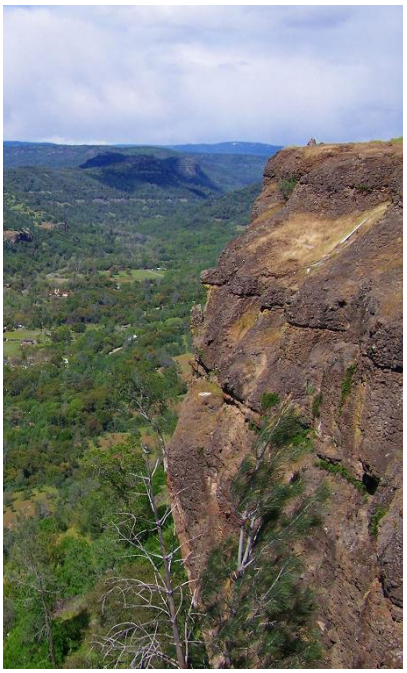
Prepared for County of Butte

September 30, 2017 | FINAL REPORT

Stable Isotope Recharge Study Final Report



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FINAL

Stable Isotope Final Report

Prepared for
Butte County
September 30, 2017

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Stable Isotope Final Report

September 30, 2017

Part 1 // Executive Summary 1-1

Part 2 // Introduction and Background 2-1

Project Objectives 2-2
Stable Isotope Background 2-3
Overview of Previous Studies 2-4
Data Collection and Sampling Rationale 2-5
Surface Water Sampling Locations 2-5
Groundwater Sampling Locations 2-9
Sampling and Analytical Methods 2-9
Sampling Frequency 2-9
Data Management 2-10
QA/QC 2-10
Data Usability 2-10
Additional Data 2-11

Part 3 // Findings 3-1

Finding 1 – Surface water and groundwater data adhere to the GMWL with some evidence of evaporation 3-2
Finding 2 – Surface water sample locations exhibit seasonal variation in stable isotope values 3-7
Finding 3 – Probable sources of recharge in groundwater wells 3-9
Finding 4 – Groundwater-surface water interactions 3-12
Finding 5 – Updated Conceptual Site Model 3-19

Part 4 // Conclusions and Recommendations 4-1

References REF-1

Appendix A: Stable Isotope Data

Appendix B: QA/QC Data

Appendix C: Hydrographs

Appendix D: Shallow Ground-Water Quality Study

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Part 1 // Executive Summary

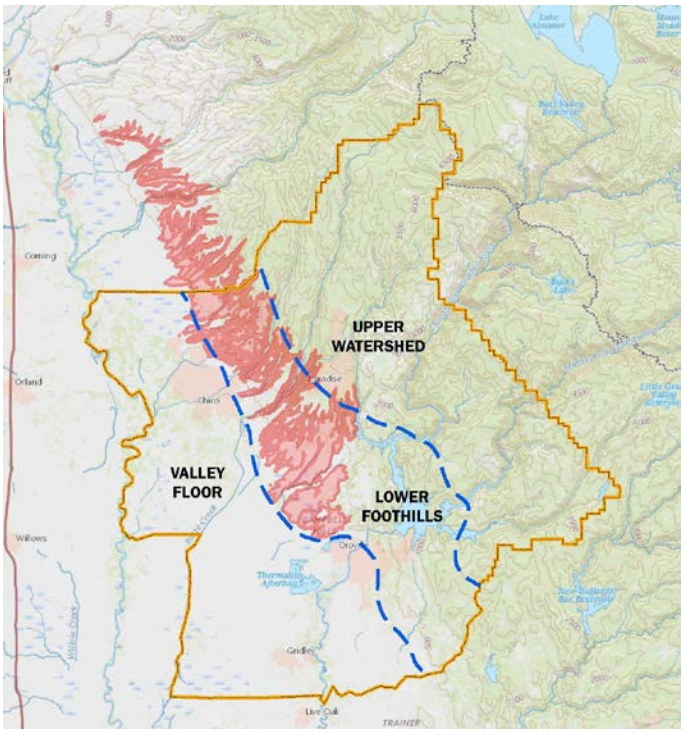
This Final Report for the Butte County Stable Isotope Recharge Study (Study) is submitted in accordance with Attachment III of the County of Butte Contract Number X21825, dated September 15, 2015 between Butte County and Brown and Caldwell (BC).

Stable isotopes are naturally occurring components of water. The stable isotope abundance changes with elevation and evaporation processes and can be used to identify sources of groundwater recharge.

The purpose of this Study is to use stable isotopes to gain an improved understanding of groundwater recharge in eastern/central Butte County (the Focus Area of this Study). This Study included preparation of a Technical Memorandum that summarized existing isotope data in Butte County, preparation of a Field Sampling and Analysis Plan to obtain stable isotope data from 30 groundwater wells at 10 individual locations and 10 separate surface-water locations along creeks and rivers. Samples were collected in October 2015, June 2016, October 2016 and March 2017. Thus, samples were collected near the end of an historic drought period in 2015, at the end of seasonally wet and dry periods in 2016, and during one of the wettest winters on record in early 2017. The analysis of the data supports the following findings.

A. Isotopic Variation by Season – Surface Water

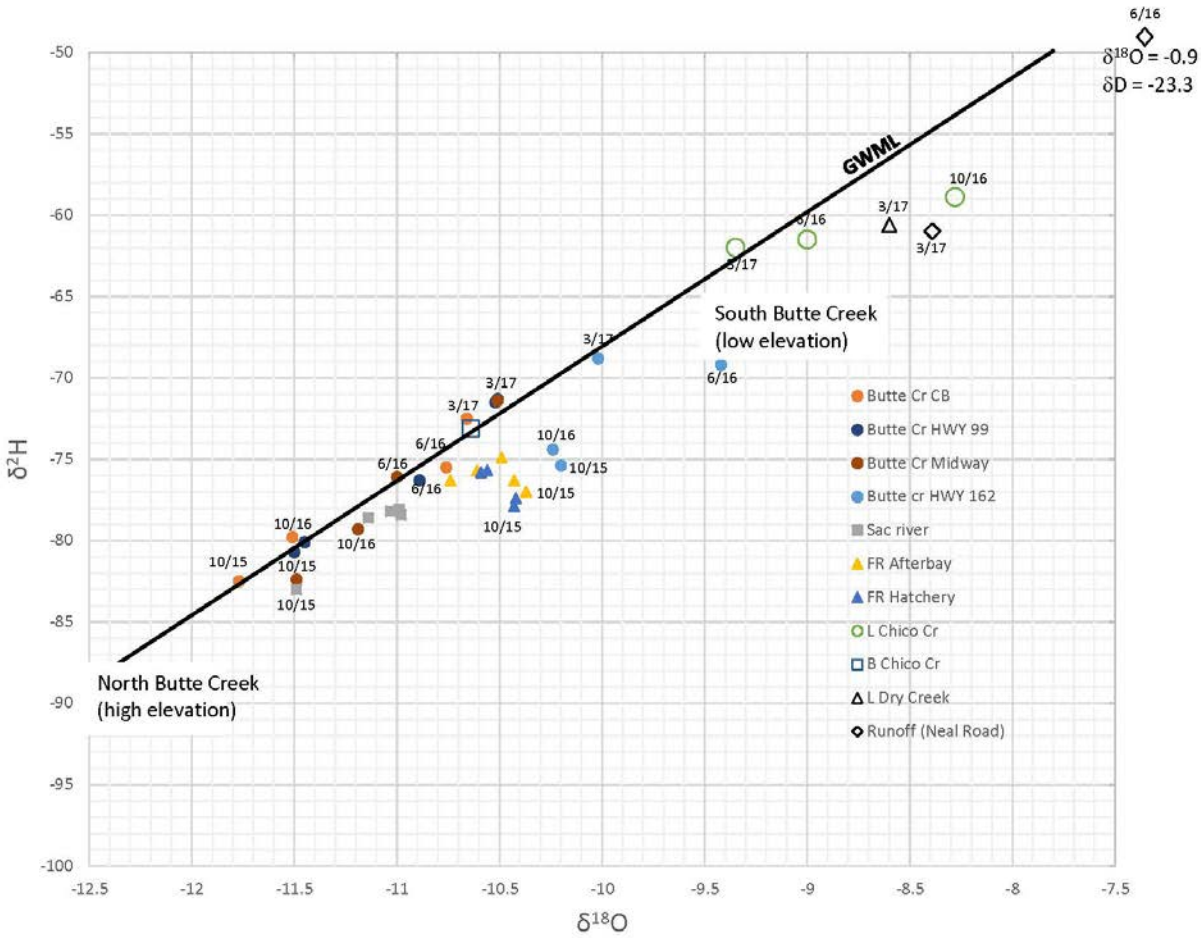
Stable isotope abundance in surface water is seasonally variable in the creek samples that flow from the Upper Watershed to the Valley Floor (e.g. Butte Creek, Big Chico Creek, Little Chico Creek) as shown in Figure ES-1. In contrast, samples from the Sacramento, Feather Rivers (Upper Watershed) do not show much seasonality, due to mixing that occurs in reservoirs that supply water to these Rivers.



ES-1. Range of Precipitation Types in Butte County

Butte Creek headwaters are located near Cirby Meadows, which is 6,260 feet (ft) above mean sea level (amsl), within the Upper Watershed. The Butte Creek samples collected in late winter (March) indicate that most of the runoff is from lower-elevation part of the Upper Watershed rainfall (~2,900 ft amsl), based on stable isotope results. In June, the stable isotope ratios indicate a mix of high elevation snowmelt with lower-elevation rainfall from the Upper Watershed. In October, Butte Creek samples have isotope patterns consistent with snowmelt (~4,800 ft amsl). The seasonal pattern of isotope data in Little Chico Creek (with headwaters at about 2,415 ft amsl) was reversed compared to Butte Creek, suggesting watershed elevation may have an effect on the seasonal variation of isotopic composition.

Figure ES-2 summarizes the isotopic abundance of stable isotopes deuterium (D) and 18-oxygen (^{18}O). Surface water data close to the global meteoric water line (GMWL) suggest no significant evaporation. Data points along the GMWL also indicate elevation differences.



ES-2. δD, $\delta^{18}O$ in Surface Water Samples

Groundwater samples were much less seasonally variable than surface water in their isotopic values at all locations. To develop a better understanding of potential seasonal variability in groundwater, additional information about the subsurface flow paths from recharge locations to individual wells would need to be developed, including the timing and rate of groundwater movement.

Implications: Future recharge studies should take into consideration seasonality of water sources since this may affect the interpretation of stable isotope results from groundwater samples.

B. Variation by Area - Groundwater

Three distinct areas have been identified based on isotopic signatures in the groundwater samples (see Figure ES-3).

North Area. Shallow groundwater zones (<400 ft deep) are recharged by the Upper Watershed. Intermediate and deep portions of the basin are recharged from the upper elevations of the Lower Foothills (<1,800 ft).

East Area. Shallow portions of the basin (<200 ft deep) are recharged by local rainfall on the valley floor. Intermediate and deep portions of the basin are recharged from the Lower Foothills (<1,800 ft).

South Area. Rainfall to the Valley Floor is the primary recharge source; there is some evidence that imported irrigation water may be a source of recharge in some areas.

Implications: While the rivers and major creeks are contributors to recharge in the North Area, the Lower Foothills and Valley Floor precipitation are primary sources of recharge water throughout the North, East and South Areas. Some evidence for irrigation water recharge (associated with rice farming) is indicated, but these data are limited to one shallow well in this Study.

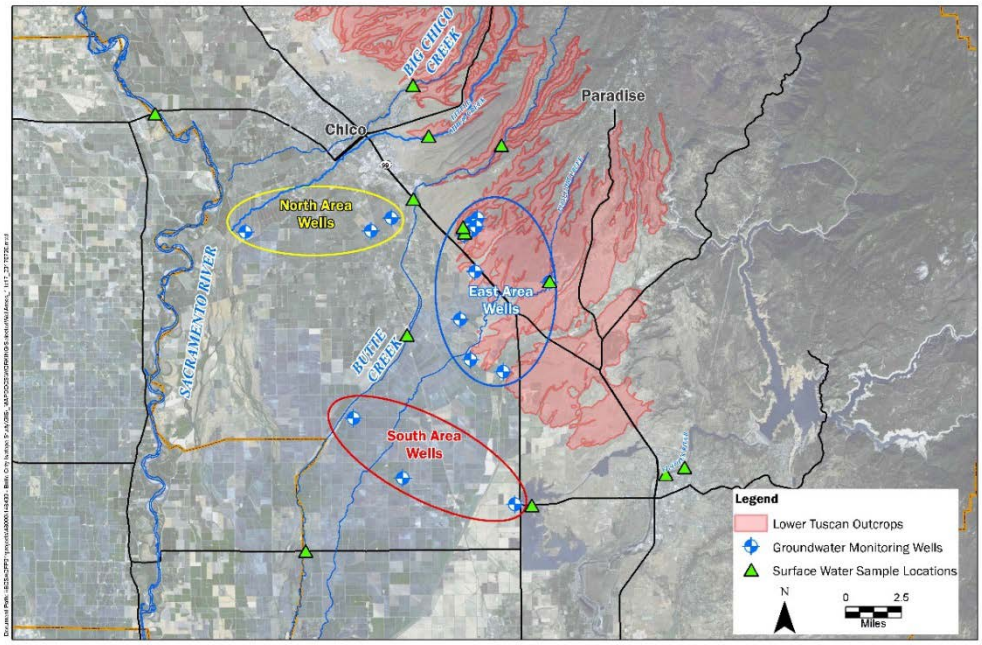


Figure ES-3. Groundwater Recharge in the Focus Area

C. Limitations of Isotopic Studies

The hydrogeologic (physical) framework of the aquifer dictates groundwater flow, including where rock crops out at the surface and allows rainwater to recharge the subsurface. In Butte County, the major geological formations (Lower Tuscan, Ione and Mehrten) often overlap and constrain groundwater movement. Isotopic studies are most effective when the local environment presents large variability in isotope signatures and can be correlated geologic formations and hydrostratigraphic layers.

D. Conceptual Site Model, Groundwater Recharge

The Lower Tuscan Aquifer Study (LTA Study; BC, 2013) presented the hydrogeological framework for the Sacramento Valley groundwater basin in Butte County by describing many aspects of the Lower Tuscan Aquifer groundwater recharge. This stable isotope Study focuses on recharge sources and mechanisms in central Butte County by sampling surface water, groundwater, and stormwater samples for stable isotope analysis. Key findings related to the Conceptual Site Model are summarized below.

Source Water Regions

There are three primary source water regions for groundwater recharge in the Focus Area:

- **Upper Watershed.** The Upper Watershed area is located topographically above the other source water regions. Geologically, it consists primarily of volcanic, granitic, and metamorphic rocks that do not have any appreciable primary porosity. Fracturing within these rock units may occur locally but the fractures are not pervasive on a regional scale, which limits the amount of water that can percolate into the bedrock geologic units and the volume of groundwater available to migrate to other regions. The Upper Watershed receives rainfall and snow, primarily during the winter and spring months. Rainfall runoff and snowmelt enters the Focus Area from major streams and rivers, including Butte Creek, the Sacramento River, and the Feather River; imported irrigation water also enters the Focus Area from Lake Oroville.
- **Lower Foothills.** The Lower Foothills region occurs within a relatively narrow topographic band along the east edge of the Sacramento Valley. The Lower Foothills region contains the outcrop of the Lower Tuscan Formation in addition to small alluvial fans and other Recent sedimentary deposits that directly overly the Lower Tuscan Formation. Rainfall that occurs in the Lower Foothills may percolate into the Lower Tuscan Formation and the Recent alluvial sediments or it may runoff through local, ephemeral streams to the Valley Floor.
- **Valley Floor.** The Valley Floor defines the lowest elevation source water region in the Focus Area. It is underlain by Recent alluvial material in most areas, although the presence of hardpan layers may affect shallow percolation in some locations. There are no significant creeks or streams that originate on the Valley Floor. Rainfall that occurs on the Valley Floor may percolate locally or it may runoff into other creeks and streams that originate at higher elevations.

Recharge Mechanisms

The recharge mechanisms may vary by both depth and area across the groundwater basin within the Focus Area.

- **North Area**. Within the shallower aquifer interval (above ~400 ft bgs), the primary source of groundwater is from the Upper Watershed region, based on the isotope data. Wells to the east may be recharged from Butte Creek, whereas wells to the west may be recharged by flow from the Sacramento River.

  The data indicate that the intermediate and deeper depth intervals are recharged from rainfall and percolation in the Lower Foothills region. There is also the potential for Upper Watershed recharge in the shallow aquifer interval to be pulled down to greater depths due to irrigation pumping, causing a mixing of recharge sources in the intermediate and possibly deep intervals in the North Area. This mixing, however, is an anthropogenic effect and not necessarily a component of natural recharge that would occur in the absence of large-scale pumping from intermediate and deep aquifer intervals in the North Area.

The isotope data demonstrate that the intermediate and deep intervals of the Lower Tuscan aquifer do not receive any appreciable recharge as a result of fracture flow or other mechanisms from the Upper Watershed.

- East Area. Recharge in the East Area wells is affected by evaporation, indicating some delay before the precipitation that forms the rainfall percolates into the subsurface. The shallow zone intervals are likely to be recharged by direct percolation primarily from Valley Floor precipitation, supplemented by some rainfall recharge at the base of the Lower Foothills. The intermediate and deep zones are recharged from the lowest elevation part of the Lower Foothills region, most likely from percolation directly into the Lower Tuscan Formation at the outcrop or through recharge into the local alluvial fans and sedimentary deposits and subsequent downward vertical migration into the underlying Tuscan aquifer units.

  The isotope data do not provide any indication that small creeks or streams originating in the Lower Foothills, or lateral movement of groundwater within the small alluvial fans and sedimentary deposits, provides any significant recharge to the shallow aquifer interval at the edge of the Valley Floor in the East Area. Because there is no data to support any water from the Upper Watershed, the stable isotope data in groundwater indicates that virtually all recharge in the East Area is from local precipitation.

- South Area. Wells completed within the Tuscan Aquifer units in the South Area all have a similar isotope signature, indicative of recharge from the lowest elevations of the Lower Foothills. This relationship infers that all recharge to these aquifer intervals occurs at the outcrop of the Tuscan Formation or through local alluvial fans and other sedimentary material directly overlying the Lower Tuscan Formation. The uniform isotope results with depth may also suggest the potential for mixing between different aquifer intervals.

Well 35C in the South Area is screened very shallow (<100 ft bgs) and is likely within the alluvium overlying the Tuscan Aquifers units. The isotope data indicates that the recharge for this well comes, in part, from imported irrigation water from the Feather River used for rice farming. Given the shallow nature of this well, it is also likely that some recharge of local rainfall occurs in the shallow alluvium. The isotope data are also consistent with aquifer pumping test results from the LTA Study that demonstrate that the shallow alluvium is not in hydraulic communication with the underlying Tuscan Aquifers.

Recommendations for Further Study

Methodology

- Seasonal sampling should be performed as part of future surface water and groundwater isotope studies for purposes of assessing groundwater recharge.
- Monitoring wells with multiple screened intervals (multi-completion monitoring wells) are recommended to assess stable isotope data at different depths. Sampling locations in this study with a single well-screen interval do not provide nearly as much insight as sampling locations with wells screened at multiple depths.
- Monitoring wells with relatively short screened zones (20 ft or less) are preferred to minimize mixing between aquifer zones or between aquifer zones and residual water retained within the aquitard zones between aquifers. The LTA Study determined that the aquitards can release large volumes of water to the aquifer in areas where large volumes of groundwater are extracted.

General

- **South Area wells.** Conduct general mineral analysis on groundwater samples to evaluate whether elevated electrical conductivity (EC) values observed during sampling for this study are due to irrigation influences (e.g. elevated nitrate, calcium, sulfate) or due to proximity to the Ione Formation (e.g. elevated sodium, chloride, and boron). This will help further characterize the recharge source.
- **Contribution of recharge from rainfall directly on the Lower Tuscan outcrop**. Stable isotope abundances indicate that a substantial proportion of local recharge is derived from elevations consistent with the outcrop of the Lower Tuscan Formation (i.e. within the Lower Foothills). Thus, it is recommended that local precipitation be collected during an entire precipitation season at varying elevations across the outcrop and analyzed for stable isotopes to better correlate or calibrate the groundwater isotope values with local precipitation sources.
- **Recharge rate**. Most well locations and depths should be sampled and analyzed for presence of tritium to help distinguish whether recharge to individual aquifer zones is occurring over periods shorter than about 60 years, or whether recharge is occurring over longer timeframes.

Part 2 // Introduction and Background

The purpose of the Butte County Stable Isotope Recharge Study is to develop a better understanding of the mixing of recharge sources and contributions of local precipitation and river water to the groundwater basin, with a primary focus on the area along Butte Creek south of Chico. This Final Report is submitted in accordance with Attachment III of the County of Butte Contract Number X21825, dated September 15, 2015 between Butte County and Brown and Caldwell (BC). Contract X21825 specifies that BC complete:

- Task 1.1 – a literature review, data compilation and interpretation of stable isotope data in the Northern Sacramento Valley presented in a Technical Memorandum (TM). The TM (BC, 2016a) provided an overview of stable isotopes data applied to hydrogeology and a summary of the available published reports.
- Task 1.2 – a Field Sampling Plan (FSP) presenting sampling and analysis methods, rationale, standard operating procedures for field sampling, laboratory analytical procedures, and data management protocols (BC, 2016b). BC presented both the FSP and TM to the Butte County Water Commission on April 6, 2016.
- Task 1.3 – BC worked with the Technical Steering Committee (TSC) to review and comment on the draft FSP and TM documents and provide oversight and direction for both deliverables.
- Task 2.1 – BC conducted field training for Butte County staff, to collect groundwater and surface water samples consistent with the FSP, including labeling, sample custody and transport to the laboratory for analysis of stable isotopes.
- Task 2.2 – this Final Report synthesizes the existing information (Task 1.1) and new data collected by Butte County staff using the methods described in the FSP (Task 1.2) and training conducted in Task 2.1. After completing the field program, Butte County provided BC with electronic copies of lab analyses and field monitoring data. BC's scope is to review and interpret the data collection in a final report. The final report outline as documented in the contract is presented below:
  - Executive Summary
  - Project Objectives
  - Stable isotope background and basics related to how this type of data provides insights on recharge processes
  - Overview of previous studies and pertinent preexisting data/conclusions to be used in current analysis
  - Rationale for collecting samples
  - Sampling and analytical methods
  - Results and Discussion
  - Recommendations for future work
  - Conclusions

This Final Report is organized into four Parts: the Executive Summary (Part 1); Introduction and Background (Part 2); Findings (Part 3); Conclusions and Recommendations. Part 3 (Findings) presents the stable isotope data, analysis and implications for recharge.

Project Objectives

The objective of the Butte County Isotope Recharge Study (Isotope Study) is to better understand groundwater recharge throughout Butte County, by sampling and analyzing stable isotopes in groundwater and surface water samples. This study collected information and water samples in eastern/central Butte County (Figure 1) so that information and observations developed from this Focus Area could be extended throughout Butte County.

The groundwater recharge process begins with local rainfall, runoff from the surrounding foothills and high elevation snowmelt, surface waters in rivers, creeks and streams and includes agricultural irrigation water. As the different source waters mix and enter the subsurface, infiltration and integration of stable isotope values continue; groundwater wells provide an opportunity to sample specific water bearing zones and may confirm the predominant source water, revealing recharge mechanisms.

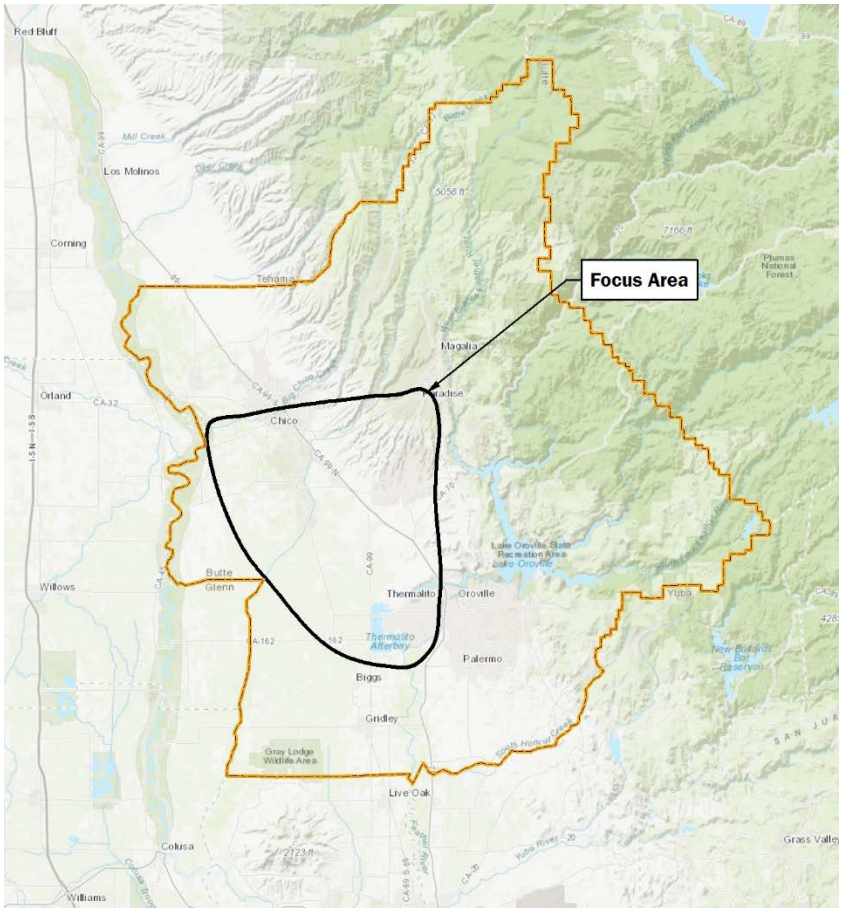


Figure 1. Focus Area Location

Stable Isotope Background

A detailed discussion of stable isotope geochemistry is presented in the TM (BC, 2016a). A brief summary of that discussion is provided below.

Stable isotope analysis of water samples is based on the principal that the hydrogen and oxygen atoms that form water molecules contain different isotopic forms. Stable isotopes are those that do not undergo radioactive decay and, thus, do not change composition over time. The most prevalent stable isotopes in water are hydrogen (H) and oxygen-16 (^{16}O), which make up ≥99.8 percent of all the hydrogen and oxygen on earth. The next most prevalent stable isotopes in water are deuterium (^{2}H or D) and oxygen-18 (^{18}O). D and ^{18}O are present in water at 150 parts per million and 2 parts per thousand range, respectively.

D and ^{18}O have atomic masses that are greater than those of the most common isotopes, H and ^{16}O. It is this difference in mass that allows stable isotope analysis to provide important insight into the sources of recharge for groundwater.

As water vapor moves inland from the ocean and yields precipitation, the ratios of the stable isotopes (e.g. H vs D) in the water is affected by the temperature, altitude and distance from the ocean. Since D and ^{18}O have higher masses, they preferentially form precipitation that falls at lower latitudes, near the coast, and/or lower altitudes resulting in a higher proportion of the D and ^{18}O compared to precipitation that falls farther to the north, farther inland, and at higher altitudes. This process is shown in Figure 2.

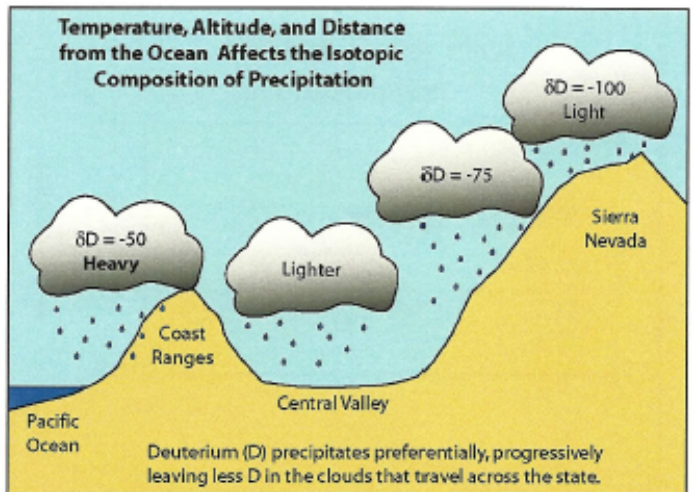


Figure 2. Schematic Diagram - δD in Precipitation

The isotopic values are generally reported in the "delta" or "del" of the less abundant stable isotope, using the prefix "δ" (for example, $\delta^{2}H$, δD, or $\delta^{18}O$). The "del" value is based on the ratio of the stable isotopes in a sample divided by the ratio of the stable isotopes defined in an internationally recognized standard, for instance:

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) 1000$$

where *R* is the isotope ratio of interest for the *sample* and *standard*, respectively.

For almost all studies of stable isotope of water, the standard is referred to as Vienna Standard Mean Ocean Water (VSMOW). Most δD and $\delta^{18}O$ data from water samples are negative numbers because the heavier isotope becomes depleted compared to the VSMOW standard as water passes through the hydrologic zone. Some researchers refer to the Global Meteoric Water Line (GMWL) because stable isotope data of precipitation fall along the same line throughout the world (Craig, 1961,).

Stable isotope studies can also be conducted on other elements that are part of minerals or other chemicals that become dissolved in water. Other elements with stable isotopes that have been studied in water include sulfur, nitrogen, carbon, and boron. However, stable isotopes of elements other than

hydrogen and oxygen do not provide additional insight for the objectives of this Study and, therefore, were not tested as part of this study (BC, 2016a).

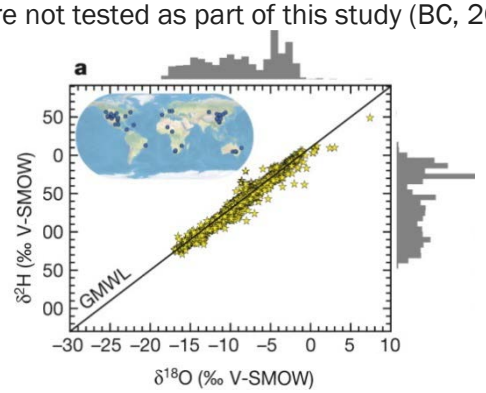


Figure 3. δD, δ¹⁸O in Groundwater from 47 Locations Throughout the World

Figure 3 presents the classic relationship between stable isotopes of hydrogen and oxygen in groundwater derived directly from precipitation (Evaristo et al., 2015). Figure 3 demonstrates that regardless of location, the ratio of δD to $\delta^{18}O$ remains linear in groundwater. Unlike groundwater, surface water is open to the atmosphere and prolonged evaporation causes points to fall below the GMWL shown in Figure 3.

When meteoric water from a particular elevation evaporates prior to recharge, the relationship between δD and $\delta^{18}O$ deviates from the GMWL. Figure 4 shows an example of a combination of meteoric water with and without evaporation. Meteoric water from a given altitude that evaporates also forms a linear δD and $\delta^{18}O$ trend (dashed line), with a different slope and y-intercept compared to the GMWL. Evaporated water samples fall to the right/below the GMWL. If rainfall from a different elevation was sampled and was evaporated, a different dashed line would likely form around the water samples. In Figure 4, samples that have undergone little or no evaporation fall along the GMWL (lower left portion of Figure 4).

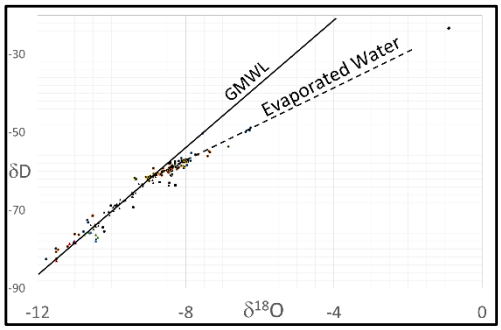


Figure 4. δD, δ¹⁸O in Groundwater from 23 Locations in Butte County, 2015 to 2017

Overview of Previous Studies

BC completed a TM describing existing data by searching for stable isotope data throughout the Northern Sacramento Valley from Red Bluff to the Sutter Buttes including the Focus Area (BC, 2016a). BC reviewed data from a variety of public entities including the Groundwater Ambient Monitoring and Assessment (GAMA) program, the California Department of Water Resources (DWR), Lawrence Livermore National Laboratory (LLNL) and the California State Water Resources Control Board (SWRCB). BC also requested unpublished data from DWR and LLNL. The requests for published reports with stable isotope data in the Focus Area identified a total of seven relevant studies; three relevant studies from the GAMA program, two DWR studies and one study conducted by the United States Geological Survey (USGS) initiated in 1997 as part of their National Water Quality Assessment Program (NAWQA). The Lower Tuscan Aquifer Study (LTA Study) conducted by Butte County in 2010 (BC, 2013). The LTA Study characterized the hydraulic properties and recharge characteristics of the Lower Tuscan Aquifer (LTA) system because of its importance to the groundwater resources within Butte County and the Sacramento Valley. In addition to sampling and analyzing groundwater and surface water quality, the LTA Study included aquifer performance tests, stream flow analyses, and surface soil infiltration measurements. Stable isotope analysis of surface water and monitoring wells were used to assess groundwater recharge.

These studies provided the following observations:

- The $\delta^{18}O$ data from southern Butte County and vicinity (including Yuba County), especially the large number of samples collected east of the Feather River by DWR, suggest recharge of lower elevation sources, with samples ranging from approximately -7 to -9 parts per thousand (‰) $\delta^{18}O$ (DWR, 2008).
- USGS groundwater samples collected west of the Sacramento River, west of Butte County (including in Yolo, Colusa and Glenn counties), have reported $\delta^{18}O$ of approximately -9‰ +/- 1‰ with surprising consistency, indicating the potential for consistent recharge mechanisms on the west side of the Sacramento Valley (Schmitt et al., 2008).
- USGS, LTA Study and some unpublished data collected from groundwater wells near Butte Creek and along the Sacramento River generally appear to be indicative of recharge of higher elevation, ranging from -9 to -10‰ $\delta^{18}O$. There also is an apparent trend toward isotopically lower value (higher elevation) waters toward the south, with $\delta^{18}O$ values ranging from -10 to -11‰ or lower. There are, however, some notable exceptions (Dawson, 2001) of values reported higher -6 to -8‰ $\delta^{18}O$.
- The LTA Study data tend to suggest a strong influence of groundwater depth, and thus stratigraphy, on the isotopic signature.
- Groundwater samples collected adjacent to Deer and Mill Creeks in northern Butte and Tehama Counties consistently have the isotopically lowest value (i.e. highest elevation) water varying from -10 to -11.5‰ $\delta^{18}O$, which is consistent with the isotopic signatures in the surface water collected from these two creeks as part of the LTA Study (BC, 2013).

