

Prepared in cooperation with the East Bay Municipal Utility District, City of Hayward, and Alameda County Water District

# **Hydrogeologic Controls and Geochemical Indicators of Groundwater Movement in the Niles Cone and Southern East Bay Plain Groundwater Subbasins, Alameda County, California**

Scientific Investigations Report 2018–5003  
Version 1.1, February 2019



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By Nick Teague, John Izbicki, Jim Borchers, Justin Kulongoski, and Bryant Jurgens

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## Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter (mm)
inch (in.)	25,400	micrometer (μm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	
Area		
acre	4,047	square meter (m <sup>2</sup> )
acre	0.004047	square kilometer (km <sup>2</sup> )
square foot (ft <sup>2</sup> )	0.0929	square meter (m <sup>2</sup> )
square foot (ft <sup>2</sup> )	0.0011	square centimeter (cm <sup>2</sup> )
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
Volume		
gallon (gal)	3.785	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m <sup>3</sup> )
acre-foot (acre-ft)	1.233×10 <sup>9</sup>	cubic centimeter (cm <sup>3</sup> )
acre-foot (acre-ft)	1.233×10 <sup>12</sup>	micro-cubic centimeter (μcm <sup>3</sup> )
Flow rate		
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m <sup>3</sup> /yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per minute (ft/min)	0.3048	meter per minute (m/min)
foot per second (ft/s)	0.3048	meter per second (m/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m <sup>3</sup> /d)
gallon per minute (gal/min)	0.003785	cubic meter per minute (m <sup>3</sup> /min)
Density		
pound-mass per cubic foot (lb <sub>m</sub> /ft <sup>3</sup> )	0.0160	grams per cubic centimeter (g/cm <sup>3</sup> )
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$$

Specific storage is reported in units of per foot (ft<sup>-1</sup>).



Specific conductance is reported in units of microsiemens per centimeter at 25 degrees Celsius ( $\mu\text{S}/\text{cm}$  at 25 °C).

Concentrations of chemical constituents in water are reported either in units of milligrams per liter (mg/L) or micrograms per liter ( $\mu\text{g}/\text{L}$ ).

Concentrations of chemical constituents in sediment (alluvium) are reported either in units of milligrams per kilogram (mg/kg) or micrograms per cubic centimeter ( $\mu\text{g}/\text{cm}^3$ ).

Concentrations of the noble gases helium (He), neon (Ne), and krypton (Kr) are reported in units of micro-cubic centimeters (at standard temperature and pressure) per kilogram of water ( $\mu\text{cm}^3(\text{STP})/\text{kg}$ ).

Concentrations of the noble gas argon (Ar) are reported in units of cubic centimeters (at standard temperature and pressure) per kilogram of water ( $\text{cm}^3(\text{STP})/\text{kg}$ ).

Deep crustal flux of helium-4 is reported in units of cubic centimeters (at standard temperature and pressure) per square centimeter per year ( $\text{cm}^3(\text{STP})\text{cm}^{-2}\text{yr}^{-1}$ ).

Concentrations of excess air are reported in units of cubic centimeters (at standard temperature and pressure) per kilogram of water ( $\text{cm}^3/\text{kg}$ ).

Concentrations of uranium (U) and thorium (Th) are reported in units of milligrams per kilogram of alluvium (mg/kg, ppm).

Concentrations of tritium ( $^3\text{H}$ ) are reported in units of tritium units (TU). The conversion of tritium units (TU) to picocuries per liter, based upon a tritium half-life of 12.32 years (Lucas and Unterweger, 2000), is 1 TU = 3.22 picocuries per liter.

Helium-3 ( $^3\text{He}$ ) data are reported as  $\delta$  values computed from the formula:

$$\delta = \left[ \left( \frac{R_x}{R_{STD}} \right) - 1 \right] 100$$

where  $R_x$  is the ratio of  $^3\text{He}$  to  $^4\text{He}$  in the sample,  $R_{STD}$  is the  $^3\text{He}$  to  $^4\text{He}$  ratio of the reference standard air ( $1.384 \times 10^{-6}$ ), and  $\delta^3\text{He}$  is expressed in parts per hundred.

Stable isotopes of water are reported as  $\delta$  values computed from the formula:

$$\delta = \left[ \left( \frac{R_x}{R_{STD}} \right) - 1 \right] 1,000$$

where  $R_x$  is the ratio of  $^2\text{H}$  to  $^1\text{H}$  or  $^{18}\text{O}$  to  $^{16}\text{O}$  in the sample,  $R_{STD}$  is the  $^2\text{H}$  to  $^1\text{H}$  or  $^{18}\text{O}$  to  $^{16}\text{O}$  ratio of the reference standard Vienna Standard Mean Ocean Water (VSMOW), and  $\delta^2\text{H}$  or  $\delta^{18}\text{O}$  is expressed in parts per thousand.

Stable isotopes of carbon are reported as  $\delta$  values computed from the formula:

$$\delta = \left[ \left( \frac{R_x}{R_{STD}} \right) - 1 \right] 1,000$$

where  $R_x$  is the ratio of  $^{13}\text{C}$  to  $^{12}\text{C}$  in the sample,  $R_{STD}$  is the  $^{13}\text{C}$  to  $^{12}\text{C}$  ratio of the reference standard Vienna Pee Dee Belemnite, and  $\delta^{13}\text{C}$  is expressed in parts per thousand.

## Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), unless otherwise noted.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Mean sea level is 6.75 feet above the station datum for station 9414750, Alameda, California, of 3.56 feet (NAVD 88).

## Abbreviations

$A_0$	initial carbon activity
ACWD	Alameda County Water District
ANOVA	analysis of variance
Ar	argon
ARP	aquifer reclamation program
ASR	aquifer storage and recovery
BGP	Bayside Groundwater Project
°C	degrees Celsius
$^{14}\text{C}$	carbon-14, in percent modern carbon
CE	closed system equilibrium
cfs	cubic feet per second
$\text{CO}_2$	carbon dioxide; molecular formula
DIC	dissolved organic carbon
DOD	U.S. Department of Defense
EBMUD	East Bay Municipal Utility District
EPA	U.S. Environmental Protection Agency
GMWL	Global Meteoric Water Line
$\text{H}_2\text{O}$	water; molecular formula
$^2\text{H}$	deuterium
$^3\text{H}$	tritium
He	helium
$^3\text{He}$	helium-3; isotope of helium
$^3\text{He}_{\text{trit}}$	tritogenic helium-3
$^4\text{He}$	helium-4; isotope of helium
$^4\text{He}_{\text{ex}}$	excess helium-4
InSAR	interferometric synthetic aperture radar

## Abbreviations—Continued

Kr	krypton
kyr	thousand years
MCL	maximum contaminant level
Myr	million years
NGT	groundwater recharge temperature
Ne	neon
$\Delta$ Ne	neon oversaturation
NWQL	National Water Quality Laboratory
$^{18}\text{O}$	oxygen-18
pmC	percent modern carbon
ppm	parts per million
PR	partial reequilibration
SFPUC	San Francisco Public Utilities Commission
SI	saturation indexes
SMCL	secondary maximum contaminant level
STP	standard temperature and pressure
SWP	State Water Project
TU	tritium unit
UA	unfractionated air
USGS	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water
ybp	years before present



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## Abstract

Beginning in the 1970s, Alameda County Water District began infiltrating imported water through ponds in repurposed gravel quarries at the Quarry Lakes Regional Park, in the Niles Cone groundwater subbasin, to recharge groundwater and to minimize intrusion of saline, San Francisco Bay water into freshwater aquifers. Hydraulic connection between distinct aquifers underlying Quarry Lakes allows water to recharge the upper aquifer system to depths of 400 feet below land surface, and the Deep aquifer to depths of more than 650 feet. Previous studies of the Niles Cone and southern East Bay Plain groundwater subbasins suggested that these two subbasins may be hydraulically connected. Characterization of storage capacities and hydraulic properties of the complex aquifers and the structural and stratigraphic controls on groundwater movement aids in optimal storage and recovery of recharged water and provides information on the ability of aquifers shared by different water management agencies to fulfill competing storage and extraction demands. The movement of recharge water through the Niles Cone groundwater subbasin from Quarry Lakes and the possible hydraulic connection between the Niles Cone and the southern East Bay Plain groundwater subbasins were investigated using interferometric synthetic aperture radar (InSAR), water-chemistry, and isotopic data, including tritium/helium-3, helium-4, and carbon-14 age-dating techniques.

InSAR data collected during refilling of the Quarry Lakes recharge ponds show corresponding ground-surface displacement. Maximum uplift was about 0.8 inches, reasonable for elastic expansion of sedimentary materials experiencing an increase in hydraulic head that resulted from pond refilling. Sodium concentrations increase while calcium and magnesium concentrations in groundwater decrease along groundwater flowpaths from the Niles Cone groundwater subbasin through the Deep aquifer to the northwest toward the southern East Bay Plain groundwater subbasin. Residual effects of pre-1970s intrusion of saline water from San Francisco Bay, including high chloride concentrations in

groundwater, are evident in parts of the Niles Cone subbasin. Noble gas recharge temperatures indicate two primary recharge sources (Quarry Lakes and Alameda Creek) in the Niles Cone groundwater subbasin. Although recharge at Quarry Lakes affects hydraulic heads as far as the transition zone between the Niles Cone and East Bay Plain groundwater subbasins (about 5 miles), the effect of recharged water on water quality is only apparent in wells near (less than 2 miles) recharge sources. Groundwater chemistry from upper aquifer system wells near Quarry Lakes showed an evaporated signal (less negative oxygen and hydrogen isotopic values) relative to surrounding groundwater and a tritium concentration (2 tritium units) consistent with recently recharged water from a surface-water impoundment.

Uncorrected carbon-14 activities measured in water sampled from wells in the Niles Cone groundwater subbasin range from 16 to 100 percent modern carbon (pmC). The geochemical reaction modeling software NETPATH was used to interpret carbon-14 ages along a flowpath from Quarry Lakes toward the East Bay Plain groundwater subbasin. Model results indicate that changes in groundwater chemistry are controlled by cation exchange on clay minerals and weathering of primary silicate minerals. Old groundwater (lower carbon-14 activities) is characterized by high dissolved silica and pH. Interpreted carbon-14 ages ranged from 830 to more than 7,000 years before present and are less than helium-4 ages that range from 2,000 to greater than 11,000 years before present. The average horizontal groundwater velocity along the studied flowpath, as calculated using interpreted carbon-14 ages, through the Deep aquifer of the Niles Cone groundwater subbasin is between 3 and 12 feet per year. The groundwater velocity decreases near the boundary of the transition zone to the southern East Bay Plain groundwater subbasin to about 0.5 feet per year. These changes may result from water recharged from different sources converging in flowpaths north of the transition zone, or a boundary to flow between the Niles Cone and southern East Bay Plain groundwater subbasins, likely owing to changes in lithology caused by depositional patterns.

## Introduction

Water agencies in the east San Francisco Bay area are developing alternate water supplies to supplement current sources largely imported from reservoirs in the Sierra Nevada or the Sacramento–San Joaquin River Delta. Conjunctive-use practices utilizing artificial storage and recovery of surface water in aquifers are being implemented as means to address water-supply issues related to the growing demand for municipal and industrial water and the temporal variability of the surface-water supply. In addition, increased development of local groundwater through managed aquifer recharge has been proposed as an alternative to imported water as a means to address the potential interruption of aqueduct flows during seismic or other emergencies (Alameda County Water District, 2001b).

The study area, the Niles Cone and southern East Bay Plain groundwater subbasins, is in the alluvial plain south of Oakland, California, on the eastern shore of the south San Francisco Bay (fig. 1). The area is underlain by a complex aquifer system at least 650 feet (ft) thick (fig. 2). Several water management projects are being developed as alternate and emergency water sources in the area. The Alameda County Water District (ACWD) recharges aquifers by infiltrating surface water from local reservoirs and from the South Bay Aqueduct (not shown on figures) through abandoned gravel quarries at Quarry Lakes Regional Park and at impoundments behind inflatable rubber dams in the channel of Alameda Creek (Alameda County Water District, 2001a). The City of Hayward has constructed five deep water-supply wells in the aquifers underlying Hayward, Calif., to provide emergency water supply. The East Bay Municipal Utility District (EBMUD) has tested the feasibility of artificial storage and recovery (ASR) of water through deep wells near the San Francisco Bay (Bayside), just south from San Lorenzo Creek (fig. 1; Luhdorff and Scalmanini Consulting Engineers, 2003).

Conjunctive-use programs store a combination of surface water and groundwater, and therefore, they require aquifer systems capable of storing and subsequently yielding large quantities of water (Mariño, 2001). The ability of aquifers shared by different water management agencies to fulfill competing storage and extraction demands may be difficult to evaluate in the absence of regional hydrogeology data. Characterization of storage capacities and hydraulic properties of the complex aquifers and the structural and stratigraphic controls on groundwater movement aids in optimal storage and recovery of recharged water.

Local water agency staff, their consultants and representatives, and the U.S. Geological Survey (USGS) are collaborating to develop an understanding of hydrogeologic factors that affect groundwater development and successful operation of conjunctive-use facilities in the study area. Previously, the USGS, in cooperation with EBMUD, investigated the hydrogeology and geochemistry of aquifers underlying the southern East Bay Plain groundwater subbasin (Izbicki and others, 2003; Sneed and others, 2015). They found that (1) most recent recharge to the aquifer system is restricted to shallow aquifers near the mountain front;

(2) recharge occurs as infiltration of streamflow during the winter and as infiltration from more diffuse sources such as precipitation, irrigation, and septic discharge; and (3) large amounts of recharge from imported water leaking from water supply pipes is not apparent. This report extends that work further south, describing the results of an investigation of parts of the Deep aquifer underlying the southern East Bay Plain and the northern Niles Cone groundwater subbasins that was completed cooperatively with ACWD, City of Hayward, and EBMUD.

