the upper SAR, and from its off-channel recharge basins, and flow to the immediate west, toward Anaheim Lake and just south of the lake (Fig. 11). Further downstream along the SAR, the groundwater levels form a steep gradient that indicate river recharge flows away from the river in a northwest direction before turning west. Groundwater flowpaths that originate from Anaheim Lake, Kraemer Basin and Miller Basin recharge should flow directly west away from these recharge points.

In the case of the Anaheim Lake, Kraemer Basin, and Miller Basin recharge, preferred groundwater flowpaths correlate to geologic layers of coarse grain size and high permeability. These layers lie within 400 feet of ground surface and are continuous with areas west of

Highway 57. Upgradient in the Yorba Linda area, geologic data of similar detail are not available, but permeable layers forming preferred flowpaths likely occur here also, which direct groundwater from the upper SAR toward areas beneath Anaheim Lake, above and below the confining layer at ~400 feet. This is suggested by the $\delta^{18}O$ data collected during the initial Colorado River recharge experiment at Anaheim Lake. This data indicated that in wells A-28 and ABS-2, mixing occurred between the recharged Colorado River and a water with an SAR isotopic signature (see Fig. 13b).

Conventional Groundwater Flowrate Calculations

Groundwater flow rates along the flowpaths can be estimated in several ways in the Forebay. For instance, a conventional hydrogeologic approach is to estimate the hydraulic conductivity of the aquifer material and combine it with the hydraulic gradient, defined by the groundwater elevations, to estimate travel times. Groundwater flowrates can be calculated from a simple formulation of the Darcy groundwater flow equation such that

$$v = \frac{K}{p} \nabla h \qquad (1)$$

where v is a linear flow rate, K is the average hydraulic conductivity, p is the average effective porosity of the geologic material, and ∇h in general is the change in groundwater elevation between two horizontal points. Although the porosity term has some uncertainty, the hydraulic conductivity parameter can vary on a logarithmic scale. Therefore, K may vary several orders of magnitude within small distances, so that travel time calculations, particularly those of short duration, may result in large uncertainties. Reducing this uncertainty by conventional means requires additional geologic data, which can only be collected by drilling new wells and performing numerous aquifer hydraulic tests.

One of the goals of this research is to reduce the uncertainty in groundwater travel time estimates within the Forebay. Isotopic data provide a means to either directly age date groundwater or derive an age from tracer data. The age is an important determination since we can independently derive a linear flow velocity such that

$$v = \frac{distance\ from\ source}{groundwater\ age} \qquad (2)$$

The uncertainties related to this calculation reside in the uncertainties of the direct age measurement (i.e. ^3H-^3He ages; see Davisson et al., 1996a), or in the knowledge of recharge source and timing in the case of using a natural or artificial tracer for age determinations. In general, these uncertainties are far smaller than uncertainties related to estimated hydraulic conductivity parameters by conventional means.

<u>Calculations of Groundwater Flow Rates Using $\delta^{18}O$</u>

Anaheim Lake, Kraemer Basin, and Miller Basin Recharge - Young groundwater exhibits changes in $\delta^{18}O$, which reflect changes in $\delta^{18}O$ of the recharge source. An inspection of first-order variations in the $\delta^{18}O$ data of the Forebay groundwater reveal general groundwater flow rates. For example, the 1994 recharge pulses of Colorado River water that originated in Anaheim Lake, Kraemer Basin, and Miller Basin were observed in wells AM-9, AM-10, ABS-2, and SCWC-PLJ2 in the spring of 1995. Approximately a year later, Colorado River water was absent in these wells. During that year no Colorado River water was recharged, therefore, groundwater travel times to these sampling points from the recharge area was on a one year time-scale.

We can further resolve detail in the travel times defined by the Colorado River $\delta^{18}O$ values by analyzing the time-series data collected for well SCWC-PLJ2 (Fig. 9b). In this well, we observed that the groundwater recharge source changed from a predominantly Colorado River water to an SAR water in ~1.5 years. If we assume that the initial $\delta^{18}O$ measured in April, 1995 was the steady-state value for the Colorado River recharge reaching this well, and that the final $\delta^{18}O$ measured was the steady-state value for SAR water, then 18 months was required to change from one source to the other. This suggests a total groundwater transit time from the recharge point to the SCWC-PLJ2 of ~18 months. However, the last of the Colorado River recharge was introduced into Anaheim Lake, Kraemer Basin, and Miller Basin in November of 1994, and it was observed only 6 months later, where it was already migrating out of SCWC-PLJ2, as defined by the trailing edge of $\delta^{18}O$ values (Fig. 9b).

There were actually two separate pulses of Colorado River water recharged into Anaheim Lake, Kraemer Basin, and Miller Basin in 1994. The first was ~40,000 acre-ft introduced from January through June, with the bulk of the recharge from April to June. The second was ~15,000 acre-ft and lasted from October to December. On closer inspection of figure 9b, we can see evidence for both of these pulses in SCWC-PLJ2. For example, between days ~100 and ~240, the change in $\delta^{18}O$ is small, suggesting that the initial $\delta^{18}O$ measurement was near a steady-state $\delta^{18}O$ value. Between days ~240 and ~320, the change in $\delta^{18}O$ follows a steep linear slope. After day 320, the change in the $\delta^{18}O$ followed a more gradual slope. This change in slope indicates a change in the recharge source. This change likely corresponds to the arrival of the second, smaller volume (15,000 acre-ft) of Colorado River water. Therefore, if we extrapolate the slope formed by the points between days 240 and 320, that is the trailing edge of the first pulse, then its intersection with an SAR $\delta^{18}O$ value is at day ~400. This would be the time that groundwater would be completely replaced in SCWC-PLJ2 with SAR water if only the 40,000 ace-ft were recharged. The $\delta^{18}O$ signature of the second, 15,000 acre-ft pulse of Colorado River recharge becomes noticeable after day ~320, which is recorded as the change in slope. Since the second recharge pulse was less than half the volume of the first, its influence on the $\delta^{18}O$ value of water observed in SCWC-PLJ2 was minimized.

Because the subsurface below the Forebay comprises geologic material with variable permeabilities, we anticipate that a tracer pulse, such as Colorado River water, traveling through permeable layers will disperse and mix with other groundwater. This dispersion will cause the leading and trailing edges of the tracer signal to increase and decrease, respectively, with time. In the case of the $\delta^{18}O$ data for SCWC-PLJ2 (Fig. 9b), the data only exhibits the trailing edges of both the 1994 Colorado River recharge pulses, and their leading edges are absent. Ideally, travel time would best be determined from the leading edge when the concentration of the tracer is 50% of the total. Since the leading edge is not observed, we may assume that the tracer curves have a symmetrical bell-shape, and that day ~100 is the mid-point, in which case the 50% concentration of the 40,000 acre-ft pulse would be around mid-June, 1994. That suggests a minimum travel time of only 2-3 months from the recharge basins to SCWC-PLJ2. Alternatively, if we only assume that day ~100 is the mid-point of the 40,000 acre-ft recharge pulse, which was in the recharge basins in May, 1994, then this would provide a maximum travel time of around 10-11 months. Using the same approach, a similar range in transport rates can be gleaned from the trailing edge of the 15,000 acre-ft recharge pulse.