Data Collection and Sampling Rationale

Based on the existing data presented in the TM, BC prepared the FSP for Butte County to document additional data collection for isotope analysis (BC 2016b). The FSP provided the rationale for the sampling and analysis program, a description of analytical methods and laboratory quality control procedures, an overview of data evaluation methodologies, standard operating procedures for field methods, and data management protocols. The sampling rationale was developed to meet the Project Objective which is to develop a better understanding of recharge processes, including identifying recharge sources, contributions of local precipitation and river water to the groundwater basin. As shown on Figure 5, the primary focus of this study is along Butte Creek bounded to the north by Chico, to the east by Paradise and Tuscan Formation outcrops, to the south by the Lake Oroville Afterbay and west by the Sacramento River. To accomplish Project objectives, additional sampling efforts included surface water and storm water runoff, in addition to groundwater samples collection.

Figure 5 presents the locations where additional surface water, groundwater and storm water samples were collected. These proposed locations were primarily located within the Focus Area. These wells were selected based on their location within the Focus Area, as well as being screened in aquifer zones that meet project criteria. All sampling locations are included in Figure 5.

Surface Water Sampling Locations

Surface water sampling was conducted at the following locations shown in Figure 5:

- Butte Creek - four locations were sampled. These locations were selected to vary from high to low elevations with the higher elevations to the north crossing LTA outcrops. The southern-most elevation location was selected to evaluate potential effects of agricultural return water entering Butte Creek.

- Little Chico Creek northeast of the Focus Area.
- Big Chico Creek also northeast of the Focus Area.
- Little Dry Creek south of the Focus Area.
- Two locations along the Feather River including the hatchery and to the southwest at the Afterbay.
- One location along the Sacramento River at State Route 32 to the northwest of the Focus Area.
- Storm Water Sampling Locations

To evaluate the potential influence of storm water runoff on recharge, a retention pond at Neal Road Landfill was sampled. The presence of contaminants in the groundwater beneath the landfill demonstrates that recharge is occurring in this part of the Focus Area. Collecting samples from the storm water retention pond was conducted to allow a direct comparison of the isotopic signature of the storm water at the landfill site with the isotopic signature present in the first two aquifer zones beneath the landfill.

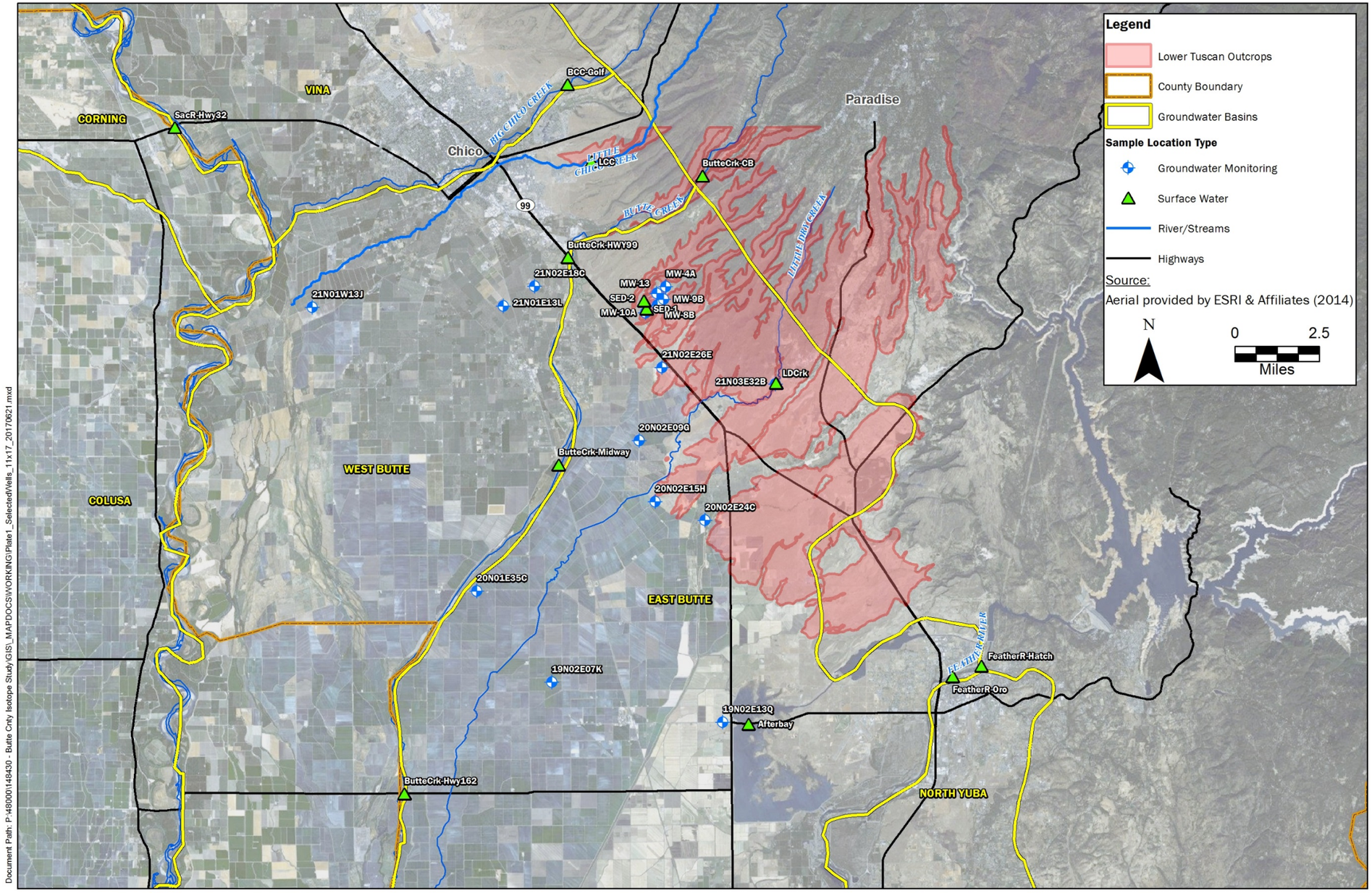


Figure 5. Groundwater and surface water sampling locations replace?

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Groundwater Sampling Locations

Groundwater wells were selected for sampling based on a hydrostratigraphic model developed from the LTA Study that included the results of previous isotopic analysis. Based on this model and groundwater data quality objectives, wells with screen intervals that monitor specific aquifer zones were selected to provide insight into recharge sources. Groundwater monitoring network included the following:

- Wells completed at or near the water table. To assess influence of recharge from Butte Creek through the shallow alluvium, wells were selected in this zone at varying distances from the creek.
- Wells with screen intervals isolated to specific aquifer zones and not wells that screen multiple zones within the Tuscan Formation.
- Wells screened in or near the contact with the Ione Formation.

Sampling and Analytical Methods

Samples from surface water, storm water runoff, and groundwater were collected in accordance with standard operating procedures (SOPs) presented in the FSP (BC, 2016b). Surface water samples were collected using grab samples and dipping cups as described in SOP-1. Storm water runoff samples are collected with the identical method described in surface water grab samples.

Groundwater samples were collected using the EPA approved sampling method using a Hydrasleeve as described in SOP-2 in the FSP (BC, 2016b). The Hydrasleeve is a flexible polyethylene bag with a reed valve that allows depth discrete groundwater sampling adjacent to the well screen. The Hydrasleeve is lowered into the well to the appropriate depth, the valve is opened and left for 24-48 hours to equilibrate with the formation water. After equilibration, the Hydrasleeve is removed from the well and the water sample is transferred into laboratory glass sample containers sealed tightly to prevent evaporation. The containers are packed with padding to prevent breakage, and each sample is documented in a chain-of-custody form, and transported by courier to Isotech Laboratory Inc. in Champaign, Illinois for stable isotope analysis.

After the sample container is filled, the remaining water sample is tested for water temperature, pH and electrical conductivity (EC) in the field using calibrated field instruments. SOP-4 of the FSP presents the instrument calibration and measurement procedures for routine analysis of water samples in the field.

Isotech Laboratory performed all water analyses presented in this study utilizing a cavity ring-down spectrometer (CRDS) that receives a direct injection of water vapor. Isotech routinely evaluates standard water samples prepared by the certified National Institute of Standards and Technology (NIST) in addition to their own internal standards. Isotech calibrates the raw data produced by the instrument against all these standards.

Sampling Frequency

The data presented in this Final Report included four sample events in October 2015, June 2016, October 2016 and March 2017. The October 2015 sampling event was not included in the original contract; however, given the drought, groundwater levels were at historic lows therefore Butte County conducted this sampling event prior to the completion of the FSP. For the October 2015 sampling round, BC assisted Butte County to collect groundwater samples using conventional purging (i.e. three casing volumes) prior to collecting the groundwater sample. The sample dates corresponded to the end of the

dry season (October 2015, October 2016), in the wet season (March 2017), and at the transition from wet to dry conditions, relative to streamflow and recharge (June 2016).

Field parameters including pH, EC and temperature were also collected from groundwater and surface water sampling events.

Data Management

After receiving the laboratory reports and electronic deliverable data generated by Isotech, Butte County transmitted the reports and electronic data to BC. BC compiled all laboratory data, field parameters, and joined those data with sample latitude, longitude and groundwater well screen interval. This relational database is presented as an electronic file on compact disc in Appendix A.

QA/QC

The methodology employed by Butte County for quality assurance and quality control (QA/QC) focused on submitting "blind duplicates" and an internal standard to the laboratory for routine analysis of δD and $\delta^{18}O$. Blind duplicates test the laboratory's ability to analyze samples that are from an identical water sample. Table B-1 in Appendix B presents the quality assurance/quality control (QA/QC) analyses, including the relative percent difference from blind duplicates and the internal standard.

The EPA typically accepts blind duplicate samples with less than 30% relative percent difference (RPD; EPA, 2015). In this Study the 11 blind duplicate sample pairs tested for both δD and $\delta^{18}O$ (22 duplicate analyses) with 21 of the 22 samples reporting between 0.0 and 1.85% RPD; one sample initially reported a 4.2% RPD for $\delta^{18}O$, still excellent precision. In the one case where the $\delta^{18}O$ RPD was 4.2% (Table B-1 yellow highlighted), the lab re-ran the samples and yielded a precision of less than 1.1% RPD. The same precision resulted for the internal standard for two separate analyses.

Isotech Laboratory performed the analyses utilizing a CRDS that receives a direct injection of water vapor. Isotech routinely injects certified NIST water standards as well as their own internal standards. Isotech calibrates the raw data produced by the instrument against all these standards. The lab's reporting precision is ±0.3 per mil (‰) $\delta^{18}O$ and ±1.0 ‰ δD. This is a conservative estimate of precision. This project sought to establish the actual precision on a batch basis by collecting blind duplicates that can be compared to each other after analysis.

The internal standard was also collected from a single water source (named "308Nelson") and kept tightly sealed at Butte County Water and Resource Conservation Department. Two aliquots of this internal standard were submitted to the lab for analysis and compared.

Data Usability

Based on the QA/QC data presented in Appendix B (Table B-1) the internal precision of the stable isotope analysis for this project was ±0.1 ‰ $\delta^{18}O$ and ±1.0 ‰ δD, consistent with a magnetic sector mass spectrometer. The QA/QC samples presented in Appendix B suggest that Isotech Laboratory achieved excellent precision, well within EPA standards and within data quality objectives identified in the FSP.

Additional Data

Two additional data sets provided beneficial insights into the interpretation of the stable isotope analytical data and assessment of recharge mechanisms. Water level data from the sampled groundwater wells were provided to BC by Butte County and used to generate hydrographs. The hydrographs and a discussion of local water level trends are provided in Appendix C. Field parameters, including pH, EC, and temperature were collected during purging and sampling of the groundwater wells for this study and are provided in Appendix A. Review of these data indicate that there are some areas with elevated EC that may relate either to the underlying geologic conditions (i.e. the presence of the Ione Formation at shallower depths than in other parts of the Study Area) or relate to surface activities (i.e. intensive agriculture with a high proportion of percolation). Further clarification of the cause of the elevated EC will help assess the potential recharge contribution from irrigation water in the affected area, as discussed further in our Recommendations.

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Part 3 // Findings

This section presents a discussion and interpretation of water sample results and hydrogeological data as they relate to groundwater recharge. These data and interpretations are then integrated into a conceptual model that describes our current understanding of key elements of recharge in the Focus Area. This section has been organized into five findings that address the overall project objectives and contract requirements. These findings are:

- **Finding 1** – Surface water and groundwater data adhere to the GMWL with some evidence of evaporation
- **Finding 2** – Surface water sources that potentially contribute to recharge can exhibit significant seasonal variation in stable isotope data
- **Finding 3** – Probable sources of recharge including local precipitation versus stream recharge in water sampled at each well
- **Finding 4** – Groundwater-surface water interactions
- **Finding 5** – Updated conceptual model of recharge processes in the Focus Area

The hydrogeologic background developed for the Lower Tuscan Aquifer Study provides the foundation for this current work in assessing recharge in the Focus Area. The LTA Study (BC, 2013) summarizes three years of field investigation and interpretation; for additional background on the hydrogeologic background in Butte County, we encourage interested parties to review the LTA Study located on the Butte County website at https://www.buttecounty.net/Portals/26/Tuscan/LTAFinalReport.pdf. Based on our experience in developing the LTA Study we have prepared a series of hydrographs for all wells investigated as part of this study. These hydrographs and a discussion of their relevance to stable isotopes and recharge is presented as Appendix C.

To clarify the types of precipitation associated with elevation ranges encountered in the Butte County, three elevation ranges with different isotopic water will be considered and referred to in this Study:

Upper Watershed. The Upper Watershed area is located topographically above the other regions above approximately 1,800 ft amsl. The Upper Watershed receives rainfall and snow, primarily during the winter and spring months. Rainfall runoff and snowmelt enters the Focus Area from major streams and rivers, including Butte Creek, the Sacramento River, and the Feather River; imported irrigation water also enters the Focus Area from Lake Oroville.

Lower Foothills. The Lower Foothills region occurs within a relatively narrow topographic band along the east edge of the Sacramento Valley with an elevation ranging from approximately 300 to 1,800 ft amsl, with nearly all of the precipitation fell as rainfall rather than snow. The total precipitation in the Lower Foothills is less than the Upper Watershed. Varying from approximately 30 to 60 inches per year (Paradise).

Valley Floor. The Valley Floor defines the lowest elevation source water region in the Focus Area, approximately 100 to 300 ft amsl. The total precipitation in the Valley Floor varies from approximately 20 to 25 inches per year (Gridley, Chico).

Figure 6 shows the approximate extent of these elevation ranges in Butte County as described in this Study.

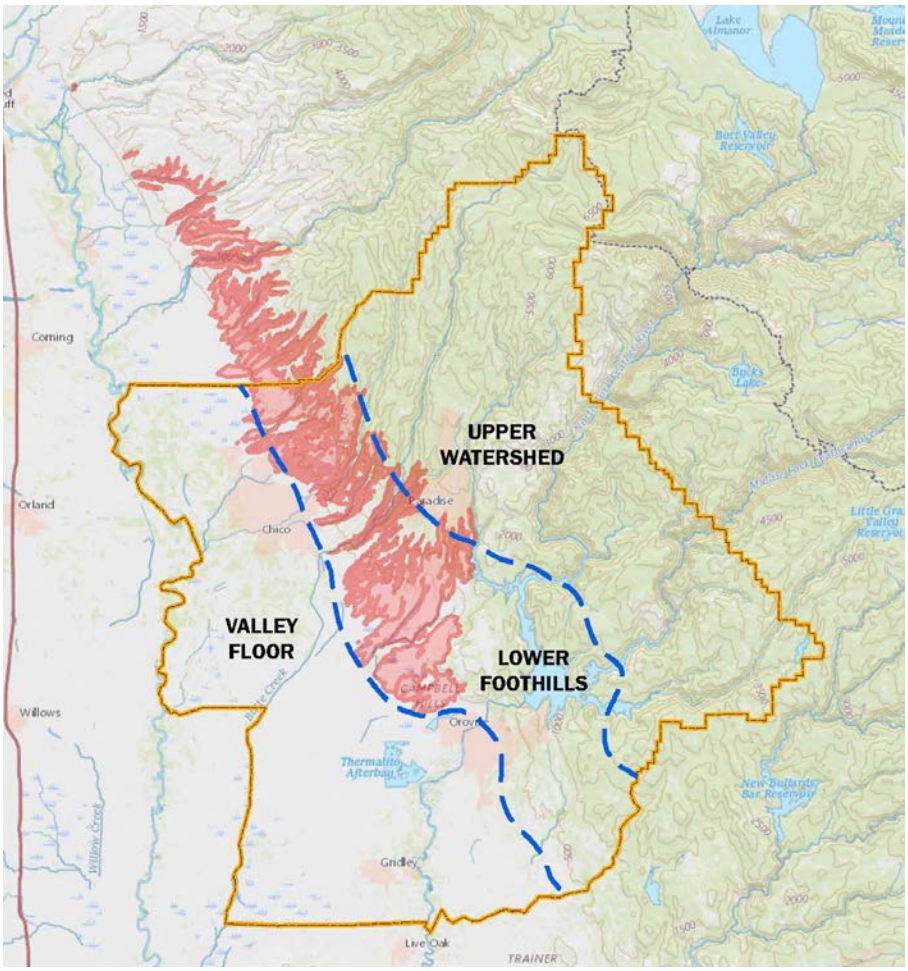

Figure 6. Range of Precipitation Types in Butte County

Finding 1 – Surface water and groundwater data adhere to the GMWL with some evidence of evaporation

Figure 7 presents all stable isotope data to initiate a general discussion of the stable isotope data. A plot of δD versus $\delta^{18}O$ is typically used in stable isotope studies to distinguish different populations of water as they relate to the elevation of precipitation. The solid line on Figure 7 is the Global Meteoric Water Line (GMWL), reflects a linear relationship between δD and $\delta^{18}O$ in meteoric water (Craig, 1961).

$$\delta D=(8.0)*(\delta^{18}O)+10 \quad \text{[Equation 1]}$$

Figure 7 surface water samples (open symbols) tends to fall along more negative regions (lower left quadrant) of the GMWL, which is characteristic of high elevation snow melt sources of runoff. Water samples that fall below or to the right of the GMWL indicate that the water sample has undergone some evaporation as described in Part 2 of this report. Evaporated water samples form linear correlations with flatter, more horizontal slope as shown by the dashed line to the right of the GMWL in Figure 7.

The slope of the GMWL (slope of $\delta D/\delta^{18}O = 8.0$) has been supported by numerous studies throughout the world (Craig, 1961). The slope of the evaporated groundwater (dashed line) in Figure 7 has a slope

of $\delta D/\delta^{18}O$ = 4.8. The slope of 4.8 is consistent with surface water evaporation trends observed in the Sacramento Valley (Davisson and Criss, 1993; Criss and Davisson, 1996).

Rose et al. (1996) developed an empirical equation correlating the inferred recharge elevation and $\delta^{18}O$ in the water sample. This equation was developed for a transect from Redding to the eastern side of the Hat Creek rim. Equation 2 applies to meteoric water in Northern California that does not show evidence of evaporation.

$$\delta^{18}O = -0.000641Z - 8.62; \quad Z = \text{elevation (amsl)} \quad \text{[Equation 2]}$$

This relationship developed by Rose et al. was based on 55 surface water and spring samples collected from approximately 700 to 5,400 ft amsl in Northern California in May 1994 (no effect of seasonal variability was considered). Therefore, the relationship between $\delta^{18}O$ and elevation is well supported by relevant local data but the predicted accuracy of recharge elevation is approximate.

The North Area Wells groundwater data (solid triangles, Figure 7) conform to the GMWL. Equation 2 suggests that the original recharge elevation ($\delta^{18}O$ as low as -10.5 ‰) was from precipitation was from the Upper Watershed (Figure 6) at an elevation of approximately 3,000 ft.

The East Area Wells samples (solid circles – Figure 7) show evidence of evaporation because they deviate from the GMWL. Figure 7 shows that the East Area groundwater samples conform to the dashed line with a slope of 4.8 (rather than the GMWL, slope of 8.0). If we attempt to correct for evaporation, we predict that the East Area Well $\delta^{18}O$ samples would vary from -8.5 to -9.8 ‰ $\delta^{18}O$ (average -8.8 ‰ $\delta^{18}O$). Assuming this correction for evaporation, Equation 2 predicts East Area groundwater recharge source water was primarily from the Lower Foothills (Figure 6).

During recharge water moves through porous media, mixing and displacing stored water. Surface precipitation, irrigation or surface water moves laterally and vertically as it mixes with groundwater. Groundwater pumping induces lateral and vertical gradients greatly exaggerating groundwater flow and mixing. However, the precise cause and extent of mixing are largely unknown and difficult to quantify.

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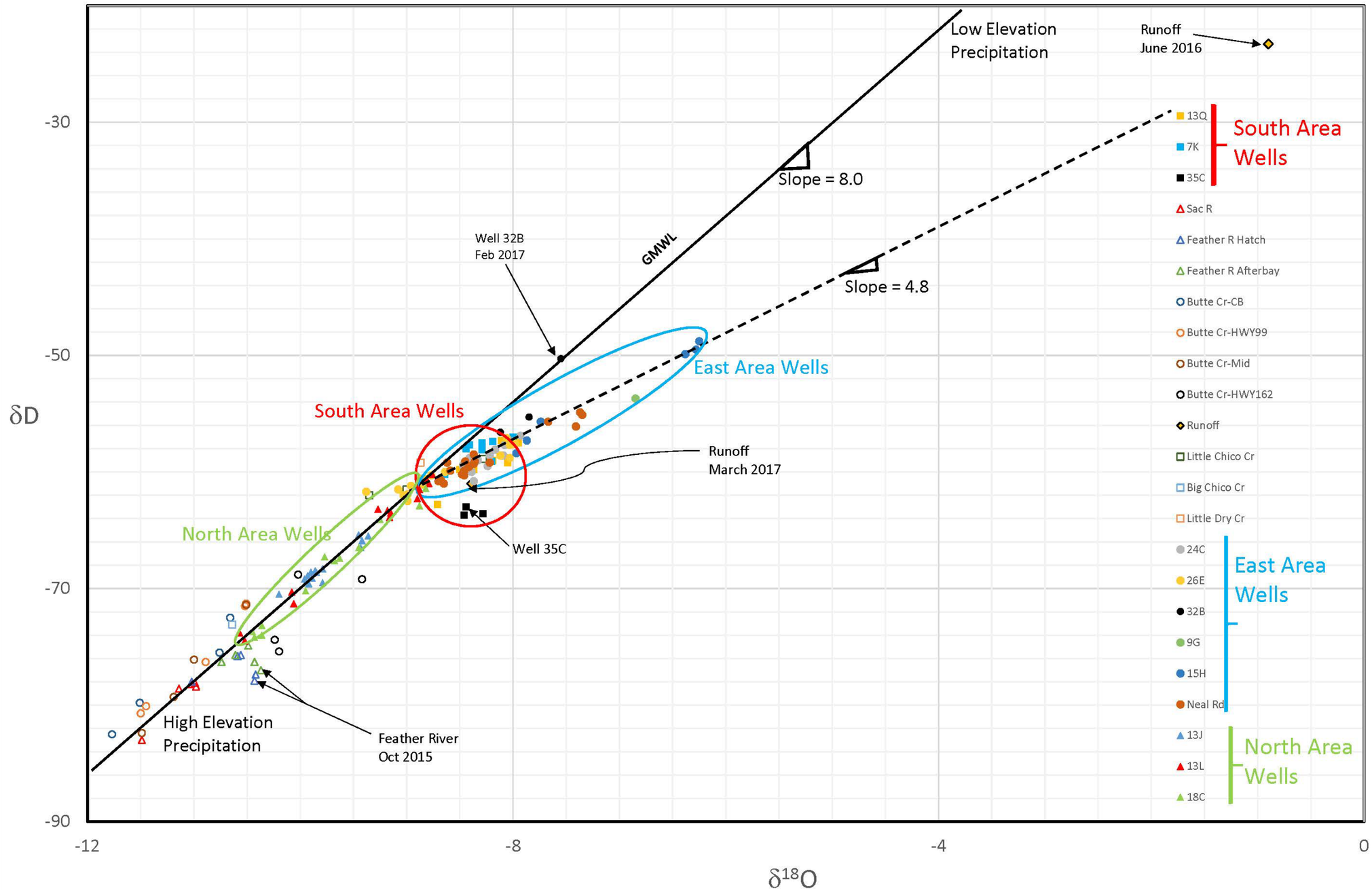

Figure 7. δD versus $\delta^{18}O$ in surface water, groundwater and storm water runoff samples.

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Finding 2 – Surface water sample locations exhibit seasonal variation in stable isotope values

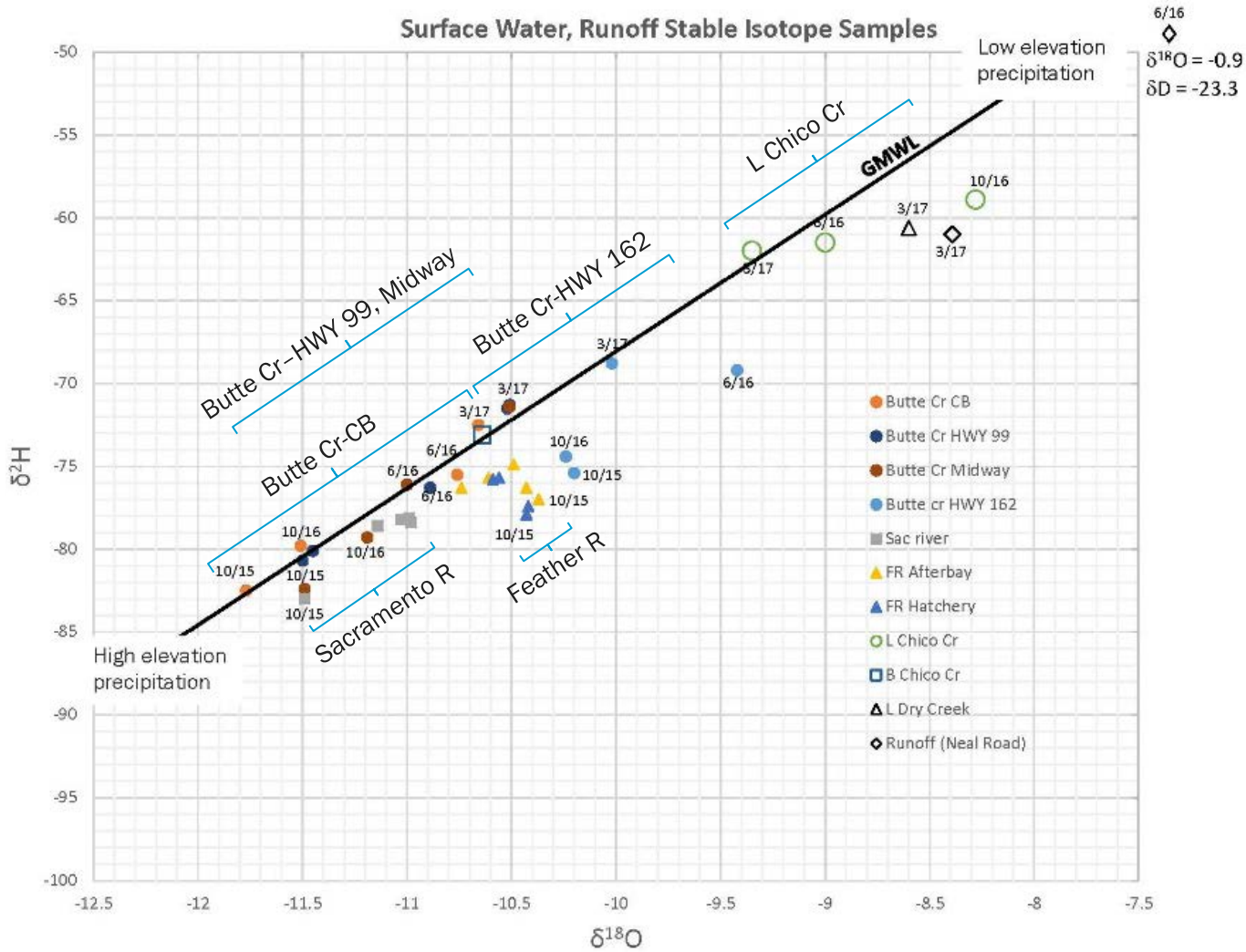

Figure 8. δD, $\delta^{18}O$ in Surface Water Samples

The isotopic values of creek surface water samples depend on whether the precipitation is generated locally or derived from Upper Watershed rainfall or snow melt. Each of these conditions impart a unique isotope signature.

Figure 8 shows that Butte Creek samples have significant variation over time in all four sample locations:

1. The lower isotopic composition in the late season (October) suggests flow in Butte Creek is primarily derived from the Upper Watershed, approximately 3,000 to 5,000 ft amsl (based on Equation 2).
2. Winter flows (March) appear to be sourced primarily from Lower Foothills runoff.

3. June is transitional with a combination of source water from Upper Watershed and Lower Foothills.
4. Three of the four samples collected from Butte Creek at Hwy 162 plot to the right of the GMWL, suggesting evaporation. The Highway 162 sample is likely a mix of Upper Watershed and Lower Foothills mixed with evaporated irrigation return water in this downstream segment of the creek.

Little Chico Creek samples show a seasonal variation but the order is reversed compared to Butte Creek, with October samples showing higher isotopic value, inferring Valley Floor precipitation with March samples indicating Lower Foothills precipitation. Overall, the water in Little Chico Creek is derived from primarily from Lower Foothills compared to the water from Butte Creek water primarily from the Upper Watershed.

The single sample collected from Big Chico Creek in October 2015 suggests that it originated from approximately 3,000 ft elevation (based on Equation 2).

The isotopic value of the single sample collected from Little Dry Creek in March 2017 is above -8.8 ‰ $\delta^{18}O$, suggesting the recharge source was from the Lower Foothills. There was no flow in Little Dry Creek in October 2015, June 2016 and October 2016.

The river water samples from the Sacramento and Feather Rivers show much less seasonal variation compared to the creek samples. The river water samples show consistent and predominant source from the Upper Watershed. Seasonal variation is limited because of association with large reservoirs (Lake Oroville and Lake Shasta) that provide consistent isotopic composition because of mixing and storage.

The Feather River samples collected at the Fish Hatchery, have a slight evaporative signature (plots below the GMWL, see Figures 7 and 8). In contrast, the March 2, 2017 sample was on the GMWL and indicates the high flow in the Feather River at that time (coincident with high releases due to structural failure of the Oroville Dam spillway) was recent meteoric water. The Feather River samples from the Afterbay consistently plot below the GMWL (see Figure 8), indicating an evaporative influence at this location.

The Sacramento River samples plot close to the GMWL (see Figure 8), indicating minor evaporation. The three samples from 2016 and 2017 cluster close together at about -11 ‰ $\delta^{18}O$, which suggests that the precipitation originated at an average elevation of approximately 3,700 ft amsl in the Upper Watershed. The October 2015 sample from the Sacramento River has a $\delta^{18}O$ value of -11.5 ‰, suggesting a source elevation of approximately 4,500 ft amsl also in the Upper Watershed.

Neal Road Landfill sediment pond contains local runoff from the Lower Foothills. These two samples from June 2016 and March 2017 show the extreme seasonality of runoff water that is open to the atmosphere and allowed to evaporate for any length of time. The June 2016 runoff water sample was the most evaporated, least $\delta^{18}O$ enriched sample observed in this study (Figure 7).

The surface water data demonstrate that there can be significant seasonal variation in the isotope signatures along the local creeks on the Lower Foothills. While large reservoirs on the Sacramento River and Feather River tend to provide a more consistent isotopic signature in the river samples, seasonal variations may still occur due to major storm events that are not fully retained by the reservoirs or due to modification (e.g. evaporation) downstream from the reservoirs. The seasonal changes in the isotope data in the potential recharge sources suggests that seasonal changes may also occur in water samples collected from appropriately located groundwater monitoring wells.

Finding 3 – Probable sources of recharge in groundwater wells

A total of 120 groundwater samples were collected from 32 groundwater wells from 16 locations (5 in Neal Road Landfill) with screened intervals from 13 to 990 ft bgs. The groundwater samples were collected from October 2015 to March 2017. These Focus Area wells locations extend from the Lower Foothills, in the Paradise area, west to Valley Floor including the Sacramento River and south to the Thermalito Afterbay.

Table 1 presents a summary of probable sources of recharge at each well monitored in this Study. The recharge source water is tied to the range of the observed $\delta^{18}O$ values in the groundwater samples, therefore the $\delta^{18}O$ is listed as a key parameter in assessing probable recharge source. Based on the data presented in Figure 7, $\delta^{18}O$ values that varied from -6 to -8‰ do not conform to the GMWL (except for Well 32B), indicating that the recharge source was likely to be from the Valley Floor, with varying degrees of evaporation (yellow highlighting Table 1). Groundwater samples where $\delta^{18}O$ varied from approximately -8 to -8.8‰ indicate that source water is from Valley Floor at less than 300 ft elevation, based on Equation 2 (green highlighting, Table 1).

When the $\delta^{18}O$ values vary from approximately -8.8 to -10‰, evaporation is not observed and recharge is primarily from the Lower Foothills (light blue highlighting, Table 1). The recharge could occur from rivers, creeks, ephemeral streams, or local precipitation on the Lower Tuscan Formation outcrop. Water samples with no evaporation indicated and $\delta^{18}O$ values lower than -10‰, suggest river and creek recharge is from the Upper Watershed with source waters originating at elevations above approximately 1,800 to 2,000 ft amsl (darker blue highlighting, Table 1).