## Purpose and Scope

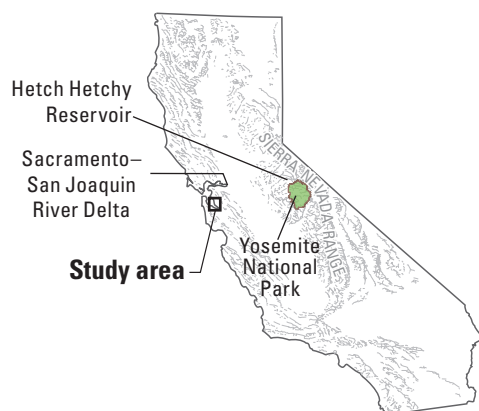
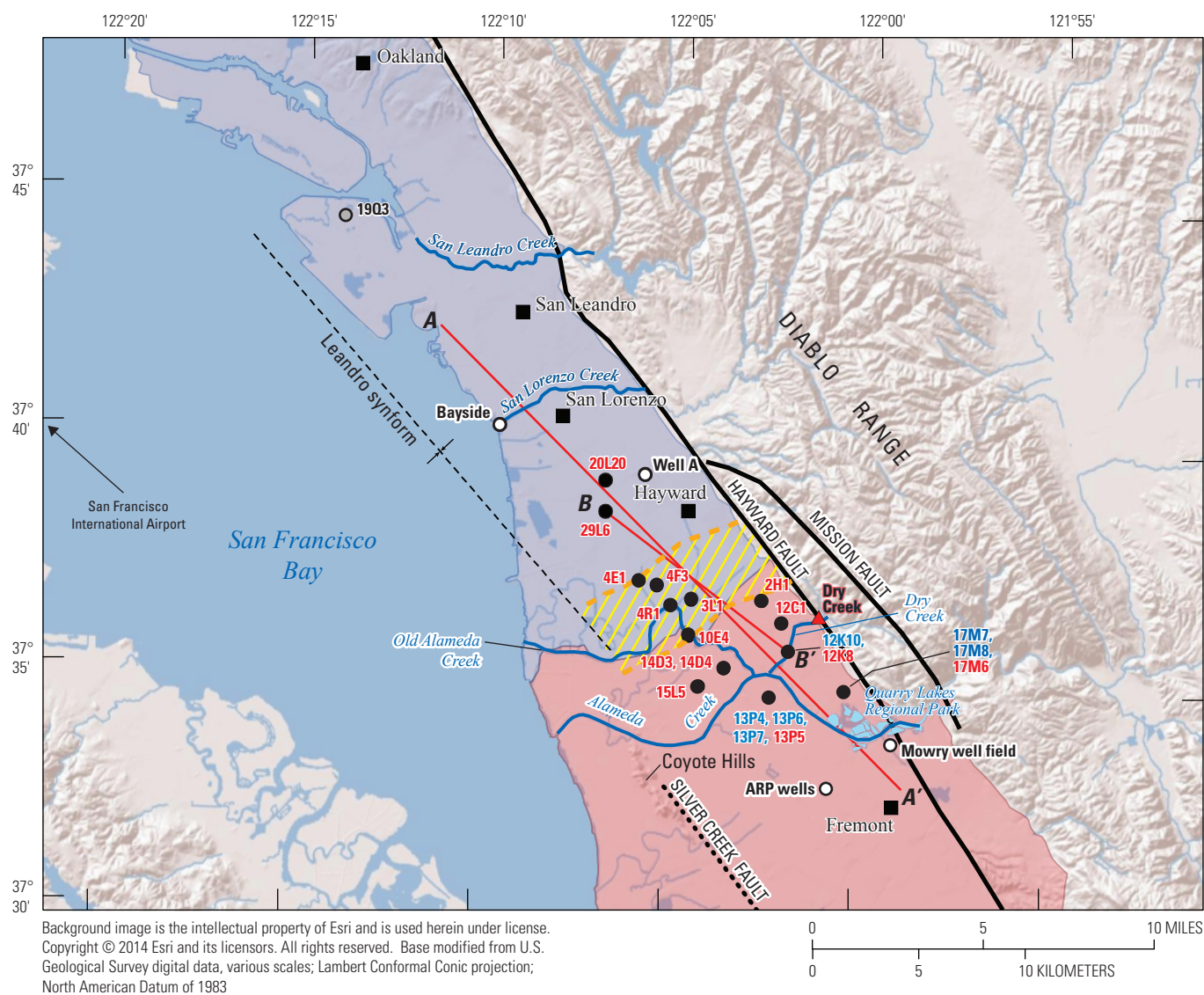
Given increasing demands on groundwater resources and often competing groundwater management projects in aquifers underlying the Niles Cone and southern East Bay Plain groundwater subbasins, local management agencies require improved understanding of the movement of recharged water within and between aquifers and the potential effect of groundwater recharge projects in urban areas. The purpose of this report is to document the methods and results of an evaluation of the geologic and hydrologic controls on groundwater movement through aquifers between the Niles Cone and southern East Bay Plain groundwater subbasins on the east side of San Francisco Bay, California.

The scope of this report includes the methods for collection of hydrologic, InSAR, and geochemical data for 2002 and 2003; the description of the analysis of the data to evaluate movement of water from the Quarry Lakes Regional Park recharge ponds and Alameda Creek into the aquifer system of the Niles Cone groundwater subbasin; and the interaction of groundwater in the Niles Cone and southern East Bay Plain groundwater subbasins.

## Description of the Study Area

The study area is composed of the alluvial fans (locally referred to as cones) of the San Lorenzo and Alameda Creeks and smaller tributaries, and it is separated into two distinct groundwater subbasins: the East Bay Plain groundwater subbasin and the Niles Cone groundwater subbasin. The East Bay Plain groundwater subbasin is about 120 square miles of tidal marshes and alluvial lowlands near Oakland, Calif., on the east side of San Francisco Bay (fig. 1). The Niles Cone groundwater subbasin is formed by the alluvial plain of Alameda Creek and is 103 square miles. The area has a Mediterranean climate with mild, wet winters and warm, dry summers. The average annual temperature is 15 °C and ranges from 11 °C (December–February) to 18 °C (June–September; National Oceanic and Atmospheric Administration, 2012). Most precipitation falls as rain between November and March and averages 23 inches (in.) annually (Muir, 1997). The area is highly urbanized with diverse residential, commercial, and industrial land uses. Although agriculture was important in the past, there is little agricultural land use in the study area at the present time.

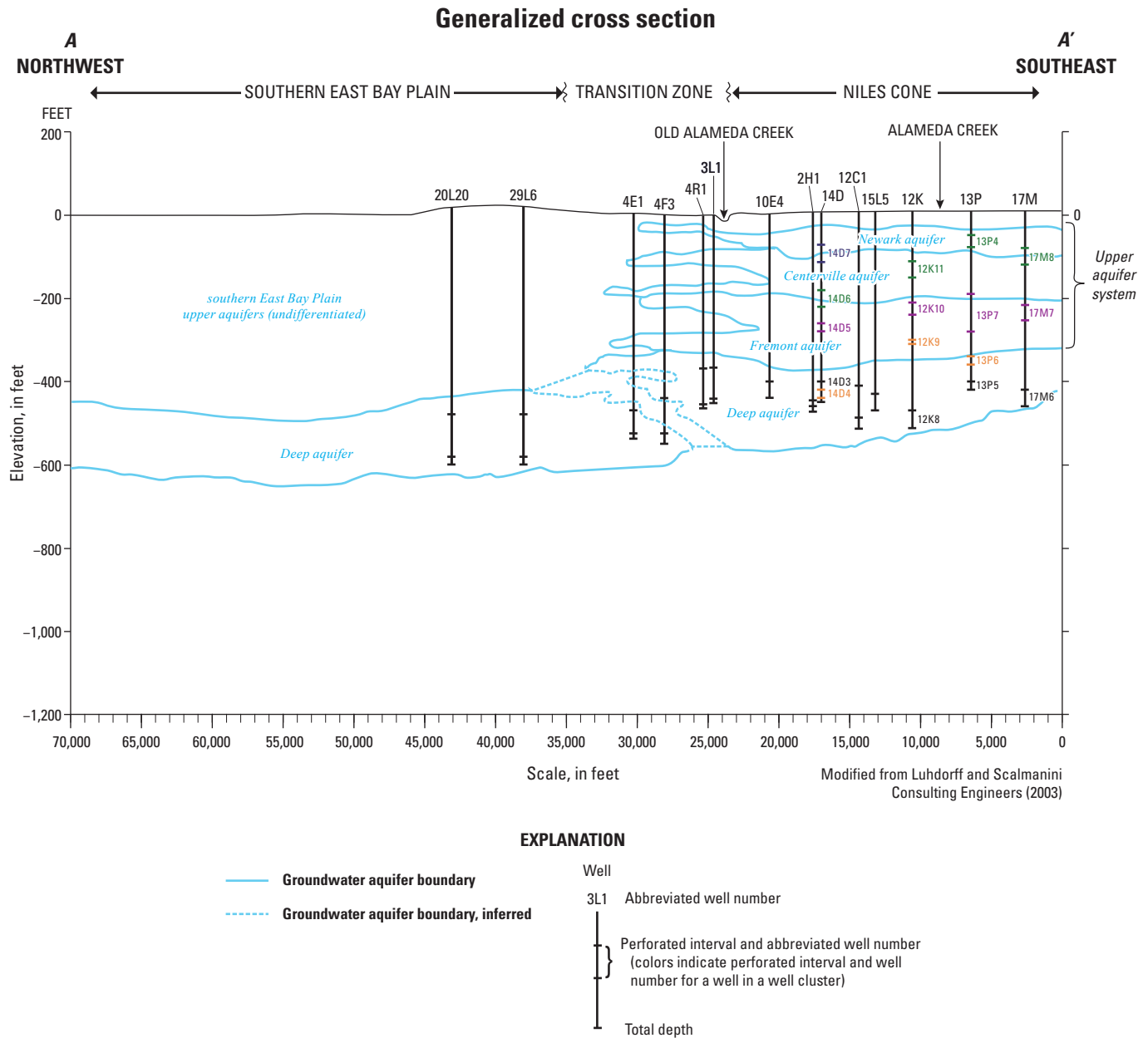




## EXPLANATION

- Well A ○ Municipal wells
- 1903 ○ Wells sampled by Izbrick and others, 2003
- 12K10 ● Wells sampled as part of this study
- 13P5 ● Upper aquifer system wells
- Deep aquifer wells
- ▲ Surface water site
- Transition zone (Luhdorff and Scalmanini Consulting Engineers, 2003)
- East Bay Plain subbasin
- Niles Cone subbasin
- A — A' Line of hydrogeologic section

**Figure 1.** Location of the Niles Cone and southern East Bay Plain groundwater subbasins and municipal wells, including aquifer reclamation program (ARP) wells, Alameda County, California.



**Figure 2.** Generalized A–A' cross section showing groundwater aquifers of Niles Cone and southern East Bay Plain groundwater subbasins and well location and well construction for wells sampled as part of this study, Alameda County, California.

## Hydrogeology

The study area is located where the right-lateral San Andreas Fault splays into a number of active subparallel right-lateral fault zones, including the Hayward Fault (fig. 1). The San Francisco Bay, surrounding marshes, and alluvial plains lie in a depression in the San Francisco Bay block, a structural province between the Diablo Range and the Hayward fault zone to the east and the Santa Cruz Mountains and San Andreas Fault to the west (not shown on figures). East from the Hayward Fault, Tertiary volcanic and sedimentary rocks; pre-Tertiary, unmetamorphosed rocks of the Great Valley sequence; and rocks of the Franciscan complex crop out in the Diablo Range (Wallace, 1990; Graymer and others,

1995; Graymer, 2000; Graymer, 2003). Within the structural depression, sedimentary deposits of variable thickness overlie the buried erosional surface of consolidated Franciscan Complex bedrock (Rogers and Figuers, 1991). The underlying Franciscan bedrock is of limited importance for water supply (Fugro West Inc., 2000, 2001; Dave Thomas, California Department of Transportation, written commun., 2002). Where water is present within these deposits, it is more mineralized and less desirable for human consumption than fresher groundwater in the overlying alluvium. The thickness, extent, structure, and texture of the alluvial aquifer systems have been influenced by tectonic movement in the Hayward fault zone, paleoclimate and sea level changes, and differences in sediment source areas.

The principal water-bearing units in the Niles Cone and southern East Bay Plain groundwater subbasins are located west of the Hayward Fault, which acts as an effective groundwater boundary (Clark, 1915). Four primary aquifers composed of Quaternary sedimentary deposits underlie the Niles Cone groundwater subbasin and southern East Bay Plain groundwater subbasins (California Department of Water Resources, 2003). The California Department of Water Resources (2003) delineated the subbasin boundaries by considering the geomorphic expression of present day alluvial fans, location of groundwater divides, political boundaries, and other factors. The aquifers (from shallowest to deepest) are the Newark, Centerville, Fremont, and Deep aquifers (fig. 2). The aquifers were first defined in the Niles Cone groundwater subbasin (California Department of Water Resources, 1967) and projected to the southern East Bay Plain groundwater subbasin by Brown and Caldwell (1986), Maslonkowski (1988), and Figuers (1998). Collectively, the aquifers consist of alluvial sand and gravel deposited by flood flows in Alameda Creek, presumably during glacial periods about 20,000, 120,000, and 240,000 years ago (Maslonkowski, 1988; Koltermann and Gorelick, 1992), and are separated by estuarine mud or fine-grained alluvial flood-plain deposits. The Newark, Centerville, and Fremont aquifers are thicker and more continuous in the Niles Cone groundwater subbasin than in the East Bay Plain groundwater subbasin to the north (Luhdorff and Scalmanini Consulting Engineers, 2003).

### The Upper Aquifer System

In the Niles Cone groundwater subbasin, the Newark aquifer crops out at land surface, near the apex of the Alameda Creek alluvial fan, where it is 140 ft thick and lies 140 ft below land surface on the western edge of the area, where it thins to about 20 ft thick (California Department of Water Resources, 1967, 1968). Groundwater in the Newark aquifer is confined except near recharge areas along the mountain front (California Department of Water Resources, 2003). The Centerville aquifer lies at an average depth of 180 to 200 ft below land surface and, similar to the Newark aquifer, thins to the west (California Department of Water Resources, 2003). The Fremont aquifer lies between 300 and 390 ft below land surface, also thinning to the west. Groundwater in the Centerville and Fremont aquifers is confined (California Department of Water Resources, 2003). In parts of the Niles Cone groundwater subbasin where clay-rich aquitards are absent or thin, the Centerville and Fremont aquifers are hydraulically connected (Alameda County Water District, 2001a). Given the Centerville and Fremont aquifers are adjacent and hydraulically connected to each other, they are often referred to as a single aquifer unit, the Centerville-Fremont aquifer.