We can use a combination of equations (1) and (2) to calculate linear flow velocities and hydraulic conductivities for groundwater originating from the recharge ponds and flowing to SCWC-PLJ2. For example, if all the recharge originated from Anaheim Lake (the furthest distance from SCWC-PLJ2), and recharge requires anywhere from 2 to 11 months to arrive there, then a calculated range in linear flow velocity is 140 to 25 ft/day. Assuming a groundwater elevation drop of ~40 ft over this distance, and an average porosity of 30%, then we calculate a range in hydraulic conductivity of 8900 to 1600 ft/day. If we assume that all the recharge originated from Kraemer Basin (shortest distance), then the range in linear flow velocity is 90 to 16 ft/day, and the hydraulic conductivity is 5800 to 1000 ft/day. This range in hydraulic conductivity values calculated are consistent for known values of coarse gravel (e.g. Dominico and Schwartz, 1990).

Groundwater velocities were calculated from $\delta^{18}O$ measurements collected during the Colorado River recharge experiment at Anaheim Lake. Here, arrival times of the tracer to wells AMD-9 level 1, A-27, A-28, and ABS-2 were ~15 days from the time of recharge (Figs. 13a and 13b). Since all these wells are within 200 feet of the shoreline of Anaheim Lake, the travel times will actually be a combination of lateral and vertical flow components. In general, the effective distance that the Colorado River recharge travels to these wells is approximately equivalent to the average depth of each well. Therefore, approximate flow velocities calculated for wells AMD-9 level 1, A-27, A-28, and ABS-2 are respectively, 14 ft/day, 16 ft/day, 20 ft/day, and 11 ft/day. These velocities are lower than that calculated for well SCWC-PLJ2, since these wells have a higher ratio of vertical to lateral flow components than for SCWC-PLJ2. Vertical hydraulic conductivities are always lower than horizontal hydraulic conductivities.

SAR Recharge - The SAR watershed is 2670 mi^2 and spans a geographic area from the San Bernadino Mts. in the east to the Santa Ana Hills in the west. Because large variations in mean $\delta^{18}O$ values of precipitation exist over this geographic expanse (Williams and Rodoni, 1997), large variations in $\delta^{18}O$ of SAR flow is also anticipated. Almost all of the SAR storm flow is temporarily stored behind Prado Dam. Storage can be quite variable depending on amount and intensity of storm events, but rarely exceeds 50,000 acre-ft. Annual SAR flow averaged over an 11-year period from 1985 to 1996 was 328,500 acre-ft per year (Tim Sovich, pers. com.). Even with maximum storage behind Prado, several storage volumes of SAR water are turned over annually in the Prado Basin area. Therefore, it is unlikely that effects such as evaporation (as seen in Anaheim Lake) cause the significant variations in the $\delta^{18}O$ of the SAR water observed in figure 5. These variations are likely due instead to different surface water sources in the SAR channel caused by either storm events or changes in baseflow sources. Figure 14 shows that rapid and significant changes in $\delta^{18}O$ can occur in storm water below Prado Dam. In particular, the two storms collected showed that $\delta^{18}O$ increased from approximately -8.0 to -6.5 per mil with initial increase in stream flow. This likely results from a predominance of local storm water runoff, rather than runoff from higher elevations in the watershed region where $\delta^{18}O$ values are much lower.

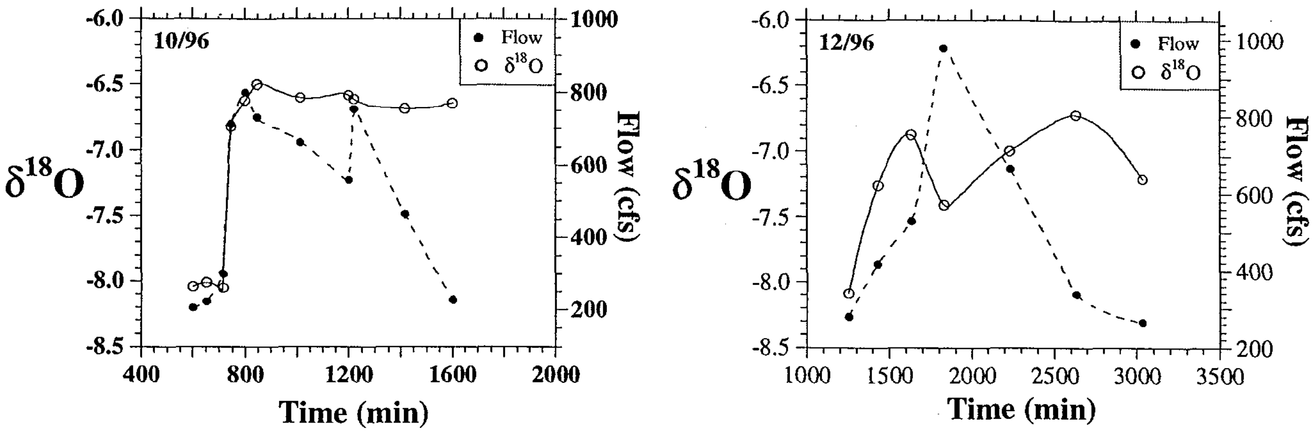

Fig. 14. The $\delta^{18}O$ of SAR of two storms in late 1996 showed significant increases in response to increased flow. The magnitude and rapidity of $\delta^{18}O$ change in SAR suggests that sample collection for time-series data in figure 5 was not frequent enough to capture all the variation.

Base flow in the SAR has a much lower $\delta^{18}O$ value (around -8.0 per mil) than storm water. This probably results from a combination of 1) a component of surface water flow derived from higher in the watershed, 2) waste-water discharge from upstream communities that use lower $\delta^{18}O$ water sources, and 3) discharge of State Water Project water ($\delta^{18}O$ = -9.0 per mil) into the SAR to supplement water demands. The relative proportions of these three sources at any given time probably cause variations in the $\delta^{18}O$ of SAR water during base flow periods.

Given the transient nature of $\delta^{18}O$ in the SAR and the rapidity of its change at least during storm events, the comparison of SAR $\delta^{18}O$ values with wells HG-1 and YLWD-11 in figure 7 is likely not valid. This is because the frequency of $\delta^{18}O$ change in the SAR water is greater than the frequency of sampling performed during the course of this investigation, and key time intervals relating SAR water to the well waters may be missing. This may explain in part why the SAR and HG-1 show no correlative trends in figure 7 even though HG-1 is ~50 feet from the river bed.