Table 1 shows only minor variation in $\delta^{18}O$ with season in individual screened intervals at each well location over time, typically less than 0.5 ‰. The one location that varied more than 0.5 ‰ was Well 18C intermediate zone (varied 1.13‰) and deep zone (varied 0.89‰) on different sampling events. One possible explanation for the variability of these two intervals is that both had exceptionally long screened interval of 260 ft (intermediate) and 110 ft (deep), possibly resulting in seasonal variations in the mixing of waters from different water bearing zones (e.g. depending on seasonal pumping in the area). All other well screens in this study were between 10 and 50 ft length.

Table 1. Probable Sources of Recharge to Individual Groundwater Wells

Well Name	Type	Recharge Source	Screen Interval (ft)	$\delta^{18}O$ range (‰)	Evaporation Indicated?
20N02E15H	observation	Valley Floor precipitation that has been evaporated; shallow zone more evaporated than deeper zone	55-65 (S)	-6.25/-6.38	Yes
			170-180 (S)	-7.74/-7.98	
20N02E24C	observation	Valley Floor precipitation, slightly evaporated; shallower zones more evaporated than deeper zone	124-134 (S)	-7.93/-8.33	Yes
			336-377 (I)	-8.09/-8.24	
			484-505 (I)	-8.37/-8.47	
20N02E09G	observation	Valley Floor precipitation, moderate evaporation	130-170 (S)	-6.85	Yes
21N03E32B	irrigation	This very shallow well is adjacent to Little Dry Creek, recharge likely from Little Dry Creek and/or local Valley Floor precipitation.	13-57 (S)	-7.55/-8.12	?
21N02E26E	observation	Valley Floor/Lower Foothills precipitation that has been evaporated	105-150 (S)	-7.98/-8.12	Yes
		Valley Floor/Lower Foothills precipitation	265-290 (I)	-8.77/-8.84	Slight
		Valley Floor/Lower Foothills precipitation	400-484 (I)	-8.64/-8.96	No
		Lower Foothills up to ~1,000 ft elevation	610-620 (D)	-8.99/-9.38	No
MW-9B	observation	Valley Floor/Lower Foothills precipitation that has been slightly evaporated	220-253 (I)	-8.36/-8.42	Slight
MW-4A	observation	Valley Floor/Lower Foothills precipitation that has been slightly evaporated	280-310 (I)	-8.46/-8.7	Slight
MW-10A	observation	Valley Floor/Lower Foothills precipitation moderate evaporation	115-145 (S)	-7.35/-7.67	Yes
MW-13	observation	Valley Floor/Lower Foothills precipitation that has been evaporated	212-242 (I)	-8.41/-8.65	Yes
MW-8B	observation	Valley Floor/Lower Foothills precipitation that has been evaporated	202-222 (I)	-8.22/-8.62	Yes
20N01E35C	residential	Valley Floor with return water from rice irrigation water	50-92 (S)	-8.28/-8.46	Yes
19N02E07K	observation	Valley Floor precipitation that has been evaporated	140-150 (S)	-8.04/-8.41	Slight
			330-340 (I)	-8.0	
			560-570 (I)	-8.2/-8.64	
19N02E13Q	observation	possible mixture of Afterbay water, evaporation, with Valley Floor precipitation	130-200 (S)	-8.19/-8.71	Yes
			470-480 (I)	-7.99/-8.11	
			670-680 (D)	-8.05/-8.37	
20N02E18C	observation	mostly Butte Creek (Upper Watershed)	130-200 (S)	-10.36/-10.43	No
		mixture of Butte Creek and Lower Foothills precipitation	360-620 (I)	-8.82/-9.95	

Table 1. Probable Sources of Recharge to Individual Groundwater Wells

Well Name	Type	Recharge Source	Screen Interval (ft)	$\delta^{18}O$ range (‰)	Evaporation Indicated?
		mixture of Butte Creek and Lower Foothills precipitation	770-880 (D)	-8.88/-9.77	
21N01E13L	observation	mostly Butte Creek (Upper Watershed)	240-340 (I)	-10.06/-10.57	No
		mixture of Butte Creek and Lower Foothills precipitation	540-560 (I)	-9.15/-9.27	
		mixture of Lower Foothills and Valley Floor precipitation	735-760 (D)	-8.76/-8.88	
21N01W13J	observation	mixture of Sacramento River (Upper Watershed) and Valley Floor precipitation	355-385 (I)	-9.85/-10.2	No
		mixture of Sacramento River (Upper Watershed) and Valley Floor precipitation	570-591 (I)	-9.79/-9.9	
		Valley Floor precipitation	780-820 (D)	-9.36/-9.35	

Likely Recharge Source, Water Characteristics	Valley Floor (moderate evaporation)	Valley Floor/Lower Foothills (slight evaporation)	Lower Foothills/ Upper Watershed (no evaporation)	Upper Watershed (no evaporation)

(S) shallow – 0-200 ft bgs; (I) intermediate – 200-600 ft bgs; (D) deep - >600 ft bgs

Finding 4 – Groundwater-surface water interactions

The groundwater isotope data suggests that recharge has a strong spatial component. Figure 9 identifies three areas each with common recharge patterns observed in the isotopic data.

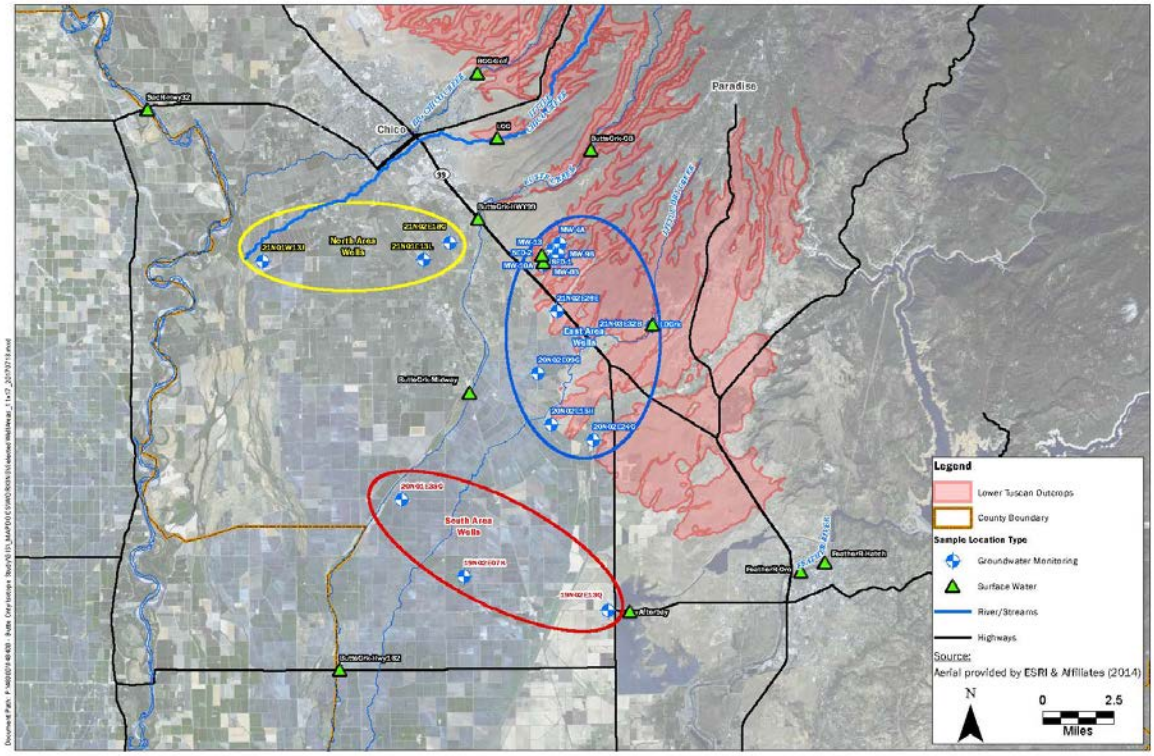

Figure 9. Recharge Types in the Focus Area

North Area Wells – The North Area includes wells 13J, 18C, and 13L in an area dominated by groundwater pumping for irrigation. Some limited areas utilize diverted Butte Creek and Sacramento River Water for irrigation. Well 13J is near the Sacramento River and Little Chico Creek. Wells 18C and 13L are located west of Butte Creek in the Valley Floor. The data from the North Area wells plot along the GMWL (see Figure 7), indicating that the water present in these wells has not experienced any appreciable evaporation prior to percolating into the subsurface and reaching the aquifer zones.

As indicated on Figures 10 and 11, the shallower samples from the North Area (400 ft bgs or shallower) have $\delta^{18}O$ values consistent with recharge from the Upper Watershed. Intermediate and deep zone intervals in the North Area wells have $\delta^{18}O$ values that are consistent with recharge sources from the Lower Foothills, or a mixture of water from the Upper Watershed and Lower Foothills.

The isotope signatures in the North Area wells indicate that higher elevation rainfall and snowmelt from the Upper Watershed is recharging the shallower aquifer depths through recharge from the Sacramento River (Well 13J) and Butte Creek (wells 18C and 13L) once these river and stream channels reach the

valley floor in general proximity to the North Area wells[1]. The intermediate and deeper zones may be receiving recharge from direct percolation in the Lower Foothills region or by lower elevation creeks (e.g. Little Chico Creek). The LTA Study suggested that there may be some mixing of water from the shallow and deep intervals within wells in the North Area, possibly due to deep pumping for irrigation. Thus, the recharge in the intermediate zone, and possibly the deep zone, aquifers in the North Area is most likely due to a combination of direct recharge from the Lower Foothills and downward migration of groundwater from the shallower zones (i.e. Upper Watershed water recharged locally from rivers and streams) due to deep pumping.

Figure 10 presents the pattern of $\delta^{18}O$ values compared with depth for each of these three areas. Figure 11 presents the patterns of $\delta^{18}O$ values compared with depth for each sample date in each individual well.

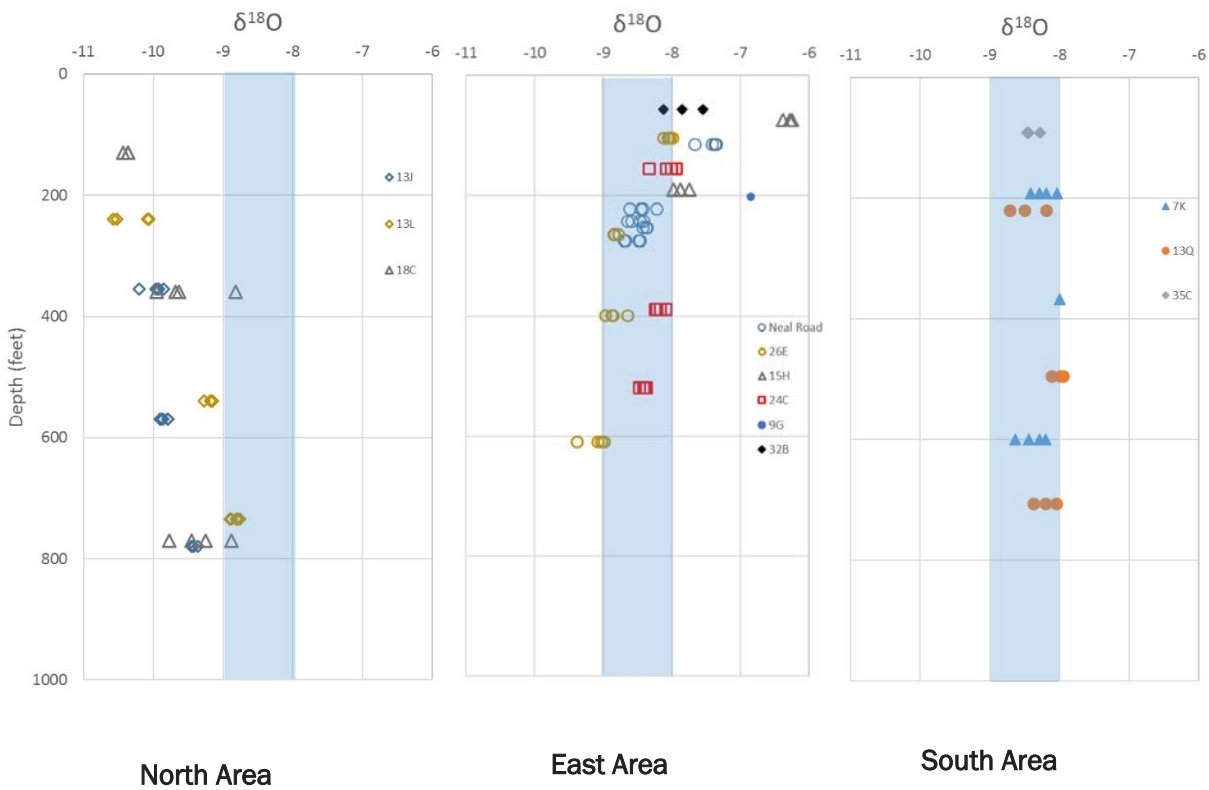

Figure 10. $\delta^{18}O$ in Groundwater Samples from the Focus Area

[1] Hydrographs presented in the LTA Study report indicate an influence on groundwater levels in wells in the North Area due to changes in flow in the Sacramento River, further supporting recharge of rainfall and snowmelt from the Upper Watershed within the North Area.

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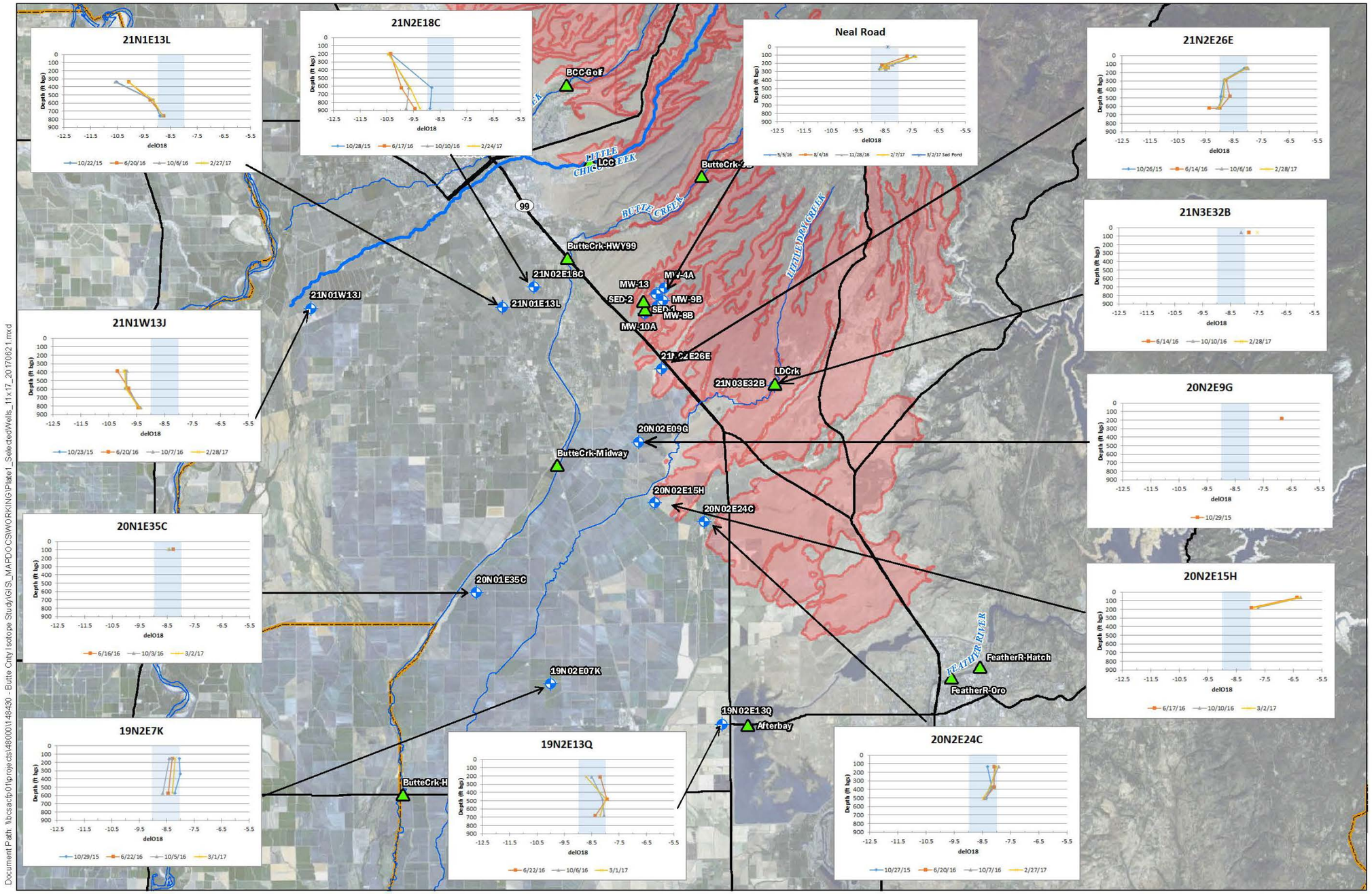

Figure 11. $\delta^{18}O$ in Groundwater Samples from the Focus Area

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East Area Wells – The East Area incudes wells 26E, 32B, 9G, 15H, 24C, and the Neal Road Landfill monitoring wells. These wells are located at the eastern edge of the Valley Floor, adjacent to the Lower Foothills. Most of the East Area wells are located on the southwestern (downslope) edge of the Lower Tuscan Formation outcrop or on alluvial material immediately overlying the Lower Tuscan Formation. As discussed in Finding 1, the isotope data from the East Area wells deviate from the GMWL and conform to the dashed evaporated-water line with a slope of 4.8 on Figure 7. The evaporated-water line on Figure 7 intersects the GMWL at a point consistent with rainfall from elevations that are transitioning from the Valley Floor to the Lower Foothills region. The evaporated-water line on Figure 7 also projects through the water sample collected from the stormwater retention pond at the Neal Road Landfill (sample labeled "Runoff June 2016" in the upper right corner of Figure 7). Figures 10 and 11 indicate that shallower samples from the East Area wells (400 ft bgs or shallower) have $\delta^{18}O$ values that suggest recharge sources from Lower Foothills; especially when evaporation of East Area wells are considered (Figure 7). Groundwater samples from the intermediate and deep screened intervals from the East Area wells suggest that recharge source is from Lower Foothills; however, much less evaporation is observed in groundwater samples below 400 ft bgs than shallow groundwater samples above that level.

The isotope signatures indicate that East Area groundwater (all depths) recharge source is a combination Valley Floor rainfall and runoff within local streams and creeks from the westernmost part of the Lower Foothills. The intermediate and deep intervals in the east area may also receive some recharge from direct percolation in the Lower Foothills immediately adjacent to the Valley Floor. Unlike the North Area, recharge from rivers (e.g. Sacramento River) or from major streams that are sourced from the Upper Watershed (e.g. Butte Creek) does not occur in the East Area.

South Area Wells – The South Area includes wells 35C, 7K, and 13Q. Well 35C is a shallow domestic well (total depth of 92 ft bgs) located near Butte Creek. Well 13Q is located to the west of Thermalito Afterbay. Well 7K is located between wells 35C and 13Q. The South Area has historically received surface irrigation water from the Feather River, primarily for rice farming. As indicated on Figure 5, the water that recharges the South Area wells has experienced some evaporation, but not to the same extent as the East Area wells. Figures 10 and 11 indicate that the groundwater samples from the South Area wells have $\delta^{18}O$ values that are similar at all depths.

The isotopic data from Well 35C plot below all other South Area data points (see call-out for Well 35C on Figure 7). The Well 35C data points are comparable to data developed by the US Geological Survey (USGS; Dawson, 2001) in a large study of rice field recharge in western Butte County. The USGS measured isotopic abundances and water quality for wells in rice fields adjacent to the Sacramento River in Butte and eastern Glenn County. The USGS found that shallow wells formed an evaporation line that intersects the GMWL at a $\delta^{18}O$ value of -10.5 ‰, equivalent to the $\delta^{18}O$ values for the Feather River samples shown on Figures 7 and 8 of this report. The USGS also found that the rice wells evaporation line has a slope of 5.7 (steeper than Figure 7), passing through isotopic values identical to Well 35C (Dawson, 2001). Because this is such a relevant study, this reference is attached as Appendix D. A key figure from that publication is reproduced as Figure 12 with the data from Well 35C (large orange circle) shown in alignment with the extensive shallow groundwater data from the rice fields (small red circles). This is solid evidence that the groundwater sampled from Well 35C has been recharged by irrigation water seepage returns over the many decades rice has been cultivated in the South Area.

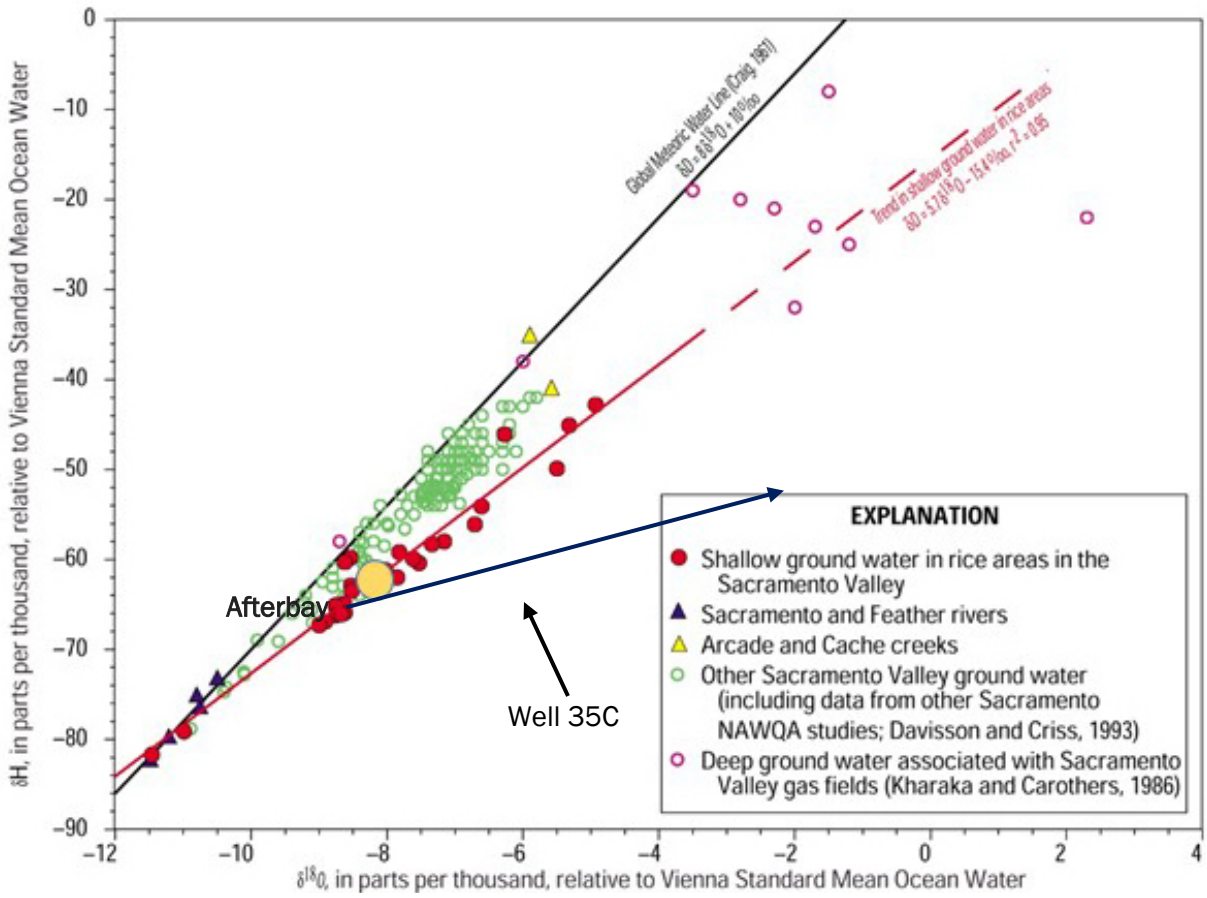

Figure 12 Relation between in ground water and surface water in parts of the Sacramento Valley, California

From Dawson (2001). Data from Well 35C plotted for comparison (orange circle)

In contrast with Well 35C, the isotope values for all depth intervals in wells 7K and 13Q project back to the GMWL at a $\delta^{18}O$ value of approximately -8.8 ‰. Using Equation 2, this value represents rainfall from an elevation of 250 ft msl, which is near the boundary between the Valley Floor and the Lower Foothill regions, as defined in this study. Thus, recharge at all depths in wells 7K and 13Q is a result of recharge of local rainfall in the eastern portion of the Valley Floor and perhaps Lower Foothills, with minor evaporation. This finding is somewhat surprising given that Well 13Q is located adjacent to the Thermalito Afterbay and the area encompassing both wells has received irrigation water from Feather River sources for many decades. Despite the proximity to the Afterbay and the long history of imported irrigation water use in the South Area, the groundwater isotope data from wells 7K and 13Q do not support recharge from the Upper Watershed (Feather River).

The difference in apparent recharge source between Well 35C and wells 7K and 13Q may be related to the depths of the screened intervals (see Table 1) and geologic conditions. Well 35C is screened from 50 to 92 ft bgs. The screened intervals in wells 7K and 13Q range from 130 ft bgs to as deep as 680 ft bgs. Data from the LTA Study indicates that wells in this area that are screened shallower than approximately 100 ft bgs to 150 ft bgs are completed within Quaternary alluvial deposits and not within the underlying Tuscan Formation aquifers. An aquifer pumping test conducted at Rancho Esquon (near the southwest edge of the East Area) as part of the LTA Study demonstrated that there is an apparent aquitard separating the Quaternary alluvial deposits and the Tuscan Formation in that area, preventing vertical groundwater mixing between those geologic deposits. Thus, the shallow Quaternary alluvial zones in the South Area may be recharged by irrigation water while the underlying Tuscan Formation aquifers appear to be recharged from the Lower Foothills.

Finding 5 – Updated Conceptual Site Model

The LTA Study presented the hydrogeological framework for the Sacramento Valley groundwater basin in Butte County by describing many aspects of the Lower Tuscan Aquifer groundwater recharge. The LTA Study included aquifer performance tests, stream flow analyses, and surface soil infiltration measurements. Limited analysis of stable isotope data from surface water and groundwater monitoring wells were used to provide a preliminary assessment of groundwater recharge sources.

This Study focuses on recharge sources and mechanisms in central Butte County by sampling surface water, groundwater, and stormwater samples for stable isotope analysis. The interpretation of the stable isotope data, as described in Findings 1 through 4 of this report, provides further refinement of the understanding of the source waters and recharge processes for the primary groundwater aquifers in Butte County. Key findings related to the Conceptual Site Model are summarized below relative to source water regions and recharge mechanisms.

Source Water Regions

As defined in Finding 3, there are three primary source water regions for groundwater recharge in the Focus Area:

Upper Watershed. The Upper Watershed area is located topographically above the other source water regions. Geologically, it consists primarily of volcanic, granitic, and metamorphic rocks that do not have any appreciable primary porosity. Fracturing within these rock units may occur locally but the fractures are not pervasive on a regional scale, which limits the amount of water that can percolate into the bedrock geologic units and the volume of groundwater available to migrate to other regions. The Upper Watershed receives rainfall and snow, primarily during the winter and spring months. Rainfall runoff and snowmelt enters the Focus Area from major streams and rivers, including Butte Creek, the Sacramento River, and the Feather River; imported irrigation water also enters the Focus Area from Lake Oroville.

As described in Finding 2, flows in Butte Creek show a very strong seasonal variation in isotopic data. Flows in Butte Creek appear to be sourced by lower-elevation (Lower Foothills) rainfall runoff during the winter and by Upper Watershed snowmelt late in the dry season. In early summer, the flow is a mix of rainfall runoff and snowmelt.

Both the Sacramento River and the Feather River have large reservoirs that act to mix water from different seasons. As a result, the isotopic signature in the runoff from the large river systems is more uniform seasonally.

Lower Foothills. The Lower Foothills region occurs within a relatively narrow topographic band along the east edge of the Sacramento Valley. The Lower Foothills region contains the outcrop of the Lower Tuscan Formation in addition to small alluvial fans and other Recent sedimentary deposits that directly overly the Lower Tuscan Formation. Rainfall that occurs in the Lower Foothills may percolate into the Lower Tuscan Formation and the Recent alluvial sediments or it may runoff through local, ephemeral streams to the Valley Floor.

Little Chico Creek is an ephemeral stream that originates just above the Lower Foothills. The isotopic data from Little Chico Creek shows seasonal variability that is the opposite of that from Butte Creek. In the winter months, the flows in Little Chico Creek appear to be from higher elevation portions of the Lower Foothills while the late season flows are from rainfall that occurred at lower elevations. However, the runoff in Little Chico Creek is derived from rainfall that occurred at lower elevations than any of the samples from Butte Creek.

Runoff from the Upper Watershed passes through the Lower Foothills crossing over the Lower Tuscan Formation (e.g. Butte Creek and other streams). However, the LTA Study did not find any evidence that

appreciable quantities of surface water from streams percolate where they pass over the Lower Tuscan Formation outcrops within the Lower Foothill region.

Valley Floor. The Valley Floor defines the lowest elevation source water region in the Focus Area. It is underlain by Recent alluvial material in most areas, although the presence of hardpan layers may affect shallow percolation in some locations. There are no significant creeks or streams that originate on the Valley Floor. Rainfall that occurs on the Valley Floor may percolate locally or it may runoff into other creeks and streams that originate at higher elevations.

Recharge Mechanisms

The recharge mechanisms may vary by both depth and area across the groundwater basin within the Focus Area.

North Area. Within the shallower aquifer interval (above about 400 ft bgs), the primary source of groundwater is from the Upper Watershed region, based on the isotope data. Wells to the east may be recharged from Butte Creek, whereas wells to the west may be recharged by flow from the Sacramento River. As discussed in Finding 4, the LTA Study found that changes in flow in the Sacramento River appear to be correlated with changes in water levels in shallow interval wells (less than 400 ft bgs), consistent with a Sacramento River recharge source further north in the valley.

The data indicate that the intermediate and deeper depth intervals are recharged from rainfall and percolation in the Lower Foothills region. Rainfall in this region percolates directly into the Lower Tuscan Formation at the outcrop, or may percolate into the small alluvial fans and other sedimentary deposits in the Lower Foothills. Aquifer testing conducted as part of the LTA Study indicated that there is also the potential for Upper Watershed recharge in the shallow aquifer interval to be pulled down to greater depths due to irrigation pumping, causing a mixing of recharge sources in the intermediate and possibly deep intervals in the North Area. This mixing, however, is an anthropogenic effect and not necessarily a component of natural recharge that would occur in the absence of large-scale pumping from intermediate and deep aquifer intervals in the North Area.

The isotope data demonstrate that the intermediate and deep intervals of the Lower Tuscan aquifer do not receive any appreciable recharge as a result of fracture flow or other mechanisms from the Upper Watershed. The only route by which the Upper Watershed provides recharge within the North Area is indirect, by surface flow onto the Valley Floor through Butte Creek and the Sacramento River, providing water to the shallow zone.

East Area. Recharge in the East Area wells is affected by evaporation, indicating some delay before the precipitation that forms the rainfall percolates into the subsurface. The shallow aquifer intervals are likely to be recharged by direct percolation primarily from Valley Floor precipitation, supplemented by some rainfall recharge at the base of the Lower Foothills. The intermediate and deep aquifer intervals are recharged from the lowest elevation part of the Lower Foothills region, most likely from percolation directly into the Lower Tuscan Formation at the outcrop or through recharge into the local alluvial fans and sedimentary deposits and subsequent downward vertical migration into the underlying Tuscan aquifer units.

The isotope data do not provide any indication that small creeks or streams originating in the Lower Foothills, or lateral movement of groundwater within the small alluvial fans and sedimentary deposits, provides any significant recharge to the shallow aquifer interval at the edge of the Valley Floor in the East Area. Because there is no data to support any water from the Upper Watershed, the stable isotope data in groundwater indicates that virtually all recharge in the East Area is from local precipitation.

South Area. Wells completed within the Tuscan Aquifer units in the South Area all have a similar isotope signature, indicative of recharge from the lowest elevations of the Lower Foothills. This relationship infers that all recharge to these aquifer intervals occurs at the outcrop of the Tuscan Formation or through local alluvial fans and other sedimentary material directly overlying the Lower Tuscan Formation. The uniform isotope results with depth (see Figure 10) may also suggest the potential for mixing between different aquifer intervals.

Well 35C in the South Area is screened very shallow (less than 100 ft bgs) and is likely within the alluvium overlying the Tuscan Aquifers units. The isotope data indicates that the recharge for this well comes, in part, from imported irrigation water from the Feather River used for rice farming. Given the shallow nature of this well, it is also likely that some recharge of local rainfall occurs in the shallow alluvium. The isotope data are also consistent with aquifer pumping test results from the LTA Study that demonstrate that the shallow alluvium is not in hydraulic communication with the underlying Tuscan Aquifers.

Figure 13 provides a matrix of likely Source Water Regions and Recharge Mechanisms for each area of the basin and each aquifer depth, highlighting the most plausible mechanisms and other potential mechanisms based on the isotope data from this study and the LTA Study. The matrix in Figure 13 demonstrates that the Lower Foothills region may be the most critical water source for recharge of the Lower Tuscan Aquifer zones in Butte County.