Near the apex of the Niles Cone groundwater subbasin, the Hayward Fault hydraulically partitions the alluvial deposits (Clark, 1915), and Alameda County Water District

(2001) manages groundwater upgradient and downgradient from the Hayward Fault as separate aquifer systems. Lithologic data from wells and aquifer-test data indicate that the Newark and Centerville aquifers extend westward under and beyond San Francisco Bay (California Department of Water Resources, 1967). Lithologic data also indicate that the aquifers of the Niles Cone groundwater subbasin thin and become finer grained to the southwest, eventually disappearing in a clay-rich zone in northern Santa Clara Valley (California Department of Water Resources, 1967). For the purpose of this study, the Newark, Centerville, and Fremont aquifers are collectively referred to as the upper aquifer system.

Unlike the Niles Cone groundwater subbasin to the south, alluvial fans in the southern East Bay Plain groundwater subbasin were deposited by lower energy streams. It is difficult to correlate sand and gravel layers over great distances between wells in the southern East Bay Plain groundwater subbasin (Muir, 1993). Fine-grained sediments deposited between alluvial fans interrupt lateral continuity of coarse-grained layers and inhibit interfan flow of groundwater. The Hayward Fault forms the eastern boundary of aquifers in the southern East Bay Plain groundwater subbasin. Alluvial deposits in the area east of the Hayward Fault are thin and contain insubstantial amounts of groundwater.

The degree of hydraulic connection between the three shallow aquifers in the Niles Cone groundwater subbasin and their time-equivalent units in the southern East Bay Plain groundwater subbasin is not well defined, although aquifer sediments in the two areas may become more hydraulically connected with depth (Figuers, 1998). For example, the Fremont aquifer in the Niles Cone groundwater subbasin may be connected hydraulically to the Fremont aquifer in the southernmost East Bay Plain groundwater subbasin because both are thought to be composed of sediment deposited in the alluvial fan of Alameda Creek. Fremont-age sediment has been translated about 1.5 miles to the northwest from the Niles Cone groundwater subbasin into the southern East Bay Plain groundwater subbasin by right-lateral motion on the Hayward Fault (assuming an average geologic rate of movement of 30 ft per thousand years; Maslonkowski, 1988; Koltermann and Gorelick, 1992).

### Deep Aquifer

Permeable sand and gravel layers that underlie the three shallowest aquifers (the upper aquifer system) in the study area are termed the Deep aquifer. Because relatively few wells have been drilled into the Deep aquifer, the thickness, areal extent, sedimentology and structure of the Deep aquifer is less well described than for the upper aquifer system. Permeable sand and gravel beds within the Deep aquifer are shallowest in the Niles Cone groundwater subbasin and deepen to the north, where they lie between 500 and 650 ft below land surface (fig. 2). In some areas, the aquifer can be as much as 150 ft thick.



Thickness of the Deep aquifer does not decrease near the edge of the Niles Cone groundwater subbasin. In fact, the Deep aquifer is thickest and most continuous south of San Leandro, Calif. (Maslonkowski, 1988), and eventually thins, nearly disappearing to the north of the study area (not shown on [fig. 2](#); CH2M-Hill, Inc., 2000). It is likely that the source of sediments in the Deep aquifer beneath San Lorenzo Creek alluvial fan, and perhaps even further north, is the Alameda Creek watershed and that tectonic activity has shifted the sediments to the north (Koltermann and Gorelick, 1992).

## Recharge and Discharge

Under predevelopment (before the late 1850s) conditions, recharge to the aquifer systems occurred primarily as infiltration of streamflow from San Leandro, San Lorenzo, and Alameda Creeks. Smaller amounts of recharge are believed to have occurred as infiltration of precipitation. Muir (1996a) estimated that annual recharge from infiltration of streamflow and direct infiltration of precipitation in the East Bay Plain groundwater subbasin was about 3,500 and 800 acre-feet (acre-ft), respectively. In the Niles Cone groundwater subbasin, recharge from infiltration of streamflow was about 14,000 acre-feet per year (acre-ft/yr; Bailey, 1919; California Department of Water Resources, 1968). Bailey (1919) regarded recharge from infiltrating precipitation in the Niles Cone groundwater subbasin as insignificant, but California Department of Water Resources (1968) estimated such recharge at about 7,400 acre-ft/yr. As noted earlier, some inflow to the Deep aquifer in the southern East Bay Plain groundwater subbasin may have occurred as groundwater that flowed northward from the Deep aquifer in the Niles Cone groundwater subbasin.

The Hayward Fault is a barrier to groundwater flow between sedimentary deposits east and west of the fault. Under predevelopment conditions, groundwater discharging along the fault from sediments to the east maintained flow of springs (Figuers, 1998) that discharged groundwater at a rate of about 5,000 acre-ft/yr to extensive willow marshes north of San Lorenzo Creek and to other locations (Grossinger and Brewster, 2003). West of the Hayward Fault, groundwater flowed toward San Francisco Bay, where it discharged to tidal wetlands or continued to flow west under San Francisco Bay (Muir, 1996b). Where westward flow of groundwater was impeded by Franciscan Formation rocks in the subsurface near the Coyote Hills, groundwater discharged to wetlands or was diverted north and south from the Coyote Hills (Figuers, 1998).

As a result of agricultural and urban development beginning in the late 1800s, groundwater pumping became an important discharge mechanism in the study area. More than 15,000 wells were drilled in the southern East Bay Plain groundwater subbasin between 1886 and 1950 (Figuers, 1998). Most of these wells were less than 100 ft deep, although some wells were more than 400 ft deep, and a few were drilled to depths greater than 1,000 ft. About 250 wells within the ACWD service area are more than 400 ft deep

(James Ingle, ACWD, written commun., 2004). In 1917, 1,450 wells withdrew 19,000 acre-ft from the aquifers of the Niles Cone groundwater subbasin (Bailey, 1919). In 1960, 1,042 wells withdrew about 46,500 acre-ft from wells in the aquifers of the Niles Cone groundwater subbasin (California Department of Water Resources, 1960). In 1990, estimated withdrawal was 32,000 acre-ft from the aquifers of the Niles Cone groundwater subbasin (Fio and Leighton, 1995). Groundwater pumping in excess of recharge caused water levels to decline to more than 100 ft below sea level during the mid-1920s, mid-1930s, and late 1940s (Figuers, 1998). Salty water from San Francisco Bay, or salt water evaporation ponds at the margin of San Francisco Bay, migrated inland through shallow aquifers to areas where sediments generally are coarser grained and more permeable than shoreward sediments. The California Department of Water Resources (1960) attributed increasing chloride concentrations in the Niles Cone groundwater subbasin to vertical flow from overlying intruded aquifers through permeable sediments in recharge areas near the mountain front, through gaps in clayey aquicludes, and through leaking and abandoned wells.

Muir (1996a) estimated that recharge from leaky underground water-supply and sewer pipes was about 3,100 acre-ft/yr in the southern East Bay Plain groundwater subbasin. However, Izbicki and others (2003), using stable isotope data from groundwater samples, suggested that recharge from leaking pipes may be less important than reported by Muir (1996a) or may not be uniformly distributed across the southern East Bay Plain groundwater subbasin. Natural recharge may have decreased as a result of urbanization because streams were channelized and lined with concrete, and permeable soil surfaces were paved.

## Groundwater Management

In the mid-1900s, water imported to the study area reduced the dependence on local groundwater for public supply (California Department of Water Resources, 1963). The EBMUD imported surface water from the Sierra Nevada and also collected surface water in reservoirs in the hills east of the study area. The City of Hayward contracted with the San Francisco Public Utilities Commission (SFPUC) to purchase water for public supply from Hetch Hetchy Reservoir in northern Yosemite National Park. The ACWD also contracted with the SFPUC to purchase water from the Hetch Hetchy Reservoir and with the State Water Project to import water originating in the Sierra Nevada through the South Bay Aqueduct from the Sacramento–San Joaquin River Delta (Alameda County Water District, 2001a). The SFPUC and ACWD also collected runoff in local reservoirs. As the area became increasingly urbanized, agricultural pumping declined, and recharge from infiltration of imported water used for landscape irrigation increased. Groundwater levels recovered to near predevelopment conditions owing to the decreased dependence on local groundwater supplies (California Department of Water Resources, 1963).

Managed aquifer recharge in the Niles Cone groundwater subbasin includes water infiltrated at the Quarry Lakes Regional Park and behind two rubber dams that are inflated seasonally to impound water in Alameda Creek. The Quarry Lakes are a series of abandoned gravel quarries that were graded and plumbed to allow ACWD to operate them as artificial groundwater recharge facilities (fig. 1). The sources of water to Quarry Lakes are runoff in the Alameda Creek watershed, State Water Project (SWP) water imported since 1962 from central California (primarily snowmelt from the Sierra Nevada), and water discharged from reservoirs in the Alameda Creek watershed, which contain both local runoff and SWP water. Part of the flow of Alameda Creek is groundwater pumped from gravel quarries in upstream parts of the watershed (Moran and Halliwell, 2004). During drought years prior to importation of SWP water, or later when SWP water was not available for flow augmentation in Alameda Creek, effluent discharged from wastewater treatment plants was a substantial component of streamflow (Lopp, 1981). In conjunction with managed aquifer recharge, ACWD's Aquifer Reclamation Program (ARP) wells (fig. 1), which extract stratigraphically-trapped salty water, has substantially decreased the area of the Niles Cone groundwater subbasin affected by salt-water intrusion. The ACWD adds about 30,000 acre-ft/yr to groundwater storage at Quarry Lakes and the rubber dam impoundments, and ACWD usually extracts less than 10,000 acre-ft/yr from ARP wells. The ACWD estimated that pumping of local groundwater for public and private supplies in the Niles Cone groundwater subbasin averaged about 24,000 acre-ft/yr during 1997–99 (Moran and Halliwell, 2004).

An interferometric synthetic aperture radar (InSAR) interferogram (change from July 3, 1999, to January 29, 2000) indicated that land surface near ACWD's managed aquifer recharge facilities and along Alameda Creek to the west is displaced upward as much as 0.8 in. (20 millimeters, mm) relative to areas northwest and southwest of the facilities. Land surface displacements related to rising groundwater levels in recharge areas has been demonstrated in other areas of California (Galloway and others, 1999; Lu and Danskin, 2001; Bawden and others, 2001). These displacements may be a cause for concern in urban areas or may indicate potential for permanent (inelastic) subsidence of aquifer deposits should groundwater pumping lower water levels beyond previous levels (Galloway and others, 1999).

In addition to managed aquifer recharge projects operated by ACWD, the City of Hayward has constructed five deep water-supply wells in the aquifers underlying Hayward, Calif., to provide emergency water supply, and EBMUD has tested the feasibility of artificial storage and recovery (ASR) of water through deep wells near the shore of San Francisco Bay, just south from San Lorenzo Creek (fig. 1; Luhdorff

and Scalmanini Consulting Engineers, 2003). The EBMUD's Bayside Groundwater Project (BGP) may ultimately include 7 to 10 production/injection wells completed 500–650 ft below land surface, with groundwater extraction rates between 1 to 3 million gallons per day per well. During wet periods, EBMUD planned to inject treated surface water from reservoirs in the Sierra Nevada at a rate of about 1 million gallons per day per well and store it for use during droughts or times of surface-water scarcity (California Regional Water Quality Control Board, 2007). Projects operated by agencies in the Niles Cone and East Bay Plain groundwater subbasins may compete for limited groundwater storage capacity during wet periods, and because the subbasins may be hydraulically connected, recharged water may be extracted by nonparticipating agencies during dry periods.

## Methods

Data collection included measurement of groundwater levels in wells; InSAR data compilation; streamflow measurements; measurements of physical parameters from streamflow and natural discharge; water-quality sample collection from 21 wells, 1 surface water site, and 1 precipitation sampler; and collection of core material for mineralogical analysis. Groundwater-level data were collected in accordance with the protocols established by the "Groundwater Technical Procedures of the U.S. Geological Survey" (Cunningham and Schalk, 2011), which provides standardized technical procedures of many aspects of groundwater science, including site and measuring-point establishment and measurement of water levels (Wilde and others, 1999a, b). Water-quality data were collected in accordance with the protocols established by the USGS National Field Manual (Wilde and others, 1999a). The water-quality sampling protocols ensure that a representative sample is collected at each site and that the samples are collected and handled in a way that minimizes the potential for contamination of samples.

## Groundwater-Level Measurement

Groundwater levels were measured by USGS and ACWD personnel in 21 wells perforated in the Deep aquifer and in 24 wells perforated in the upper aquifer system during the spring and fall of 2002. All sites and water-level data were entered into the USGS National Water Information System (NWIS) database and are available from <http://waterdata.usgs.gov/nwis>. Location, construction, and water-level data for wells measured as part of this study are provided in appendix 1.

## InSAR Data Processing

InSAR imagery was processed and analyzed to measure the long-term surface displacement patterns and magnitudes within the Niles Cone and southern East Bay Plain groundwater subbasins. Shorter-term interferograms, maps of relative surface displacement constructed from InSAR data, were processed to assess if InSAR could be used to detect the effects of groundwater management strategies. The ACWD recharges groundwater through infiltration ponds and impoundments at Quarry Lakes Regional Park near Fremont, Calif. (fig. 1), near the apex of the Alameda Creek alluvial fan in the Niles Cone groundwater subbasin.