Despite their proximity to the SAR, wells HG-1 and YLWD-11 both have a measurable ^{3}H-^{3}He age (see Table 1), with HG-1 at approximately one year, and YLWD-11 at 4 years. This suggests that a mixture of different water sources influence the $\delta^{18}O$ values of these two wells and may explain some of the departure from SAR values. It should also be noted that the timing and direction of $\delta^{18}O$ change in these two wells are similar, with YLWD-11 lagging approximately 120 days and having a smaller overall variation (Fig. 7). This similarity suggests that YLWD-11 lies down-gradient, along the same flow path as HG-1. Assuming this hypothesis is correct, this further suggests that a total travel time of 120 days is required for groundwater to flow between these two wells, and suggests a linear flow velocity of ~63 ft/day. Given a hydraulic gradient of 0.0063 for this area, a hydraulic conductivity of ~3200 ft/day is calculated. Along that flow path, an older groundwater mixes and increases the ^3H-^3He age and dampens the $\delta^{18}O$ variation in YLWD-11.

Groundwater ages are older under the SAR further downstream. This is best shown in wells SAR-6 and SAR-7, whose ^3H-^3He ages are ~10 years old at depths <400 feet. These wells coincide with the area having steep changes in groundwater levels. To date no young groundwater ages have been found adjacent to this part of the lower SAR. This suggests that groundwater recharge from the SAR in this area may be limited. Furthermore, the steep groundwater gradient may reflect a zone of lower aquifer transmissibility. This may be due to local faulting in this area that constricts groundwater flow. If so, then groundwater would more likely flow to shallower levels, and recharge would be somewhat restricted. This may explain why groundwater ages are fairly old (e.g. 10 years old) at shallow depths in SAR-6 and SAR-7.

Groundwater sampled above 800 ft in SAR-6 and SAR-7 have $\delta^{18}O$ values consistent with SAR water measured during this study. Deeper groundwater below 800 feet (Fig. 8) has lower $\delta^{18}O$ values. Assuming this groundwater was also recharged by SAR, the lower $\delta^{18}O$ value suggests that a greater amount of upstream water sources contributed to river flow in the past.

Groundwater recharge probably occurs beneath the SAR between Prado Dam and Imperial Highway, and flows parallel to the river. This recharge flows slower than the river water and acquires increasing ^3H-^3He ages as it flows down-gradient, where it mixes and induces ^3H-^3He ages on wells HG-1, YLWD-11, SAR-7, and SAR-6. Ultimately, much of this groundwater may rise to shallower levels in the lower SAR, where faulting is hypothesized and where the groundwater gradient increases sharply.

Calculations of Groundwater Flow Rates Using ^3H-^3He Ages

Most groundwater ages determined by the ^3H-^3He method in the Forebay are mean ages. This is due to mixing of groundwater with different ages along aquifer layers and in production wells with multiple perforation levels (see Davisson et al., 1996a). Unlike the $\delta^{18}O$ variations, the ^3H-^3He ages are not necessarily linked to identifiable recharge events. In addition, because ^3H concentrations were higher in the past, mixing between older water (<35 years old) and young water is non-linear, and is reflected in an older mean age. Therefore, calculating flow rates and hydraulic conductivity parameters from the ^3H-^3He ages between two points will yield apparent values rather than actual values. Although apparent flow rates derived from the ^3H-^3He ages do not provide quantitative knowledge needed to fully address regulatory issues for reclaimed water, they may provide the necessary input data for groundwater modeling. In modeling, a mass balance between recharge areas and subsequent flow across various element boundaries must be achieved for a groundwater system. Each element of a model requires a mean groundwater hydraulic conductivity parameter, which represents the average hydraulic conductivity of all the geologic material within that element. Since the ^3H-^3He ages reflect the mean transport rates within a given segment of the Forebay, they should be directly proportional to the mean hydraulic conductivity within that segment.

Linear Velocities, Hydraulic Conductivity, and Mass Balance Calculations - These calculations can be performed on three general flow paths in the Forebay region. For instance, groundwater from wells AMD-9 level 1, AM-10, AM-9, and AM-14 systematically increase from 0 to 2 years, suggesting flow from Anaheim Lake, Kraemer Basin, and Miller Basin recharge to west of Highway 57. All these wells are completed to depths within a relatively high permeability zone. If Anaheim Lake alone recharges this flow path, then the distance and age suggest a linear flow rate within this zone of ~16 ft/day. Using a hydraulic gradient of 0.005 and a porosity of 0.3, we calculate an average hydraulic conductivity of ~990 ft/day. If recharge to AM-10, AM-9, and AM-14 were derived from Kraemer Basin instead, then a linear flow velocity of 12 ft/yr is calculated. Using the same hydraulic gradient and porosity, a mean hydraulic conductivity of ~700 ft/day is calculated.

Flow from AMD-9 level 1 to AM-7, AM-8, and SCWC-PLJ2 is slower, requiring ~3 years to transcend this distance. If Anaheim Lake recharges this flow path, then this suggests a linear flow rate of ~8 ft/yr. Using again a hydraulic gradient of 0.005 and the same porosity, we calculate a mean hydraulic conductivity of ~490 ft/day. If Kraemer and Miller Basins were the principal recharge points for AM-7, AM-8, and SCWC-PLJ2, then a linear velocity of ~5 ft/yr is calculated with an average hydraulic conductivity of ~400 ft/day.

Distinct flow paths are difficult to delineate from the upper SAR toward Anaheim Lake. However, if we assume that A-42, A43, and A-44 are recharged from the SAR, then their mean ages suggest that groundwater flow requires 11 to 18 years to transcend this distance. This suggests a range in the average linear flow rate of 2 to 4 ft/day. Combined with a hydraulic gradient of 0.008, a range in the average hydraulic conductivity would be 80 to 130 ft/day. No other distinct flow rates can be defined from the available data, particularly since at this time distinct flow paths from the SAR to areas south and southwest of Anaheim Lake are still difficult to delineate from the isotopic data. There may be faster flow paths in the recharge upgradient of Anaheim Lake, but they have not yet been identified by isotopic data. All of the hydraulic conductivity values calculated thus far are consistent with porous material comprising sand to coarse gravel (e.g. Dominico and Schwartz, 1990).

We can validate the general accuracy of the ^3H-^3He ages simply by comparing the calculated average of all the age determinations in Table 1 to the capacity of the Forebay aquifer system. For example, the Forebay aquifer system east of highway 57 (Fig. 11) generally reflects a wedge-shaped form with a length of ~24,000 feet, a base width of ~12,000 feet (along Hwy. 57), and an average thickness of ~1250 feet. Assuming a 30% porosity, and no change in storage, we can calculate a total volume of this wedge-shape to be 4 x10^{10} ft^3, or 930,000 acre-ft. Dividing this number by the annual recharge of ~250,000 acre-ft into the Forebay region, we then can calculate that the average turnover rate of the groundwater should be ~4 years. This turnover rate is generally reflected by the mean ^3H-^3He age in Table 1, which is 5.3 years.