Source Water Region		Upper Watershed					Lower Foothills					Valley Floor		
Recharge Mechanism		Runoff to Valley Floor via Large Streams and Rivers	Percolation in Lower Foothills from Creeks Crossing the Tuscan Outcrop	Percolation from Snowshed through Fractures	Irrigation Water (Sacramento, Feather River or Butte Creek Diversions)	Mixing from Other Depth Zones due to Pumping	Local Percolation through Tuscan Outcrop or Alluvium	Runoff to Valley Floor in Large Streams and Rivers	Runoff to Valley Floor in Local/Ephemeral Creeks	Local Percolation and Subsurface Flow to Valley Floor through Alluvium	Mixing from Other Depth Zones due to Pumping	Direct Percolation	Runoff into Creeks and Stream Channels	Mixing from Other Depth Zones due to Pumping
Area	Depth Interval													
North	Shallow													
	Intermediate													
	Deep													
East	Shallow													
	Intermediate													
	Deep													
South	Alluvium													
	Shallow													
	Intermediate													
	Deep													

Depth Intervals

Shallow: less than 200 feet bgs; Intermediate: 200-600 ft bgs; Deep: greater than 600 ft bgs

Most Plausible Mechanism based on Isotope Data and LTA Study

Possible Mechanism based on Isotope Data and LTA Study

No Supporting Evidence in Isotope Data or LTA Study

Figure 13. Conceptual Site Model - Source Water Region and Recharge Mechanism Matrix

Part 4 // Conclusions and Recommendations

Conclusions

1. There is no single source of groundwater recharge throughout the Focus Area.
2. Different parts of the basin are recharged from one or more of the following sources:
    a. Rainfall on the Lower Foothills (North and East Areas, intermediate and deep zones);
    b. Creeks (North Area shallow wells);
    c. Rivers (North Area shallow zones);
    d. Irrigation water (South Area);
    e. Local rainfall on the Valley Floor (East Area shallow and South Area)

    The rate of recharge from each source is not known.
3. Seasonal variation and effects of evaporation in potential recharge source waters can be significant. Therefore, groundwater isotope data from previous studies should be used with caution and all future studies should include sampling during multiple seasons.
4. Based on an analysis of probable source of recharge from individual groundwater wells the $\delta^{18}O$ data suggests general sources of recharge:
    a. Highly evaporated water - $\delta^{18}O$ values from -6 to -8‰; these water samples do not conform to the GMWL (except for Well 32B).
    b. Valley Floor precipitation - $\delta^{18}O$ from approximately -8 to -8.8‰ some evaporation is typically occurring.
    c. Sacramento River recharge, minimal evaporation, minimal local precipitation - $\delta^{18}O$ values vary from approximately -11 to -11.5‰.
    d. Butte Creek water recharge, minimal evaporation, with a seasonally large effect of local precipitation (in surface water) - $\delta^{18}O$ from approximately -8.5 to -11.5‰.
    e. In the South Area shallow zone, the isotope data isotope data indicates that recharge includes imported irrigation water for rice fields from the Feather River.
5. Groundwater-surface water interactions in the Focus Area are spatially dependent, and can be divided into three distinct areas:
    a. The North Area Wells have distinct groundwater-surface water interactions. The shallow and intermediate screened intervals (<400 ft) appear to be greatly influenced by the Upper Watershed sources (Sacramento River and Butte Creek). The intermediate and deep screened intervals show progressively more influence from Lower Foothills.
    b. The recharge source for East Area Wells appears to be Valley Floor rainfall with some recharge contribution from the base of the Lower Foothills. The shallow zone groundwater appears to be strongly evaporated. Intermediate and deep zone well sample (>400 ft) data suggests precipitation from Lower Foothills followed by slow percolation.
    c. The South Area wells are likely to be affected by evaporated Valley Floor precipitation and in one case agricultural surface water irrigation. The uniform isotope results with depth (see Figure 10) may also suggest the potential for mixing between different aquifer intervals.

Overall, the groundwater stable isotopic abundance in the intermediate and deep zones suggests that the recharge source for these zones is from Valley Floor and Lower Foothill rainfall.

7. Updated Conceptual Site Model underscores the importance of seasonal isotopic sampling in surface water and to a lesser degree in groundwater. Defining the source water is the first step. There may be large areas within Butte County where shallow groundwater recharge has apparently not influenced the intermediate and deep zone recharge. The shallow zone isotopic groundwater near the Sacramento Rivers and Butte Creek are greatly affected by surface water. Aquifer testing conducted as part of the LTA Study suggest the potential for Upper Watershed recharge from North Area shallow zones to be pulled down to intermediate and deep zones by irrigation pumping. This mixing, is an anthropogenic effect and not natural recharge.
8. The hydrogeologic (physical) framework of the aquifer dictates groundwater flow, including where rock crops out at the surface and allows rainwater to recharge the subsurface. In Butte County, the major geological formations (Lower Tuscan, Ione and Mehrten) often overlap and constrain groundwater movement. Isotopic studies are most effective when the local environment presents large variability in isotope signatures and can be correlated geologic formations and hydrostratigraphic layers.

Recommendations

Methodology

- Seasonal sampling should be performed as part of future surface water and groundwater isotope studies for purposes of assessing groundwater recharge.
- Monitoring wells with multiple screened intervals (multi-completion monitoring wells) are recommended to assess stable isotope data at different depths. Sampling locations in this study with a single well-screen interval do not provide nearly as much insight as sampling locations with wells screened at multiple depths.
- Monitoring wells with relatively short screened zones (20 ft or less) are preferred to minimize mixing between aquifer zones or between aquifer zones and residual water retained within the aquitard zones between aquifers. The LTA Study determined that the aquitards can release large volumes of water to the aquifer in areas where large volumes of groundwater are extracted.

General

- South Area Wells – Conduct general mineral analysis on groundwater samples to evaluate whether elevated EC values observed during sampling for this study are due to irrigation influences (e.g. elevated nitrate, calcium, sulfate) or due to proximity to the Ione Formation (e.g. elevated sodium, chloride, and boron). This will help further characterize the recharge source.
- Contribution of Recharge from Rainfall Directly on the Lower Tuscan Outcrop – Stable isotope abundances indicate that a substantial proportion of local recharge is derived from elevations consistent with the outcrop of the Lower Tuscan Formation. Thus, it is recommended that local precipitation be collected during an entire precipitation season at varying elevations across the outcrop and analyzed for stable isotopes to better correlate or calibrate the groundwater isotope values with local precipitation sources.

- Recharge Rate - Most well locations and depths should be sampled and analyzed for presence of tritium to help distinguish whether recharge to individual aquifer zones is occurring over periods shorter than about 60 years, or whether recharge is occurring over longer timeframes.
- Water budgets can be helpful to define quantities of water inflow.

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Appendix A: Stable Isotope Data

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Appendix A - Stable Isotope Data, 2015 to 2017

Date	delta_2_H	delta_18_O	Location_ID	Sample_Type	CoordX	CoordY	Total_Depth	Perf_Top	Perf_Bottom	pH	Temp	EC
10/29/2015 0:00	-59.1	-8.2	19N02E07K002M	GW	-121.788	39.5118	600	560	570	7.99	66.28	186
6/22/2016 0:00	-58	-8.44	19N02E07K002M	GW	-121.788	39.5118	600	560	570	7.28	22.3	170.1
10/5/2016 0:00	-60.2	-8.64	19N02E07K002M	GW	-121.788	39.5118	600	560	570	7.36	20.4	450
3/1/2017 0:00	-58.1	-8.29	19N02E07K002M	GW	-121.788	39.5118	600	560	570	7.7	15.4	142.6
10/29/2015 0:00	-57	-8	19N02E07K003M	GW	-121.788	39.5118	368	330	340	7.48	62.43	211
10/29/2015 0:00	-57.6	-8.04	19N02E07K004M	GW	-121.788	39.5118	192	140	150	7.64	63.97	182
6/22/2016 0:00	-57.7	-8.29	19N02E07K004M	GW	-121.788	39.5118	192	140	150	7.17	20.8	
10/5/2016 0:00	-57.5	-8.29	19N02E07K004M	GW	-121.788	39.5118	192	140	150	7.26	20.6	179.4
3/1/2017 0:00	-57.4	-8.19	19N02E07K004M	GWD	-121.788	39.5118	192	140	150	7.58	15.9	146.5
10/5/2016 0:00	-57.7	-8.41	19N02E07K004M	GWD	-121.788	39.5118	192	140	150			
6/22/2016 0:00	-59	-8.19	19N02E13Q001M	GW	-121.693113	39.49442	221	130	210	7.37	22	125.7
10/6/2016 0:00	-59.8	-8.5	19N02E13Q001M	GW	-121.693113	39.49442	221	130	210	7.66	21.9	159.4
3/1/2017 0:00	-62.8	-8.71	19N02E13Q001M	GW	-121.693113	39.49442	221	130	210	8.03	17.1	126.7
6/22/2016 0:00	-57.5	-7.95	19N02E13Q002M	GW	-121.6932	39.4944	495	470	480	7.54	23.9	188.3
10/6/2016 0:00	-57.3	-8.11	19N02E13Q002M	GW	-121.6932	39.4944	495	470	480	7.37	19.3	151.8
3/1/2017 0:00	-57.2	-7.99	19N02E13Q002M	GW	-121.6932	39.4944	495	470	480	8.15	16.5	135
6/22/2016 0:00	-59.8	-8.37	19N02E13Q003M	GW	-121.6932	39.4944	706	670	680	6.86	23.2	186.2
10/6/2016 0:00	-59.2	-8.05	19N02E13Q003M	GW	-121.6932	39.4944	706	670	680	6.92	21.3	158.1
3/1/2017 0:00	-59	-8.2	19N02E13Q003M	GW	-121.6932	39.4944	706	670	680	7.48	15.9	136.7
6/16/2016 0:00	-63.6	-8.28	20N01E35C001M	GW	-121.829437	39.551074	92	49.5	92	7.26	18.6	728
10/3/2016 0:00	-63	-8.44	20N01E35C001M	GW	-121.829437	39.551074	92	49.5	92	7.26	18.4	635
3/2/2017 0:00	-63.7	-8.46	20N01E35C001M	GW	-121.829437	39.551074	92	49.5	92	7.52	17	553
10/29/2015 0:00	-53.7	-6.85	20N02E09G001M	GW	-121.73913	39.615459	202	130	179.6			
6/17/2016 0:00	-58.4	-7.97	20N02E15H001M	GW	-121.730317	39.589093	190	170	180	6.86	21.6	388
10/10/2016 0:00	-55.7	-7.74	20N02E15H001M	GW	-121.730317	39.589093	190	170	180	6.86	21.6	271
3/2/2017 0:00	-57.3	-7.87	20N02E15H001M	GW	-121.730317	39.589093	190	170	180	7.07	17.7	257
6/17/2016 0:00	-49.9	-6.38	20N02E15H002M	GW	-121.730404	39.589151	75	55	65	7.33	19	607
10/10/2016 0:00	-48.8	-6.25	20N02E15H002M	GW	-121.730404	39.589151	75	55	65	7.37	20.7	612
3/2/2017 0:00	-49.5	-6.28	20N02E15H002M	GW	-121.730404	39.589151	75	55	65	7.4	18	547
10/27/2015 0:00	-59	-8.33	20N02E24C001M	GW	-121.7026	39.5812	155	124	134	7.44	64.42	182
6/20/2016 0:00	-57.7	-8.08	20N02E24C001M	GW	-121.7026	39.5812	155	124	134	7.19	23.5	571
10/7/2016 0:00	-56.9	-7.93	20N02E24C001M	GW	-121.7026	39.5812	155	124	134	7.22	19.6	416
2/27/2017 0:00	-57.4	-8.01	20N02E24C001M	GW	-121.7026	39.5812	155	124	134	6.96	17.2	343
10/27/2015 0:00	-58.1	-8.17	20N02E24C002M	GW	-121.7026	39.5812	390	336	377	7.19	62.96	445
6/21/2016 0:00	-58.6	-8.09	20N02E24C002M	GW	-121.7026	39.5812	390	336	377	8.25	25.6	340
10/7/2016 0:00	-59.5	-8.24	20N02E24C002M	GW	-121.7026	39.5812	390	336	377	8.27	20.3	354
2/27/2017 0:00	-58.6	-8.22	20N02E24C002M	GW	-121.7026	39.5812	390	336	377	8.09	16.9	153.3
10/27/2015 0:00	-60.8	-8.37	20N02E24C003M	GW	-121.7026	39.5812	520	484	505	7.65	65.71	192

Appendix A - Stable Isotope Data, 2015 to 2017

Date	delta_2_H	delta_18_O	Location_ID	Sample_Type	CoordX	CoordY	Total_Depth	Perf_Top	Perf_Bottom	pH	Temp	EC
6/21/2016 0:00	-58.8	-8.41	20N02E24C003M	GW	-121.7026	39.5812	520	484	505	7.96	23.7	173
10/7/2016 0:00	-60	-8.39	20N02E24C003M	GW	-121.7026	39.5812	520	484	505	8	21.5	171.2
2/27/2017 0:00	-59.4	-8.47	20N02E24C003M	GWD	-121.7026	39.5812	520	484	505	7.95	17.4	160.6
2/27/2017 0:00	-59.5	-8.47	20N02E24C003M	GWD	-121.7026	39.5812	520	484	505			
10/22/2015 0:00	-62.3	-8.9	21N01E13L002M	GWD	-121.8144	39.67348	771	735	760	7.84	64.06	250
6/20/2016 0:00	-60.2	-8.76	21N01E13L002M	GW	-121.8144	39.67348	771	735	760	6.53	20.1	364
10/6/2016 0:00	-61	-8.79	21N01E13L002M	GW	-121.8144	39.67348	771	735	760	7.32	20.8	226
2/27/2017 0:00	-60.7	-8.81	21N01E13L002M	GW	-121.8144	39.67348	771	735	760	7.32	14.9	189.3
10/22/2015 0:00	-61.5	-8.88	21N01E13L002M	GWD	-121.8144	39.67348	771	735	760			
10/22/2015 0:00	-63.9	-9.16	21N01E13L003M	GW	-121.8144	39.67348	574	540	560	7.77	61.71	224
6/20/2016 0:00	-63.2	-9.27	21N01E13L003M	GW	-121.8144	39.67348	574	540	560	7.08	23.8	218.2
10/6/2016 0:00	-63.3	-9.18	21N01E13L003M	GW	-121.8144	39.67348	574	540	560	7.37	19.9	215.6
2/27/2017 0:00	-63.5	-9.15	21N01E13L003M	GW	-121.8144	39.67348	574	540	560	7.6	15.7	172.1
10/22/2015 0:00	-74.5	-10.52	21N01E13L004M	GW	-121.8144	39.67348	353	240	340	7.41	60.51	251
6/20/2016 0:00	-71.3	-10.06	21N01E13L004M	GW	-121.8144	39.67348	353	240	340	7.16	21.4	228
10/6/2016 0:00	-73.8	-10.57	21N01E13L004M	GW	-121.8144	39.67348	353	240	340	7.29	19.2	210.9
2/27/2017 0:00	-70.3	-10.08	21N01E13L004M	GW	-121.8144	39.67348	353	240	340	6.97	16.8	178.4
10/23/2015 0:00	-66.5	-9.43	21N01W13J001M	GW	-121.9206	39.673024	830	780	820	7.94	64.25	200
6/20/2016 0:00	-65.4	-9.45	21N01W13J001M	GW	-121.9206	39.673024	830	780	820	7.29	22.5	284.5
10/7/2016 0:00	-65.5	-9.36	21N01W13J001M	GW	-121.9206	39.673024	830	780	820	7.46	20.9	182.3
2/28/2017 0:00	-65.9	-9.42	21N01W13J001M	GW	-121.9206	39.673024	830	780	820	7.43	14.4	150.7
10/23/2015 0:00	-68.6	-9.9	21N01W13J002M	GWD	-121.9206	39.673024	610	570	591	7.84	63.03	220
6/20/2016 0:00	-69.5	-9.79	21N01W13J002M	GW	-121.9206	39.673024	610	570	591	7.43	22.1	203.5
10/7/2016 0:00	-68.5	-9.86	21N01W13J002M	GW	-121.9206	39.673024	610	570	591	7.43	21	202.2
2/28/2017 0:00	-69.1	-9.89	21N01W13J002M	GW	-121.9206	39.673024	610	570	591	7.5	15.3	168.8
10/23/2015 0:00	-68.3	-9.79	21N01W13J002M	GWD	-121.9206	39.673024	610	570	591			
10/23/2015 0:00	-69.6	-9.92	21N01W13J003M	GW	-121.9206	39.673024	400	355	385	7.73	60.65	297
6/20/2016 0:00	-70.5	-10.2	21N01W13J003M	GW	-121.9206	39.673024	400	355	385	7.17	21.8	278
10/7/2016 0:00	-68.6	-9.85	21N01W13J003M	GW	-121.9206	39.673024	400	355	385		19.7	267
2/28/2017 0:00	-69.2	-9.96	21N01W13J003M	GWD	-121.9206	39.673024	400	355	385	7.47	14.7	238
2/28/2017 0:00	-68.9	-9.93	21N01W13J003M	GWD	-121.9206	39.673024	400	355	385			
10/28/2015 0:00	-62.9	-8.88	21N02E18C001M	GW	-121.797	39.682	914	770	880	8.03	66.91	245
6/17/2016 0:00	-66.5	-9.45	21N02E18C001M	GW	-121.797	39.682	914	770	880	6.73	19.7	231
10/10/2016 0:00	-67.3	-9.77	21N02E18C001M	GW	-121.797	39.682	914	770	880	7.33	18.4	227
2/24/2017 0:00	-64.1	-9.25	21N02E18C001M	GW	-121.797	39.682	914	770	880	6.83	12.9	189.4
10/28/2015 0:00	-61.4	-8.82	21N02E18C002M	GW	-121.797	39.682	701	360	620	7.79	63.67	276
6/20/2016 0:00	-70.2	-9.95	21N02E18C002M	GW	-121.797	39.682	701	360	620	6.46	19.8	235
10/10/2016 0:00	-67.6	-9.68	21N02E18C002M	GW	-121.797	39.682	701	360	620	7.49	18.9	241

Appendix A - Stable Isotope Data, 2015 to 2017

Date	delta_2_H	delta_18_O	Location_ID	Sample_Type	CoordX	CoordY	Total_Depth	Perf_Top	Perf_Bottom	pH	Temp	EC
2/24/2017 0:00	-67.4	-9.63	21N02E18C002M	GW	-121.797	39.682	701	360	620	7.01	15.5	188.9
10/28/2015 0:00	-74	-10.36	21N02E18C003M	GW	-121.797	39.682	240	130	200	7.11	61.95	296
6/17/2016 0:00	-73.2	-10.36	21N02E18C003M	GW	-121.797	39.682	240	130	200	6.95	19.1	260
10/10/2016 0:00	-74.2	-10.43	21N02E18C003M	GW	-121.797	39.682	240	130	200	6.88	19.9	263
2/24/2017 0:00	-73.7	-10.45	21N02E18C003M	GW	-121.797	39.682	240	130	200	6.12	15.8	230
10/26/2015 0:00	-62.5	-8.99	21N02E26E003M	GW	-121.7263	39.6468	660	610	620	7.8	70.65	210
10/6/2016 0:00	-61.5	-9.08	21N02E26E003M	GW	-121.7263	39.6468	660	610	620	7.1	22.9	196.6
2/28/2017 0:00	-62	-9.03	21N02E26E003M	GW	-121.7263	39.6468	660	610	620	7.35	18.9	173.1
6/14/2016 0:00	-61.9	-8.99	21N02E26E003M	GWD	-121.7263	39.6468	660	610	620	7.09	24.6	208.7
6/14/2016 0:00	-61.7	-9.38	21N02E26E003M	GWD	-121.7263	39.6468	660	610	620			
10/26/2015 0:00	-61.2	-8.96	21N02E26E004M	GW	-121.7263	39.6468	518	400	484	7.5	70.34	205
6/14/2016 0:00	-60	-8.64	21N02E26E004M	GW	-121.7263	39.6468	518	400	484	7.55	24.5	210.2
10/6/2016 0:00	-60.6	-8.87	21N02E26E004M	GW	-121.7263	39.6468	518	400	484	7.55	21.7	275
2/28/2017 0:00	-60.9	-8.85	21N02E26E004M	GW	-121.7263	39.6468	518	400	484	7.9	19.9	180
10/26/2015 0:00	-61.1	-8.84	21N02E26E005M	GW	-121.7263	39.6468	315	265	290	7.51	68.76	222
6/14/2016 0:00	-60.3	-8.77	21N02E26E005M	GW	-121.7263	39.6468	315	265	290	7.52	24.7	221
10/6/2016 0:00	-60.6	-8.83	21N02E26E005M	GW	-121.7263	39.6468	315	265	290	7.48	22.6	211.1
2/28/2017 0:00	-60.8	-8.83	21N02E26E005M	GW	-121.7263	39.6468	315	265	290	7.73	19.8	191.5
10/26/2015 0:00	-58.6	-8.12	21N02E26E006M	GW	-121.7263	39.6468	179	105	150	6.89	67.83	208
6/14/2016 0:00	-58.8	-8.03	21N02E26E006M	GW	-121.7263	39.6468	179	105	150	6.82	25.1	214.2
10/6/2016 0:00	-57.6	-7.98	21N02E26E006M	GW	-121.7263	39.6468	179	105	150	6.99	21.8	224
2/28/2017 0:00	-57.7	-8.03	21N02E26E006M	GW	-121.7263	39.6468	179	105	150	7.43	19.7	181.7
10/6/2016 0:00	-57.1	-8.06	21N02E26E006M	GW	-121.7263	39.6468	179	105	150			
6/14/2016 0:00	-55.3	-7.85	21N03E32B001M	GW	-121.663376	39.639578	57	13	57	5.85		123.6
10/10/2016 0:00	-56.6	-8.12	21N03E32B001M	GW	-121.663376	39.639578	57	13	57	6.42	20.6	115.9
2/28/2017 0:00	-50.3	-7.55	21N03E32B001M	GW	-121.663376	39.639578	57	13	57	6.24	17.5	107.9
5/5/2016 0:00	-56.1	-7.41	MW-10A	GW	-121.735393	39.670483	114	94	114			
8/4/2016 0:00	-55.7	-7.67	MW-10A	GW	-121.735393	39.670483	114	94	114			
11/28/2016 0:00	-54.9	-7.37	MW-10A	GW	-121.735393	39.670483	114	94	114			
2/6/2017 0:00	-55.1	-7.35	MW-10A	GW	-121.735393	39.670483	114	94	114			
5/8/2016 0:00	-61	-8.65	MW-13	GW	-121.729055	39.678674	242	212	242			
8/4/2016 0:00	-59.9	-8.46	MW-13	GW	-121.729055	39.678674	242	212	242			
11/28/2016 0:00	-59.5	-8.41	MW-13	GW	-121.729055	39.678674	242	212	242			
2/7/2017 0:00	-59.9	-8.59	MW-13	GW	-121.729055	39.678674	242	212	242			
5/5/2016 0:00	-60.8	-8.7	MW-4A	GW	-121.724057	39.681712	275	245	275			
8/4/2016 0:00	-60.3	-8.46	MW-4A	GW	-121.724057	39.681712	275	245	275			
11/28/2016 0:00	-60.2	-8.48	MW-4A	GW	-121.724057	39.681712	275	245	275			
2/7/2017 0:00	-60.7	-8.68	MW-4A	GW	-121.724057	39.681712	275	245	275			

Appendix A - Stable Isotope Data, 2015 to 2017

Date	delta_2_H	delta_18_O	Location_ID	Sample_Type	CoordX	CoordY	Total_Depth	Perf_Top	Perf_Bottom	pH	Temp	EC
5/6/2016 0:00	-59.6	-8.42	MW-8B	GW	-121.728658	39.67367	222	202	222			
8/4/2016 0:00	-59.2	-8.62	MW-8B	GW	-121.728658	39.67367	222	202	222			
11/29/2016 0:00	-59.2	-8.22	MW-8B	GW	-121.728658	39.67367	222	202	222			
2/7/2017 0:00	-59.1	-8.45	MW-8B	GW	-121.728658	39.67367	222	202	222			
5/5/2016 0:00	-59.6	-8.42	MW-9B	GW	-121.725282	39.676257	253	220	253			
8/4/2016 0:00	-58.5	-8.37	MW-9B	GW	-121.725282	39.676257	253	220	253			
11/29/2016 0:00	-59.3	-8.37	MW-9B	GW	-121.725282	39.676257	253	220	253			
2/7/2017 0:00	-59.1	-8.36	MW-9B	GW	-121.725282	39.676257	253	220	253			
6/22/2016 0:00	-75.8	-10.5	308Nelson	Int STD	-121.5713412	39.52438072						
6/20/2016 0:00	-75	-10.45	308Nelson	Int STD	-121.5713412	39.52438072						
3/9/2017 0:00	-75.1	-10.56	308Nelson	Int STD	-121.5713412	39.52438072						
10/29/2015 0:00	-77	-10.37	Afterbay	SW	-121.6789417	39.49347778						
6/21/2016 0:00	-75.7	-10.61	Afterbay	SW	-121.6789417	39.49347778						
10/3/2016 0:00	-76.3	-10.43	Afterbay	SW	-121.6789417	39.49347778						
3/2/2017 0:00	-76.3	-10.74	Afterbay	SW	-121.6789417	39.49347778				6.68	14.3	51.4
10/3/2016 0:00	-74.9	-10.49	Afterbay	SWD	-121.6789417	39.49347778						
10/27/2015 0:00	-73.1	-10.64	BCC-Golf	SW	-121.7784232	39.76853954						
6/21/2016 0:00	-75.5	-10.76	ButteCrk-CB	SW	-121.703492	39.729067						
10/27/2015 0:00	-82.5	-11.77	ButteCrk-CB	SW	-121.703492	39.729067						
10/4/2016 0:00	-79.8	-11.51	ButteCrk-CB	SW	-121.703492	39.729067						
3/2/2017 0:00	-72.5	-10.66	ButteCrk-CB	SW	-121.703492	39.729067				6.49	10.2	46.3
10/22/2015 0:00	-75.4	-10.2	ButteCrk-HWY 162	SW	-121.8699028	39.46402222						
6/21/2016 0:00	-69.2	-9.42	ButteCrk-HWY 162	SW	-121.8699028	39.46402222						
10/3/2016 0:00	-74.4	-10.24	ButteCrk-Hwy162	SW	-121.8699028	39.46402222						
3/2/2017 0:00	-68.8	-10.02	ButteCrk-Hwy162	SW	-121.8699028	39.46402222				6.75	10.8	81
6/21/2016 0:00	-76.3	-10.89	ButteCrk-HWY99	SW	-121.778361	39.694228						
10/22/2015 0:00	-80.7	-11.5	ButteCrk-HWY99	SW	-121.778361	39.694228						
10/4/2016 0:00	-80.1	-11.45	ButteCrk-HWY99	SW	-121.778361	39.694228						
3/2/2017 0:00	-71.5	-10.52	ButteCrk-HWY99	SWD	-121.778361	39.694228						
3/2/2017 0:00	-71.3	-10.51	ButteCrk-HWY99	SWD	-121.778361	39.694228				6.58	11.4	114.3
10/22/2015 0:00	-82.4	-11.49	ButteCrk-Midway	SW	-121.7838556	39.60516944						
6/21/2016 0:00	-76.1	-11	ButteCrk-Midway	SW	-121.7838556	39.60516944						
10/5/2016 0:00	-79.3	-11.19	ButteCrk-Midway	SW	-121.7838556	39.60516944						
3/2/2017 0:00	-71.4	-10.51	ButteCrk-Midway	SW	-121.7838556	39.60516944				6.22	11	40.8
10/29/2015 0:00	-77.9	-10.43	FeatherR-Hatch	SWD	-121.5498056	39.51799444						
6/21/2016 0:00	-75.8	-10.59	FeatherR-Hatch	SW	-121.5498056	39.51799444						
10/3/2016 0:00	-75.7	-10.56	FeatherR-Hatch	SW	-121.5498056	39.51799444						
10/29/2015 0:00	-77.4	-10.42	FeatherR-Hatch	SW	-121.5498056	39.51799444						

Appendix A - Stable Isotope Data, 2015 to 2017

Date	delta_2_H	delta_18_O	Location_ID	Sample_Type	CoordX	CoordY	Total_Depth	Perf_Top	Perf_Bottom	pH	Temp	EC
3/2/2017 0:00	-78	-11.02	FeatherR-Oro	SW	-121.5656583	39.51346944				6.7	13.9	64.6
6/21/2016 0:00	-61.5	-9	LCC	SW	-121.76525	39.73529722						
10/4/2016 0:00	-58.9	-8.28	LCC	SW	-121.76525	39.73529722						
3/2/2017 0:00	-62	-9.35	LCC	SW	-121.76525	39.73529722				6.55	12.6	55.2
3/2/2017 0:00	-59.2	-8.87	LDCrk	SW	-121.6631222	39.64003889				6.81	12.7	65.1
10/27/2015 0:00	-83	-11.49	SacR-HWY32	SW	-121.9970444	39.75017222						
10/4/2016 0:00	-78.2	-11.03	SacR-Hwy32	SW	-121.9970444	39.75017222						
3/2/2017 0:00	-78.6	-11.14	SacR-Hwy32	SW	-121.9970444	39.75017222				6.51	11	73.3
6/21/2016 0:00	-78.1	-10.99	SacR-Hwy32	SWD	-121.9970444	39.75017222						
6/21/2016 0:00	-78.4	-10.98	SacR-Hwy32	SW	-121.9970444	39.75017222						
3/2/2017 0:00	-61	-8.39	SED-1	SW	-121.7350222	39.67198609				7.24	15.1	191.3
6/15/2016 0:00	-23.3	-0.9	SED-2	SW	-121.7362749	39.6756222						

Notes:

GW - groundwater sample

GWD - groundwater duplicate sample

Int Std - internal standard

SW - surface water sample

SWD - surface water duplicate sample

Appendix B: QA/QC Data

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Table B-1. QA/QC Data - Blind Duplicate and Internal Standard Data

Isotech Lab No.	Sample Name	Sample Date	Analysis Date	δD H_2O	$\delta^{18}O$ H_2O	δD H_2O	$\delta^{18}O$ H_2O
				‰	‰	Re-Analysis	
571308	FeatherR-Hatch	10/29/2015	7/1/2016	-77.9	-10.43		
571351	FeatherR-HatchB	10/29/2015	7/3/2016	-77.4	-10.42		
			avg	-77.7	-10.4		
			stdev	0.35	0.01		
			RPD (%)	0.64	0.1		
571320	13J002M	10/23/2015	7/2/2016	-68.6	-9.90		
571350	13J002MB	10/23/2015	7/3/2016	-68.3	-9.79		
			avg	-68.5	-9.8		
			stdev	0.21	0.08		
			RPD (%)	0.44	1.1		
571323	13L002	10/22/2015	7/2/2016	-62.3	-8.90		
571349	13L002B	10/22/2015	7/3/2016	-61.5	-8.88		
			avg	-61.9	-8.9		
			stdev	0.57	0.01		
			RPD (%)	1.3	0.22		
595106	21N02E26E003MA	6/14/2016	1/20/2017	-61.9	-8.99	-61.9	-9.03
595107	21N02E26E003MB	6/14/2016	1/20/2017	-61.7	-9.38	-61.5	-9.04
			avg	-61.8	-9.19	-61.7	-9.04
			stdev	0.14	0.28	0.28	0.01
			RPD (%)	0.32	4.2	0.65	0.11
595114	SacR-Hwy32A	6/21/2016	1/20/2017	-78.1	-10.99		
595115	SacR-Hwy32B	6/21/2016	1/20/2017	-78.4	-10.98		
			avg	-78.3	-10.99		
			stdev	0.21	0.01		
			RPD (%)	0.38	0.09		
595128	Afterbay	10/3/2016	1/27/2017	-76.3	-10.43		
595136	Afterbay North	10/3/2016	1/28/2017	-74.9	-10.49		
			avg	-75.6	-10.46		
			stdev	0.99	0.04		
			RPD (%)	1.85	0.57		
595138	19N02E07K004M	10/5/2016	1/25/2017	-57.5	-8.29		
595139	19N02E07K005M	10/5/2016	1/25/2017	-57.7	-8.41		
			avg	-57.6	-8.35		
			stdev	0.14	0.08		
			RPD (%)	0.35	1.4		
604056	20N02E24C003M	2/27/2017	3/27/2017	-59.4	-8.47		
604094	20N02E24C004M	2/27/2017	3/29/2017	-59.5	-8.47		

Table B-1. QA/QC Data - Blind Duplicate and Internal Standard Data

Isotech Lab No.	Sample Name	Sample Date	Analysis Date	δD H_2O	$\delta^{18}O$ H_2O	δD H_2O	$\delta^{18}O$ H_2O
				‰	‰	Re-Analysis	
			avg	-59.5	-8.5		
			stdev	0.07	0.00		
			RPD (%)	0.17	0		
604062	21N01W13J003M	2/28/2017	3/28/2017	-69.2	-9.96		
604092	21N01W13J004M	2/28/2017	3/29/2017	-68.9	-9.93		
			avg	-69.1	-9.9		
			stdev	0.21	0.02		
			RPD (%)	0.43	0.30		
604081	ButteCrk-HWY99N	3/2/2017	3/29/2017	-71.3	-10.51		
604093	ButteCrk-HWY99	3/2/2017	3/29/2017	-71.5	-10.52		
			avg	-71.4	-10.5		
			stdev	0.14	0.01		
			RPD (%)	0.28	0.10		
Internal Standard							
595127	308Nelson	6/20/2016	1/27/2017	-75.0	-10.45		
571346	308Nelson	6/22/2016	7/3/2016	-75.8	-10.50		
			avg	-75.4	-10.48		
			stdev	0.57	0.04		
			RPD (%)	1.1	0.48		

Appendix C: Hydrographs

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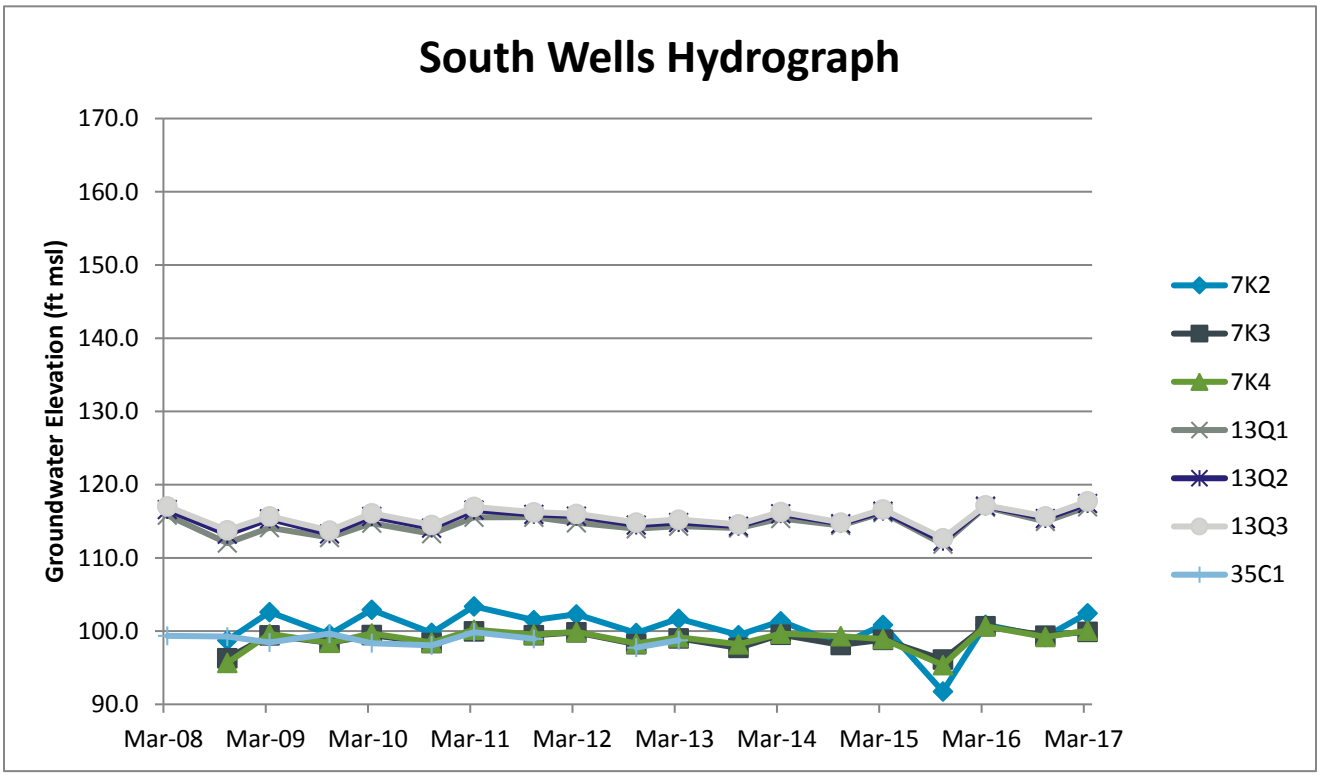
Presented below are three hydrographs and a brief discussion of the groundwater elevations in the wells that were sampled for stable isotopes. The well groupings for the hydrographs are comparable to the general geographic categories identified based on the stable isotope data evaluation. All three hydrographs use the same scales for the date on the x-axis and for the groundwater elevation in feet (ft) above mean sea level (amsl) on the y-axis to help facilitate comparison. All wells were measured in March and October each year, to provide a comparison of late winter and end-of-summer groundwater levels. In the Sacramento Valley, these two months typically correspond to the seasonal high and low groundwater levels, respectively. The general characteristics observed for each group of wells is summarized after each figure.