The synthetic aperture radar (SAR) data (radar scenes) used to construct the interferograms are from the SAR instrument on the European Space Agency ERS-2 satellite. The ERS-2 satellite has a steep look-angle (about 23° from vertical), which provides data sensitive to vertical deformation of the land surface (uplift and subsidence). The interferograms were constructed by the two-pass method using a USGS 30-meter digital elevation model and both Diapason and GAMMA InSAR processing software packages (Centre National d'Etudes Spatiales, 1997; Werner and others, 2000). The images were processed using methods similar to those used by Stork and Sneed (2002). The resolution of a pixel in the interferograms is 323 square feet (ft<sup>2</sup>; 30 square meters). The interferogram measurements are range change (distance: positive, or uplift, and negative, or subsidence) in the radar line-of-sight, where one complete cycle of the color fringe (warm to cool) on the interferograms (the scale factor) is 1.1 in. (28.3 mm). Under ideal conditions, it is possible to resolve changes in elevation on the order of 0.2 to 0.4 in. (5 to 10 mm) at the scale of one pixel (Galloway and others, 2000).

Because of the high frequency of seismic activity in the densely populated San Francisco Bay area, scientists and government agencies are interested in monitoring techniques that provide information that may elucidate processes responsible for seismic geohazards. Each satellite can scan the same area every 35 days. Data were collected from January 1992 to May 1996 for ERS1 and from September 1995 to 2003 for ERS2. Interpretation and construction of interferograms from ERS2 data after December 2002 were difficult owing to a gyroscope failure that caused the satellite to wobble at a level that limited interferogram generation. The two satellites are coordinated so that they can scan the same track and frame grid location at approximately the same local time, but with a temporal offset that varies by a number of days. Interferograms can be constructed from scenes from either or both satellites.

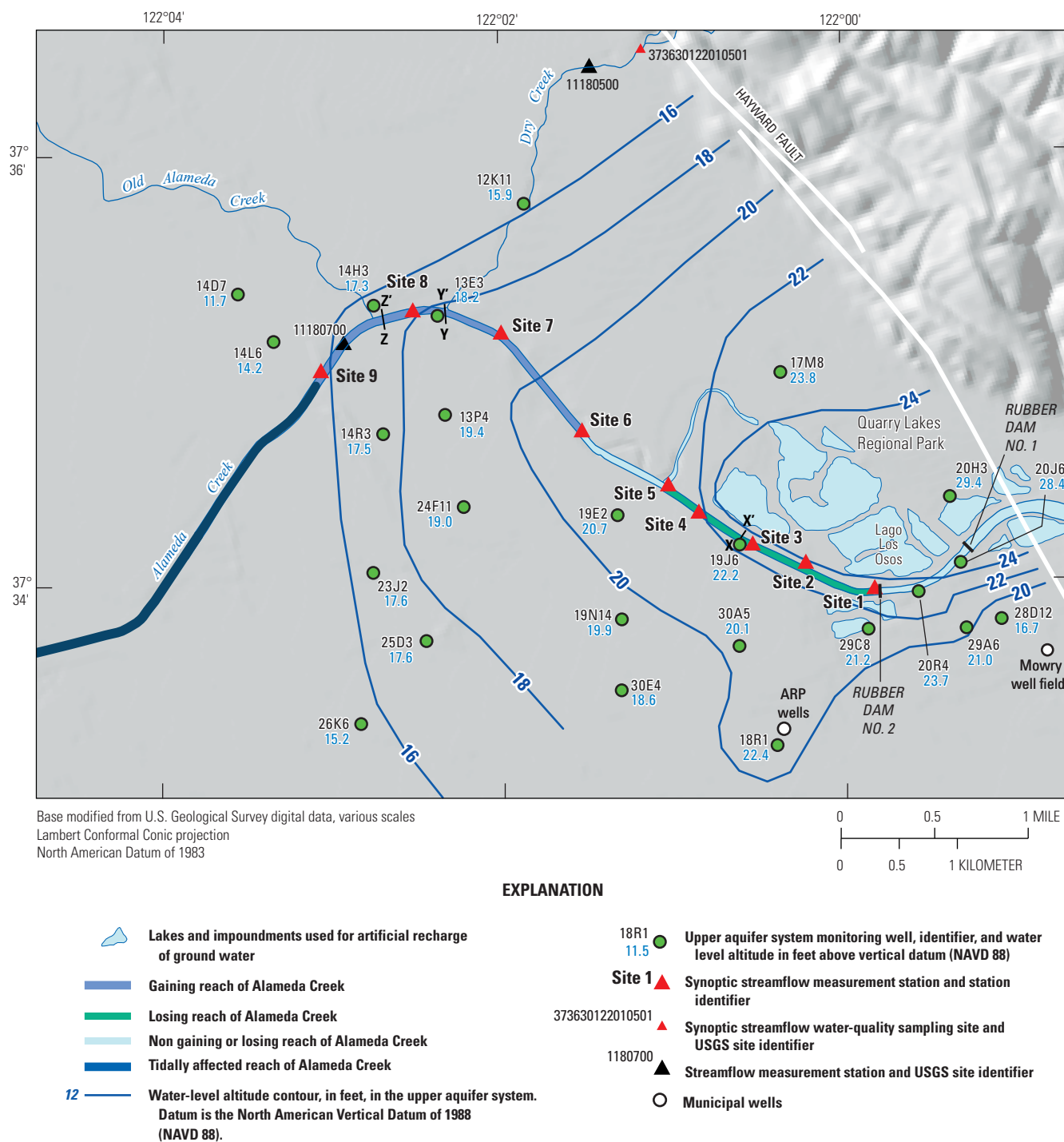
## Streamflow Gains and Losses Estimation

To provide information needed to interpret results from groundwater-flow modeling by ACWD, the interaction between Alameda Creek and the adjacent aquifer was investigated by a reconnaissance-level survey of flow gains

and losses along Alameda Creek in April 2002. Streamflow gains and losses were determined by a series of streamflow measurements between Rubber Dam No. 2 and the tidally affected stream reach downstream from USGS stream gage 11180700 (Alameda Creek at Union City, Calif.; fig. 3). To assess chemical differences between stream water loss and groundwater, water temperature, pH, and specific electrical conductance were measured using standard field instruments and techniques (Wilde, 1998) at streamflow measurement sites and at three groundwater seeps and springs where they emerged from the flood plain and levee base. A potentiometric surface map (fig. 3) was constructed from water levels measured in ACWD observation wells monitoring the upper aquifer system (appendix 1) to provide information on the direction of groundwater flow in shallow sediments adjacent to Alameda Creek. The precipitation record from a nearby National Oceanic and Atmospheric Administration climate station (Newark, CA US) shows no precipitation in the area for at least 7 days prior to the streamflow measurements recorded on April 24, 2002 (<https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00046144/detail>), and gage height measured in USGS gage 11180700 ([https://nwis.waterdata.usgs.gov/nwis/measurements/?site\\_no=11180700&agency\\_cd=USGS&amp;](https://nwis.waterdata.usgs.gov/nwis/measurements/?site_no=11180700&agency_cd=USGS&amp;)) remained consistent over the period of the survey (morning April 24, 2002, to midday April 25, 2002). The absence of precipitation and the consistency of the flow in Alameda Creek indicate that flows were stable in the studied reaches during the measurements and were therefore comparable between stations.

Most streamflow measurements were made using velocity-area methods (Rantz and others, 1982) using a Price pygmy current meter with a top setting wading rod. One day prior to velocity-area measurements, uniform-flow measuring sections were constructed by removing large cobbles from the stream bed and focusing flow to a single channel (where feasible) between parallel banks built using sand bags and planks. Where velocities were less than 0.2 feet per second (ft/s) and stream depths were less than 0.3 ft, streamflow measurements were made with modified 3-in. Parshall flumes. Flumes were used to measure small inflows from two tributary streams and were installed several hours prior to use. Streamflow measurements were rated from excellent to poor, depending on measurement technique and flow conditions. Poor ratings imply greater uncertainty and corresponded to measurements made with Price pygmy meters where stream depth and velocity approached the limitations of the method, less than 2 in. and 0.1 ft/s, respectively. Generally, streamflow measuring conditions were unsuitable in areas where water ponded behind stream channel vegetation or where the stream channel braided. Where feasible, streamflow measurement sites were selected in areas where sediment and vegetation had been recently removed by the Alameda County Flood Control and Water Conservation District to improve conveyance of winter storm flows. In the absence of these maintenance activities in Alameda Creek, it is likely that streamflow measurement would have been infeasible in most of the measured reaches.





**Figure 3.** Water-level elevation contours and water-level elevations in wells screened in the upper aquifer system, gaining and losing reaches along Alameda Creek, Quarry Lakes Regional Park recharge area, Alameda Creek, and Alameda County Water District (ACWD) aquifer reclamation program (ARP) wells, Alameda County, California, April 2002.

## Water Sample Collection and Analysis

In this study, samples were evaluated for major ions, selected minor ions, selected trace elements, stable isotopes of water, and age-dating tracers to determine groundwater quality, the sources of high chloride water to wells, and the effects of managed aquifer recharge on groundwater of the Niles Cone and southern East Bay Plain groundwater subbasins. The spatial distribution of surface sources of industrial chemicals, such as volatile organic carbon compounds or trace elements, was not evaluated as part of this study.

Most samples collected as part of this study were from monitoring or production wells. Samples from monitoring wells in the Deep aquifer provide information on groundwater chemistry within the part of the Deep aquifer in which the monitoring well is screened and not necessarily for all of the Deep aquifer. Samples from production wells are a mix of groundwater that entered the well throughout the entire screened interval. As a result, it may be difficult to interpret samples collected from production wells that are screened in more than one aquifer. Samples also were collected from shallow monitoring wells (not in the Deep aquifer) in Deep aquifer recharge areas near Alameda Creek, Dry Creek, and Quarry Lakes at the head of the Alameda Creek alluvial fan. Comparisons of samples from the Deep aquifer and samples from shallow monitoring wells in recharge areas provide information on changes in groundwater chemistry and recharge age with depth.

Twenty-three water samples were collected from 21 wells, 1 surface water site, and 1 precipitation sampler in the study area during 2002 to 2003. Water-quality samples were collected following the USGS field procedures outlined in the “U.S. Geological Survey Field Manual for Collection of Water Quality Data” (Wilde, 1999a). Samples were collected from production and monitoring wells after three casing volumes were removed from the well and field parameters stabilized. Existing pumps were used to collect samples from production wells. Temporary, positive-displacement sample pumps were used to collect samples from monitoring wells. Temperature, specific conductance, and pH were monitored in water from domestic, production, and monitoring wells during purging prior to sample collection. Sample collection, preservation, and analytical methods are given in [appendix 2](#) at the back of this report. The precipitation sample is a composite of samples collected near Quarry Lakes from November 8, 2002, to June 5, 2003, and the stable-isotopic data can be considered as average values for winter and spring rainfall.

The field parameters temperature, specific conductance, pH, and alkalinity were measured at the time of sample collection using calibrated thermometers and portable meters. Meters were calibrated in the field prior to measurement. Dissolved oxygen also was measured in the field using the colorimetric indigo-carmin method just prior to sample collection. Water samples for analyses of major ions, nutrients,

and selected trace elements were pressure-filtered in the field using capsule filters that had a pore size of 0.45 micrometer ( $\mu\text{m}$ ). Samples for the laboratory analysis of pH and specific conductance were not filtered.

Noble-gas samples were analyzed by the USGS Noble Gas Laboratory in Reston, Virginia, following the methods of Poreda and others (1988), Bayer and others (1989), Solomon and others (1992, 1996), and Beyerle and others (2000). Recharge temperatures and excess air concentrations were determined from dissolved Neon (Ne), Argon (Ar), Krypton (Kr), and Xenon (Xe) using methods described in Aeschbach-Hertig and others (1999). Tritogenic helium-3 ( $^3\text{He}_{\text{trit}}$ ) was computed as described in Solomon and Cook (2000). Water samples for carbon isotopes and carbon-14 activities were analyzed by the University of Waterloo laboratory under contract with the USGS using mass spectroscopy and accelerator mass spectroscopy, respectively.

Statistical analysis of constituents was done using Kruskal-Wallis rank sum tests [ $\text{kruskal.test}(x, g)$ ] in the computer program R (R Development Core Team, 2008). The Kruskal-Wallis test is used when there is one nominal variable and one measurement variable, and it does not require assumptions about the specific shape of the probability distribution. Data are ranked based on their measurement value from smallest to largest before the test statistic is calculated. The loss of information due to substituting ranks for original data make the test less powerful; however, data do not need to be normally distributed as in an analysis of variance (ANOVA) test. Small P-values (less than 0.05) at a significance level of 95 percent show that differences in the distribution of data between two or more groups are not due to random sampling error only, but in fact that at least one group has a statistically significant difference in the distribution; conclusions about the differences in the distribution of data cannot be made with P-values of 0.05 or greater.

## Collection and Analysis of Core and Cuttings Material

Mineralogic analyses were done on four samples collected by drilling and coring. Drill cuttings and core material were collected from well 14D3 and of a composite of coarse-grained outcrop material at Quarry Lakes recharge pond. The elemental composition of cores and cuttings was determined by inductively coupled plasma-mass spectrometry (ICP-MS; Briggs and Meier, 2002). The mineralogy of selected cores and cuttings was determined by X-ray diffraction (Amonette and Zelazny, 1994). Images of selected materials were obtained using a scanning electron microscope equipped with a spectral analyzer to determine the primary or secondary minerals that might participate in dissolution-precipitation reactions as groundwater interacts with sediments in the aquifer system and to determine the uranium and thorium composition of aquifer materials (Amonette and Zelazny, 1994). Information about the collection and analysis, as well as results from the analysis, is provided in [appendix 3](#).

## Hydrogeology

Data and various analyses were used to evaluate the effect of groundwater management practices on the aquifer systems and movement of water through the Deep aquifer, including between subbasins. This section of the report presents and discusses results for groundwater movement, vertical displacement of the land surface, and streamflow gains and losses in the recharge area near the apex of the Alameda Creek alluvial fan.

### Groundwater Movement

Water-level contours indicate that groundwater generally flows from the eastern recharge areas at Quarry Lakes and Alameda Creek to the north and west (figs. 3 and 4). Closely spaced contours to the south in the Deep aquifer (fig. 4) are the result of pumping from the nearby Mowry well field and Aquifer Reclamation Program (ARP) wells. Water-level data from wells completed solely in the upper aquifer system to the north of Old Alameda Creek were unavailable because the deposits that compose the upper aquifer system in this area are finer-grained, yield less water to wells than deposits to the south, and therefore, are not ideal locations for wells. Measurements collected in 2002 show that the elevation of water levels in wells completed in the upper aquifer system (wells 4S/1W-17M7, -17M8; 4S/2W-12K9, -12K10, -12K11; 4S/2W-13P4, -13P6, -13P7; and 4S/2W-14D5, -14D6, -14D7) were as much as 20 ft higher than water levels in wells completed in the Deep aquifer (wells 4S/1W-17M6; 4S/2W-12K8; 4S/2W-13P5, and 4S/2W-14D3, -14D4; appendix 1).