We can make a similar calculation for just the area under the influence of Anaheim Lake, Kraemer Basin, and Miller Basin recharge. In this case, if we chose an area ~5000 feet wide and 10,000 feet long with an aquifer thickness of 500 feet and a porosity of 30%, we calculate a volume of ~172,000 acre-ft. The 500 ft thickness was chosen based on the Colorado River recharge results (Fig. 13), which suggest most recharge water from Anaheim Lake flows laterally down-gradient above the ~400 ft confining layer. In addition, in shallower aquifer depths, groundwater ages tend to be young and the $\delta^{18}O$ is variable over time, whereas deeper aquifer layers tend to be older and exhibit little $\delta^{18}O$ change (see Table 1 and Davisson et al., 1996a). The annual recharge rate into these three recharge basins is ~150,000 acre-ft. Comparing this rate to the dimensions selected above, this suggests that aquifer turnover rates affected by recharge from these three basins is a little over one year. The average of all the ^3H-^3He ages in this particular area is 1.5 years. However, the range in ^3H-^3He ages is 0-3 years. This result suggests that 1) some groundwater flow paths transcend this area on the order of <1 year, 2) older groundwater derived from the upper SAR mixes along these flow paths, causing an apparent decrease in the groundwater flow rates, or 3) a region wider than 5000 feet and deeper than 500 feet is influenced by recharge from these three basins. Evidence for the latter explanation has not been identified at this time, and likely a combination of the first two hypotheses is more consistent with the $\delta^{18}O$ data presented above.

Effects of Groundwater Mixing - Several examples of groundwater mixing can be shown in the Forebay groundwater. For instance, as discussed before, groundwater in wells HG-1 and YLWD-11 both have a mixture of older water that causes their ^3H-^3He ages to be greater than one year. In the case of well YLWD-11, the well casing is screened from 115 to 514 feet below the surface, and it can be argued that the well perforates different aquifer layers that have groundwater with different ages. For well HG-1, however, the screening interval is from only 40 to 60 feet and the likelihood that the perforations intercept multiple aquifer layers is reduced. Therefore, it may be more likely that mixing of young and old groundwater occurs within the aquifer that HG-1 perforates. Similarly, SAR water may not percolate at this location because the aquifer here is thin and "full".

An even better example is wells A-28 and ABS-2, both of which are adjacent to, but on opposite sides of Anaheim Lake, and were monitored during the Colorado River recharge experiment. Well ABS-2 is a monitoring well with perforations at 155 to 165 feet below the surface, while A-28 is a production well with perforations at 249 to 361 feet below the surface. These wells responded nearly identically to each other, both receiving about 50% of the Colorado River recharge pulse (Fig. 13b). The Colorado River water tracer duration was longer than in other wells, lasting nearly 150 days. In addition, the ^{3}H-^{3}He ages of ABS-2 and A-28 were 5 and 3 years, respectively. Therefore, an appreciable amount of older groundwater was mixed in the discharge of these wells, and this older water attenuated the Colorado River tracer signal (compare Figs. 11 and 13b). In the case of A-28, it is possible that mixing of different groundwaters occurs within the well casing due to perforation of multiple aquifer layers, but in the case of ABS-2, the screened interval is only 10 feet, and consequently it is more likely that mixing within the aquifer is more prevalent in the region of this well.

Mixing appears to be somewhat limited in the depth-specific samples from the deep A-42, A-43, A-44 wells (Fig. 10). The $\delta^{18}O$ values and the ^{3}H-^{3}He ages vary with depth. For example, in A-42 groundwater ages vary from 17 to 23 years old with the youngest at the deepest depth. The composite age of this water from previous measurements, however, was 18 years, suggesting that groundwater >20 years old in the shallower depths has a small contribution to the mixture. The composite age of ~11 years for well A-44 is most similar to its shallowest level, suggesting that this perforation level contributes to most of the discharge. These examples demonstrate mixing in multiply-perforated well casings is dependent on the relative flow contributions from each level.

A last line of evidence for groundwater mixing is the noble gas concentrations. In particular, groundwater excess air and recharge temperatures in well HG-1, as derived from the noble gas concentrations, suggest that there is little or no vadose zone encountered during its recharge and that its recharge temperature varies widely, similar to the SAR surface water temperatures. Groundwaters down-gradient in the YLWD wells, however, have higher excess air contents and recharge temperatures, more consistent with mean annual soil temperatures. This suggests that groundwater recharge from the SAR mixes with other groundwater that recharged through a vadose zone. In particular, it may mix with recharge from off-channel ponds in the upper SAR area where fluctuating levels may create temporary vadose zones.

In a similar trend, groundwater from well A-27 beneath Anaheim Lake also shows widely varying recharge temperatures as well as excess air contents. This is undoubtedly due to variation in surface water temperatures and a periodic vadose zone beneath Anaheim Lake. Nevertheless, groundwater down-gradient in wells AM-10 and AM-9 has consistent recharge temperatures and excess air contents, again suggesting mixing and homogenization.

RECOMMENDATIONS

Using the ^{3}H-^{3}He age-dating method and the natural $\delta^{18}O$ variation in groundwater in the Forebay provided valuable data for establishing a detailed framework of groundwater flow. In regards to water quality issues that demand groundwater age determinations that are less than one year, and quantitative groundwater dilution criteria, the large uncertainty in these isotopic data limit their utility. Since groundwater flow transcends large distances in less than one year in the Forebay, it is feasible and strongly recommended to introduce inert, non-toxic tracers into recharge points and trace their arrival and dilution to nearby wells. In particular, we recommend:

- Introducing a sulfur-hexafluoride tracer into the upper SAR stream and adjacent recharge basins in order to quantify transit times and dilution of SAR water to nearby wells.

- Introducing distinct xenon isotope tracers into Anaheim Lake, Kraemer, Basin and Miller Basin to determine the extent of their individual connection to various aquifer layers down-gradient and the timing of groundwater flow.

We further recommend that more knowledge be gained about the timing and extent of fast groundwater flow away from the recharge basins toward production wells west of Highway 57. In this case, measurement of $\delta^{18}O$ and ^{3}H-^{3}He ages in wells west of Highway 57 will help map the preferred flow paths and flow rates.

REFERENCES

Davisson, M.L., Hudson, G.B., Herndon, R.L., Niemeyer, S., Beiriger, J., 1996a, Report on the feasibility of using isotopes to source and age-date groundwater in the Orange County Water District's Forebay region, Orange County, California. Lawrence Livermore National Laboratory, UCRL-ID-123953, 31 pp.

Davisson, M.L., Clark, J.F., Hudson, G.B., 1996b, Letter report to OCWD on water quality data depth profiles of recharge basins.