Figure 9 of the Stable Isotope Final Report shows the well locations and the groundwater stable isotope data for each well location and each sample date.

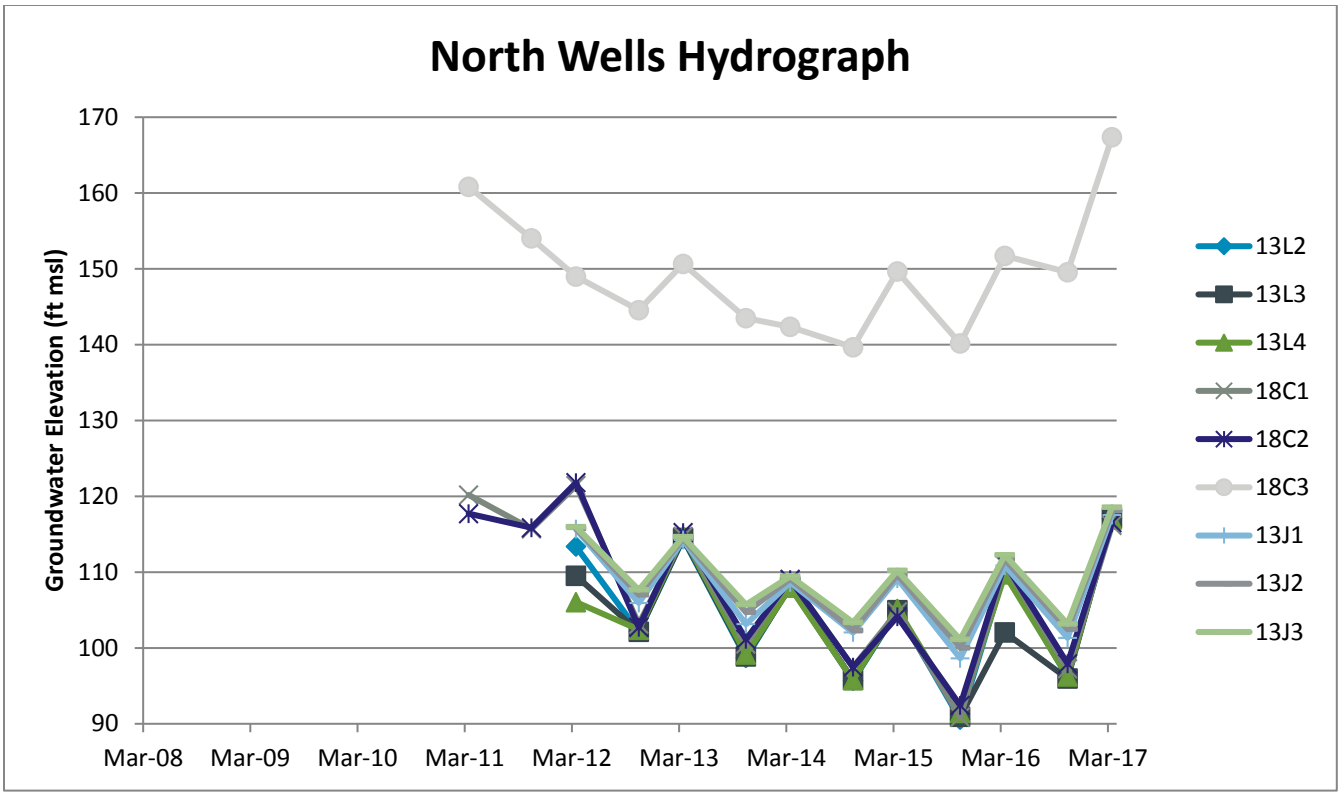


South Wells. The seasonal fluctuations in the south area wells are consistently small, generally less than five ft between the late winter and end-of-summer measurements. The groundwater elevations are also relatively consistent from year to year from 2008 to 2017. The lack of any significant water level decline between 2012 and 2015 suggests that the recent drought has not affected groundwater conditions in the south area, with the possible exception of the October 2015 data. The characteristics observed in the south area wells are consistent with a situation where groundwater extraction and groundwater recharge are in balance. The lack of any major observable difference between major wet and dry periods is consistent with the use of imported surface water for irrigation. If the water imports and the rate of irrigation remain relatively consistent from year to year, then percolation of excess irrigation water will tend to minimize any seasonal or long-term climatic influences in the groundwater elevations. The south area wells show the smallest variation in del18O isotope concentrations with depth, which is also consistent with a relatively uniform recharge source throughout the south area.

East Wells. Seasonal fluctuations in the east area wells range from less than five ft in Well 26E6 to as much as 30 ft in Well 26E4. The east area wells also show an apparent influence from the recent drought, with groundwater levels typically declining by an average of about 10 ft from 2012 through 2015. Well 32B1 is located approximately two miles east of State Route 99 along Little Dry Creek, at a higher elevation and farther east within the outcrop of the Lower Tuscan Formation than any of the other east area wells. To be able to plot the groundwater hydrograph for Well 32B1 on the same scale as the other east area wells, the groundwater elevations for each data point for Well 32B1 were reduced by a factor of 100. In other words, the actual groundwater elevations for Well 32B1 are 100 ft above sea level higher than those shown on the East Wells Hydrograph figure. Despite being located farther east and within the Lower Tuscan Formation outcrop area, the seasonal and long-term trends in the water levels in Well 32B1 are comparable to those observed in the other east area wells, except that the recent drought has only caused the water levels to decrease by about two to three ft overall. Since Well 32B1 is farther from the pumping within the groundwater basin than the other east area wells, the trends and magnitude of fluctuations observed in the water levels in Well 32B1 during the recent drought (2012-2015 water years) may be indicative of the effects of fluctuating natural recharge. As a result, any observed fluctuations in the other east area wells that are larger than those that occurred in Well 32B1 during the drought may indicate the incremental effect of additional groundwater pumping due to the drought in the area of the basin adjacent to the foothills.

The groundwater elevations for most of the east area wells are within a similar range, as shown on the East Area Hydrograph. The two main exceptions are Well 32B1, as discussed above, and Well 15H2. The groundwater elevation in Well 15H2 is consistently 10 to 15 ft higher than the water level in Well 15H1. The difference in groundwater elevations in these two wells from the same location indicates that the recharge source for Well 15H2 occurs at a higher elevation than that for Well 15H1. The del18O values at the 15H location also show a fairly significant difference with depth, also potentially consistent with different recharge sources for the two different depths. The 26E east area well group also has a fairly significant variation in del18O levels between the shallow well screen (26E6) and the deeper screened intervals (26E3, 26E4, and 26E5). The deeper screened intervals have very similar groundwater elevations but the shallow well screen consistently has a lower groundwater elevation and a smaller seasonal variation. Therefore, similar to the Well 15H group, the Well 26E cluster appears to have a different recharge source for the shallow interval than for the deeper screened intervals.

The groundwater data from the east area wells indicates that groundwater extraction and groundwater recharge were in balance prior to 2012 but that during the recent drought, extraction exceeded recharge. It is not clear if a reduction in recharge or an increase in groundwater pumping had a more significant influence in upsetting the balance during the drought period. If increased groundwater pumping was the primary cause of the imbalance, it follows that the seasonal variation would increase during the drought since the excess pumping would occur primarily during the summer (and be reflected in the end-of-summer water levels) while the late winter water levels would not be affected by pumping since winter water use is relatively independent of rainfall for both municipal and agricultural users. As indicated on the East Wells Hydrograph, there is not a readily apparent difference in the magnitude of the seasonal variation between pre-drought and drought periods in the east area wells, which suggests that the drought-related effect on water levels is due primarily to reduction in recharge.



North Wells. Seasonal fluctuations in the north area wells range from approximately 10 to 15 ft. The north area wells also show an apparent influence from the recent drought, with groundwater levels typically declining by an average of about 10 ft from 2012 through 2015. The three north area wells each have three separate screened intervals, with the lowest-numbered interval being the deepest and the highest-numbered interval being the shallowest. In well clusters 13L and 13J, the water levels from all three depths are very similar. The two deeper intervals from the 18C cluster have groundwater elevations that are similar to those from the 13L and 13J. However, the groundwater elevation in the shallowest well from the 18C cluster (18C3) is about 35 to 45 ft higher than all of the other north area wells. The screened interval for 18C3 is shallow than that for 13L3 and 13J3. Thus, it is possible that 18C3 is screened within the alluvial deposits overlying the Lower Tuscan aquifer units. Recharge of the shallow intervals for all three North Area wells comes from the major creeks and rivers in the area (Butte Creek and Sacramento River). The LTA Study also indicates that the overlying alluvium may not be in direct hydraulic communication with the underlying Tuscan Formation. Direct recharge from Butte Creek into the alluvium, along with irrigation pumping from the Tuscan Formation could cause the appreciable downward vertical gradient observed between Well 18C3 and all other North Area wells.

There are very few groundwater level measurements in the north area wells prior to 2012. Therefore, it is not possible to assess the potential contribution of increased pumping versus reduced recharge to the overall decline of water levels from 2012 to 2015.

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Appendix D: Shallow Ground-Water Quality Study

Shallow Ground-Water Quality Beneath Rice Areas in the Sacramento Valley, California, 1997 by Barbara J. Milby Dawson, U.S. Geological Survey, Water-Resources Investigations Report 01-4000, National Water-Quality Assessment Program

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Shallow Ground-Water Quality Beneath Rice Areas in the Sacramento Valley, California, 1997

by Barbara J. Milby Dawson

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 01-4000

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

6205-15

Sacramento, California
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

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FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. (http://www.usgs.gov/). Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity and quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. (http://water.usgs.gov/nawqa). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. (http://water.usgs.gov/nawqa/nawqamap.html). Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings. (http://water.usgs.gov/nawqa/natsyn.html).

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch

Robert M. Hirsch
Associate Director for Water

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CONTENTS

Abstract 1
Introduction 2
Purpose and Scope 2
Acknowledgments 2
Study-Area Description 2
Climate and Population 2
Land and Water Use 4
Hydrogeology 5
Methods of Investigation 6
Well Site Selection 6
Monitoring Well Installation 7
Well Descriptions, Water Levels, and Lithology 7
Water Sample Collection and Analysis 7
Data Reporting and Analysis 8
Quality-Control Data Analyses 10
Shallow Ground-Water Quality 13
General Water Chemistry 13
Major Inorganic Constituents 14
Trace Inorganic Constituents 14
Nutrient Constituents 15
Dissolved Organic Carbon 15
Pesticides 17
Ground-Water Redox Condition 18
Analyses of Ground-Water Quality Data 19
Statistical Analyses 19
Correlations Between Shallow Ground-Water Quality and Geomorphic Unit 21
Correlations Between Shallow Ground-Water Quality and Depth to Ground Water and Top of Well Screen 21
Correlations Between Inorganic Constituents, Land Use, and Pesticides 21
Tritium Concentration, Pesticide Use, and Age of Shallow Ground-Water Recharge 25
Stable Isotopes and Possible Sources of Shallow Ground Water 25
Summary and Conclusions 29
References Cited 30

FIGURES

1. Map showing location of the rice land-use study area and the Sacramento River Basin, California 3
2. Map showing locations of wells sampled in the rice areas in the Sacramento Valley, California. 4
3. Map showing well sites and geomorphic units in the rice areas in the Sacramento Valley, California 6
4. Map showing water-level contours in the rice areas in the Sacramento Valley, California, August to October, 1997 9
5. Trilinear diagram showing major-ion composition of ground-water samples from rice areas in the Sacramento Valley, California 15
6. Map showing redox conditions in wells sampled in rice areas in the Sacramento Valley, California 20

7. Graphs showing concentrations of arsenic, boron, chloride, dissolved solids, fluoride, molybdenum, nitrate, phosphorus, potassium, silica, sodium, sulfate, and zinc detected in shallow ground water in rice areas in relation to well location and geomorphic unit, Sacramento Valley, California 22
8. Graphs showing correlations between depth to ground water and number of rice pesticides detected per well, cobalt, manganese, nickel, and nitrite concentrations; and correlations between depth to top of screen and number of pesticides detected per well, molybdenum, and sulfate concentrations in wells sampled in rice areas in the Sacramento Valley, California 24
9. Graphs showing correlations between concentrations of bentazon and tritium, and correlations between number of rice pesticides detected per well and concentrations of boron and sodium detected in shallow ground water in rice areas in the Sacramento Valley, California 26
10. Graph showing relation between δ^2H and $\delta^{18}O$ in ground water and surface water in parts of the Sacramento Valley, California 27
11. Graph showing relation between dissolved solids concentration and $\delta^{18}O$ in shallow ground water in rice areas in the Sacramento Valley, California 29

TABLES

1. Well construction information for wells sampled in rice areas in the Sacramento Valley, California 8
2. Laboratory analysis methods for measured water-quality constituents 10
3. Pesticides analyzed and reporting limits in water samples, in the Sacramento River Basin, California 11
4. Summary of mean relative standard deviations for replicate sample pairs of inorganic compounds, nutrient compounds, and dissolved organic carbon 12
5. Summary of general water chemistry in shallow ground water in rice areas in the Sacramento Valley, California 13
6. Summary of major inorganic constituents detected in shallow ground water in rice areas in the Sacramento Valley, California 14
7. Summary of trace inorganic constituents detected in shallow ground water in rice areas in the Sacramento Valley, California 16
8. Summary of nutrient constituents and dissolved organic carbon detected in ground water in rice areas in the Sacramento Valley, California 16
9. Summary of pesticides detected in shallow ground water in rice areas in the Sacramento Valley, California 17
10. Pesticides and degradation products not detected in shallow ground water in rice areas in the Sacramento Valley, California 18
11. Reported uses of pesticides detected in rice areas in the Sacramento Valley, California 19
12. Summary of isotopes measured in shallow ground water in rice areas in the Sacramento Valley, California 26

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
centimeter per year (cm/yr)	0.3937	inch per year
cubic meter (m^3)	0.0008107	acre-foot
cubic meter per day (m^3/d)	35.31	cubic foot per day
cubic meter per square kilometer (m^3/km^2)	0.0021	acre-foot per square mile
meter (m)	1.094	yard
meter per day (m/d)	3.281	foot per day
square kilometer (km^2)	0.3861	square mile

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8(°C) + 32$$

Sea level: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Acronyms and Abbreviations

δ, delta
^{2}H, deuterium
^{3}H, tritium
^{16}O, oxygen-16
^{18}O, oxygen-18
µg/L, microgram per liter
µS/cm, microsiemens per centimeter
‰, per thousand

DHS, California Department of Health Services
DNOC, 4,6-dinitro-*o*-cresol
DOC, dissolved organic carbon
EPA, U.S. Environmental Protection Agency
GC/MS, gas chromatography/mass spectrometry
GMWL, global meteoric water line
HAL, health advisory limit
HPLC, high performance liquid chromatography
MCL, maximum containment level
mg/L, milligram per liter
Mm^3/d, million cubic meters per day
NAWQA, National Water-Quality Assessment (Program)
NWQL, National Water Quality Laboratory
p, level of statistical significance (Kruskal–Wallis rank-sum test)
pCi/L, picocurie per liter
PVC, polyvinyl chloride
QC, quality control
ρ, Spearman’s rho
SMCL, secondary maximum contaminant level
USGS, U.S. Geological Survey
VSMOW, Vienna Standard Mean Ocean Water

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Shallow Ground-Water Quality Beneath Rice Areas in the Sacramento Valley, California, 1997

by Barbara J. Milby Dawson

ABSTRACT

In 1997, the U.S. Geological Survey installed and sampled 28 wells in rice areas in the Sacramento Valley as part of the National Water-Quality Assessment Program. The purpose of the study was to assess the shallow ground-water quality and to determine whether any effects on water quality could be related to human activities and particularly rice agriculture. The wells installed and sampled were between 8.8 and 15.2 meters deep, and water levels were between 0.4 and 8.0 meters below land surface. Ground-water samples were analyzed for 6 field measurements, 29 inorganic constituents, 6 nutrient constituents, dissolved organic carbon, 86 pesticides, tritium (hydrogen-3), deuterium (hydrogen-2), and oxygen-18.

At least one health-related state or federal drinking-water standard (maximum contaminant or long-term health advisory level) was exceeded in 25 percent of the wells for barium, boron, cadmium, molybdenum, or sulfate. At least one state or federal secondary maximum contaminant level was exceeded in 79 percent of the wells for chloride, iron, manganese, specific conductance, or dissolved solids. Nitrate and nitrite were detected at concentrations below state and federal 2000 drinking-water standards; three wells had nitrate concentrations greater than 3 milligrams per liter, a level that may indicate impact from human activities. Ground-water redox conditions were anoxic in 26 out of 28 wells sampled (93 percent).

Eleven pesticides and one pesticide degradation product were detected in ground-water samples. Four of the detected pesticides are or have been used on rice crops in the Sacramento Valley (bentazon, carbofuran, molinate, and thiobencarb). Pesticides were detected in 89 percent of the wells sampled, and rice pesticides were detected in 82 percent of the wells sampled. The most frequently detected pesticide was the rice herbicide bentazon, detected in 20 out of 28 wells (71 percent); the other pesticides detected have been used for rice, agricultural, and non-agricultural purposes. All pesticide concentrations were below state and federal 2000 drinking-water standards.

The relation of the ground-water quality to natural processes and human activities was tested using statistical methods (Spearman rank correlation, Kruskal–Wallis, or rank-sum tests) to determine whether an influence from rice land-use or other human activities on ground-water chemistry could be identified. The detection of pesticides in 89 percent of the wells sampled indicates that human activities have affected shallow ground-water quality. Concentrations of dissolved solids and inorganic constituents that exceeded state or federal 2000 drinking-water standards showed a statistical relation to geomorphic unit. This is interpreted as a relation to natural processes and variations in geology in the Sacramento River Basin; the high concentrations of dissolved solids and most inorganic constituents did not appear to be related to rice land use. No correlation was found between nitrate concentration and pesticide occurrence, indicating that an absence of high nitrate concentrations is not a predictor of an absence of pesticide contamination in areas with reducing ground-water conditions in the Sacramento Valley.

Tritium concentrations, pesticide detections, stable isotope data, and dissolved-solids concentrations suggest that shallow ground water in the rice-growing areas of the Sacramento Valley is a mix of recently recharged ground water containing pesticides, nitrate, and tritium, and unknown sources of water that contains high concentrations of dissolved solids and some inorganic constituents and is enriched in oxygen-18. Evaporation of applied irrigation water, which leaves behind salt, accounts for some of the

elevated concentrations of dissolved solids. More work needs to be done to understand the connections between the land surface, shallow ground water, deep ground water, and the drinking-water supplies in the Sacramento Valley.

INTRODUCTION

In 1997, the U.S. Geological Survey (USGS) initiated a ground-water quality study in rice areas of the Sacramento Valley in northern California (fig. 1). This study is one component of the USGS's National Water-Quality Assessment (NAWQA) Program, which was initiated in 1994 in the Sacramento River Basin. The NAWQA Program, which began nationwide in 1991, is described in Hirsch and others (1988). Data from studies in the Sacramento River Basin will be compared to similar studies throughout the United States in order to assess the quality of the nation's water resources, to determine any long-term changes in water quality, and to identify natural and human factors that affect water quality. This study of ground-water quality in rice areas of the Sacramento Valley is one of three ground-water studies conducted by the Sacramento River Basin NAWQA Program during 1996–1998. In 1996, the Sacramento River Basin NAWQA group began a study of ground-water quality in the southeastern part of the Sacramento Valley aquifer; in 1998, the Sacramento River Basin NAWQA group began a study of ground-water quality in the Sacramento, Calif., metropolitan area.

The Sacramento River Basin NAWQA study of ground-water quality in rice areas is the type of NAWQA study referred to as a land-use study. The objective of a NAWQA land-use study is to assess the shallow ground-water quality beneath a major land use in the basin. This rice land-use study determined the general water chemistry and quality of the ground water in the upper part of the Sacramento Valley aquifer beneath rice areas, including the occurrence and distribution of nitrate, inorganic constituents, and pesticides. A secondary objective of this study was to determine whether the observed water quality could be related to the overlying rice land-use. Rice was chosen for this study because it is the largest crop acreage in the Sacramento River Basin and rice pesticides have been detected in both surface and ground water. Previous studies have detected the rice pesticides bentazon, 2,4-D, malathion, and molinate in domestic wells in the Sacramento Valley (Bartkowiak and others, 1998).

Purpose and Scope

The purpose of this report is to describe the shallow ground-water quality beneath rice areas in the Sacramento Valley and relate that water quality to human activities (land and pesticide use) and natural factors (depth to water level and top of well screen, redox condition, and geomorphology). Ground-water samples from 28 wells (fig. 2) were analyzed for 6 field measurements, 29 inorganic constituents, 6 nutrient constituents, organic carbon, 86 pesticides, ^{3}H (tritium), ^{2}H (deuterium), and ^{18}O (oxygen-18). Observed concentrations were compared to data on geomorphic unit, well depth, ground-water level, land use, and pesticide and fertilizer use.

Acknowledgments

The author thanks the rice farmers and land-owners of the Sacramento Valley for allowing the USGS to install and sample monitoring wells on their property. The author also thanks the counties of Sacramento, Sutter, Butte, Glenn, and Colusa for allowing the USGS to install and sample monitoring wells on county property and for helping to locate sites.

STUDY-AREA DESCRIPTION

Climate and Population

The study area is located in the central part of the Sacramento Valley (fig. 1), which is the northern third of California's Central Valley. The land surface elevations range from sea level to about 152 m above sea level along the edges of the valley. The Sacramento Valley has a Mediterranean-type climate (Blair and Fite, 1957, p. 323) with hot dry summers and wet mild winters. Rainfall in the study area ranges from about 43 to 69 cm/yr (Daly and Taylor, 1998), almost all between late autumn and early spring. The population density ranges from fewer than 100 people per square kilometer throughout most of the rice area to between 965 and 4,806 people per square kilometer in the city of Colusa (Hitt, 1994).

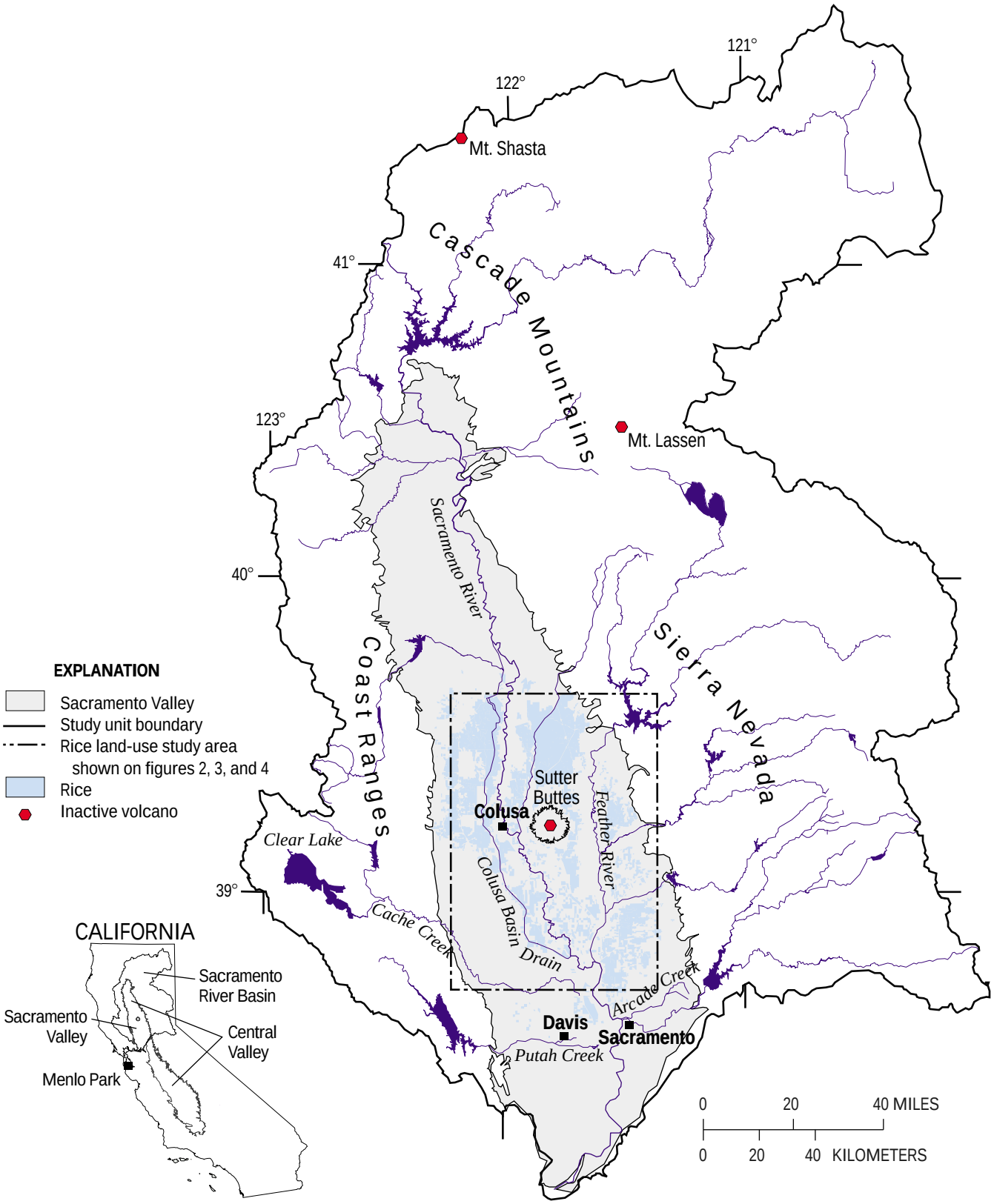


Figure 1. Location of the rice land-use study area and the Sacramento River Basin, California.

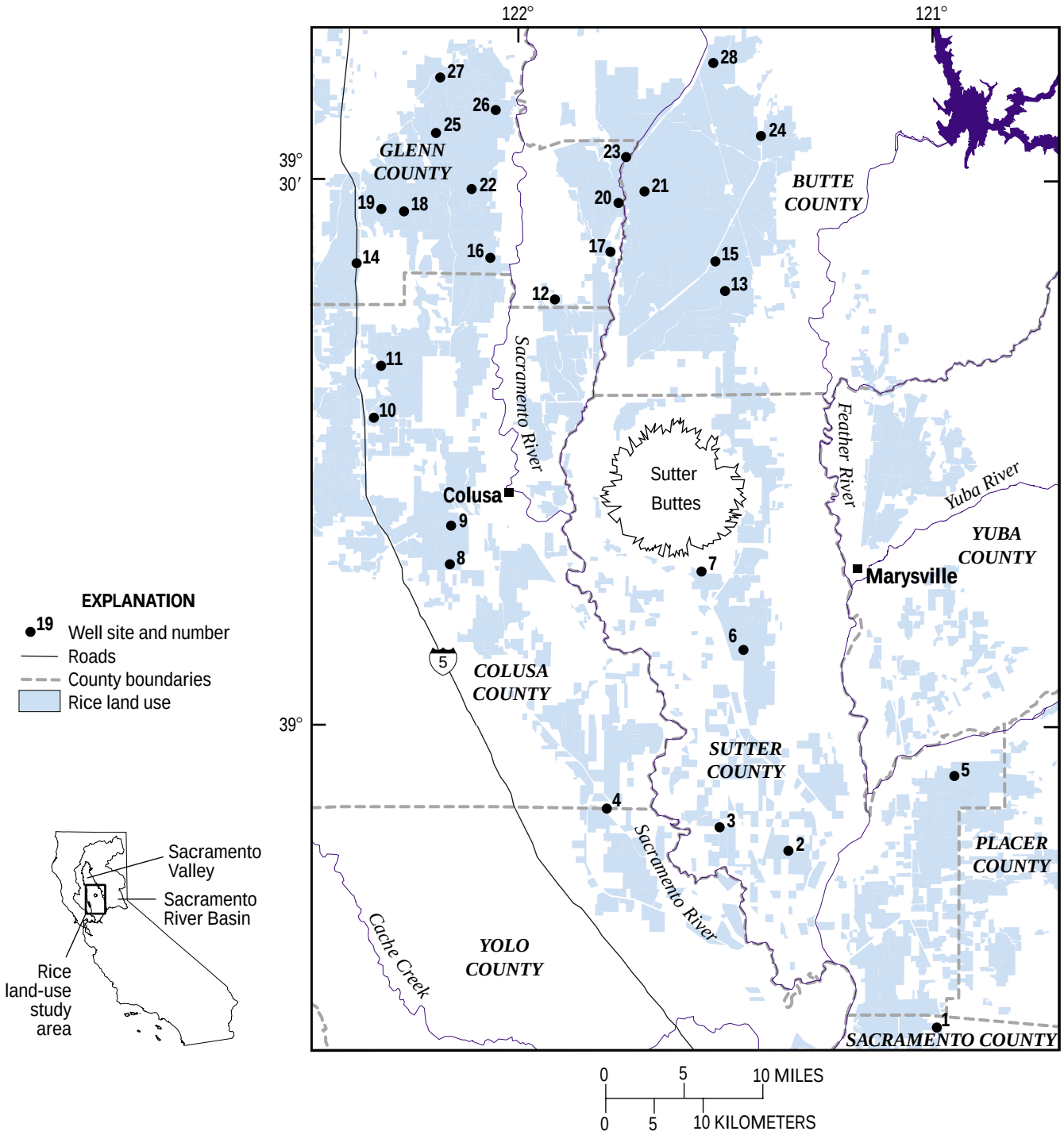


Figure 2. Locations of wells sampled in the rice areas in the Sacramento Valley, California.

Land and Water Use

Rice has been grown commercially in the Sacramento Valley since the early 1900s. Annual rice growing area currently (2000) is around 2,023 km^2, and since the 1950s has been between 1,214 and 2,023 km^2. About 30 percent of the rice fields are rotated with other crops, including safflower, corn, cotton, oats, wheat, grain sorghum, dry beans, sugarbeets, vegetable seed crops, and tomatoes; the majority of rice fields alternate between rice and fallow

seasons (Hill and others, 1997a). In addition to rice, land uses in the study area include alfalfa, grain, orchards, field crops, and wildlife/wetland areas (Domagalski and others, 1998). Rice agriculture in the Sacramento Valley uses as much as 1,800,000 to 2,286,000 m^3/km^2 of water seasonally. Rice crops are irrigated mostly using surface water and typically are flooded from April to September. Most fields are irrigated with a continuously flooded, flow-through system (Hill and others, 1997a,b). Some rice fields also are flooded during winter months to aid in rice straw decomposition and to provide winter habitat for migrating birds (Hill and others, 1997a). Detections of the rice pesticides molinate and thiobencarb in surface waters prompted a change in irrigation practices beginning in 1983, in which rice-field water must be held or recirculated in rice fields for up to 30 days after treatment in order for those pesticides to degrade or volatilize out of the water (Hill and others, 1997a; Scardaci and others, 1999). Total ground-water use in this study area in 1995 was approximately 4.78 Mm^3/d, of which about 93 percent was used for irrigation (Perlman, 1999). Both ground water and surface water are used for drinking water and irrigation in the study area. About half of the population in the study area is served by ground water; domestic and public supply ground-water use in 1995 was approximately 0.25 Mm^3/d (Perlman, 1999).