Water levels in the Deep aquifer indicate groundwater flows to the west and north from Quarry Lakes (fig. 4). The groundwater flowpath *B–B'* follows this general northwest trend and was used for the purpose of geochemical modeling described later in this report (fig. 4). Water-level elevation in the Deep aquifer were below sea level in most of the area, as low as about –9 ft in well (3L1) in the southern East Bay Plain groundwater subbasin within the transition zone (table 1–1). Water-level contours indicate that flow of groundwater in the Deep aquifer in 2002 was from recharge areas near the head of the alluvial fan of Alameda Creek to the southern East Bay Plain groundwater subbasin. The effects of tides in San Francisco Bay on groundwater levels in the Deep aquifer were not considered in figure 4. The effects of tidal loading on groundwater levels in the southern East Bay Plain groundwater subbasin measured by Izbicki and others (2003) show water levels in the Deep aquifer can change by more than 1.5 ft in a 6-hour period.

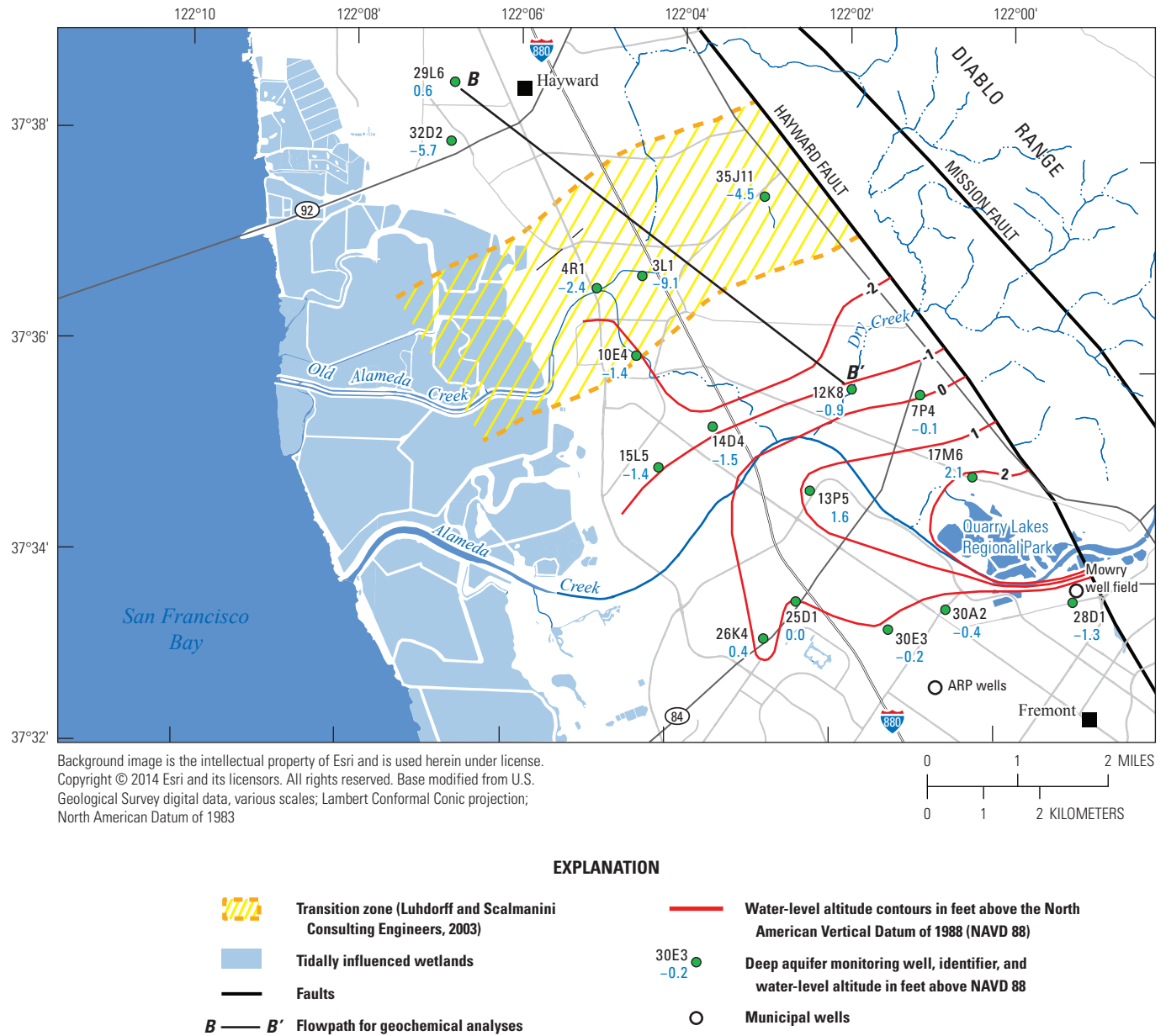
The velocity and volume of the flow within the Deep aquifer, being dependent on the hydraulic gradient, may have increased since ACWD's managed aquifer recharge activities raised groundwater levels near Quarry Lakes.

Under predevelopment conditions, the quantity of groundwater flowing to the northwest may have been substantially less than under conditions in 2002. During the mid-1900s when pumping was greater and water-level elevation dropped in some places to more than 100 ft below sea level, the magnitude and the direction of groundwater flow in the Deep aquifer was likely substantially different than today, either moving with less velocity toward the northwest or, in parts of the study area, even moving west to east from San Francisco Bay (California Department of Water Resources, 1963).

### Local Short-Term Land-Surface Displacement

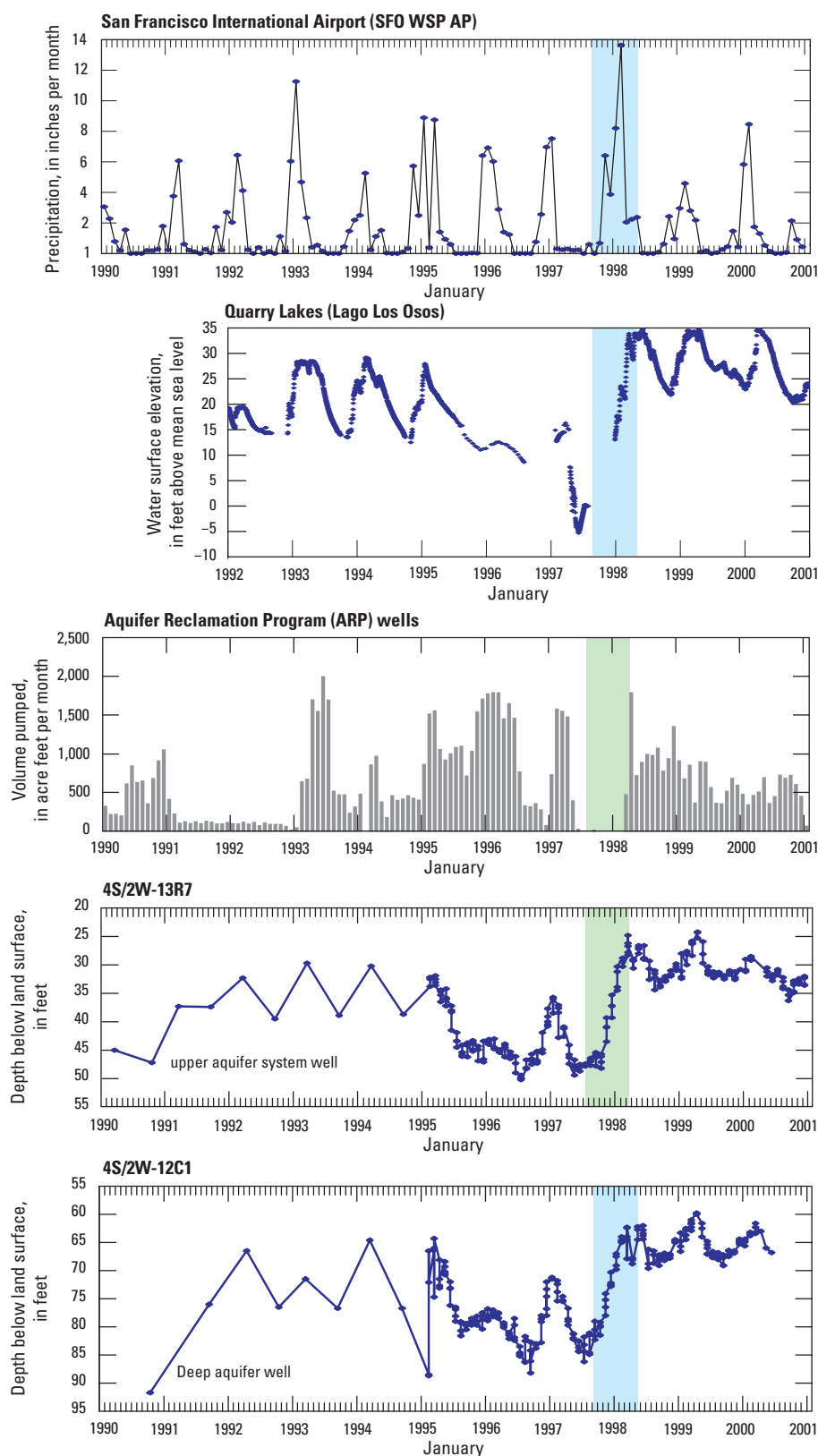
Beginning in the winter–spring of 1995, in preparation for pond reconstruction, ACWD reduced water volume in the ponds at Quarry Lakes Regional Park and increased pumping at Aquifer Reclamation Program (ARP) wells, lowering water levels in wells in both the upper aquifer system and the Deep aquifer (fig. 5). From April 10, 1997, to July 29, 1997, ACWD dewatered the ponds by pumping about 7,700 acre-ft of pond water to Alameda Creek. After reconstruction, the ponds were filled to capacity with local runoff from the Alameda Creek watershed, and ARP well pumpage was reduced (fig. 5). Above-average rainfall during fall 1997 and winter 1998 contributed to the availability of water from Alameda Creek for groundwater recharge (fig. 5). Groundwater levels in wells in the shallow aquifer system and the Deep aquifer underlying the Niles Cone groundwater subbasin increased about 20 ft during summer 1997–winter 1998 (fig. 5). InSAR was used to monitor land-surface displacement caused by pumping and subsequent recharge to the aquifer system.

Two independent interferograms span the period of the refilling of the ponds (fig. 6); both interferograms indicate that as much as 0.8 in. (21 mm) of uplift, relative to uplift occurring at the ponds, occurred during this period in the area west from the ponds. The July 17, 1997, to March 19, 1998, interferogram shows a broad uplift feature in distal (lower) parts of the Alameda Creek alluvial fan, west from the Quarry Lakes infiltration ponds. Maximum relative uplift is about 0.8 in. (21 mm). The localized area of maximum uplift to the west of Quarry Lakes may reflect the lithology of the alluvial fan of Alameda Creek. Relative uplift was greater in distal parts of the alluvial fan west of the ponds where finer-grained (clayey) deposits, which are more compressible and expandable than sand-and-gravel layers, compose a greater proportion of the sediments. Relative uplift was less (about 0.4 in. [10 mm]) in the fan near the ponds, which is composed of coarser-grained sediments. Increased hydraulic head from rising groundwater levels caused by pond refilling would be expected to translate rapidly through permeable coarse-grained parts of the aquifer system and then diffuse vertically into finer-grained, expandable deposits and clayey layers.

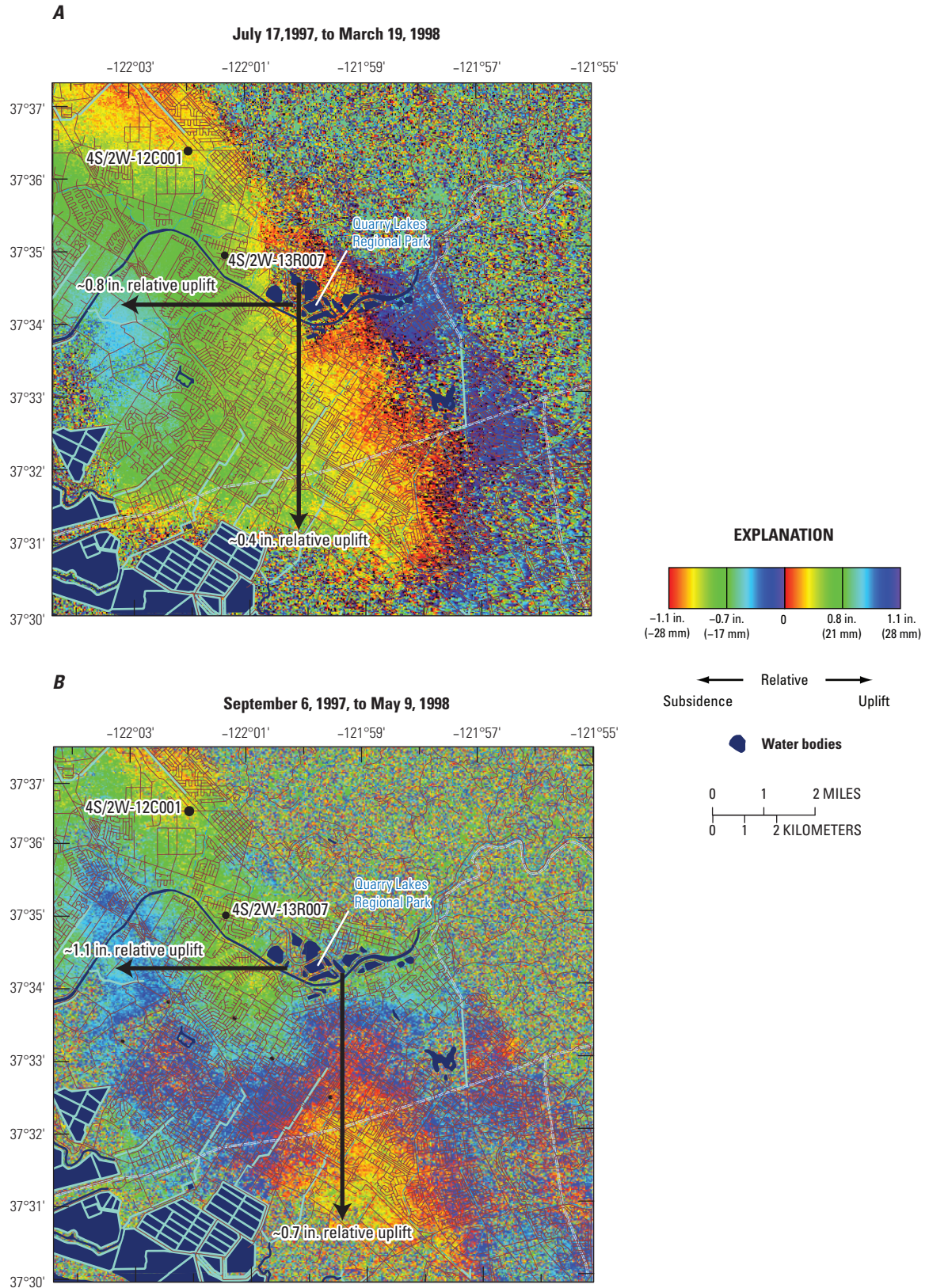


**Figure 4.** Water-level elevation contours and water-level elevations in wells screened in the Deep aquifer; Quarry Lakes Regional Park recharge area; Alameda Creek; and Alameda County Water District (ACWD) Aquifer Reclamation Program (ARP) wells, Niles Cone groundwater subbasin, Alameda County, California, 2002.