Epstein S., Mayeda T., 1953, Variation of ^{18}O content of waters from natural sources. Geochimica et Cosmochimica Acta 4, pp. 213-224.

Heaton T.H.E. and Vogel J.C., 1981, "Excess air" in groundwater. Journal of Hydrology, 50, 210-216.

Herndon, R.L., 1992, Hydrogeology of the Orange County groundwater basin - an overview. *In* The Regressive Pleistocene Shoreline, Coastal Southern California. Annual Field Trip Guide Book No. 20: South Coast Geological Society, Inc., pp. 237-259.

Hudson G.B., Davisson M.L., Velsko C.A., Niemeyer S., Esser B.K., Beiriger J., 1995, Preliminary report on isotope abundance measurements in groundwater samples from the Talbert Gap injection barrier area, Orange County Water District. Lawrence Livermore National Lab UCRL-ID-122450, 26 pp.

Mazor, E., 1991, Applied Chemical and Isotopic Groundwater Hydrology. Halsted Press: New York, 274 pgs.

Surano, K.A., Hudson, G.B., Failor, R.A., Sims, J.M., Holland, R.C., MacLean, S.C., Garrison, J.C., 1992, Helium-3 mass spectrometry for low -level tritium analysis of environmental samples. Jour. Radioanal. Nuclear Chem. Art., 161, p. 443-453.

Wesner, G.M., 1992, Annual report, Orange County Water District wastewater reclamation and recharge project, 1991. Orange County Water District, 27 pp.

West, M., 1997, City of Anaheim Production Well Nos. A-42, 43, and 44 Flowmeter Surveys. Letter Report, Orange County Water District.

Williams, A.E., 1994, Stable isotopes as tracers of reclaimed water recharge into the aquifers of Orange County, California: Feasibility Study. Report to the Orange County Water District, May 25, 1994, 36 pp.

Williams, A.E. and Rodoni, D.P., 1997, Regional isotope effects and application to hydrologic investigations in southern California. Water Resources Research, 33, 1721-1730.

Table 1: Isotope Data, Ages, and Recharge Temperatures calculated for Groundwater in the Forebay

sample	collection date	$\delta^{18}O$	^3H-^3He age (yrs)	recharge T°C	excess air (cc/LH$_2$O)
AMD-9/1	9/12/96	-	0.4	34	0.0006
AMD-9/1	10/1/96	-7.33	0.4	-	-
AMD-9/1	10/7/96	-7.37	-	32	0.0013
AMD-9/1	10/10/96	-	-	33	0.0006
AMD-9/2	9/12/96	-7.58	2.7	20	0.0173
AMD-9/2	10/7/96	-	-	20	0.0195
AMD-9/4	9/12/96	-7.73	25.3	-	-
A-27/1	4/24/95	-	0.3	12	0.0155
A-27/1	6/19/95	-7.10	0.0	21	0.0068
A27/1	9/20/95	-7.03	-	-	-
A27/1	10/19/95	-6.91	-	-	-
A27/1	11/15/95	-7.20	-	-	-
A27/1	12/1/95	-7.57	-	-	-
A-27/1	1/17/96	-7.67	-	-	-
A-27	2/28/96	-7.47	-	-	-
A-27/1	8/28/95	-	-	25	0.0023
A-27/1	10/1/96	-7.63	-	32	0.0077
A-27/1	10/7/96	-7.56	-	30	0.0065
A-28/1	6/29/96	-7.57	-	-	-
A-28/1	7/17/96	-7.70	2.8	25	0.0262
A-28/1	9/27/96	-7.70	-	25	0.0139
OCWD-KB1	6/22/95	-6.90	-0.3	19	0.0132
OCWD-KB1	7/16/96	-7.87	0.1	27	0.0014
OCWD-KB1	5/29/96	-	-	23	0.0034
OCWD-KB1	9/23/96	-	-	26	0.0042
ABS-2	3/28/95	-9.40	4.7	19	0.0113
ABS-2	9/26/96	-	-	21	0.0241
KBS-2/2	7/30/96	-	-	23	0.0104
KBS-4	9/25/96	-	-	27	0.0037

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sample	collection date	$\delta^{18}O$	^3H-^3He age (yrs)	recharge T°C	excess air (cc/LH_2O)
AMD-1/2	11/17/95	-8.33	-	-	-
AMD-1/3	11/17/95	-8.21	-	-	-
AMD-1/4	11/17/95	-8.40	-	-	-
AMD-1/5	11/17/95	-8.01	-	-	-
AMD-1/6	11/17/95	-8.07	-	-	-
AMD-1/7	11/17/95	-8.26	-	-	-
AMD-1/8	11/17/95	-8.03	-	-	-
AMD-1/9	11/17/95	-7.87	-	-	-
AMD-1/10	11/17/95	-8.07	-	-	-
AMD-1/2	Jan-96	-	-	-	-
AMD-1/3	Jan-96	-7.70	-	-	-
AMD-1/4	Jan-96	-8.46	-	-	-
AMD-1/5	Jan-96	-8.00	-	-	-
AMD-1/6	Jan-96	-8.01	-	-	-
AMD-1/7	Jan-96	-8.12	-	-	-
AMD-1/8	Jan-96	-8.05	-	-	-
AMD-1/9	Jan-96	-7.89	-	-	-
AMD-1/10	Jan-96	-8.05	-	-	-
AMD-1/4	5/22/96	-	1.6	-	-
AMD-1/4	5/22/96	-	1.8	-	-
AMD-1/4	5/22/96	-	2.1	-	-
AMD-1/7	5/22/96	-	5.9	-	-
AMD-1/8	5/22/96	-	10.3	8	0.0181
AMD-1/9	5/22/96	-	9.0	-	-
AMD-2/1	11/10/95	-8.15	-	-	-
AMD-2/2	11/10/95	-8.09	-	-	-
AMD-2/3	11/10/95	-8.08	-	-	-
AMD-2/4	11/10/95	-7.95	-	-	-
AMD-2/5	11/10/95	-6.93	-	-	-
AMD-2/6	11/10/95	-7.83	-	-	-
AMD-2/7	11/10/95	-8.01	-	-	-
AMD-2/8	11/10/95	-7.40	-	-	-
AMD-2/9	11/10/95	-7.31	-	-	-