Hydrogeology

The wells sampled during this study tap the shallow ground water in the Sacramento Valley aquifer, a heterogeneous aquifer system with no known continuous confining layers that occupies the northern third of California's Central Valley (fig. 1). The Sacramento Valley aquifer occupies a structural trough surrounded by the Sierra Nevada, Cascade, and Coast Ranges mountains and is made up of thousands of meters of sediment eroded from the surrounding mountains (Page, 1986). Fresh water (less than 3,000 µS/cm) occurs to depths of about 600 m below sea level in the Sacramento Valley; below these depths the aquifer contains saline connate water (Berkstresser, 1973; Olmsted and Davis, 1961). Saline water also occurs in fresh-water parts of the Sacramento Valley aquifer as either perched zones or upward extensions of the deeper connate water (Berkstresser, 1973; Olmsted and Davis, 1961). Dormant and extinct volcanic areas (Norris and Webb, 1990) exist in the southwestern part of the basin (Clear Lake area, extinct), in the center of the Sacramento Valley (Sutter Buttes, extinct), in the northeastern part of the basin (Mount Lassen volcano, dormant), and in the northern part of the basin (Mount Shasta volcano, dormant) (fig. 1).

Intensive development of both surface- and ground-water sources for water supply and flood control over the last 100 years has greatly altered the hydrologic system in the Sacramento Valley; both discharge and recharge have increased from natural conditions because of ground-water pumping and irrigation return (Bertoldi and others, 1991). Regional ground-water flow is from the sides of the valley toward the center and southward. Ground-water conditions grade downward from unconfined to semi-confined to confined below the upper hundred meters (Williamson and others, 1989). Recharge to the Sacramento Valley aquifer occurs mainly along the upper reaches of river channels in the valley, in irrigated areas, and to some extent from precipitation (Bertoldi and others, 1991). Ground-water discharge occurs as evapotranspiration, loss to streams, and pumpage in the southern part of the Valley (Bertoldi and others, 1991).

Rice fields generally are located on fine-textured, poorly drained soils of clay and silt with impervious hardpans or claypans (Hill and others, 1997a). Estimated soil permeabilities over most of the study area generally are less than 6 m/d, with most of the study area being less than 0.6 m/d (Bertoldi, 1974). In most areas, fine-grained sediments make up more than 50 percent of the aquifer system (Page, 1986). The surficial alluvial deposits in the rice areas range in age from Holocene (younger than 10,000 years) to Pliocene (between 1.5 and 5 million years) (Helley and Harwood, 1985) and include three geomorphic units described in Olmsted and Davis (1961, plate 1): low alluvial plains and fans of the Sierra Nevada (referred to in this report as "eastern alluvial plain"), flood basins (referred to in this report as "central flood basins"), and low alluvial plains and fans on the west side of the valley (referred to in this report as "western alluvial plain") (fig. 3). These deposits consist of clay, silt, sand, and gravels eroded from the surrounding mountains, transported and deposited by the Sacramento River and its tributaries. The sediment source areas to the east consist of metamorphic, granitic, and volcanic rock types of the Sierra Nevada and Cascade Ranges; to the west, the sediment source areas consist

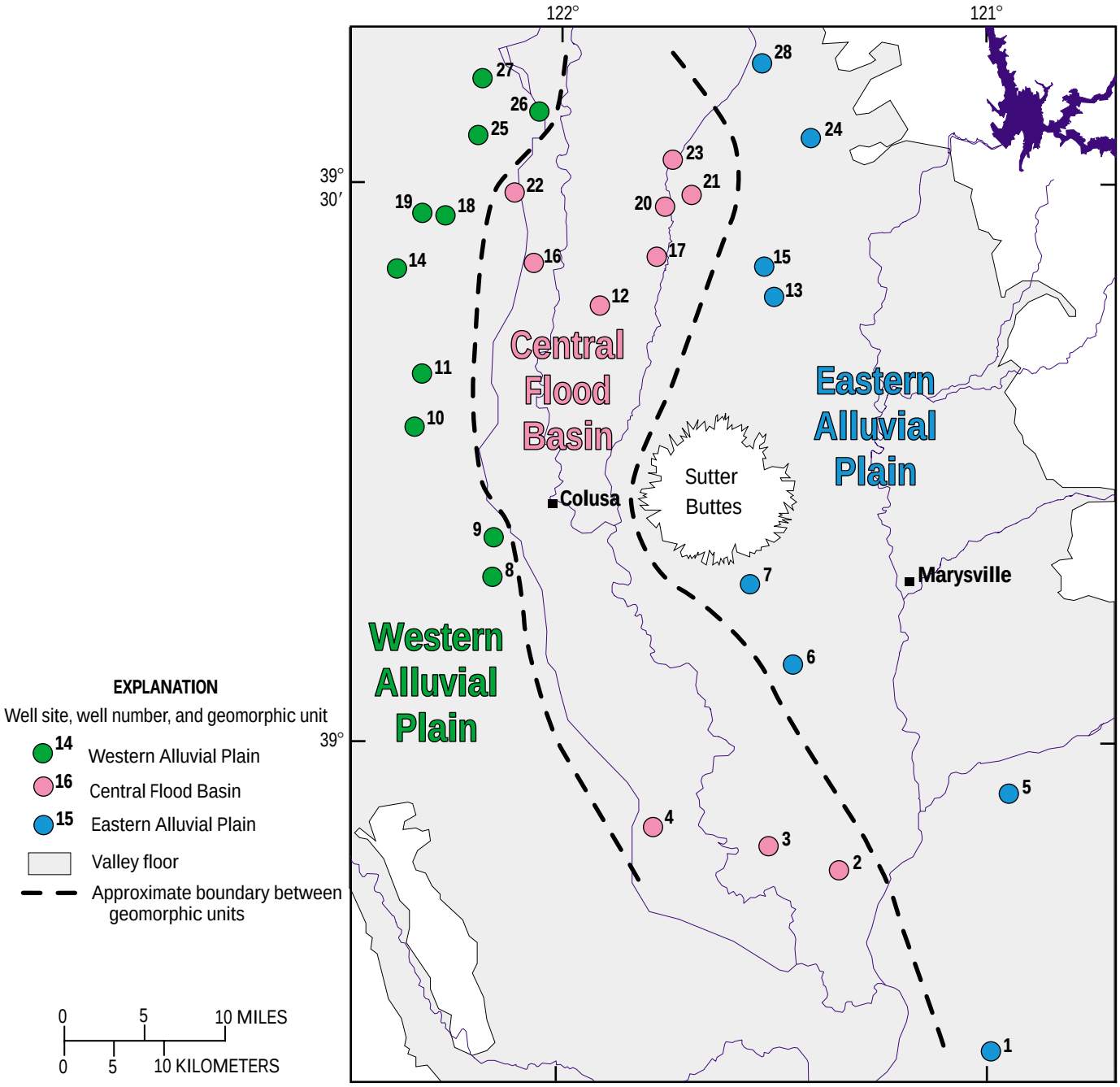


Figure 3. Well sites and geomorphic units in the rice areas in the Sacramento Valley, California.

of metamorphic, volcanic, and marine sedimentary rocks of the Coast Ranges (Helley and Harwood, 1985; Page, 1986).

METHODS OF INVESTIGATION

Well Site Selection

The criteria used for well site selection in this study follow those published in Lapham and others (1997). The principal criterion used for site selection was that the wells must be located in deposits that make up the Sacramento Valley aquifer. The boundaries for rice land-use areas (fig. 1) located on the Sacramento Valley aquifer were determined from the California Department of Water Resources land-use data (California Department of Water Resources, 1985, 1990, 1991, 1994a,b,c, and 1995a,b) and verified during field inventorying of sites. After the boundaries of the rice land-use areas were

determined, a computer geographic information system was used to divide the total rice area (the blue areas on fig. 1) into 30 equal-area cells (Scott, 1990). A computer program then randomly selected and ordered sites located in each of the 30 cells. The names of property owners were obtained from the County Assessors near the selected sites, and letters were sent to owners explaining this study and requesting permission to drill and sample a monitoring well. Permission also was obtained from some of the counties in which the selected sites were located to install wells on county right-of-way property. Field inventories of the randomly selected sites and a final evaluation of each site for drilling was completed and permission obtained from the land owners. Wells were sited where, at the time of the field inventory, they were surrounded by at least 75 percent rice farmland within 500 m. Because of crop rotations at some sites, some wells are surrounded by less than 50 percent rice farm-land in some years. In many cases, permission could not be obtained to put a well near the randomly selected points, and the search was expanded to other available property within that cell or adjacent cells. Seven wells used in this study are located in right-of-way areas next to rice fields; the rest are located adjacent to rice fields along field roads or rice equipment areas, or in farm or home yards surrounded by rice fields.

Monitoring Well Installation

The monitoring wells were drilled between May and July 1997, using a hollow-stem auger rig. All wells were constructed according to the guidelines in Lapham and others (1997) and according to California and local standards for well construction. Casing was 5-cm polyvinyl chloride (PVC) with PVC screens, sand-packed and sealed with bentonite or concrete, or both. All drilling equipment was steam-cleaned on-site before moving to the next drilling site, and well casing and screens were steam-cleaned before installation. After installation, all wells were developed using a combination of pumping and surging until the turbidity was zero or until specific conductance measurements were stable. Lithology was determined from cuttings during drilling by the project hydrologist on-site.

Well Descriptions, Water Levels, and Lithology

Well construction data for the wells installed and sampled in this study are shown in table 1. The wells range in depth from 8.8 to 15.2 m below land surface, with most wells being 10.7 m deep. Water-level altitudes ranged from 39.7 m above to 1.4 m below sea level, indicating that regional ground-water flow in the shallow part of the Sacramento Valley aquifer is southward and away from the sides of the valley (fig. 4). Lithology, as determined from cuttings during drilling, consisted of clay, silt, sand, and gravels; sediment sizes were generally clay or silt, or both, with varying amounts of sand and gravel. Interlayering and changes in sediment size occurred on scales ranging from centimeters to tens of meters. Although borehole lithology varied between individual wells, no differences in general borehole lithology were found between geomorphic units.

Water Sample Collection and Analysis

The wells installed for this study were sampled between August and October 1997. Sampling equipment consisted of a portable, stainless-steel submersible pump attached to Teflon lines with stainless-steel fittings. Samples were collected following the protocols in Koterba and others (1995), with the exception of dissolved organic-carbon samples, which were collected using a Teflon filter holder and an electric, oil-free vacuum pump to filter the sample. At wells with low dissolved oxygen or with sulfide odor, samples also were analyzed in the field for the presence or absence of ferrous iron and sulfide, using colorimetric methods. After all the samples were collected, sampling equipment was cleaned and stored in plastic bags. Periodically, quality-control samples were collected to document sample bias and variability. Methods used to analyze water samples are given in table 2. Method reporting limits for pesticides are given in table 3. All samples were analyzed at the USGS's National Water Quality Laboratory (NWQL) in Arvada, Colo., except for tritium samples, which were analyzed at the USGS Tritium Laboratory in Menlo Park, Calif., and stable isotope samples, which were analyzed at the USGS Isotope Laboratory in Reston, Va. All ground-water chemistry data collected in this study are available on the Web at <http://infotrek.er.usgs.gov/wdbctx/nawqa/nawqa.home>.

Table 1. Well construction information for wells sampled in rice areas in the Sacramento Valley, California

[masl, meters above sea level; mbls, meters below land surface; USGS, U.S. Geological Survey. mm/dd/yy, month per day per year]

Well number	USGS site ID	State well number	Land surface altitude (masl)	Well depth (mbls)	Screened interval (mbls)	Depth to ground water (mbls)	Water-level altitude (masl)	Date water-level measured (mm/dd/yy)
1	384330121293901	010N004E13F001M	6.7	15.2	10.7–13.7	8.1	–1.4	8/11/97
2	385314121401701	012N003E18H001M	6.7	15.2	12.2–13.7	1.7	5.0	10/3/97
3	385431121451401	012N002E09B002M	6.7	8.8	5.8–7.3	1.4	5.3	9/8/97
4	385528121532001	012N001E05C001M	7.0	10.7	7.6–9.1	1.2	5.8	8/12/97
5	385720121282401	013N004E24Q001M	20.4	14.6	11.6–13.1	4.0	16.4	10/2/97
6	390416121433601	014N002E10R001M	11.0	13.4	10.4–11.9	0.4	10.6	8/18/97
7	390832121463601	015N002E20D001M	12.5	10.7	7.6–9.1	1.7	10.8	8/19/97
8	390856122044301	015N002W16R001M	16.8	10.7	7.6–9.1	0.6	16.1	8/13/97
9	391059122043601	015N002W03E001M	14.9	10.7	7.6–9.1	0.8	14.1	9/17/97
10	391653122101401	017N003W35M001M	22.6	10.7	7.6–9.1	0.5	22.1	8/14/97
11	391947122094501	017N002W14G001M	24.4	10.7	7.6–9.1	1.5	22.9	9/16/97
12	392328121571501	018N001W27B001M	20.7	10.2	7.2–8.7	1.4	19.3	9/29/97
13	392358121450301	018N002E21G001M	24.7	13.1	8.5–11.6	1.1	23.6	9/9/97
14	392524122113401	018N003W09R001M	29.3	11.3	8.2–9.8	1.1	28.1	9/17/97
15	392542121452501	018N002E09L001M	26.2	10.7	7.6–9.1	1.1	25.1	8/19/97
16	392545122015201	018N002W12G002M	23.8	10.7	7.6–9.1	2.8	20.9	9/30/97
17	392604121531801	018N001E08D001M	21.9	11.7	8.7–10.2	1.3	20.6	8/21/97
18	392810122080901	019N003W25R001M	29.6	11.7	8.7–10.2	2.1	27.4	9/30/97
19	392824122091401	019N003W25E001M	29.9	10.7	7.6–9.1	0.8	29.1	8/14/97
20	392848121523901	019N001E20R001M	25.3	14.8	10.2–13.3	1.5	23.8	9/10/97
21	392924121504801	019N001E22B001M	26.2	10.7	7.6–9.1	0.4	25.8	8/21/97
22	392931122031701	019N002W23E001M	24.4	10.8	7.8–9.3	0.7	23.7	8/20/97
23	393119121521001	019N001E09C001M	27.7	14.0	11.0–12.5	1.8	25.9	9/10/97
24	393230121422201	020N002E35J002M	37.8	10.7	7.6–9.1	0.9	36.9	9/11/97
25	393235122055301	020N002W32J001M	32.9	10.7	7.6–9.1	1.1	31.8	9/18/97
26	393353122013501	020N002W25A001M	29.3	10.7	7.6–9.1	0.5	28.8	8/15/97
27	393538122053201	020N002W16D001M	38.1	10.8	7.8–9.3	1.5	36.6	10/1/97
28	393630121455401	020N002E08A001M	41.5	10.7	7.6–9.1	1.7	39.7	9/9/97

Data Reporting and Analysis

In this report, water temperature is reported in degrees Celsius (°C). Specific conductance values are reported in microsiemens per centimeter (µS/cm). Alkalinity and hardness are reported in milligrams per liter as calcium carbonate (mg/L as $CaCO_3$). Dissolved concentrations of oxygen, solids (residue-on-evaporation at 180°C), organic carbon, and inorganic constituents are reported in milligrams per liter (mg/L). Nitrate plus nitrite, nitrate, nitrite, and ammonia are reported in mg/L as nitrogen. Phosphorus and orthophosphorus are reported in mg/L as phosphorus. Pesticide concentrations are reported in micrograms per liter (µg/L). Tritium concentrations are reported in picocuries per liter (pCi/L). The stable isotopes ^{2}H and ^{18}O are reported as ratios per mil (‰, or per thousand) of ^{2}H to H and ^{18}O to ^{16}O, respectively, and are referenced to Vienna Standard Mean Ocean Water (VSMOW). In the discussion of stable isotopes, the term “lighter” refers to waters with less ^{18}O and ^{2}H (and therefore more negative per mil

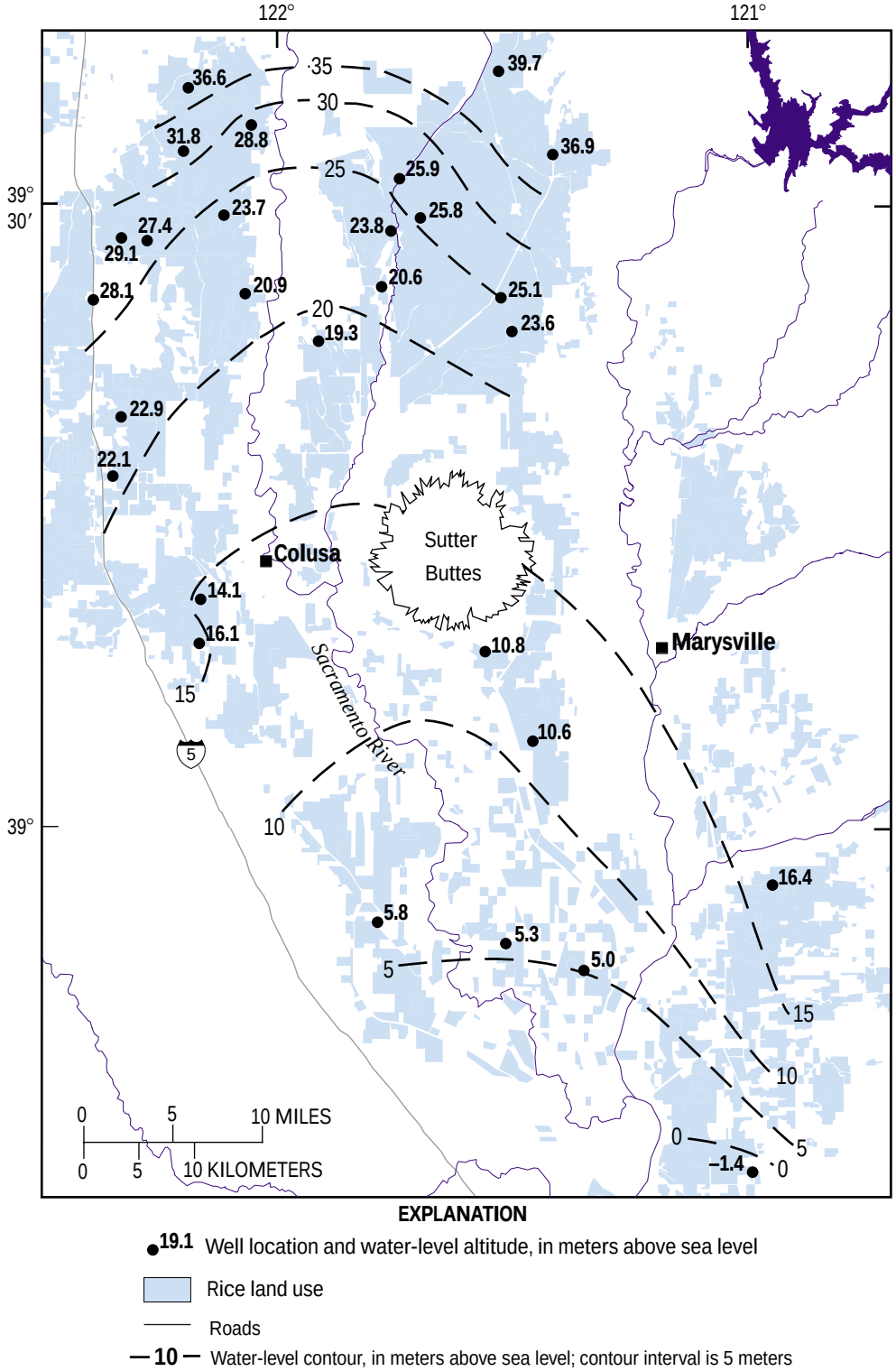


Figure 4. Water-level contours in the rice areas in the Sacramento Valley, California, August to October, 1997.

values), whereas the term "heavier" refers to waters that have more ^{18}O and ^{2}H (and therefore less negative per mil values). All chemical constituents except ^{3}H, ^{2}H, and ^{18}O were determined from filtered water samples and reported as dissolved concentrations.

Water-quality constituents were compared to federal 2000 drinking-water standards set by the U.S. Environmental Protection Agency (EPA) (U.S. Environmental Protection Agency, 2000) and California State 2000 drinking-water standards set by the

Table 2. Laboratory analysis methods for measured water-quality constituents

[^{18}O, oxygen-18; ^{16}O, oxygen-16]

Constituent	Method	Reference
Deuterium/hydrogen	Hydrogen equilibrium and mass spectrometry	Coplen and others (1991)
Dissolved organic carbon	Ultra-violet-promoted persulfate oxidation and infrared spectrometry	Brenton and Arnett (1993)
Major inorganics	Atomic absorption spectrometry, Colorimetry, Ion-exchange chromatography, Inductively-coupled plasma atomic emission spectrometry, and mass spectrometry	Fishman and Friedman (1989), Fishman (1993), and Struzeski and others (1996)
Nutrients	Colorimetry	Patton and Truitt (1992), Fishman (1993)
$^{18}O/^{16}O$	Carbon dioxide equilibrium	Epstein and Mayeda (1953)
Pesticides	Solid-phase extraction on a carbon-18 cartridge and gas chromatography/mass spectrometry	Zaugg and others (1995)
Pesticides	Solid-phase extraction on a Carbopak-B cartridge and high performance liquid chromatography with ultraviolet detection	Werner and others (1996)
Trace inorganics	Atomic absorption spectrometry or Inductively coupled plasma mass spectrometry	Faires (1993)
Tritium	Electrolytic enrichment with gas counting	Ostlund and Dorsey (1975)

California Department of Health Services (DHS) (California Department of Water Resources, 1997). DHS standards are used for constituents not currently regulated by the EPA and for those constituents with a DHS standard lower than that set by the EPA. Drinking-water standards used for comparison are the primary maximum contaminant level (MCL), which is the maximum concentration of a contaminant permissible in a public water system; the secondary maximum contaminant level (SMCL), which is a guideline for taste, odor, and other, nonaesthetic effects of drinking water; and the lifetime health advisory limit (HAL), which is the concentration of a chemical in drinking water that is not expected to cause adverse noncarcinogenic effects over a lifetime of exposure (U.S. Environmental Protection Agency, 2000; California Department of Water Resources, 1997).

Summary statistics include median values, and nonparametric statistical methods were used for data analysis, as most ground-water chemistry data have non-normal distributions and many outliers. The Spearman rank correlation test was used to determine the degree of correlation between two variables (Helsel and Hirsch, 1995). The rank-sum test (also known as the Mann-Whitney or Wilcoxon rank-sum test) was used to determine whether one group of data had statistically larger values than a second group (Helsel and Hirsch, 1995). The Kruskal–Wallis test was used to determine whether two or more data groups were statistically different (Helsel and Hirsch, 1995). A significance level of 95 percent was used for all statistical tests in this report. The words “significant” and “correlation” are always used in terms of the statistical results.

Quality-Control Data Analyses

Quality control (QC) samples were collected to evaluate the bias and variability of the ground-water chemistry data in this study. QC sample types collected included field blank samples, replicate ground-water samples, and field-spiked ground-water samples.

Table 3. Pesticides analyzed and reporting limits in water samples, in the Sacramento River Basin, California

[*, transformation product; (0.04) method reporting limit, in micrograms per liter]

Compound	Compound	Compound
Amides		
Alachlor (0.002)[1]	Napropamide (0.003)[1]	Propanil (0.004)[1]
Metolachlor (0.002)[1]	Propachlor (0.007)[1]	Propyzamide (0.003)[1]
Carbamates		
Aldicarb (0.016)[2]	Carbofuran, 3-Hydroxy* (0.014)[2]	Pebulate (0.004)[1]
Aldicarb sulfone* (0.016)[2]	EPTC (0.002)[1]	Propham (0.035)[2]
Aldicarb sulfoxide* (0.021)[2]	Methiocarb (0.026)[2]	Propoxur (0.035)[2]
Butylate (0.002)[1]	Methomyl (0.017)[2]	Thiobencarb (0.002)[1]
Carbaryl (0.003)[1], (0.008)[2]	Molinate (0.004)[1]	Triallate (0.001)[1]
Carbofuran (0.003)[1], (0.028)[2]	Oxamyl (0.018)[2]	
Chlorophenoxy herbicides		
2,4,5-T (0.035)[2]	Dacthal, mono-acid* (0.017)[2]	MCPB (0.035)[2]
2,4-D (acid) (0.035)[2]	Dichlorprop (2,4-DP) (0.032)[2]	Silvex (2,4,5-TP) (0.021)[2]
2,4-DB (0.035)[2]	MCPA (0.05)[2]	Triclopyr (0.05)[2]
Dinitroanilines		
Benfluralin (0.002)[1]	Trifluralin (0.002)[1]	Pendimethalin (0.004)[1]
Ethafluralin (0.004)[1]	Oryzalin (0.019)[2]	
Organochlorines		
Chlorothalonil (0.035)[2]	Dichlobenil (0.02)[2]	alpha-HCH* (0.002)[1]
Dacthal (DCPA) (0.002)[1]	Dieldrin (0.001)[1]	GAMMA -HCH (0.004)[1]
p,p′-DDE* (0.006)[1]		
Organophosphates		
Azinphos-methyl (0.001)[1]	Ethoprop (0.003)[1]	Parathion (0.004)[1]
Chlorpyrifos (0.004)[1]	Fonofos (0.003)[1]	Phorate (0.002)[1]
Diazinon (0.002)[1]	Malathion (0.005)[1]	Terbufos (0.013)[1]
Disulfoton (0.017)[1]	Methyl parathion (0.006)[1]	
Triazine herbicides:		
Atrazine (0.001)[1]	Cyanazine (0.004)[1]	Prometon (0.018)[1]
Atrazine, desethyl* (0.002)[1]	Metribuzin (0.004)[1]	Simazine (0.005)1
Uracils		
Bromacil (0.035)[2]	Terbacil (0.007)[1]	
Ureas		
Fenuron (0.013)[2]	Fluometuron (0.035)[2]	Neburon (0.015)[2]
Diuron (0.020)[2]	Linuron (0.002)[1], (0.018)[2]	Tebuthiuron (0.010)[1]
Miscellaneous		
2,6-Diethylanaline* (0.003)[1]	Chloramben (0.011)[2]	DNOC (0.035)[2]
Acetochlor (0.002)[1]	*cis*-Permethrin (0.05)[1]	Norflurazon (0.024)[2]
Acifluorfen (0.035)[2]	Clopyralid (0.05)[2]	Picloram (0.05)[2]
Bentazon (0.014)[2]	Dicamba (0.035)[2]	Propargite (0.013)[1]
Bromoxynil (0.035)[2]	Dinoseb (0.035)[2]	

[1] Solid-phase extraction and gas chromatography/mass spectrometry (GC/MS) correspond to the method reporting limit.

[2] Solid-phase extraction and high performance liquid chromatography (HPLC) with ultraviolet light spectrometry correspond to the method reporting limit.

Field-blank samples were collected to evaluate bias in ground-water chemical data from contamination introduced during sample collection and analysis for dissolved organic carbon, pesticides, nutrients, and inorganic constituents. Evidence of contamination from field-blank samples affecting ground-water data was found for aluminum, ammonia, copper, and dissolved organic carbon (DOC). Some of the concentrations of these constituents measured in ground water were within 3 standard deviations of the mean of the concentrations measured in field-blank samples, which indicates that concentrations may be partly or entirely due to contamination introduced during sampling or analysis; these data are not used for analyses in this report. Ammonia was detected in 10 out of 28 wells (36 percent), but in all but one well, ammonia concentrations were within the range of blank sample detections and may be the result of sample contamination. Information from the NWQL indicates that the detections of aluminum in field-blank samples and in all ground-water samples may have been introduced by the nitric acid preservative used in the samples (T. Maloney, USGS NWQL, unpub. data, 1998). Detections of DOC in field blanks indicate that concentrations measuring below 1.8 mg/L in ground water in this study may be partly or entirely due to sample contamination during collection or analysis. DOC contamination in field-blank samples may have come from the cleaning methods that were used to prevent contamination of other organic constituents during sampling; this contamination may not be present in the ground-water samples because it may only have been introduced into the field-blank samples. Sources of ammonia and copper contamination are not known.

Replicate samples were collected to determine variability of the ground-water chemical data for inorganic constituents and for DOC. A total of 11 replicate sample pairs were used for this evaluation. The mean relative standard deviations between sample pairs for all constituents were less than 25 percent and for most constituents were less than 5 percent (table 4). The relative standard deviation in this study is defined as the ratio of the standard deviation to the mean concentration for each replicate pair of samples. One to three individual replicate pairs for some constituents (as indicated by the footnote in table 4) had a relative standard deviation of greater than 20 percent. Mean relative standard deviations of less than 20 percent are considered acceptable in this report. Data for three constituents with mean relative standard deviations greater than 20 percent—aluminum, cadmium, and chromium—will not be used for analyses in this report.

Table 4. Summary of mean relative standard deviations for replicate sample pairs of inorganic compounds, nutrient compounds, and dissolved organic carbon

[%, percent; $CaCO_3$, calcium carbonate]

Less than 5%	Less than 10%	Less than 15%	Less than 25%
Arsenic	Ammonia[1]	Boron[1]	Aluminum
Barium	Dissolved organic carbon[1]	Bromide[1]	Cadmium[1]
Calcium	Fluoride[1]	Copper[1]	Chromium[1]
Chloride[1]	Nickel	Orthophosphorus[1]	
Cobalt	Nitrate[1]	Zinc[1]	
Dissolved solids	Phosphorus[1]		
Hardness as $CaCO_3$			
Iron			
Magnesium			
Molybdenum			
Nitrite			
Potassium			
Selenium			
Silica			
Sodium			
Sulfate			
Uranium			

[1] One to three individual replicate pairs had a relative standard deviation of greater than 20 percent.

Surrogates (constituents that behave like pesticide analytes) were added to all pesticide samples to evaluate the ability of the sampling and analysis methods to detect the pesticides in each ground-water sample and to determine whether the ground-water chemistry of each sample would interfere with the pesticide analysis (generally referred to as matrix interference). The mean recoveries of the surrogates in all ground-water samples for pesticides were within the control limits determined by the NWQL for 1997 (M.P. Schroeder, USGS NWQL, unpub. data, 1998; R. W. Brenton, USGS NWQL, unpub. data, 1998).

Spike solutions containing known amounts of some pesticides were added to some replicate ground-water samples to evaluate bias of those pesticide analyses. Seventy-seven out of eighty-six pesticides were evaluated with field-spiked samples; seventy-six had mean recoveries within NWQL's 1997 control limits, indicating that the methods of sampling and analysis used in this study adequately detected those pesticides and that there were no major matrix interferences on those pesticide analyses. The mean recovery of dicamba was lower than the lower 1997 control limit, indicating that dicamba may not have been detected if present in low concentrations in some ground-water samples. Some pesticides analyzed in this study were not present in the spike solutions, and recoveries for these pesticides could not be evaluated. The pesticides are chloramben, chlorothanlonil, dichlobenil, DNOC (4.6-dinitro-*o*-cresol), methyl azinphos, carbaryl, carbofuran, desethyl atrazine, and terbacil.

SHALLOW GROUND-WATER QUALITY

General Water Chemistry

Summary statistics for general water chemistry measurements are listed in table 5. The SMCL drinking-water standard for specific conductance (900 µS/cm) (California Department of Water Resources, 1997) was exceeded in 12 out of 28 wells (43 percent), and the SMCL for dissolved solids (500 mg/L) (U.S. Environmental Protection Agency, 2000) was exceeded in the same wells plus 4 other wells (16 out of 28 wells, or 57 percent). The median concentration for dissolved solids measured in this study (532 mg/L) is higher than the national NAWQA median concentration measured in other shallow ground-water areas (290 mg/L) (Gilliom and others, 1998, p. 18). Three of the wells sampled in this study had dissolved-solids concentrations over 2,000 mg/L, which is considered to be a limit for fresh water (Berkstresser, 1973). The well with the highest dissolved-solids concentration (8,730 mg/L) is located south of Sutter Buttes, an area in which high dissolved-solids concentrations have been found in wells between 15 and 90 m deep in previous studies (California State Water Resources Board, 1952, p. 34–38).

Table 5. Summary of general water chemistry in shallow ground water in rice areas in the Sacramento Valley, California

[°C, degrees Celsius; $CaCO_3$, calcium carbonate; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligram per liter; SMCL, secondary maximum contaminant level; —, no value or standard available]

General Water Chemistry	Minimum	Median	Maximum	Drinking-water standard	Type of standard	Number of wells exceeding a drinking-water standard
Alkalinity, mg/L as $CaCO_3$	110	370	580	—	—	—
Dissolved oxygen, mg/L	0.2	0.4	6.6	—	—	—
Dissolved solids, mg/L, residue on evaporation at 180°C	168	532	8,730	500	SMCL[1]	16
Hardness, total, mg/L as $CaCO_3$	110 (moderately hard)	340 (very hard)	4,000 (very hard)	—	—	—
pH, standard units	6.7	7.4	7.8	6.5–8.5	SMCL[1]	0
Specific conductance, µS/cm	267	854	13,600	900	SMCL[2]	12
Water temperature, °C	17.5	19.0	22.5	—	—	—

[1] U.S. Environmental Protection Agency, 2000.
[2] California Department of Water Resources, 1997.

Major Inorganic Constituents

The major inorganic constituents detected in this study are listed in table 6. Drinking-water standards were exceeded for chloride and sulfate. Four out of twenty-eight wells (14 percent) exceeded the MCL for sulfate, 500 mg/L (U.S. Environmental Protection Agency, 2000). Two out of twenty-eight wells (7 percent) exceeded the SMCL for chloride, 250 mg/L (U.S. Environmental Protection Agency, 2000).

The major water types found in this study (fig. 5) were magnesium and calcium bicarbonate waters with some wells having more sodium sulfate water types. Wells located on the eastern alluvial plain have the more magnesium-calcium-bicarbonate water, while wells located on the western alluvial plain have the more sodium-sulfate water types; wells in the central flood basins were intermediate between the two. One well, located south of Sutter Buttes in the central flood basins, yields sodium-calcium chloride water, distinctly different from the other wells sampled in this study; this is the same well discussed above, with the highest dissolved-solids concentration measured in this study.