**Figure 5.** Precipitation at San Francisco International Airport, water-level elevation at infiltration pond Lago Los Osos, total pumpage from Alameda County Water District's Aquifer Reclamation Program (ARP) wells, and groundwater elevations in selected wells north from Alameda Creek in the Niles Cone groundwater subbasin, Alameda County, California. The highlighted areas mark the (green) period for the interferogram shown in [figure 6A](#) (July 17, 1997, to March 19, 1998) and (blue) period for the interferogram shown in [figure 6B](#) (September 6, 1997, to May 9, 1998).



**Figure 6.** InSAR interferogram displaying relative subsidence or uplift in the Niles Cone groundwater subbasin during refilling of infiltration ponds at Quarry Lakes Regional Park, Alameda County, California. A, July 17, 1997, to March 19, 1998; B, September 6, 1997, to May 9, 1998. [Abbreviations: in., inch; mm, millimeter; ~, about].



Similar relative uplift south of Quarry Lakes is indicated on the September 6, 1997, to May 9, 1998, interferogram; however, a region of relative subsidence is indicated southwest (band of dark blue between Quarry Lakes and the region of uplift) from Quarry Lakes (fig. 6B). The uplift feature on this interferogram is likely a continuation of the uplift seen on the previous interferogram that has increased in magnitude from March (the end date of the first interferogram, fig. 6A) to May (the end date of the second interferogram, fig. 6B) as the hydrostatic pressure from recharging water continued to propagate from the ponds. The subsidence feature is likely due to pumping of groundwater wells in the area, as the interferogram extends into May, which is within the beginning of the pumping season. Incoherent areas (areas of indiscernible color on figures 6A and 6B) in the western parts of the interferogram limit interpretation of the data in this area.

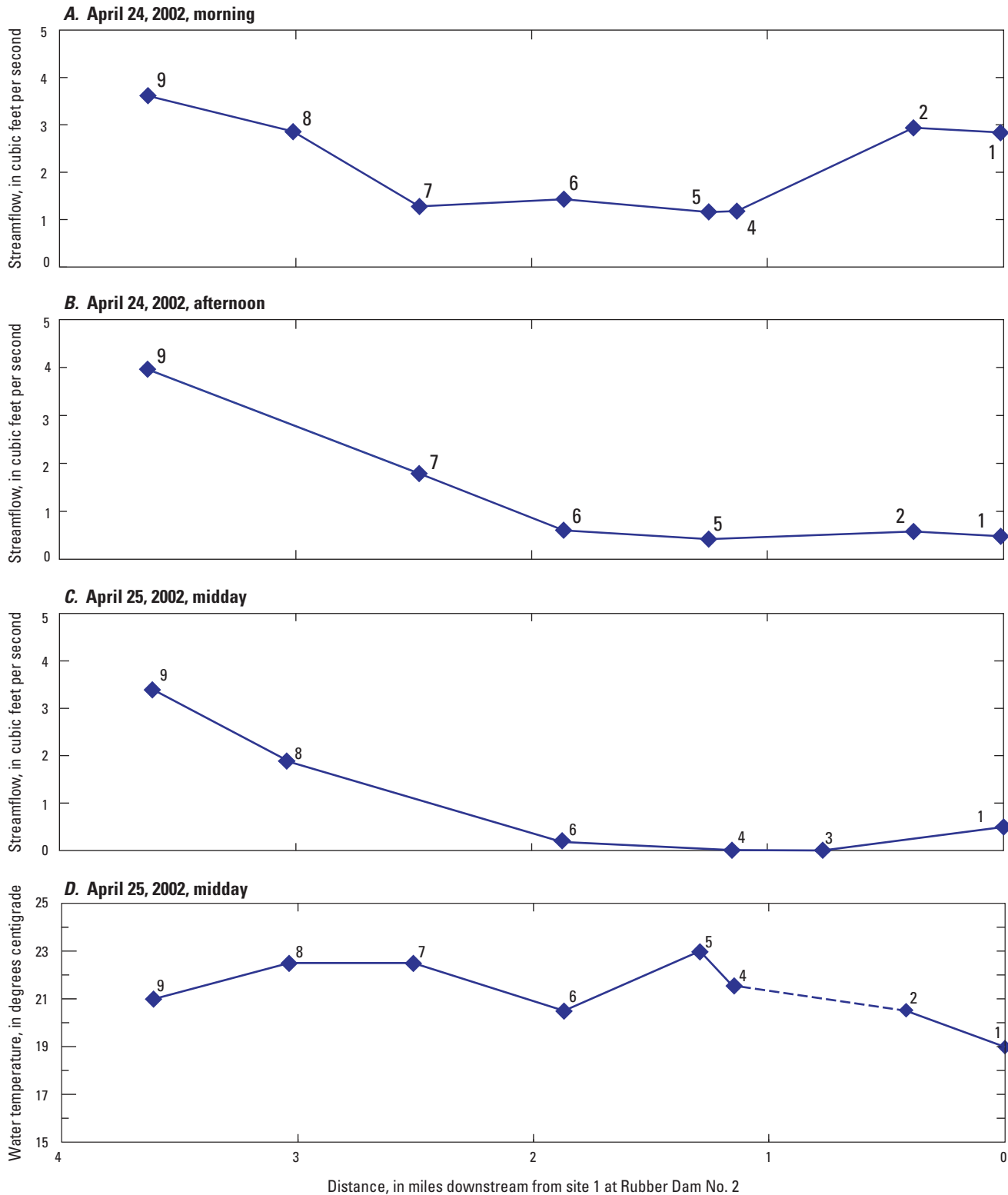
The magnitude of relative uplift west from the recharge ponds is reasonable for elastic expansion of sedimentary materials experiencing an increase in hydraulic head similar to that resulting from pond refilling. Calculated expansion for 600 ft of unconsolidated sediment after a 20-ft increase of hydraulic head ranges from 0.3 to 1.1 in. (7 to 29 mm) for aquifer-system specific storage values ranging from  $2 \times 10^{-6}$  to  $8 \times 10^{-6}$ , respectively (Francis Riley, USGS emeritus, written commun., 2004). Uncertainties regarding the mechanical properties and thickness of sedimentary deposits of the aquifer system preclude estimating a narrower range of likely uplift and complicate the assessment of differences in range change indicated on the interferograms. Elastic compaction of the aquifer system that occurred when ACWD lowered groundwater levels by about 20 ft in the Niles Cone groundwater subbasin prior to construction at the infiltration ponds (winter 1995–fall 1997) could have produced land subsidence of a magnitude similar to expansion of the aquifer indicated on the interferogram (fig. 6); unfortunately, compatible data bracketing the period of water-level decline are unavailable.

## Streamflow Gains and Losses in Alameda Creek

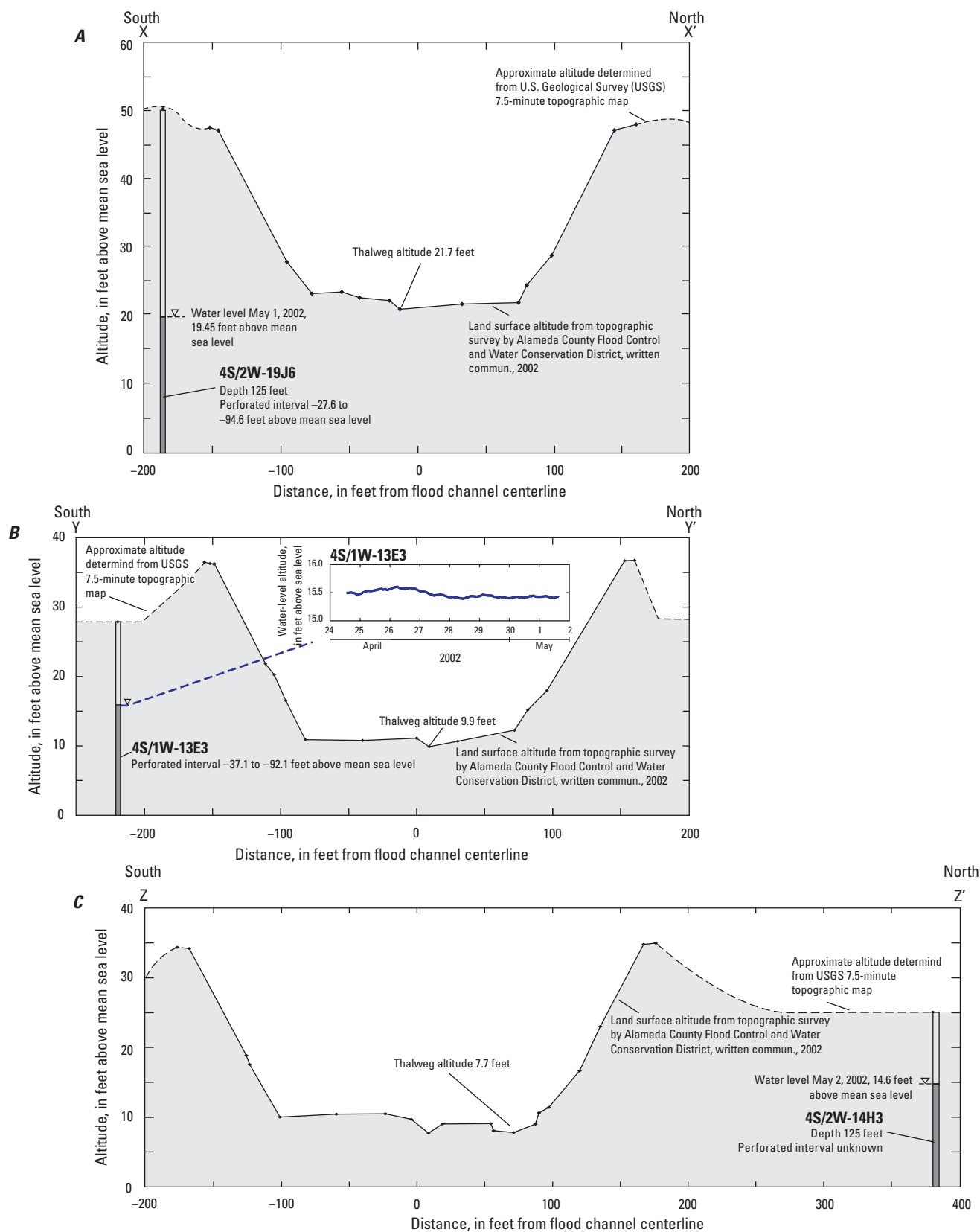
Gaining and losing sections of Alameda Creek (fig. 3) were determined using streamflow measurements (fig. 7),

along with comparisons of stream channel bathymetry with water levels from adjacent wells (fig. 8). Streamflow data are presented in appendix 4. The reach between site 1 and site 5 is generally a losing reach, and streamflow along this reach decreases with increasing distance downstream. The water level measured in well 4S/2W-19J6, located southwest of the channel just downstream from site 3, is lower in elevation than the thalweg of the channel (fig. 8A). Water from this reach likely recharges the upper aquifer system and the Deep aquifer because of the hydraulic connection between the two near Quarry Lakes. The reach from site 6 to just downstream of site 9 is gaining where the mound caused by groundwater recharge at Quarry Lakes intersects the stream, and streamflow along this reach increases with increasing distance downstream. Comparisons of two channel cross sections along the reach, between site 6 and site 9, with adjacent wells, one north of the channel (4S/2W-14H3) and one south of the channel (4S/2W-13E3; fig. 8B), show that water levels in the wells are higher in elevation than the thalweg of the channel. Additional groundwater discharge, in the form of seeps and springs, were present along this reach. Streamflow was measured during a low-flow period, and stream stage data from nearby gage 11180700 suggest that during high winter flows the reach between site 6 and site 9 may be losing. The seepage run results suggest that during the summer low-flow period, Alameda Creek gains about 3.5 cubic feet per second (cfs) between sites 6 and 9. This equates to about 1,270 acre-ft/yr, or about 4 percent of the 30,000 acre-ft/yr estimated to be infiltrated (“Groundwater Management” section), about 5 percent of local groundwater pumping of 24,000 acre-ft/yr, and about 13 percent of pumping at the ARP wells of 10,000 acre-ft/yr.

The water temperature in Alameda Creek was measured at each stream gaging site (fig. 7) and ranged from 19 °C at site 1 to 23 °C at site 5 and averaged 21.3 °C. Water temperature in Alameda Creek was greater than the historical average summer temperature of the area, 18 °C, and was generally warmest downstream from Quarry Lakes. Temperature decreased in the downstream (between sites 6 and 9) gaining reaches of Alameda Creek as a result of groundwater discharge.