Table 1: Isotope Data, Ages, and Recharge Temperatures calculated for Groundwater in the Forebay

sample	**collection date**	**$\delta^{18}O$**	**^3H-^3He age (yrs)**	**recharge T°C**	**excess air (cc/LH$_2$O)**
AMD-2/1	Jan-96	-7.73	-	-	-
AMD-2/2	Jan-96	-8.04	-	-	-
AMD-2/3	Jan-96	-8.04	-	-	-
AMD-2/4	Jan-96	-7.94	-	-	-
AMD-2/5	Jan-96	-7.39	-	-	-
AMD-2/6	Jan-96	-7.93	-	-	-
AMD-2/7	Jan-96	-7.97	-	-	-
AMD-2/8	Jan-96	-7.39	-	-	-
AMD-2/9	Jan-96	-7.30	-	-	-
AMD-2/1	5/21/96	-	4.9	-	-
AMD-2/4	5/21/96	-	6.7	-	-
AMD-2/4	5/21/96	-	9.0	-	-
AMD-2/5	5/21/96	-	15.9	17	0.0103
AMD-2/7	5/21/96	-	30.6	10	0.0164
AMD-2/8	5/21/96	-	23.9	-	-
SAR-6/1	5/6/96	-8.09	-	-	-
SAR-6/2	5/6/96	-8.01	-	-	-
SAR-6/3	5/6/96	-8.01	-	-	-
SAR-6/4	5/6/96	-8.04	-	-	-
SAR-6/5	5/6/96	-8.01	-	-	-
SAR-6/6	5/6/96	-8.04	-	-	-
SAR-6/7	5/3/96	-8.46	-	-	-
SAR-6/8	5/3/96	-8.40	-	-	-
SAR-6/9	5/3/96	-8.40	-	-	-
SAR-6/10	5/3/96	-8.44	-	-	-
SAR-6/2	6/25/96	-	9.9	-	-
SAR-6/2	6/25/96	-	10.6	-	-
SAR-6/4	6/25/96	-	15.3	-	-
SAR-6/6	6/25/96	-	-	-	-
SAR-6/7	6/25/96	-	-	-	-

Table 1: Isotope Data, Ages, and Recharge Temperatures calculated for Groundwater in the Forebay

sample	collection date	$\delta^{18}O$	^3H-^3He age (yrs)	recharge T°C	excess air (cc/LH_2O)
SAR-7/1	1/30/96	-7.87	-	-	-
SAR-7/2	1/30/96	-7.91	-	-	-
SAR-7/3	1/30/96	-7.93	-	-	-
SAR-7/4	1/30/96	-7.86	-	-	-
SAR-7/5	1/30/96	-7.87	-	-	-
SAR-7/6	1/30/96	-7.86	-	-	-
SAR-7/7	1/30/96	-8.23	-	-	-
SAR-7/8	1/30/96	-8.51	-	-	-
SAR-7/9	1/30/96	-8.36	-	-	-
SAR-7/1	5/30/96	-7.92	-	-	-
SAR-7/2	5/30/96	-7.94	-	-	-
SAR-7/3	5/30/96	-7.98	-	-	-
SAR-7/4	5/30/96	-7.97	-	-	-
SAR-7/5	5/30/96	-7.75	-	-	-
SAR-7/6	5/30/96	-7.85	-	-	-
SAR-7/7	5/30/96	-8.23	-	-	-
SAR-7/8	5/30/96	-8.50	-	-	-
SAR-7/9	5/30/96	-8.36	-	-	-
SAR-7/4	6/25/96	-	10.1	-	-
SAR-7/5	6/25/96	-	6.8	-	-
SAR-7/6	6/25/96	-	7.8	-	-
SAR-7/7	6/25/96	-	8.7	7	0.0158
AM-6	4/24/95	-8.10	3.4	19	0.0154
AM-6	7/9/96	-	3.4	18	0.01
AM-7	6/26/95	-7.70	2.3	18	0.0147
AM-7	7/17/96	-	2.5	26	0.0136
AM-7	5/28/96	-7.37	-	19	0.0224
AM-8	7/9/96	-	2.3	20	0.01
AM-9	6/22/95	-9.50	0.0	18	0.0165
AM-9	7/17/96	-7.88	1.2	19	0.0174

Table 1: Isotope Data, Ages, and Recharge Temperatures calculated for Groundwater in the Forebay

sample	collection date	$\delta^{18}O$	^3H-^3He age (yrs)	recharge T°C	excess air (cc/LH_2O)
AM-10	4/24/95	-9.70	0.0	17	0.014
AM-10	7/9/96	-	-	17	0.02
AM-10	5/29/96	-	0.2	18	0.0168
AM-13	7/8/96	-	3.1	17	0.0116
AM-14	7/9/96	-	1.9	25	0.0753
SCWC-PLJ2	4/24/95	-10.50	2.1	-	-
SCWC-PLJ2/	8/30/95	-10.13	-	-	-
SCWC-PLJ2	9/20/95	-9.91	-	-	-
SCWC-PLJ2/	10/25/95	-9.41	-	-	-
SCWC-PLJ2	11/20/95	-9.03	-	-	-
SCWC-PLJ2	12/1/95	-8.92	-	-	-
SCWC-PLJ2/	1/19/96	-8.65	-	-	-
SCWC-PLJ2	5/2/96	-7.91	-	-	-
SCWC-PLJ2	5/15/96	-7.80	-	-	-
SCWC-PLJ2	6/17/96	-7.67	-	-	-
SCWC-PLJ2	7/31/96	-	3.1	22	0.0126
SCWC-PLJ2	5/28/96	-7.76	2.6	23	0.0125
SCWC-PBF4	5/23/96	-8.56	27.9	19	0.0141
SCWC-PBF4	9/27/96	-8.47	-	18	0.0176
YLWD-5	6/21/95	-8.00	11.4	15	0.0061
YLWD-5	7/23/96	-7.82	-	-	-
YLWD-11	6/21/95	-8.00	3.6	15	0.0095
YLWD-11	3/9/95	-8.00	3.9	13	0.0092
YLWD-11	9/21/95	-7.81	-	-	-
YLWD-11/1	10/18/95	-7.72	-	-	-
YLWD-11/1	11/15/95	-7.73	-	-	-
YLWD-11/1	12/11/95	-7.75	-	-	-
YLWD-11/1	1/22/96	-7.78	-	-	-
YLWD-11	5/16/96	-7.78	-	-	-

Table 1: Isotope Data, Ages, and Recharge Temperatures calculated for Groundwater in the Forebay