Trace Inorganic Constituents

The trace inorganic constituents detected in this study are given in table 7. Trace elements analyzed for but not detected in this study were antimony, beryllium, lead, and silver. Aluminum was not detected above the concentration range of quality-control blanks, indicating possible contamination from the nitric acid preservative.

Drinking-water standards were exceeded for barium, boron, cadmium, manganese, and molybdenum. The MCL for barium, 1 mg/L (California Department of Water Resources, 1997), was exceeded in 1 out of 28 wells (4 percent). The HAL for boron, 0.6 mg/L (U.S. Environmental Protection Agency, 2000), as well as the water quality criterion for boron in irrigation water, 0.75 mg/L (National Academy of Sciences and National Academy of Engineering, 1972), was exceeded in 5 out of 28 wells (18 percent). The MCL for cadmium, 0.005 mg/L (U.S. Environmental Protection Agency, 2000), was exceeded in 3 out of 28 wells (11 percent). The SMCL for manganese, 0.05 mg/L (U.S. Environmental Protection Agency, 2000), was exceeded in 21 out of 28 wells (75 percent). The HAL for molybdenum, 0.04 mg/L (U.S. Environmental Protection Agency, 2000), was exceeded in 1 out of 28 wells (4 percent).

None of the wells sampled in this study exceeded the current MCL for arsenic, 0.05 mg/L (U.S. Environmental Protection Agency, 1996). Lower MCLs for arsenic have been proposed (0.005 mg/L [U.S. Environmental Protection Agency, 2000]; 0.010 mg/L [U.S. Environmental Protection Agency, 2001a]); however, those MCLs are being withdrawn and a new MCL is under review (U.S. Environmental Protection Agency, 2001b). The EPA also has an HAL for arsenic of 0.002 mg/L (U.S. Environmental Protection Agency, 2000); 16 out of 28 wells (57 percent) have an arsenic concentration over the HAL.

Table 6. Summary of major inorganic constituents detected in shallow ground water in rice areas in the Sacramento Valley, California

[All detections and drinking-water standards are shown in milligrams per liter. SMCL, secondary maximum contaminant level; —, no value or standard available]

Constituent	Number of detections/number of samples	Minimum detection	Median detection	Maximum detection	Drinking-water standard	Type of standard	Number of wells exceeding a drinking-water standard
Bicarbonate, as HCO_3	28/28	140	460	710	—	—	—
Calcium, as Ca	28/28	22	62	810	—	—	—
Chloride, as Cl	28/28	2.3	12	4,800	250	SMCL[1]	2
Magnesium, as Mg	28/28	13	46	480	—	—	—
Potassium, as K	28/28	0.5	1	9	—	—	—
Silica, as SiO_2	28/28	16	40	70	—	—	—
Sodium, as Na	28/28	12	50	1,300	—	—	—
Sulfate, as SO_4	27/28	5.0	42	1,500	250	SMCL[1]	5

[1] U.S. Environmental Protection Agency, 2000.

Nutrient Constituents

Nutrient constituents detected in this study included ammonia, nitrate, nitrite, and phosphorus (table 8). No nutrients were detected at levels above any drinking-water standards. Ammonia was detected in 10 out of 28 wells (36 percent), but in all but one well, ammonia concentrations were within the range of blank sample detections and may be the result of sample contamination. Ammonia plus organic nitrogen was detected in 3 out of 28 wells (11 percent). Nitrate concentrations ranged from 0.08 to 6.2 mg/L. Three out of twenty-eight wells (11 percent) had nitrate concentrations over 3 mg/L, a level that may indicate an impact from human activities (Hull, 1984, p. 19; Madison and Brunett, 1984). Nitrite was detected in 11 out of 28 wells (39 percent); detected concentrations ranged from 0.01 to 0.1 mg/L, with a median of 0.01 mg/L. The median concentration of nitrate plus nitrite in this study (0.58 mg/L) was less than the National NAWQA median of 2 mg/L measured in shallow ground water in other studies (Gilliom and others, 1998, p. 17). The lower nitrate concentrations may be attributable to low dissolved oxygen conditions, which would allow for the chemical reduction of nitrate to nitrogen gas.

Dissolved Organic Carbon

Dissolved organic carbon was detected in all 28 wells (100 percent) (table 8). The median concentration of DOC found in ground water in this study was 1.4 mg/L, which is higher than the median DOC concentration (0.7 mg/L) found in wells throughout the U.S. (Leenheer and others, 1974). Detections of

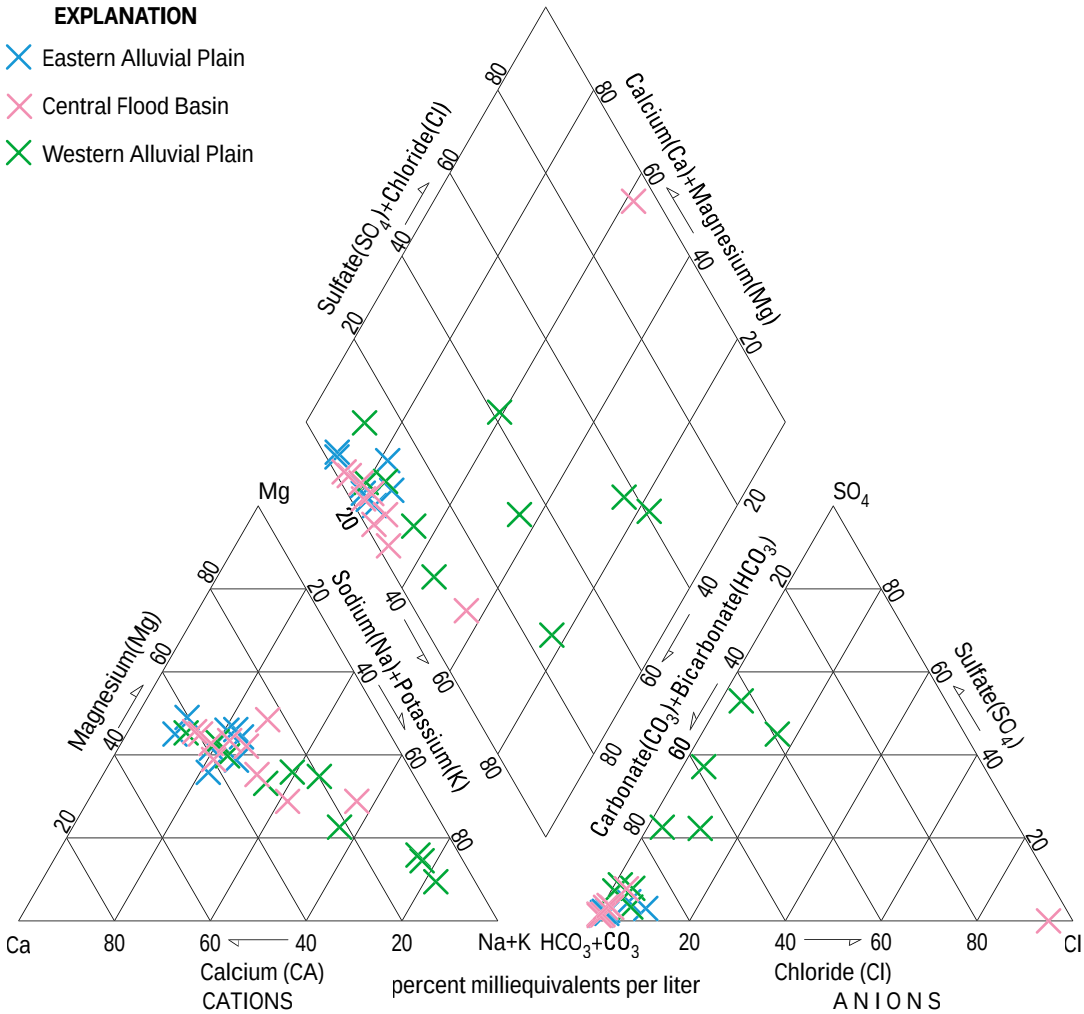


Figure 5. Trilinear diagram showing major-ion composition of shallow ground-water samples from rice areas in the Sacramento Valley, California.

Table 7. Summary of trace inorganic constituents detected in shallow ground water in rice areas in the Sacramento Valley, California

[All detections and drinking-water standards are shown in milligrams per liter. HAL, health advisory level; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; —, no value available]

Constituent	Number of detections/ number of samples	Minimum detection	Median detection	Maximum detection	Drinking-water standard	Type of standard	Number of wells exceeding a drinking-water standard
Aluminum, as Al	27/28	0.002	0.004	0.010	1	MCL [2]	0
Arsenic, as As	28/28	0.001	0.0035	0.015	0.050	MCL[3]	0
Barium, as Ba	28/28	0.01	0.063	5.05	1	MCL [2]	1
Boron, as B	28/28	0.02	0.2	1.8	0.6	HAL[1]	5
Bromide, as Br	22/28	0.03	0.05	12	—	—	—
Cadmium, Cd	3/28	0.006	0.007	0.007	0.005	MCL[1]	3
Chromium, as Cr	27/28	0.002	0.004	0.016	0.05	MCL[2]	0
Cobalt, as Co	6/28	0.001	0.002	0.004	—	—	—
Copper, as Cu	13/28	0.001	0.003	0.009	1.3	MCL[1]	0
Ferrous iron, as Fe^{+2}	19/28	—	—	—	—	—	—
Fluoride, as F	22/28	0.1	0.25	1.8	4	MCL[1]	0
Iron, as Fe	15/28	0.003	0.059	5.3	0.3	SMCL[1]	3
Manganese, as Mn	27/28	0.002	0.1	3	0.05	SMCL[1]	21
Molybdenum, as Mo	14/28	0.001	0.0045	0.051	0.04	HAL[1]	1
Nickel, as Ni	19/28	0.001	0.002	0.009	0.1	HAL[1]	0
Selenium, as Se	2/28	0.003	0.0125	0.022	0.05	MCL[1]	0
Sulfide, as S^{-}	14/28	—	—	—	—	—	—
Uranium, as U	24/28	0.001	0.0035	0.023	2,000	MCL[1]	0
Zinc, as Zn	12/28	0.001	0.002	0.017	2	HAL[1]	0

[1] U.S. Environmental Protection Agency, 2000.
[2] California Department of Water Resources, 1997.
[3] U.S. Environmental Protection Agency, 1996.

Table 8. Summary of nutrient constituents and dissolved organic carbon detected in shallow ground water in rice areas in the Sacramento Valley, California

[All detections and drinking-water standards are shown in milligrams per liter. C, carbon; HAL, health advisory level; MCL, maximum contaminant level; N, nitrogen; P, phosphorus; —, no value available]

Constituent	Number of detections/ number of samples	Minimum detection	Median detection	Maximum detection	Drinking-water standard	Type of standard	Number of wells exceeding a drinking-water standard
Ammonia, as N	10/28	0.02	0.02	0.46	30	HAL[1]	0
Ammonia + organic nitrogen, as N	3/28	0.3	0.4	0.7	30	HAL[1]	0
Nitrate + Nitrite, as N	23/28	0.08	0.92	6.2	10	MCL[1]	0
Nitrate, as N	23/28	0.08	0.58	6.2	10	MCL[1]	0
Nitrite, as N	11/28	0.01	0.01	0.10	1	MCL[1]	0
Orthophosphorus, as P	27/28	0.01	0.07	0.36	—	—	—
Phosphorus, as P	28/28	0.030	0.060	0.362	—	—	—
Dissolved organic carbon, as C	28/28	0.3	1.4	6.8	—	—	—

[1] U.S. Environmental Protection Agency, 2000.

DOC in field blanks indicate that ground-water sample concentrations measured below 1.8 mg/L in this study may be partly or entirely due to sample contamination introduced during sample collection or analysis. DOC concentrations in ground water above this value ranged from 1.9 to 6.8 mg/L in 12 out of 28 wells (43 percent), with a median of 2.7 mg/L.

Pesticides

From one to eight pesticides were detected in 25 of 28 wells (89 percent) in this study (table 9). This frequency of detection is almost twice the median frequency of a pesticide detection in shallow ground water (45.9 percent) from other NAWQA studies between 1992 and 1995 (Gilliom and others, 1998, p. 17). Eleven pesticides and one pesticide degradation product were detected in this study, indicating that human activities have affected shallow ground-water quality in the study area. Pesticides that were analyzed for but not detected are listed in table 10. All pesticide concentrations detected in this study were below state and federal 2000 drinking-water standards. The frequency of detection for all pesticides detected in this study except diuron was higher than the national median frequency for their detections in shallow ground water in agricultural areas (U.S. Geological Survey Pesticide National Synthesis Project, 1998).

Pesticide use information reported in the Sacramento Valley area is shown in table 11 and was taken from California Department of Pesticide Regulation (1997) and California Department of Food and Agriculture (1989). The pesticides bentazon and dichlorprop are not currently used in the Sacramento Valley and have not been since the late 1980s. Four of the pesticides detected in this study have been used on rice crops: bentazon, carbofuran, molinate, and thiobencarb. From one to four rice pesticides were detected in 23 out of 28 wells (82 percent). Five of the pesticides detected in shallow ground water in this study have been used for agricultural crops other than rice: atrazine, carbofuran, diuron, methyl azinphos, and simazine. Five of the pesticides detected in shallow ground water have been used for nonagricultural purposes: atrazine, dichlorprop, diuron, simazine, and tebuthiuron.

Of the rice pesticides detected in this study, only bentazon has been detected in previous studies and determined to be from a nonpoint source. Bentazon was banned for use on rice in California in 1989

Table 9. Summary of pesticides detected in shallow ground water in rice areas in the Sacramento Valley, California

[All detections and drinking-water standards are shown in micrograms per liter. E, estimated value because compound was detected at a concentration outside of instrument calibration range; HAL, health advisory level; MCL, maximum contaminant level; —, no value available]

Pesticide	Number of detections/ number of samples	Minimum detection	Median detection	Maximum detection	Drinking-water standard	Type of standard	Number of wells exceeding a drinking-water standard
Atrazine	10/28	E 0.002	E 0.003	0.026	3	MCL[1]	0
Bentazon	20/28	0.06	0.935	E 7.8	18	MCL [2]	0
Bromacil	1/28	0.19	—	—	90	HAL[1]	0
Carbofuran	4/28	0.016	0.050	0.8	18	MCL [2]	0
Desethyl atrazine	7/28	E 0.001	E 0.003	E 0.005	—	—	—
Dichlorprop	1/28	E 0.1	—	—	—	—	—
Diuron	2/28	0.04	0.06	0.09	10	HAL[1]	0
Azinphos-methyl	1/28	E 0.014	—	—	—	—	—
Molinate	7/28	E 0.002	0.005	0.056	20	MCL [2]	0
Simazine	10/28	E 0.002	E 0.003	0.027	4	MCL[1]	0
Tebuthiuron	1/28	E 0.006	—	—	500	HAL[1]	0
Thiobencarb	3/28	0.006	0.014	0.025	70	MCL [2]	0

[1] U.S. Environmental Protection Agency, 2000.
[2] California Department of Water Resources, 1997.

Table 10. Pesticides and degradation products not detected in shallow ground water in rice areas in the Sacramento Valley, California

Not detected and applied:	Propargite
2,4-D	Propham
2,4-DB	Propoxur
Alachlor	Terbacil
Aldicarb	Triclopyr
Benfluralin	Trifluralin
Bromoxynil	
Carbaryl	**Not detected and not applied:**
Chloramben	2,4,5-T
Chlorothalonil	2,4,5-TP
Chlorpyrifos	2,6-Diethylanaline
cis-Permethrin	Acetochlor
Cyanazine	Acifluorfen
Diazinon	Alpha-HCH
Dicamba	Butylate
Dichlobenil	Clopyralid
Dinoseb	Dacthal (mono-acid)
Disulfoton	DCPA
EPTC	Dieldrin
Ethoprop	DNOC
Fonofos	Esfenvalerate
Gamma-HCH	Ethalfluralin
Linuron	Fenuron
Malathion	Fluometuron
MCPA	MCPB
Methiocarb	Neburon
Methomyl	*p,p′*–DDE
Methyl parathion	Pebulate
Metolachlor	Propachlor
Metribuzin	Propyzamide
Napropamide	Silvex (2,4,5-TP)
Norflurazon	Terbufos
Oryzalin	Triallate
Oxamyl	
Parathion	**Degradation products not detected:**
Pendimethaline	Aldicarb sulfone
Phorate	Aldicarb sulfoxide
Picloram	3-Hydroxycarbofuran
Prometon	
Pronamide	

because of detections in water wells, but it continues to be detected in ground water in the Sacramento Valley (Miller-Maes and others, 1993; Bartkowiak and others, 1998). In 1989, samples were collected by the California Department of Food and Agriculture and analyzed for bentazon from domestic wells in the rice growing counties in California. Of the total number of wells sampled in that study, 134 were located in the USGS 1997 rice land-use study area; bentazon was detected in 56 of those wells, giving a detection frequency of 42 percent (Sitts, 1989). Well depth information was not available for all of the wells sampled in 1989, but the available information showed that well depths ranged from about 12 to 90 m (Bartkowiak and others, 1998), which are typical depths for domestic wells in the Sacramento Valley. Bentazon was detected in 68 percent of the shallow (less than 15 m deep) wells sampled by the USGS in 1997 at concentrations above the detection limit used in the 1989 study. Previous detections of molinate reported in the California Department of Pesticide Regulation ground-water database (Bartkowiak and others, 1998) either were determined to be from a point source or were a result of poor well construction. No detections of thiobencarb or carbofuran were reported in Bartkowiak and others (1998). The higher detection frequencies of bentazon, carbofuran, molinate, and thiobencarb in the 1997 study relative to previous studies are possibly due to the lower detection limits and shallower sampling depths used by the USGS.

Ground-Water Redox Condition

Hull (1984) demonstrated that reducing conditions in the fine-grained sediments in flood basin areas are a major factor influencing the ground water chemistry of the Sacramento Valley. The oxidation-reduction (redox) state of water can affect what constituents are present. Water with chemistry indicating oxidizing chemical conditions is referred to as oxic; water with chemistry indicating reducing chemical conditions is referred to as anoxic. Anoxic conditions are divided into post-oxic (reactions involving reduction of nitrate, iron, and manganese) and sulfidic (reactions involving reduction of sulfate to sulfide). As it is very easy to introduce oxygen into ground water during the sampling process, we based our classification of ground water as oxic or anoxic on the concentrations of several constituents that are sensitive to dissolved-oxygen concentration (such as nitrate, iron, manganese, and sulfate), rather than basing the classification solely on dissolved-oxygen concentrations. The classification of ground-water redox conditions in this study was based on the classifications used in Saad and Thorstenson (1998).

Table 11. Reported uses of pesticides detected in rice areas in the Sacramento Valley, California

Pesticide detected in this study	Years pesticide used in the Sacramento Valley[1]	Major reported use[2,3]	Other reported uses[2,3]
Atrazine	1974–present	Right-of-way weed control and other non-agricultural uses	Sorghum, corn, sudangrass
Bentazon	1978–1989	Rice	Beans, corn
Bromacil	1968–present	Right-of-way weed control and other non-agricultural uses	Citrus
Carbofuran	1974–present	Rice	Alfalfa
Dichlorprop	1980–1988	Right-of-way weed control and other non-agricultural uses	Ornamental trees, turf
Diuron	1971–present	Right-of-way weed control and other non-agricultural uses	Alfalfa
Azinphos-methyl	1975–present	Fruit and nut orchards	Row crops
Molinate	1966–present	Rice	none
Simazine	1963–present	Right-of-way weed control and other non-agricultural uses; fruit and nut orchards	Grapes
Tebuthiuron	1974–present	Right-of-way weed control and other non-agricultural uses	none
Thiobencarb	1982–present	Rice	none

[1]California Department of Pesticide Regulation,1999.
[2] California Department of Pesticide Regulation,1997.
[3] California Department of Food and Agriculture,1989.

Measurements of dissolved oxygen, nitrate, nitrite, iron, manganese, sulfate, and sulfide during this study indicated that post-oxic and sulfidic conditions exist at shallow depths beneath almost all of the rice areas in the Sacramento Valley. Wells that contained relatively high concentrations of dissolved oxygen (greater than 2.0 mg/L), nitrogen present as nitrate (no nitrite or ammonia), sulfur present as sulfate (no sulfides), and very low concentrations of manganese and iron (less than 0.002 mg/L) were classified as oxic. Wells that contained relatively low concentra-tions of dissolved oxygen (less than 2.0 mg/L); the presence of nitrite, ammonia, iron, or manganese; and sulfur as sulfate (no sulfides) were classified as post-oxic. Wells having the presence of sulfide, along with the other characteristics of post-oxic water, were classified as sulfidic. Only 2 of 28 wells (7 percent) in this study have chemistry indicating oxic conditions; 12 out of 28 wells (43 percent) have chemistry indicating post-oxic conditions; and 14 out of 28 wells (50 percent) have chemistry indicating sulfidic conditions (fig. 6). The distribution of redox conditions is not significantly different between geomorphic units. Relations between dissolved-oxygen concentrations and pesticide and nitrate occurrence in ground water have been found in other studies (Barbash and Resek, 1996; Rupert, 1997; Burow and others, 1998); however, in this study no correlations were found between (a) nitrate concentration, the number of pesticide detections, or pesticide concentrations, and (b) either dissolved-oxygen concentrations or redox condition.

ANALYSES OF GROUND-WATER QUALITY DATA

Statistical Analyses

Ground-water chemistry and other data from this study were used to evaluate possible sources and controlling factors of ground-water quality (inorganic, nutrient, and pesticide constituents) in shallow ground water beneath rice areas in the Sacramento Valley. The relation of ground-water quality to natural pro-cesses was tested by comparing water chemistry to geomorphic unit, depth to ground water, and depth to

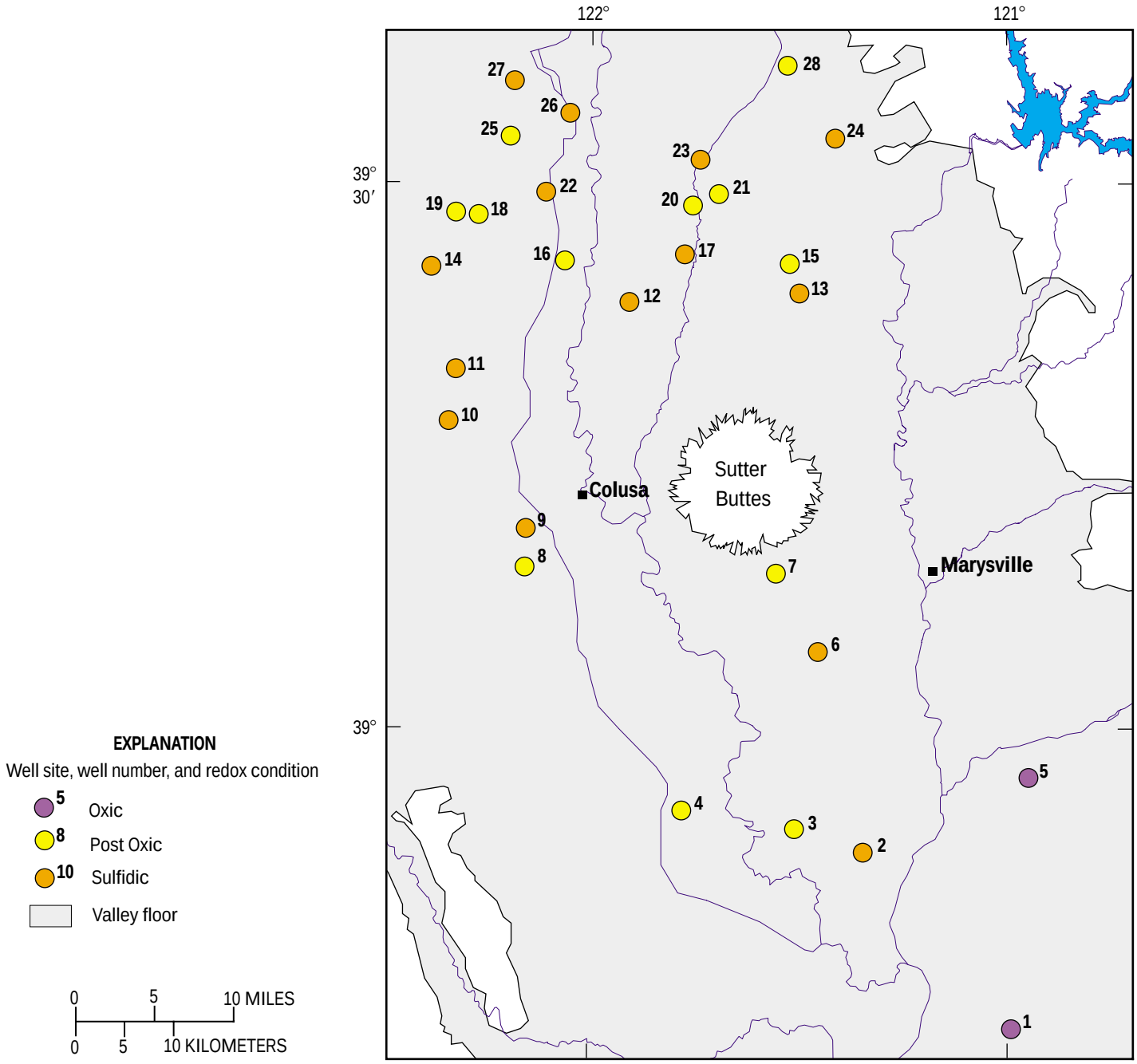


Figure 6. Redox conditions in wells sampled in rice areas in the Sacramento Valley, California.

top of well screen from land surface. The relation of ground-water quality to human activities was evaluated by comparing water chemistry to the number of pesticides detected in each well and to the type of land use within 500 m of the well (rice field, house or farm yard, road right-of-way). A relation between ground-water quality and rice land-use practices was evaluated by comparing water chemistry with the number of rice pesticides detected and the concentration of bentazon in each well and the percentage of rice within 500 m of the well in 1998. Interpretations based on correlations with bentazon would apply only to the period since the late 1970s when bentazon was first used.

The following methods were used for statistical testing. To test ground-water chemistry for significant differences when grouped by geomorphic unit or by land use type, the Kruskal–Wallis test was used on the

ranks of the chemical data to determine difference among the geomorphic units or land use types; the rank-sum test was then used to determine which geomorphic groups of chemical data were significantly higher or lower. The Spearman rank correlation was used to determine whether there were significant correlations between ground-water chemistry and depth to ground water, depth to top of well screen, percentage of rice, number of pesticides and rice pesticides detected per well, and concentrations of nitrate and bentazon.

Correlations Between Shallow Ground-Water Quality and Geomorphic Unit

Concentrations of arsenic, boron, chloride, dissolved solids, fluoride, molybdenum, nitrate, phosphorus, potassium, silica, sodium, sulfate, and zinc were found to be statistically different with 95 percent confidence when grouped by geomorphic unit (fig. 7). Concentrations of silica were significantly higher in wells on the eastern alluvial plain. Concentrations of potassium were significantly lower on the western alluvial plain. Concentrations of arsenic and phosphorus were significantly higher in wells in the central flood basins. Concentrations of nitrate were significantly lower in the central flood basins. Concentrations of boron, chloride, dissolved solids, fluoride, molybdenum, sodium, sulfate, and zinc were significantly higher in wells on the western alluvial plain.

The differences in inorganic constituent concentrations are thought to be related to the differences in recharge-water chemistry, which reflects differences in geology between the east and west sides of the Sacramento River Basin, and to the anoxic conditions in the center of the Sacramento Valley; these relations between inorganic constituents and location also were found in Hull (1984). No significant differences were found by geomorphic unit for the number of pesticides or rice pesticides detected, for bentazon concentration, or for depth to ground water or top of well screen. The inorganic chemistry in shallow ground water in the eastern alluvial plain (higher concentrations of silica, potassium, and, when compared to the western alluvial plain, arsenic, and lower concentrations of dissolved solids) reflects the recharge water chemistry influenced by the rock types in the Sierra Nevada and Cascade Mountains, particularly volcanic and granitic rocks. The shallow ground water chemistry (less nitrate and more arsenic) in the central flood basins is thought to reflect anoxic conditions. The higher concentrations of many inorganic constituents and dissolved solids in wells on the western alluvial plain are thought to reflect recharge water chemistry influenced by the sedimentary rock types of the Coast Ranges.

Correlations Between Shallow Ground-Water Quality and Depth to Ground Water and Top of Well Screen

Even though the wells sampled in this study have a small range in depth to ground water (6.4 m) and to the top of the well screen (7.6 m), correlations were found between these two factors and the number of pesticides and rice pesticides detected, and the concentrations of nitrite and some inorganic constituents (fig. 8). The number of rice pesticides detected in each well was negatively correlated with the depth to ground water (fig. 8*A*). Concentrations of cobalt, manganese, and nickel were negatively correlated with depth to ground water (figs. 8*B*, 8*C*, and 8*D*, respectively). Concentrations of nitrite, which could be due to fertilizer use, also were negatively correlated with depth to ground water (fig. 8*E*). The number of pesticides detected in each well was negatively correlated with the depth to top of well screen (fig. 8*F*). No correlation was found between depth and bentazon concentration. Concentrations of molybdenum and sulfate were negatively correlated with depth to top of well screen (fig. 8*G* and 8*H*, respectively).

Reasons for the correlations between the inorganic constituents and depths to ground water or top of well screen are not known, but the correlation suggests a source of these constituents near land surface, and could be a result of human activities or of natural processes occurring near land surface. The correlations between pesticide detections and shallower depths to top of well screen and between nitrite concentrations and shallower depths to ground water are interpreted in this report as a relation to human and rice land-use activities (pesticide and fertilizer application) at land surface.

Correlations Between Inorganic Constituents, Land Use, and Pesticides

No correlations were found between the concentrations of inorganic or nutrient constituents and the number of pesticides detected in each well, the percentage of rice within 500 m of each well, or the type of land use within 500 m of each well. No correlation

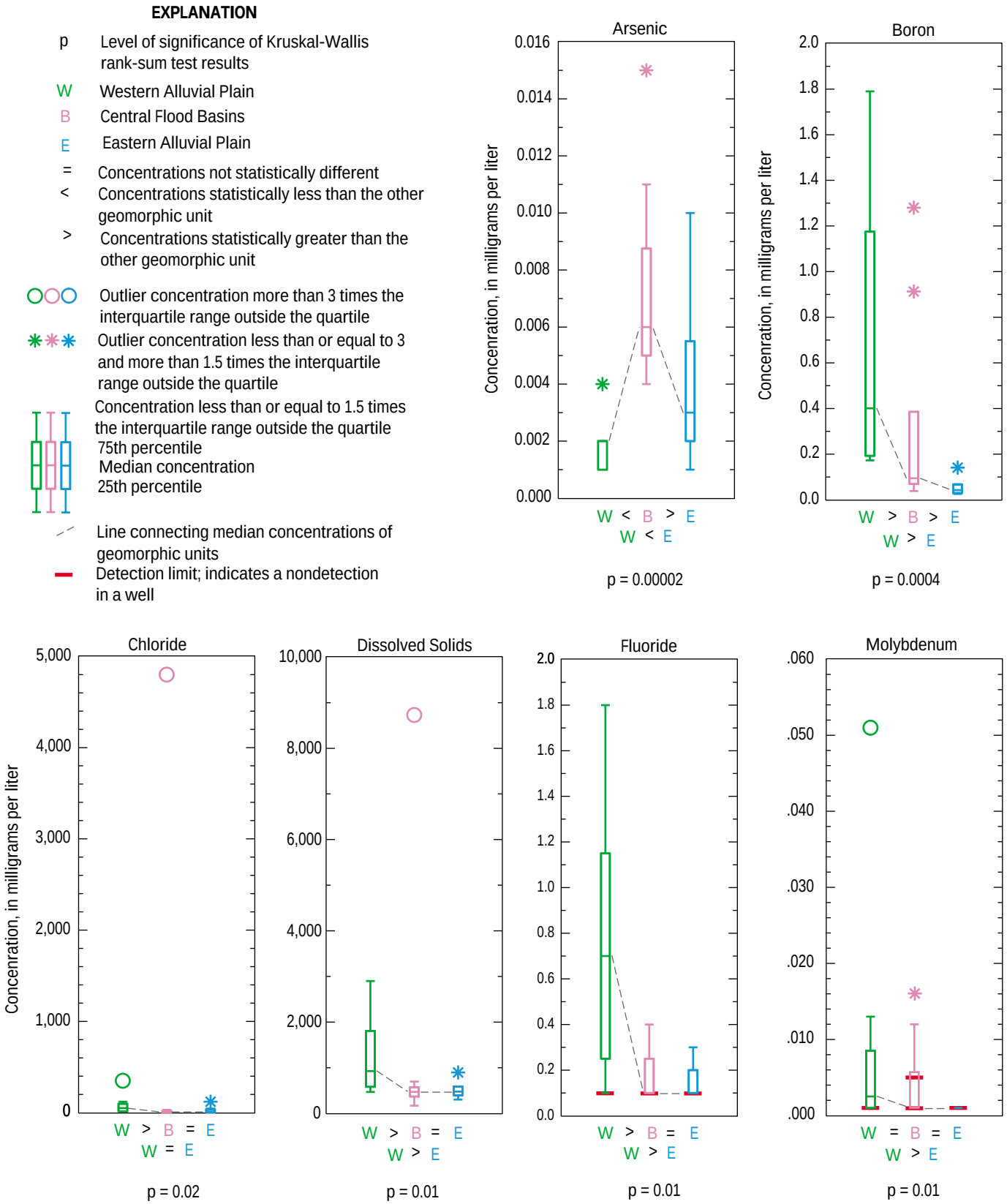
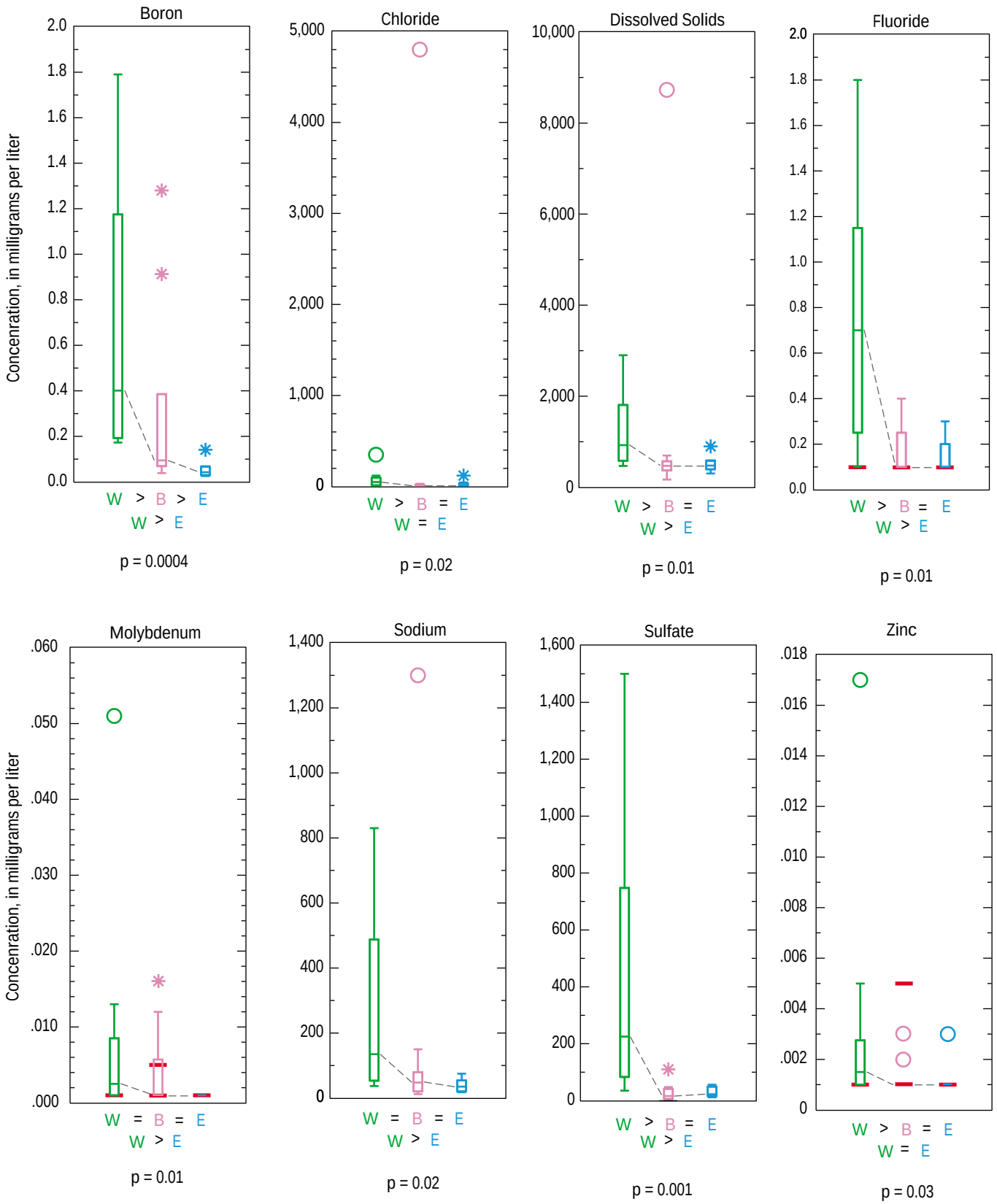


Figure 7. Concentrations of arsenic, boron, chloride, dissolved solids, fluoride, molybdenum, nitrate, phosphorus, potassium, silica, sodium, sulfate, and zinc detected in shallow ground water in rice areas in relation to well location and geomorphic unit, Sacramento Valley, California.