**Figure 7.** Streamflow and water-temperature measurements along Alameda Creek, April 24–25, 2002, Alameda County, California.



**Figure 8.** Cross-sectional bathymetry of Alameda Creek. *A*, along section X–X' with water-level elevation in adjacent well 4S/2W-19J6; *B*, along section Y–Y' with water-level elevation in adjacent well 4S/1W-13E3; and *C*, along section Z–Z' with water-level elevation in adjacent well 4S/2W-14H3, Alameda County, California.

## Geochemistry

This section begins with results and discussion of the groundwater chemistry in general and then continues with additional geochemical insights provided by analyses of ionic composition, a mixing model for a diagnostic ionic ratio, and analyses of noble gases, tritium, and other isotopes of water and dissolved carbon.

### Chemistry of Groundwater

Chemistry of water in aquifers underlying the Niles Cone and southern East Bay Plain groundwater subbasins is influenced by the chemistry of the natural and managed aquifer recharge water and the geochemical reactions that occur within the aquifer system. Also, intruding seawater, mixing with water from surrounding and underlying deposits, or mixing with water from estuarine deposits near San Francisco Bay, may alter groundwater chemistry, increase chloride concentrations, and degrade the quality of groundwater. Flow from shallow aquifers into deeper aquifers occurs naturally along the eastern boundary of the study area, along the Hayward Fault, and also through the failed and leaking casings of abandoned wells (San Francisco Bay Regional Water Quality Control Board, 1999). Water-level elevation data are consistent with recharge from the Quarry Lakes Regional Park infiltration ponds reaching the upper aquifer system and the Deep aquifer in the immediate vicinity. Seawater intrusion in aquifers underlying the Niles Cone and southern East Bay Plain groundwater subbasins has been a problem since the late 1800s and was extensively studied in the early 1960s by the California Department of Water Resources (1960, 1963). Results of chemical analysis of 23 samples from 15 deep wells, 6 shallow wells, 1 stream, and 1 precipitation station collected by the USGS are given in [appendix 5](#) at the back of this report. In addition, water chemistry results from a depth-dependent sample taken at 910 ft from 2S/3W-19Q3 (Izbicki and others, 2003) in the East Bay Plain groundwater subbasin are displayed in figures along with results from this study representing water from deep, consolidated sediments (connate water) adjacent to San Francisco Bay.

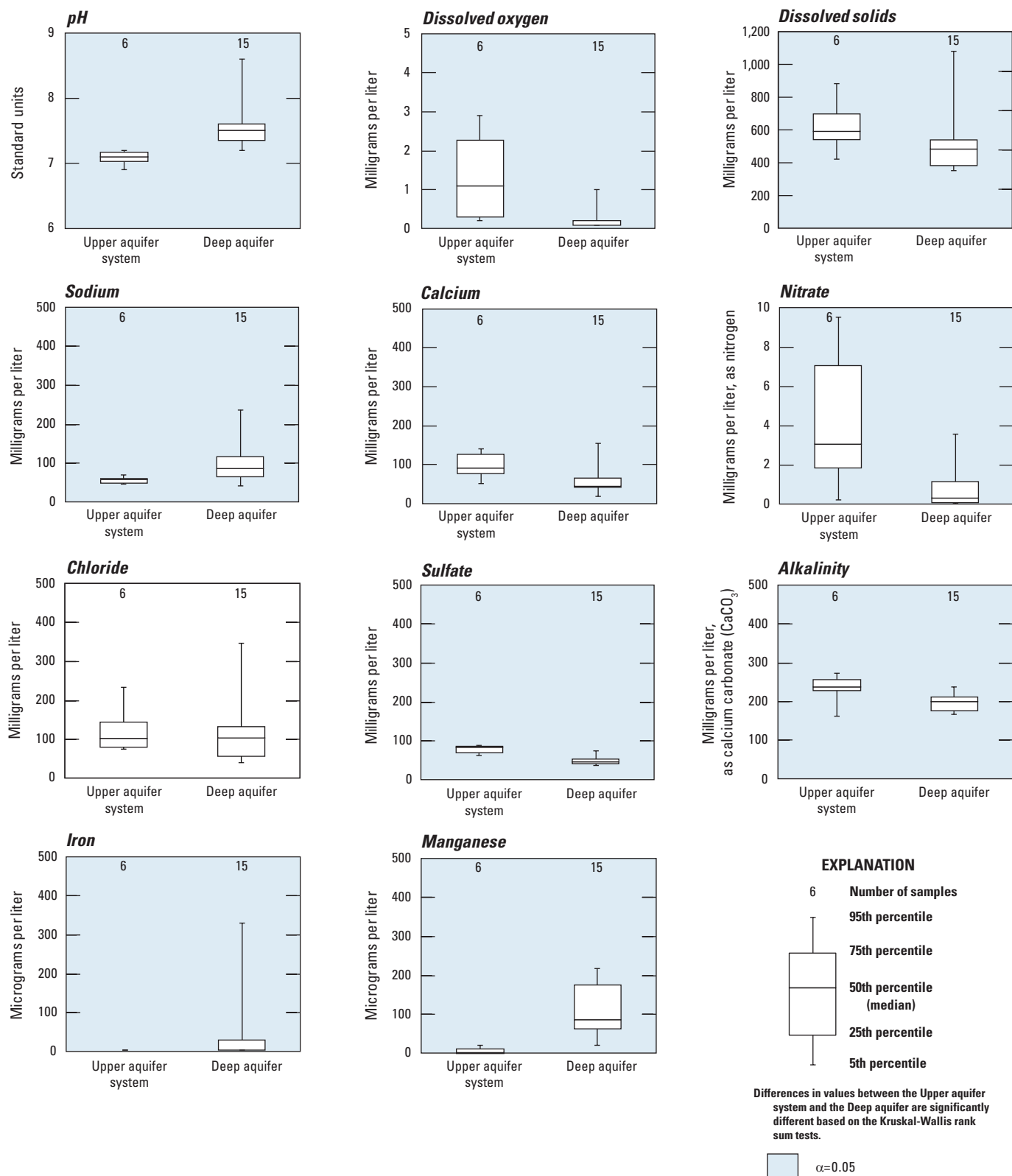
### Physical Properties and Chemical Characteristics of Groundwater

The physical properties and the chemical characteristics of water from wells perforated in the upper aquifer system are different from those of water from wells perforated in the

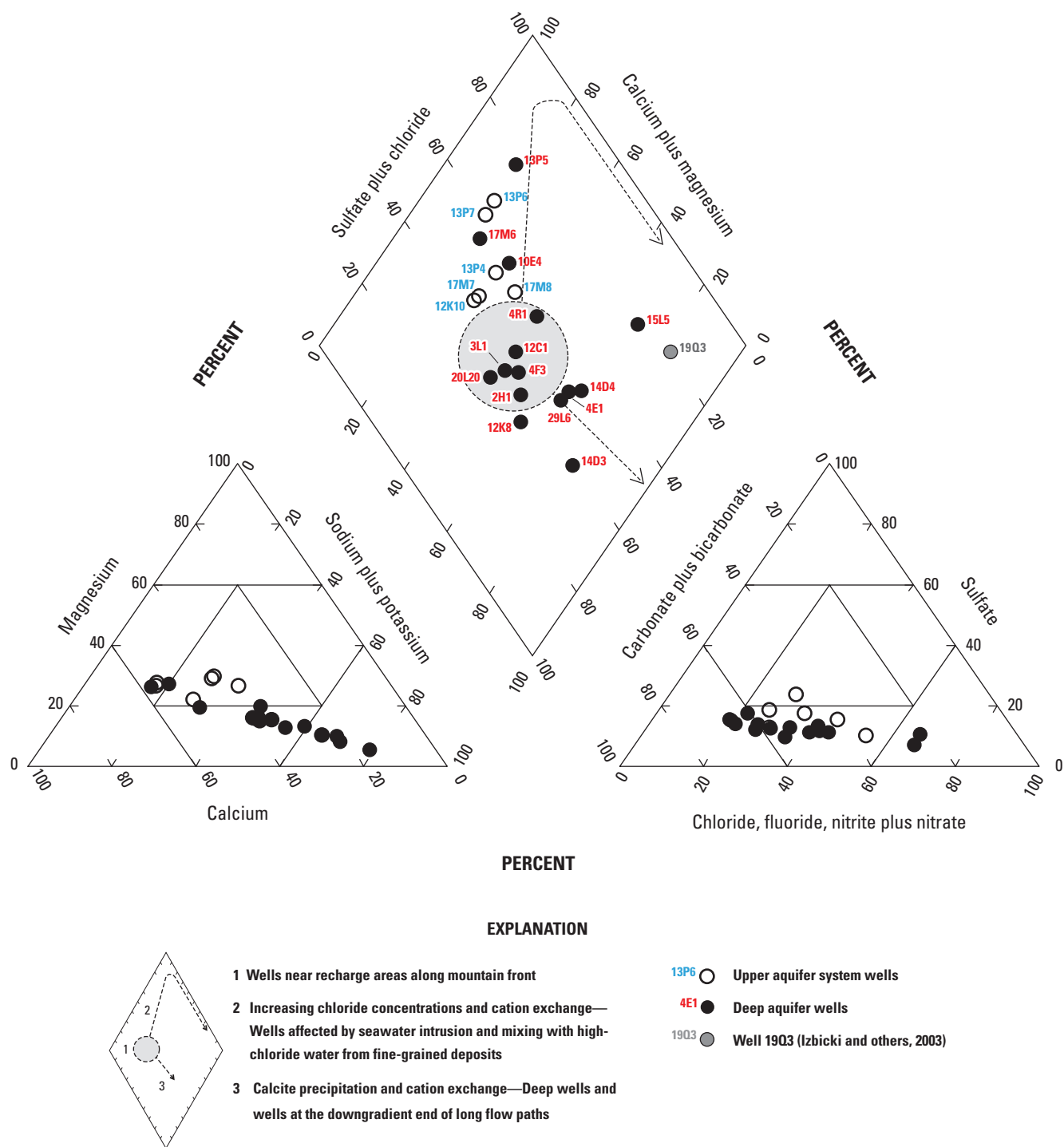
Deep aquifer ([fig. 9](#)). Infiltration of recharge water at Quarry Lakes has influenced the chemistry of water in nearby wells. In addition, water-chemistry data suggest that groundwater from wells may have been affected by seawater intrusion or mixing with poor-quality, high-chloride water from fine-grained estuarine deposits near San Francisco Bay.

The field pH of water sampled from the upper aquifer system and the Deep aquifer ranged from 6.9 to 7.2 and 7.2 to 8.6, with median pH of 7.1 and 7.5, respectively. The highest pH was in water from monitoring well 4S/2W-14D3 completed in the Deep aquifer 400 to 450 ft below land surface. The pH of groundwater from the Deep aquifer was significantly higher than the pH of groundwater from the upper aquifer system ( $P$ -value = 0.0007). In siliciclastic aquifers, groundwater pH increase from slightly acidic to neutral pH near recharge sources to more alkaline values with depth and distance along the groundwater flowpath as a result of primary mineral dissolution (feldspars and micas; Izbicki and others, 1992, 2003).

Dissolved solids (as measured by residue on evaporation) of water sampled from wells in the upper aquifer system and Deep aquifer ranged from 420 to 880 milligrams per liter (mg/L) and 350 to 1,080 mg/L, with median concentrations of 590 and 480 mg/L, respectively. Higher dissolved solids in groundwater from the Deep aquifer were generally associated with higher chloride concentrations. Two monitoring wells in the Deep aquifer, 4S2W-15L5 and 4S/2W-13P5, had dissolved solids concentrations of 880 and 1,080 mg/L, respectively, and chloride concentrations of 346 and 315 mg/L, respectively. These wells represent water that has mixed with high-salinity water intruded from San Francisco Bay and has dissolved solids and chloride values that are not representative of the aquifer systems; to avoid skewing the data, they were excluded from analyses of dissolved solids and chloride data. Excluding wells impacted by high-chloride water ( $>250$  mg/L), the median dissolved-solids concentration was significantly higher in water from wells in the upper aquifer system ([fig. 9](#)) than in water from wells in the Deep aquifer ( $P$ -value = 0.0085). Higher dissolved solids concentrations in some of the upper-aquifer-system wells may reflect changes in recharge water chemistry as the Alameda Creek watershed has become more urbanized in recent years, increasing anthropogenic effects on water chemistry. Alternatively, the lower dissolved-solids concentrations in the Deep aquifer could be the result of geochemical reactions that remove constituents from groundwater, such as sulfate through sulfate reduction under reduced conditions, or calcium and sodium through cation exchange ([fig. 10](#)), as will be discussed in the “[Major-Ion Composition](#)” section below.



**Figure 9.** pH, dissolved oxygen, and selected major-ion, nutrient, and trace-element concentrations in water from wells sampled in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.



**Figure 10.** Major-ion composition of samples from selected wells in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.



Water from wells sampled in the upper aquifer system was both oxic ( $>0.30$  mg/L) and suboxic ( $<0.30$  mg/L; Tiedje, 1988), with dissolved oxygen concentrations ranging from 2.9 to 0.2 mg/L, whereas water from wells in the Deep aquifer was generally reduced, with dissolved oxygen concentrations no greater than 1 mg/L. The dissolved oxygen concentrations of water from sampled wells in the Deep aquifer were significantly less than the concentrations in water from wells in the upper aquifer system ( $P$ -value = 0.0025). Differences in oxidation-reduction (redox) conditions between the upper aquifer system and the Deep aquifer may explain significantly lower concentrations of nitrate ( $P$ -value = 0.0124) and higher concentrations of manganese ( $P$ -value = 0.0005) and iron ( $P$ -value = 0.0325) in water from wells in the Deep aquifer compared to the upper aquifer system. Although no wells exceeded the EPA drinking water maximum contaminant level (MCL) for nitrate of 10 mg/L as nitrogen, two wells completed in the upper aquifer system near recharge areas at Quarry Lakes and along Alameda Creek, 4S/2W-12K10 and 4S/2W-13P7, had nitrate concentrations of 8.1 and 9.5 mg/L as nitrogen, respectively. Similar to dissolved solids, higher nitrate concentrations in water from these wells also could result from changing land use and increased urbanization in the Alameda Creek watershed; specific sources may include agricultural or residential fertilizer use and septic discharges.