sample	collection date	$\delta^{18}O$	^3H-^3He age (yrs)	recharge T°C	excess air (cc/LH_2O)
YLWD-11	7/17/96	-7.78	-	17	0.0084
YLWD-11	5/28/96	-7.97	3.0	16	0.0119
YLWD-11	6/20/96	-7.75	-	-	-
YLWD-11	8/27/96	-7.83	-	-	-
YLWD-15	6/20/95	-8.00	0.0	14	0.0093
YLWD-15	5/28/96	-	1.5	16	0.011
HG-1	3/29/95	-	1.3	24	0.0014
HG-1	6/26/95	-7.50	-	19	0
HG-1	9/19/95	-7.46	-	-	-
HG-1	10/17/95	-7.45	-	-	-
HG-1	11/14/95	-7.49	-	-	-
HG-1	12/12/95	-7.73	-	-	-
HG-1	1/16/96	-7.86	-	-	-
HG-1	2/22/96	-7.27	-	-	-
HG-1	3/19/96	-7.53	-	-	-
HG-1	4/16/96	-7.51	-	-	-
HG-1	5/14/96	-8.00	-	-	-
HG-1	7/16/96	-8.12	-	27	0
HG-1	5/23/96	-8.37	-	24	0.0006
HG-1	6/18/96	-7.97	-	-	-
HG-1	8/28/96	-8.05	-	-	-
A-42	4/24/95	-	17.7	16	0.009
A-42	6/19/95	-8.20	-	15	0.009
A-42	10/7/96	-	-	18	0.0087
A42/1	9/20/95	-8.16	-	-	-
A42/1	10/19/95	-8.12	-	-	-
A42/1	11/15/95	-8.11	-	-	-
A42/1	12/13/95	-8.15	-	-	-
A-42/1	1/17/96	-8.15	-	-	-
A-42/1	2/29/96	-8.24	-	-	-
A-42/1	4/17/96	-8.17	-	-	-
A-42	5/15/96	-8.10	-	-	-
A-42	6/19/96	-8.09	-	-	-
A-42	7/17/96	-8.13	-	-	-
A-42	8/28/96	-8.10	-	-	-

Table 1: Isotope Data, Ages, and Recharge Temperatures calculated for Groundwater in the Forebay

sample	collection date	$\delta^{18}O$	^3H-^3He age (yrs)	recharge T°C	excess air (cc/LH_2O)
A-43	6/19/95	-8.00	11.7	16	0.0092
A-43	9/20/95	-8.01	-	-	-
A-43	10/19/95	-7.97	-	-	-
A-43	11/15/95	-7.96	-	-	-
A-43	12/13/95	-8.08	-	-	-
A-43/1	1/17/96	-8.06	-	-	-
A-43/1	2/29/96	-8.05	-	-	-
A-43	4/17/96	-7.82	-	-	-
A-43	5/15/96	-8.00	-	-	-
A-43	6/19/96	-7.99	-	-	-
A-43	7/17/96	-8.03	-	-	-
A-43	8/28/96	-7.99	-	-	-
A-43	10/7/96	-	-	20	0.0083
A-44	10/7/96	-	-	18	0.0138
A-44	5/23/96	-8.26	-	19	0.0122
A-44	7/17/96	-7.91	11.0	-	-
EOCW-E	4/24/95	-7.10	23.9	12	0.0308
O-23	4/24/95	-6.90	28.9	-	-
OPWC	4/24/95	-6.80	-	-	-
OPWC	1/28/96	-6.74	-	-	-
OPWC	2/28/96	-6.79	-	-	-
OPWC	5/2/96	-6.92	-	-	-
OPWC	6/17/96	-6.89	-	-	-
OPWC	7/17/96	-6.95	-	-	-
OPWC	8/29/96	-6.74	-	-	-
SID-3	8/30/95	-7.24	-	16	0.0143
SID-3	4/24/95	-7.20	8.1	18	0.0223
SID-4	4/24/95	-	4.1	-	-
SID-4	9/21/95	-6.35	-	-	-
SID-4/1	1/24/96	-6.56	-	-	-
SID-4/1	3/28/96	-6.60	-	-	-
SID-4	5/2/96	-6.50	-	-	-

Table 1: Isotope Data, Ages, and Recharge Temperatures calculated for Groundwater in the Forebay

sample	collection date	$\delta^{18}O$	^3H-^3He age (yrs)	recharge T°C	excess air (cc/LH_2O)
SID-4	6/17/96	-6.56	-	-	-
SID-4	9/30/96	-6.36	-	-	-
FAIRP-1	3/8/95	-7.90	-	16	0.0033
F-AIRP/1	8/28/95	-7.99	-	-	-
A-47/1	3/8/95	-8.50	18.9	16	0.0037

Table 2: Initial Results From the Colorado River Recharge Experiment in Anaheim Lake.

SAMPLE	Date Sampled	EC	pH	T°C	DO	$\delta^{18}O$	Depth ft bgs
Anaheim Lake	10/2/96	1060	8.16	23.0	-	-11.30	
AL SITE 1T	10/11/96	1056	8.30	24.8	8.2	-11.18	
AL SITE 1M	10/11/96	1056	8.30	24.8	8.2	-11.11	
AL SITE 1B	10/11/96	1056	8.30	24.8	8.2	-11.20	
AL SITE 2T	10/11/96	1056	8.30	24.8	8.2	-11.24	
AL SITE 2B	10/11/96	1056	8.30	24.8	8.2	-11.30	
AL SITE 3M	10/11/96	1056	8.30	24.8	8.2	-11.23	
AL SITE 3B	10/11/96	1056	8.30	24.8	8.2	-11.21	
AL SITE 4M	10/11/96	1056	8.30	24.8	8.2	-11.30	
AL SITE 1	10/16/96	859	7.10	27.7	0.1	-11.22	
AL SITE 2M	10/16/96	1058	8.41	23.9	8.4	-11.29	
AL SITE 3M	10/16/96	1058	8.41	23.9	8.4	-11.26	
AL SITE 4M	10/16/96	1058	8.41	23.9	8.4	-11.25	
AMD-9/1	10/1/96	879	7.20	27.8	0.1	-7.33	200-220
	10/2/96	877	7.42	27.8	0.2	-7.27	
	10/3/96	875	7.19	27.8	-	-7.27	
	10/7/96	853	7.20	27.7	0.1	-7.37	
	10/11/96	859	7.10	27.7	0.1	-7.73	
	10/16/96	1070	7.20	26.7	0.1	-10.79	
	10/31/96	1066	7.49	24.6	-	-11.28	
	12/4/96	1106	7.30	22.7	0.3	-11.03	
	12/31/96	812	7.27	18.6	3.4	-7.73	
A-27	9/27/96	879	7.10	24.1	-	-7.53	197-287
	10/1/96	881	6.88	26.0	-	-7.63	
	10/7/96	885	7.12	25.3	0.4	-7.56	
	10/11/96	813	7.58	25.5	1.6	-7.62	
	10/16/96	996	7.55	25.5	1.5	-9.24	
	10/31/96	1050	8.00	25.6	-	-10.97	
	12/3/96	1050	8.60	21.5	1.5	-10.65	
	12/31/96	875	7.64	20.7	-	-8.63	

Table 2: Initial Results From the Colorado River Recharge Experiment in Anaheim Lake.