Boron
Chloride
Dissolved Solids
Fluoride
Molybdenum
Sodium
Sulfate
Zinc
Concenration, in milligrams per liter
W > B > E
W > E
p = 0.0004
W > B = E
W = E
p = 0.02
W > B = E
W > E
p = 0.01
W > B = E
W > E
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W > B = E
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p = 0.03

Figure 7.

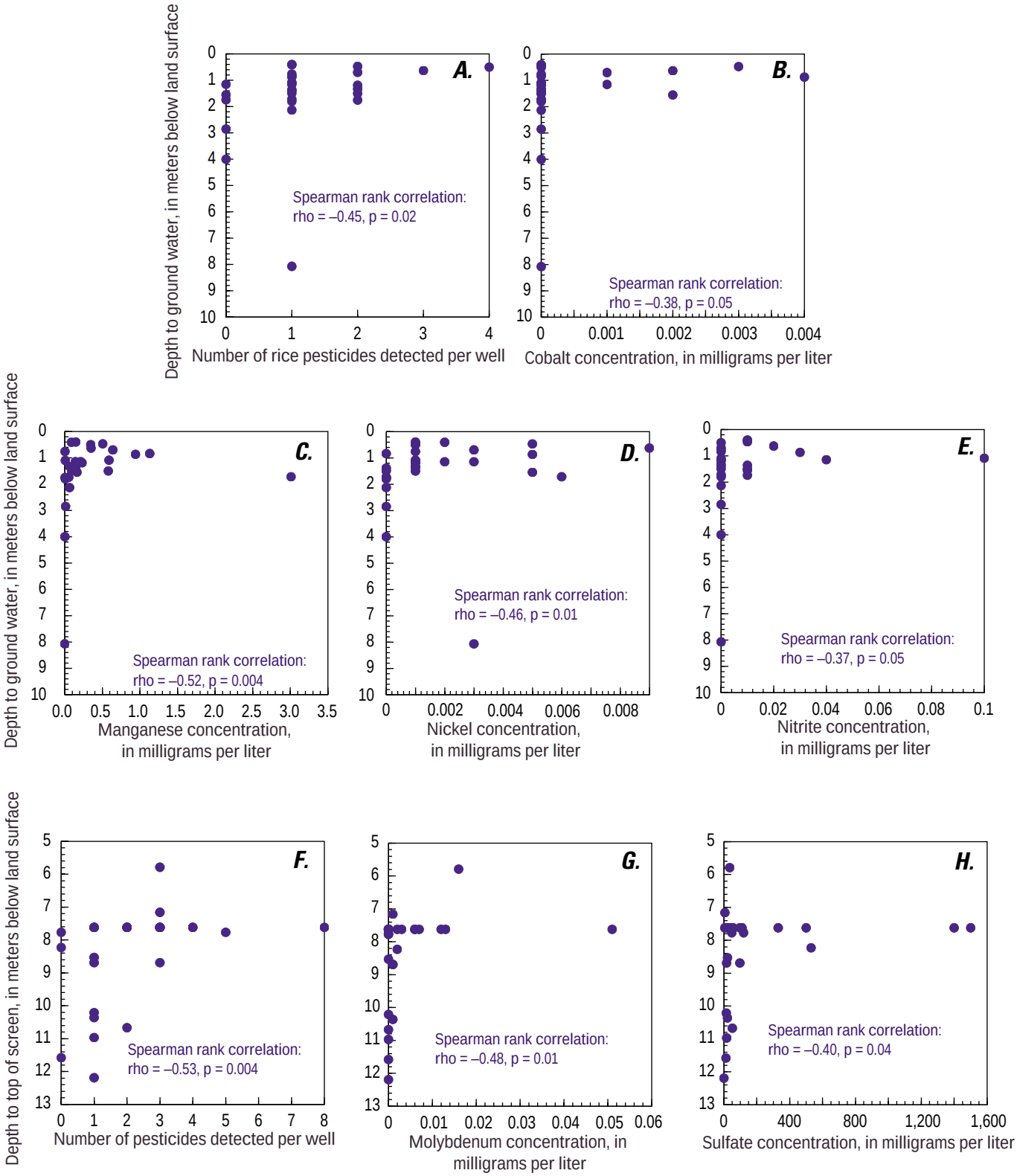

Figure 8. Correlations between depth to ground water and (*A*) number of rice pesticides detected per well, (*B*) cobalt, (*C*) manganese, (*D*) nickel, and (*E*) nitrite concentrations; and correlations between depth to top of screen and (*F*) number of pesticides detected per well, (*G*) molybdenum, and (*H*) sulfate concentrations in wells sampled in rice areas in the Sacramento Valley, California. p is the actual computed value of the level of significance of the test statistic.

was found between nitrate concentration and the number of pesticides, the number of rice pesticides, or the bentazon concentration of each well. No correlation was found between dissolved-solids concentration and the number of pesticides or rice pesticides detected in each well or bentazon concentration. Concentrations of tritium were correlated to concentrations of bentazon (fig. 9*A*); this correlation is an indication that bentazon concentration possibly is related to the recharge age of shallow ground water. Concentrations of boron and sodium were correlated to the number of rice pesticides detected in each well (figs. 9*B* and 9*C*, respectively). The correlations between boron, and sodium concentrations and either the number of rice pesticides or bentazon concentrations could be interpreted as a relation to rice land-use activities; however, the correlations of boron and sodium with geomorphic unit were higher than their correlations with the number of rice pesticides and were interpreted as an indication that the occurrence of rice pesticides, sodium, and boron is associated with similar geochemical conditions in the shallow ground water.

Tritium Concentration, Pesticide Use, and Age of Shallow Ground-Water Recharge

Tritium was detected in all wells sampled in this study, at concentrations ranging from 1 to 47 pCi/L, with a median of 18.5 pCi/L (table 12). No tritium concentrations exceeded the MCL of 20,000 pCi/L (California Department of Water Resources, 1997). Tritium, a naturally occurring and manmade radioactive isotope of hydrogen with a half-life of 12.43 years, can be used to determine whether ground water has been recharged since the early 1950s when atmospheric hydrogen bomb testing began, producing tritium levels up to 3 orders of magnitude higher than natural concentrations (Michel, 1989, p. 2). Ground water that originated as precipitation and recharged before the 1950s should have a tritium concentration of about 1 pCi/L in 1997 (Plummer and others, 1993). Current tritium concen-trations in rainfall are about 44 pCi/L (1989–1993 average in rainfall at Menlo Park, California [Inter-national Atomic Energy Agency/World Meteoro-logical Organization, 1998]). Tritium concentrations measured in this study indicate that all but one of the wells sampled in this study yield ground water that was at least partially recharged since 1950.

To further define a range of possible dates for recharge of the sampled ground water, the years of use of pesticides detected in shallow ground water were used (table 11) (California Department of Pesticide Regulation, 1999). Some of the pesticides used in the Sacramento Valley were not used until the late 1970s or 1980s, and if these pesticides are detected in the ground water, the conclusion is that at least part of the ground water was recharged since these pesticides were first used. For each of the 25 wells with pesticide detections, the detected pesticide chosen to further restrict the dates for recharge was the one with the most recent “first-use” date. For 18 of the wells sampled, this pesticide is bentazon, which was first used in the Sacramento Valley in 1978. For three wells, the pesticide used to define the recharge data is thiobencarb, first used in 1982. Pesticide detections in two wells indicated some recharge since 1974 (first use of atrazine and carbofuran). Pesticide detections in one well indicated some recharge since 1971 (first use of diuron), and in another well indicated some recharge since 1966 (first use of simazine). A recharge age since the late 1970s indicated in most of the wells sampled for this study suggests that an additional factor in the frequency of detection of pesticides in this study may be the changes in rice-field irrigation water management begun in the 1983 to protect surface water quality (Hill and others, 1997a; Scardaci and others, 1999). The holding of rice-field irrigation water after applications of molinate and thiobencarb may be allowing more recharge containing pesticides to reach shallow ground water.

Stable Isotopes and Possible Sources of Shallow Ground Water

Stable isotopes of hydrogen and oxygen in water molecules can be used to determine potential sources of ground water, or to aid in the determination of ground-water flow paths. There are two stable isotopes of hydrogen (^{1}H and ^{2}H) and two stable isotopes of oxygen (^{16}O and ^{18}O). In this report, the delta notation is used for isotope measurements. The delta (δ) notation, expressed in per mil (parts per thousand), is the relation of the abundance of a particular isotope in a sample to that of a standard. The stable isotope ^{2}H ranged from values of δ –42.8 to –81.7 per mil (table 12). The stable isotope ^{18}O ranged in values between –4.93 and –11.46 per mil (table 12). Figure 10 shows a plot of the $\delta^{2}H$ and $\delta^{18}O$

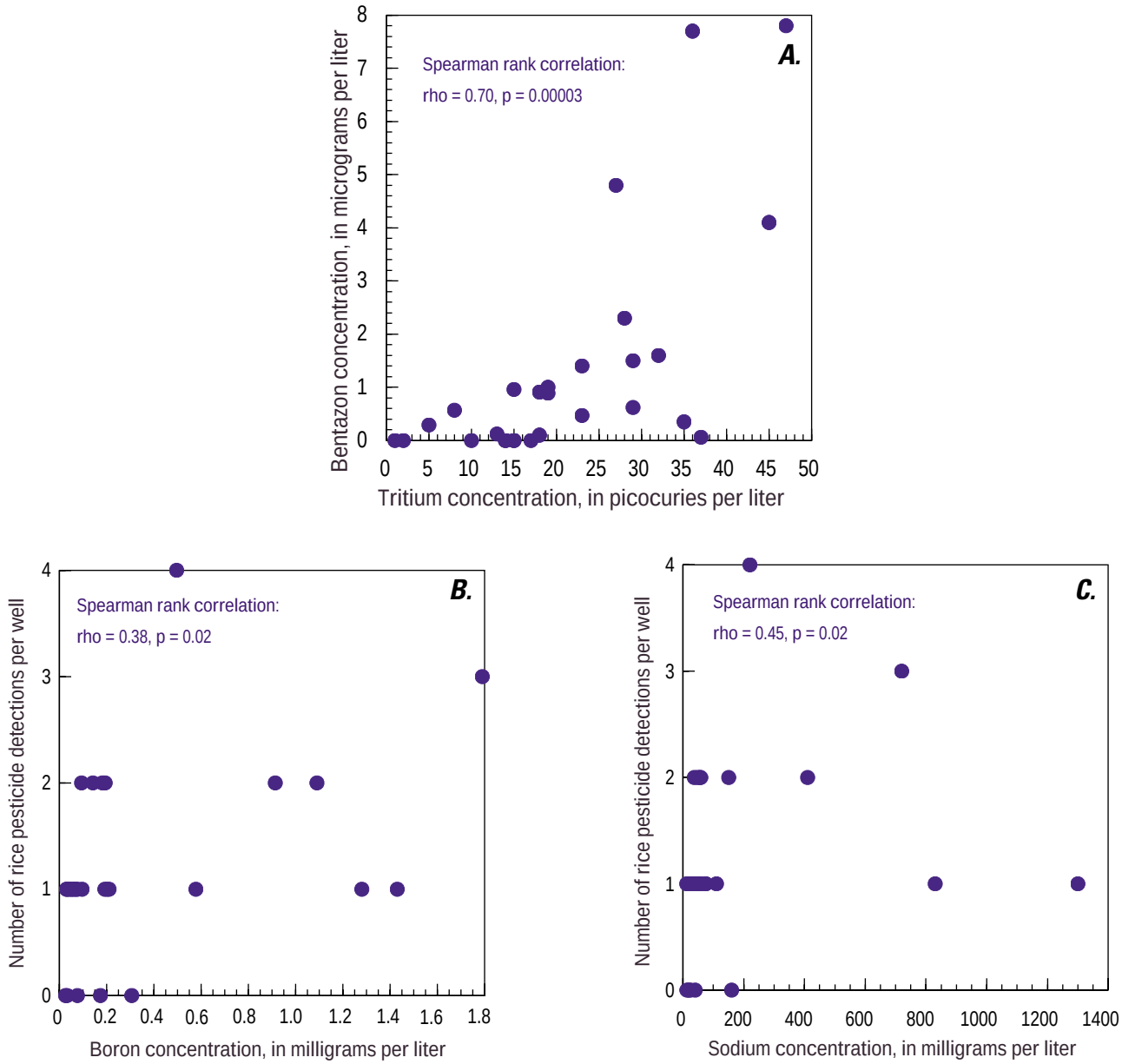

Figure 9. Correlations between (*A*) concentrations of bentazon and tritium, and correlations between number of rice pesticides detected per well and concentrations of (*B*) boron and (*C*) sodium detected in shallow ground water in rice areas in the Sacramento Valley, California. p is the actual computed value of the level of significance of the test statistic.

Table 12. Summary of isotopes measured in shallow ground water in rice areas in the Sacramento Valley, California

[δ, delta; ^{2}H, deuterium; ^{18}O, oxygen-18; MCL, maximum contaminant level]

Constituent	Units	Number of detections/ number of samples	Minimum detection	Median detection	Maximum detection	Drinking-water standard	Type of standard	Number of wells exceeding a drinking-water standard
δ^{2}H	Ratio per mil	28/28	–81.7	–61.5	–42.8	—	—	—
δ^{18}O	Ratio per mil	28/28	–11.46	–8.20	–4.93	—	—	—
Tritium	Picocuries per liter	28/28	1	18.5	47	20,000	MCL[1]	0

[1] California Department of Water Resources, 1997.

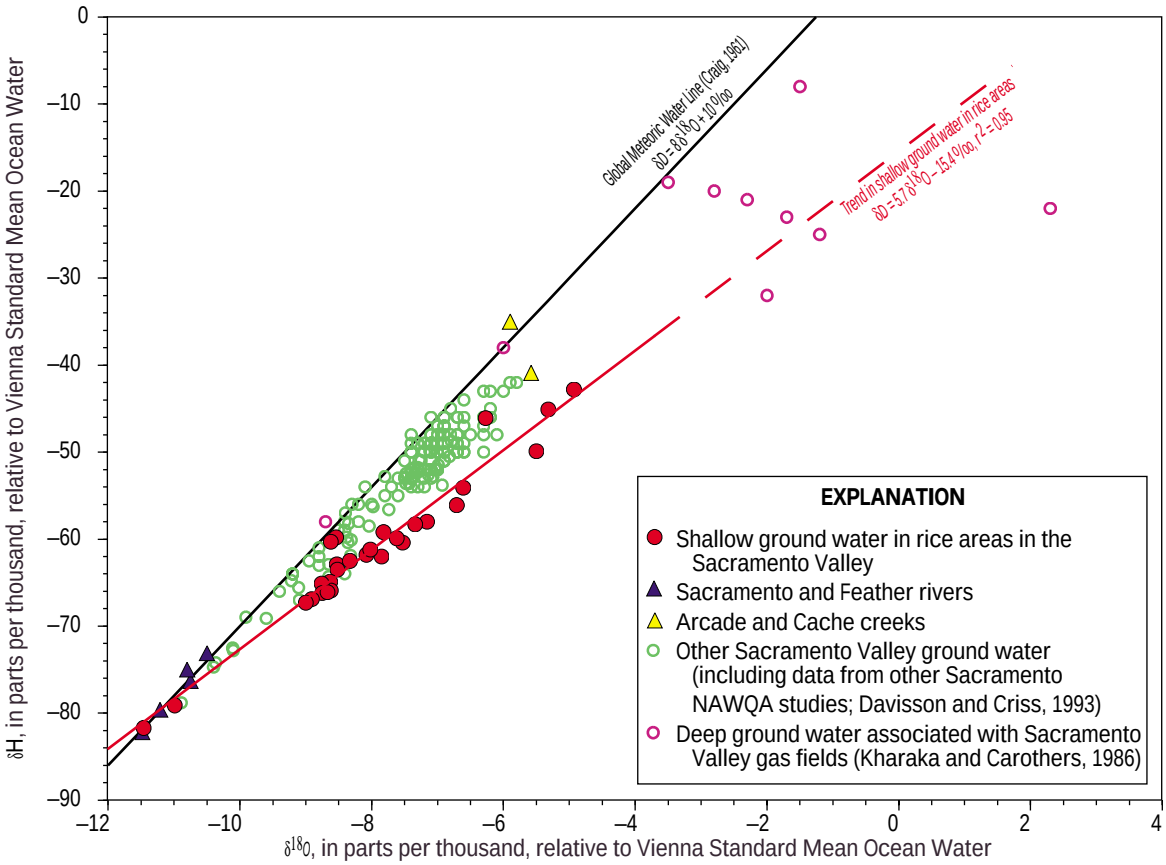

Figure 10. Relation between δ^2H and $\delta^{18}O$ in ground water and surface water in parts of the Sacramento Valley, California.

measured in shallow ground water in rice areas along with values measured in surface water and southeastern Sacramento Valley ground water for the Sacramento NAWQA Program, and values measured in ground water in previous studies (Davisson and Criss, 1993; Kharaka and Carothers, 1986). The Sacramento and Feather rivers that originate in the mountains to the north and east carry large amounts of precipitation and snowmelt (from higher elevations) that are isotopically lighter, plotted as blue triangles toward the lower left corner of the graph along the Global Meteoric Water Line (GMWL) (Craig, 1961). Smaller streams originating in the Coast Ranges to the west (Cache Creek) and eastern alluvial fans (Arcade Creek) carry rainfall that is isotopically heavier, plotted as yellow triangles along the GMWL toward the upper right corner of the graph. Stable isotope values measured in other parts of the ground water in the Sacramento Valley (including the southeastern side of the valley less than 90 m deep and in the Davis area on the southwestern side of the valley less than 600 m deep [Davisson and Criss, 1993]) plotted as green circles just below and along the GMWL, spanning the gap between the two groups of surface-water values. Stable isotope values measured in very deep ground water associated with natural gas deposits in the Sacramento Valley generally plotted as purple circles further toward the upper right corner of the graph and to the right of the GMWL; these waters have been interpreted in previous studies (Kharaka and Carothers, 1986) as a mixture of meteoric waters and connate water that has been squeezed from shales and siltstones, and have high dissolved-solids concentrations and $\delta^{18}O$ values.

While some of the ground-water data points (red circles, fig. 10) from shallow ground water in rice areas plot with the surface water along the GMWL, most plot in a group whose trend has a lower slope than the GMWL and is below the other ground-water data. Both δ^2H and $\delta^{18}O$ are statistically different in the shallow ground water in rice areas than in other ground water in the Sacramento Valley aquifer

(rank-sum test: $p \leq 0.0001$ and $p = 0.0015$, respectively; p is the actual computed value of the level of significance of the test statistic). The trend of the stable isotopes in shallow ground water intersects the GMWL in the group of data points for the Feather and Sacramento rivers, suggesting that they are one source of recharge water. This agrees with information in Hill and others (1997a) that most of the irrigation water used for rice is surface water. Although stable isotopes in surface water show a separation between eastside and westside streams, and stable isotopes in other ground water in the Sacramento valley show a statistical difference with geomorphic unit (Kruskal–Wallis test: $p \leq 0.0001$ for both δ^2H and $\delta^{18}O$), no difference was found in stable isotopes in shallow ground water from rice areas when grouped by geomorphic unit (Kruskal–Wallis test: $p = 0.12$ for δ^2H and $p = 0.23$ for $\delta^{18}O$). The trend of the shallow ground-water data points away from the GWML; the surface-water values and the other ground-water values suggest that there are additional sources of water to the shallow ground water in the center of the Sacramento Valley.

The slope of the linear trend of the shallow ground-water group, 5.7 (fig. 10), indicates that evaporated water is one possible source to shallow ground water (Coplen, 1993, p. 235). Evaporation occurs in rivers, wetlands, vernal pool areas, rice fields, and other irrigated lands in the valley, especially during the summer months when precipitation and relative humidity are very low. It is possible that the increase in the heavier stable isotopes and the high concentrations in dissolved solids in the shallow ground water may be partly due to evaporation that occurred at land surface. In a study located in the Davis, California, area to the southwest of the rice land-use study area, the increase in $\delta^{18}O$ in ground water was attributed to recharge of evaporated irrigation water and to evaporation in the vadose zone based on correlations between $\delta^{18}O$ and dissolved-solids and nitrate concentration; dissolved-solids concentrations attributed to evaporation in the Davis area ground water were between 500 and 1,300 mg/L (Davisson and Criss, 1993). A study of salinity effects on rice production conducted from 1993 to 1995 on the west side of the Sacramento Valley reported specific-conductance measurements (which are directly related to dissolved-solids concentration) in rice-field water, irrigation-source and drain waters. The salinity study showed that values for both water and soil in rice fields were generally between 500 and 1,500 µS/cm, and were measured as high as 3,500 µS/cm in some fields for brief periods of time when irrigation water was held in the fields (Scardaci and others, 1996). The median values for both dissolved-solids concentration (532 mg/L) and specific conductance (854 µS/cm) measured in shallow ground in rice areas (table 5) are in the range of values measured in both the evaporated ground water in the Davis area and rice-field water and soil on the west side of the Sacramento Valley, suggesting that the elevated dissolved-solids concentrations in the shallow ground water are at least partly due to evaporation.

Contrary to these data on $\delta^{18}O$ and dissolved solids, in the 1997 USGS rice land-use study, no correlation was found between $\delta^{18}O$ and dissolved-solids concentration (Spearman rank correlation: rho = 0.17, $p = 0.39$), suggesting that simple evaporation is not the only process affecting the stable isotope and dissolved-solids composition of shallow ground water. A more complex relation between $\delta^{18}O$ and dissolved-solids concentration was found in this study (fig. 11) than the curvilinear relation found in the Davis-area ground water (Davisson and Criss, 1993, p. 242). Three of the wells sampled in the rice areas had dissolved-solids concentrations (2,880, 2,900, and 8,730 mg/L) or specific-conductance measurements (4,060, 4,480, and 13,600 µS/cm) that were higher than those measured in ground water in Davisson and Criss (1993) or in irrigation sources or rice-field water in Scardaci and others (1996). The stable isotope and dissolved-solids data suggest the following possible sources to shallow ground water in rice areas in the Sacramento Valley:

- Sacramento and Feather river water (isotopically light with dissolved-solids concentrations less than 100 mg/L).
- Sacramento Valley precipitation (isotopically variable with dissolved-solids concentrations less than 100 mg/L).
- Coast Ranges and Sacramento Valley surface waters (isotopically heavier with dissolved-solids concentrations between 100 and 400 mg/L).
- Evaporated surface water and irrigation water (isotopically variable with dissolved-solids concentrations up to about 1,500 mg/L).

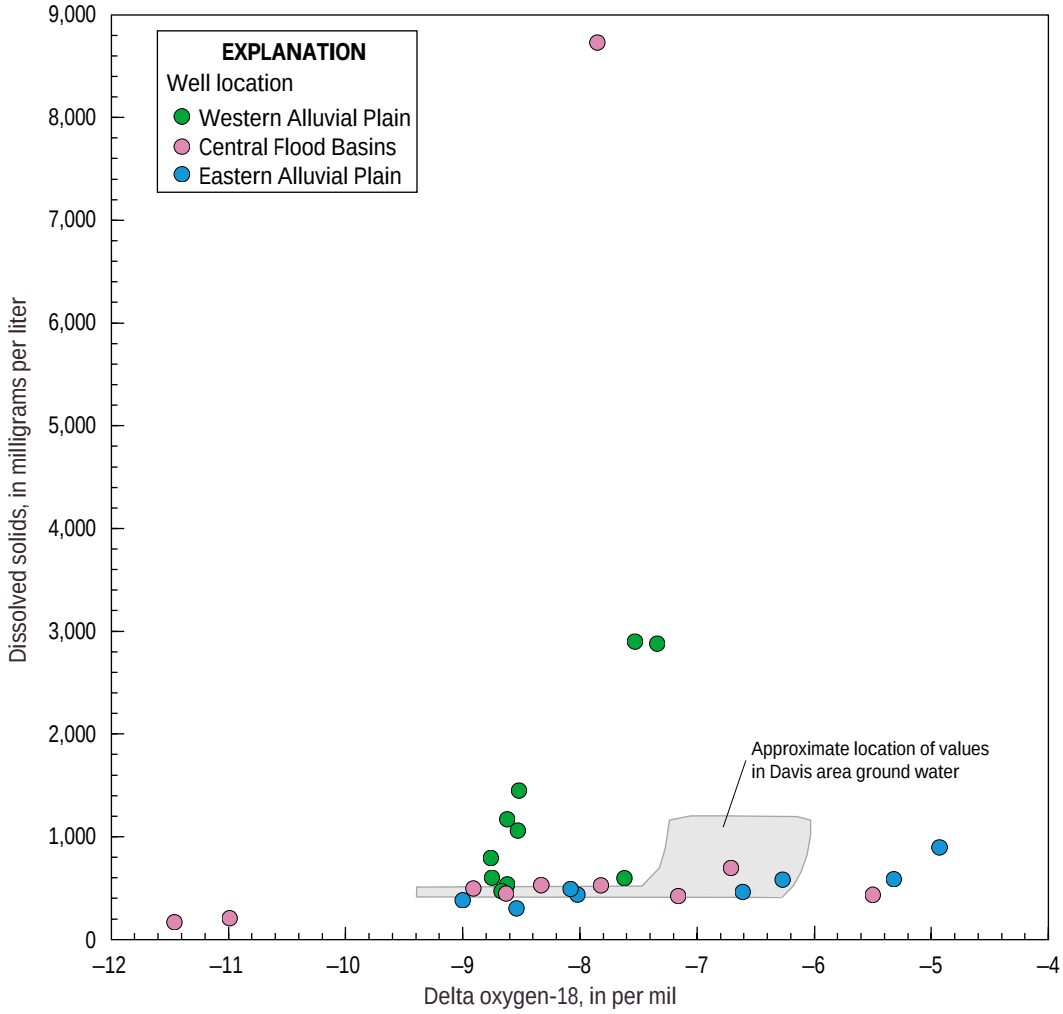

Figure 11. Relation between dissolved solids concentration and $\delta^{18}O$ in shallow ground water in rice areas in the Sacramento Valley, California.

- Other Sacramento Valley ground water (isotopically variable with dissolved-solids concentrations up to about 1,500 mg/L).
- An unknown source (isotopically heavier with dissolved-solids concentrations greater than 1,500 mg/L).

The intersection of the shallow-ground-water stable isotope trend with the group of data points from the deep ground water associated with Sacramento gas fields (fig. 10) suggests that deep, high-dissolved-solids ground water could be another possible source to the shallow ground water beneath rice areas. This possibility has been mentioned in previous studies that discuss high dissolved-solids concentrations in the central Sacramento Valley (Hull, 1984; Olmsted and Davis, 1961; California State Water Resources Board, 1952), but there is insufficient data to thoroughly evaluate this possible contribution to shallow ground water in rice areas in the Sacramento Valley.

SUMMARY AND CONCLUSIONS

In 1997, the USGS installed and sampled 28 monitoring wells in rice areas in the Sacramento Valley, California, as part of the NAWQA Program. Maximum contaminant levels (barium or cadmium) and lifetime health advisory levels (boron or molybdenum) were exceeded in 7 out of 28 wells (25 percent); at least one secondary maximum contaminant level (chloride, sulfate, dissolved solids, iron, manganese, or specific conductance) was

exceeded in 22 out of 28 wells (79 percent). Median dissolved-solids concentrations and pesticide detection frequencies were higher, and median nitrate concentrations were lower in this study than those found nationally in similar NAWQA studies from 1993 to 1995 (Gilliom and others, 1998). Ground-water redox conditions were anoxic in 26 out of 28 wells (93 percent) sampled. Low nitrate concentrations were probably due to these reducing chemical conditions; in the two oxic wells, the nitrate concentrations were in the range that suggests an effect from human activities. Evidence of the effects of human activities was found in 25 of 28 wells (89 percent) sampled in this study, as a pesticide detection or a nitrate concentration over 3 mg/L.

Pesticides were detected in 89 percent of the wells sampled, and rice pesticides were detected in 82 percent of the wells sampled. All pesticides detected in this study were in use in the Sacramento Valley in the 1980s; however, use of two of these pesticides (bentazon and dichlorprop) was discontinued after 1989. Four of the detected pesticides (bentazon, carbofuran, molinate, and thiobencarb) have been used on rice crops; of these, only bentazon has been detected in previous studies and determined to be from a nonpoint source. In a study conducted in 1989, before the use of bentazon was halted in California, bentazon was detected in 42 percent of domestic wells sampled in the 1997 rice land-use study area; the bentazon detection frequency in shallow monitoring wells in 1997, when screened at the detection limit used in the 1989 study, was 68 percent. The increase in detection frequency of rice pesticides in this 1997 study compared with the 1989 study is possibly due to the lower detection limits and shallower sampling depths used in 1997.

The relation of the ground-water-quality components to natural processes and human activities was examined using statistical methods (Spearman rank correlation, Kruskal–Wallis, and rank-sum tests) to determine whether an influence from human activities could be found in addition to the presence of pesticides. Total dissolved solids and the inorganic constituent concentrations that exceed state and federal 2000 drinking-water standards show a statistical relation to geomorphic unit; this is interpreted as a relation to natural process and variations in geology in the Sacramento River Basin. No correlation was found between nitrate concentration and pesticide occurrence, indicating that an absence of high nitrate concentrations is not a predictor of an absence of pesticide contamination in reducing ground-water conditions in the Sacramento Valley.

Tritium concentrations indicate that all wells sampled in this study with one exception yield ground water that was at least partially recharged since the 1950s. The years of use for pesticides detected in most of the wells sampled suggest that a part of the shallow ground water beneath rice areas in the Sacramento Valley was recharged since the late 1970s. An additional factor in the detection frequency of pesticides in this study may be the change in rice-field irrigation water management enacted in the 1980s to protect surface water quality. The holding of rice-field irrigation water after applications of molinate and thiobencarb may be allowing more recharge to shallow ground water of water containing pesticides.

Stable isotope, tritium, major anion, and dissolved-solids concentrations suggest that sources to shallow ground water in the rice areas of the Sacramento Valley may be a mix of recently recharged, partially evaporated water that contains pesticides and nitrate, and whose inorganic chemistry reflects well location (eastern alluvial plain, central flood basins, or western alluvial plain), and another source or mixture of sources that contain high concentrations of dissolved solids and some inorganic constituents. The water chemistry of the ground-water system in the Sacramento Valley aquifer and the effects of irrigation and ground-water pumping are extremely complex, and not thoroughly understood. More work needs to be done to understand the connections between the land surface, shallow ground water, deep ground water, and the sources of drinking water in the Sacramento Valley.

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