SAMPLE	Date Sampled	EC	pH	T°C	DO	$\delta^{18}O$	Depth ft bgs
A-28	9/27/96	892	7.34	20.2	-	-7.70	249-361
	10/1/96	889	7.15	21.6	-	-7.68	
	10/2/96	892	7.11	20.1	-	-7.62	
	10/7/96	892	7.08	20.1	1.4	-7.70	
	10/11/96	865	7.40	20.7	1.6	-7.60	
	10/16/96	533	7.48	22.0	2.8	-7.74	
	10/31/96	911	7.60	21.5	-	-8.37	
	12/3/96	975	7.50	19.2	1.0	-8.98	
	12/31/96	1001	7.38	20.6	-	-9.51	
	1/30/97	894	7.72	19.1	3.9	-8.73	
	2/18/97	-	-	-	-	-8.48	
	3/6/97	840	7.25	20.0	0.8	-8.24	
	4/1/97	782	7.40	20.5	2.1	-7.79	
	4/22/97	-	-	-	-	-7.77	
ABS-2	10/11/96	922	8.02	19.2	4.9	-7.90	155-165
	11/20/96	941	8.25	20.2	7.6	-8.84	
	12/31/96	1006	7.50	21.0	1.0	-9.52	
	2/13/97	932	7.95	21.3	2.7	-8.88	
	4/2/97	800	7.80	22.1	0.5	-8.47	
	4/25/97	-	-	-	-	-8.15	
A-42	10/31/96	1011	7.71	18.2	-	-8.11	430-1180
	12/3/96	1070	7.80	17.2	3.0	-8.02	
	12/31/96	1044	7.52	17.9	-	-8.21	
	1/30/97	990	7.16	17.6	3.5	-8.19	
	2/18/97	1030	7.20	17.5	1.4	-8.09	
	4/2/97	950	7.50	17.6	3.4	-8.12	
A-43	10/31/96	1097	7.61	19.1	-	-7.91	530-1210
	12/3/96	1080	7.70	18.0	2.5	-7.92	
	12/31/96	1138	6.97	18.9	1.4	-7.91	
	1/30/97	1041	7.03	18.6	3.5	-7.95	
	4/22/97	-	-	-	-	-7.97	
A-44	10/11/96	-	-	-	-	-7.82	450-1130
	12/3/96	1090	7.60	19.2	3.0	-7.88	
	12/31/96	1103	7.60	18.7	-	-7.99	
	1/30/97	987	7.39	19.1	3.9	-7.71	
	2/14/97	-	-	-	-	-7.82	
	4/22/97	-	-	-	-	-8.08	

APPENDIX 1

LLNL Isotope Sciences Division
Water Sampling Protocol

The following are procedures to collect water samples for stable isotopes, tritium, and noble gas.

Sampling supplies and equipment needed for each sampling site are:

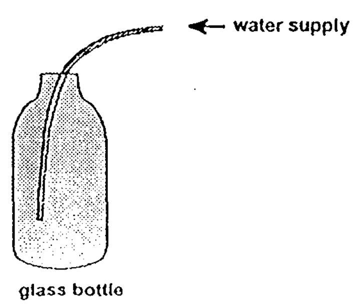
1 one 30mL glass bottle with poly-seal lined cap
2. one liter glass bottle
3. three copper tubes - 15-1/2" long
4. six metal copper tube pinch clamps
5. at least two pinch clamp bases
6. plastic tubing with hose clamps

Stable isotopes

1. Rinse a 30mL glass bottle (with poly-seal lined cap) with sample water.
2. Fill the bottle with the sample water. It is okay to leave a head space in the bottle.
3. Make sure that the bottle is tightly capped.
4. Label the bottle.

Tritium

1. Attach the plastic tubing to the outlet. Rinse off the dirt on the tubing by using the water coming out of the tubing. Do not rinse the bottle before collecting the sample. Insert the tubing near the bottom of the bottle. Fill a one-liter glass bottle with a laminar flow, preventing as much bubbling as possible. Let the water over flow the bottle by at least two bottle volumes. Pour out a little of the water to provide about a one inch head space.
2. Cap the bottle tightly.
3. Label the bottle.



Noble Gas

Three noble gas samples should be collected from each site. Do the following three times.

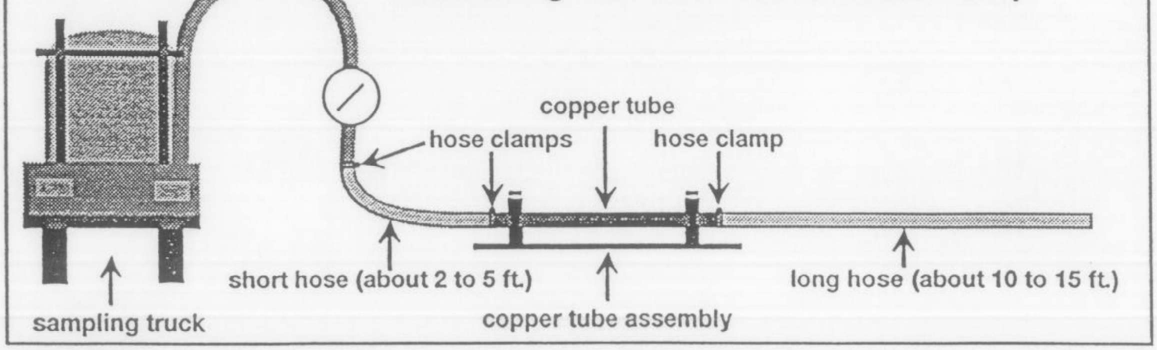
1. Use a hose clamp to attach a two to five foot (can be longer if necessary) piece of plastic tubing (approximately the same diameter as the copper tubing) to the discharge point so that no air leaks into the flow line. Note: See the diagrams below for both types of wells. Some production wells may have garden-type hose fittings at water quality sampling points. Use the garden hose connector or large diameter tubing that has been adapted to smaller diameter tubing instead of a hose clamp. This may require muliple pieces of tubing to adapt to the proper size.
2. Using a hose clamp, attach the tubing to the copper tube assembly.
3. Use a hose clamp to attach a ten to fifteen foot piece of plastic tubing (approximately same size as the copper tubing) on the other side of the copper tube assembly.
4. Flow the sample water through the copper tube assembly. If air bubbles cloud the flow line, increase the flow rate until they clear. Note: It is important to apply some back pressure when sampling Production Wells. Either use an adjustable clamp or tie the tubing into a loose knot (see the diagram below). Increase the flow until the pressure increases and the tubing swells.
5. Remove air bubbles from the line by holding it upright, and hitting the plastic tubing and copper tube assembly.
6. With a ratchet wrench, very tightly clamp the down stream end of the copper tube assembly. When a cold seal is formed, the pressure in the line will expand the plastic tubing. The valve to the discharge line can be closed at this point as long as no air is introduced (or pressure lost) before the second clamp has been tightened. Note: It is important when using a submersible pump that some of the output is released to another port so that the pump is not damaged when the clamps are tightened.
7. Clamp very tightly the up stream end of the copper tube assembly.
8. Double check the tightness of both clamps.
9. Remove the plastic tube.

9\. Label the copper tube.

10\. Separate the copper tube and clamps as one piece from the clamp base. Attach a new set of clamps and a copper tube for the next sample.

See the following page for the diagram of monitoring and production well sampling.

Monitoring Well with Submersible Pump



Production Well