## Major-Ion Composition

The major-ion composition of water from sampled wells was evaluated using a Piper (trilinear) diagram. A Piper diagram (Piper, 1944) shows the relative contribution of major cations and anions, on a charge-equivalent basis, to the total ionic content of the water. Percentage scales along the sides of the diagram indicate the relative concentration, in milliequivalents per liter, of each major ion. Cations are shown in the left triangle and anions are shown in the right triangle; the central diamond integrates the data.

Water from upper-aquifer-system wells located near Quarry Lakes, 4S/2W-13P4, 13P6, 13P7; 4S/1W-17M7–8; and 4S/2W-12K10, has a major-ion composition marked by higher calcium and magnesium percentages than water from most wells in the Deep aquifer (fig. 10). These wells are possibly influenced by water recharged at Quarry Lakes, as well as water from the ponded areas behind the inflatable dams in Alameda Creek. Most water from wells in the Deep aquifer plot below data from the upper aquifer system on figure 10, because of an increase in sodium relative to calcium plus magnesium and an increase in bicarbonate as water flows through the aquifer. In coastal aquifers in California, including the East Bay Plain groundwater subbasin, similar trends have been attributed to precipitation of calcite and (or) exchange of calcium and magnesium for sodium on clay within aquifer deposits and dissolution of carbonate minerals, respectively (Izbicki and others, 1992, 2003). Water from wells 13P5, 17M6, and 4S/2W-10E4 in the Deep aquifer has elevated chloride concentrations and plots along a line above and to the

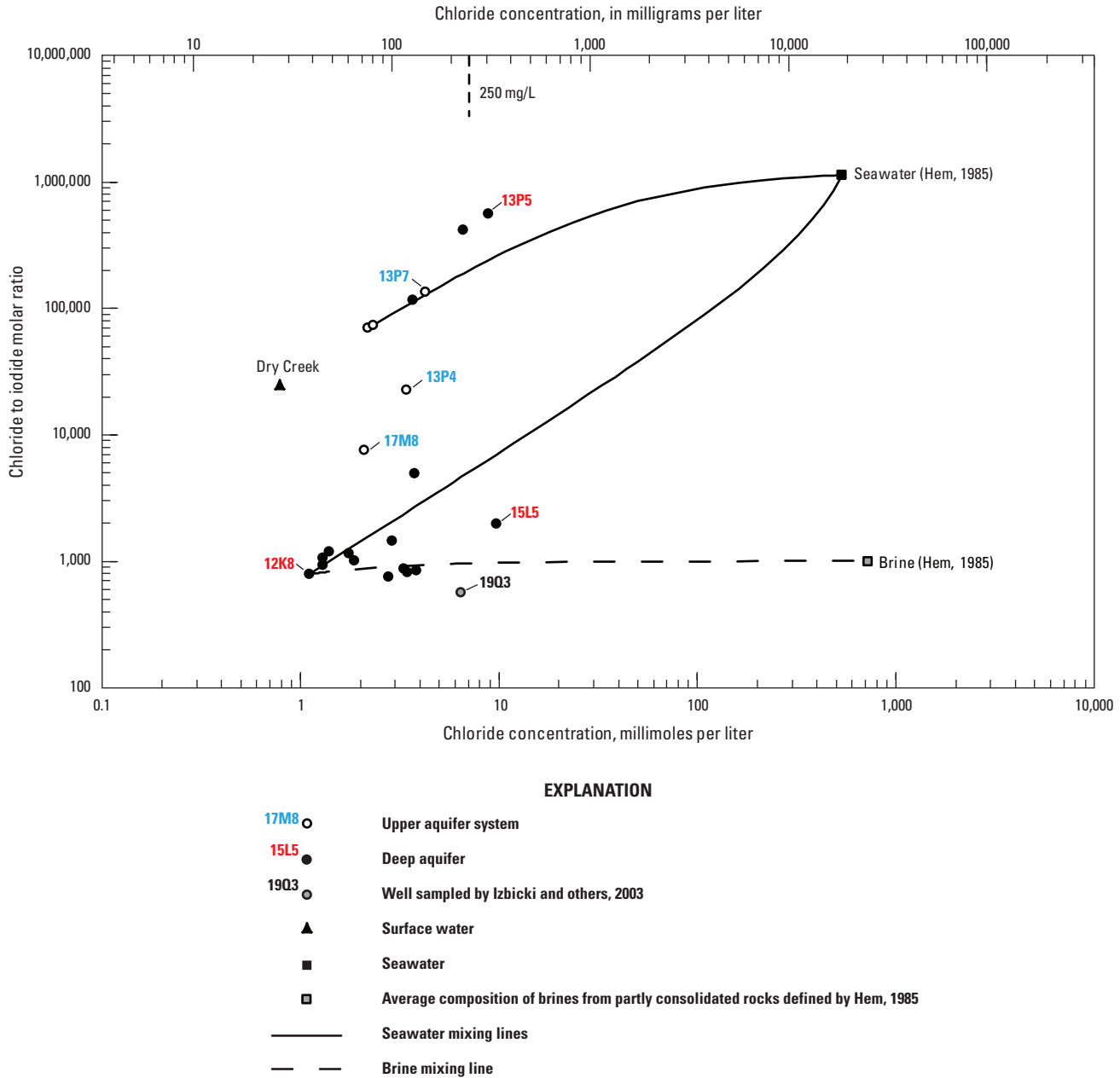
right of data from the upper aquifer system in figure 10. This pattern is characteristic of groundwater intruded by seawater (Piper and Garrett, 1953; Izbicki, 1996; Izbicki and others, 2003) and is the result of the exchange of sodium for calcium and magnesium on clay in aquifer deposits. Similar patterns have been observed in the East Bay Plain groundwater subbasin (Muir, 1997; Izbicki and others, 2003). Water from well 4S/2W-15L5 has major-ion proportions similar to well 2S/3W-19Q3, which yields water from partly consolidated sediments underlying freshwater aquifers of the East Bay Plain groundwater subbasin (Izbicki and others, 2003), suggesting the source of high-chloride water to well 15L5 is likely from partly-consolidated marine rock.

## Chloride-to-Iodide Ratios

Use of certain minor ions and trace elements to determine the source of high-chloride water to wells in the Long Beach and Santa Ana areas of southern California was demonstrated by Piper and Garrett (1953). Other studies have applied these techniques to the study of the source and movement of seawater and other brines in aquifers (Jones and Garbarino, 1999; Izbicki, 1996; Izbicki and others, 2003), and increasingly refined approaches have been developed to distinguish mixtures of native (fresh) water and seawater from mixtures of native water and high-chloride water from underlying partly consolidated rock in coastal California aquifer systems (Izbicki, 1991; Izbicki, 1996). In this report, chloride-to-iodide ratios were used to determine the source of high-chloride water to wells and to evaluate the geochemical evolution of water as it flows through unconsolidated deposits underlying the Niles Cone and southern East Bay Plain groundwater subbasins (fig. 11).

Chloride is highly soluble and not readily sorbed on mineral surfaces or organic material. In addition, with the exception of evaporite salts, chloride does not occur at high concentrations in most rock-forming minerals or aquifer materials (Feth, 1981; Davis and others, 1998).

Iodide is affected by biological and redox processes and is reactive in groundwater systems. Iodide concentrations in seawater are low, about 0.06 mg/L; however, iodide concentrations in marine rocks and unconsolidated material deposited in marine environments are elevated relative to seawater and nonmarine materials owing to concentration of iodide from seawater by nearshore marine vegetation (Hem, 1985). Previously reported iodide concentrations in high-chloride water from marine rocks that surround and underlie coastal aquifers in California are as high as 2.4 mg/L (Izbicki and others, 2003). Iodide concentrations in highly concentrated brines from some deep wells can be as high as 46 mg/L (Hem, 1985). Ratios are especially sensitive to mixing, and the addition of a small volume of water having different chloride and trace-element compositions may produce a large change in the trace-element-to-chloride ratio of water from a well.



**Figure 11.** Chloride-to-iodide ratios as a function of chloride concentration in water from wells, Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.

Iodide concentrations in water from wells underlying the Niles Cone and southern East Bay Plain groundwater subbasins ranged from 0.002 to 0.632 mg/L. Chloride-to-iodide ratios in wells in the upper aquifer system ranged from 7,600 to 135,000 (fig. 11). For waters having chloride concentrations below 250 mg/L (about 8 millimoles per liter; fig. 11), higher chloride-to-iodide ratios are typical in water from alluvium eroded from granitic terrain and from Franciscan rocks (Izbicki, 1991; Izbicki, 1996). The chloride-to-iodide ratios for water from wells 4S/1W-17M8 and 4S/2W-13P4, the uppermost wells near Quarry Lakes, are lower than those of the three other upper-aquifer-system wells in the area with data (fig. 11). These ratios are probably representative

of the water recharged at Quarry Lakes, owing to the close proximity to Quarry Lakes and shallow screens of the wells. Other upper-aquifer-system wells near the recharge area plot along a line representative of mixing of recharge through local rivers and streams, represented by a Dry Creek sample, and seawater (Hem, 1985).

Water from most wells screened in the Deep aquifer has a chloride-to-iodide ratio around 1,000, typical of alluvial deposits weathered from marine rocks and water from partly consolidated marine rock (Piper and Garrett, 1953; Izbicki, 1991; Land and others, 2002). The chloride-to-iodide ratio is greatest in Deep aquifer well 13P5, with a value of 560,000, and plots slightly above the seawater mixing line (fig. 11).

Water in this well is likely influenced by past seawater intrusion. The highest iodide concentration (0.632 mg/L) was in the water collected from well 4S/2W-15L5. The chloride-to-iodide ratio in this well plots to the right of water from most wells in the Deep aquifer and could be a three-component mixture of brine, seawater, and native Deep aquifer water. The water in well 15L5 has the most similarity in composition to high-chloride brines from partly consolidated deposits that surround and underlie coastal aquifers in California (Izbicki, 1996; Izbicki and others, 2003). Consistent with major-ion data and data from well 19Q3, water from partly consolidated marine rock may be the primary source for elevated iodide in well 4S/2W-15L5.

## Geochemical Indicators of Groundwater Movement

The major-ion and chloride-to-iodide data suggest that recently recharged water is the primary source of groundwater to wells in the upper aquifer system. Water recharged at Quarry Lakes primarily affects the uppermost and adjacent wells. Sources of recharge to other upper aquifer system wells include recharge through local rivers and streams. Major-ion composition changes caused by interactions with aquifer material as groundwater moves away from recharge sources, and laterally through the Deep aquifer, are evident in data for wells in the northern part of the Niles Cone groundwater subbasin. The major-ion and chloride-to-iodide data for water from Deep aquifer wells adjacent to Quarry Lakes is characteristic of groundwater intruded by seawater, indicating that water recharged at Quarry Lakes is not a major source of recharge to the Deep aquifer. The major-ion and chloride-to-iodide data for water from well 4S/2W-15L5 is similar to groundwater mixing with water from partly consolidated sediments underlying freshwater aquifers of the East Bay Plain groundwater subbasin, suggesting that water from partly consolidated marine rock may be an important source of chloride in the western part of the Niles Cone groundwater subbasin.

## Noble-Gas and Tritium Analysis

Dissolved noble gases measured as part of this study include helium (He), neon (Ne), argon (Ar), and krypton (Kr). The inert nature of these gases, coupled with their differences in solubility at different temperatures, makes them useful for studying groundwater chronology, paleoclimatology, and mechanisms of groundwater recharge. The solubility of the noble gases in groundwater can be estimated by Henry's law, as a function of the temperature and salinity of the water, and the atmospheric partial pressure of the gas (Ozima and Podosek, 1983). The total concentration of a gas in a sample is the sum of the equilibrium concentration and the excess air, radiogenic, and terrigenic components. Three models are commonly used to interpret dissolved gas concentrations in groundwater: (1) unfractionated air (UA) model (Heaton and

Vogel, 1981), (2) partial reequilibration (PR) model (Stute and others, 1995), and (3) closed system equilibrium (CE) model (Aeschbach-Hertig and others, 2000). The UA model assumes the excess air component is atmospheric air resulting from complete dissolution of entrapped air bubbles. The PR model assumes elemental fractionation in the excess air component (lighter gases depleted relative to heavier gases) resulting from complete bubble dissolution followed by diffusive degassing. The CE model assumes that fractionation of excess air results from incomplete dissolution of entrapped air bubbles, and the fractionation factor is related to the individual gas solubilities. Neon oversaturation (positive  $\Delta\text{Ne}$ ) has been used as a proxy for excess air and contamination during sample collection (Kipfer and others, 2002). Since Ne is not produced in the subsurface, any Ne in excess of that expected from solubility equilibrium is attributed to excess-air entrainment during recharge ( $\Delta\text{Ne}\% = [(\text{Ne}_{\text{measured}}/\text{Ne}_{\text{eq}}) - 1] * 100$ ) (Mazor, 1972). Large quantities of excess air reflect rapid recharge from focused recharge during floods (or managed aquifer recharge), resulting in the dissolution of trapped air bubbles by increased water pressure. Dissolution and reequilibration processes were evaluated using the program NOBLEGAS (Aeschbach-Hertig and others, 1999) and determined not to effect excess-air concentrations in groundwater samples from the study area. An iterative subtraction approach was used to calculate the amount of excess air in a sample and estimate groundwater temperature at the time of recharge (Stute, 1989; Stute and others, 1995). This approach uses temperature as the fit target and varies the parameter values for excess air and reequilibration, while keeping the values for salinity and atmospheric pressure constant, such that the spread of the temperatures calculated for each noble gas is minimized. The measured noble gas concentrations are corrected for excess air, and a temperature is calculated using the corrected noble gas concentration. This process is repeated until agreement between the temperatures for each gas reach a desired agreement. In this study, groundwater recharge temperatures (NGT) were estimated from neon, argon, and krypton concentrations in groundwater. Helium was not used to calculate NGT because the measured He concentrations are significantly in excess of anticipated air-equilibration values.

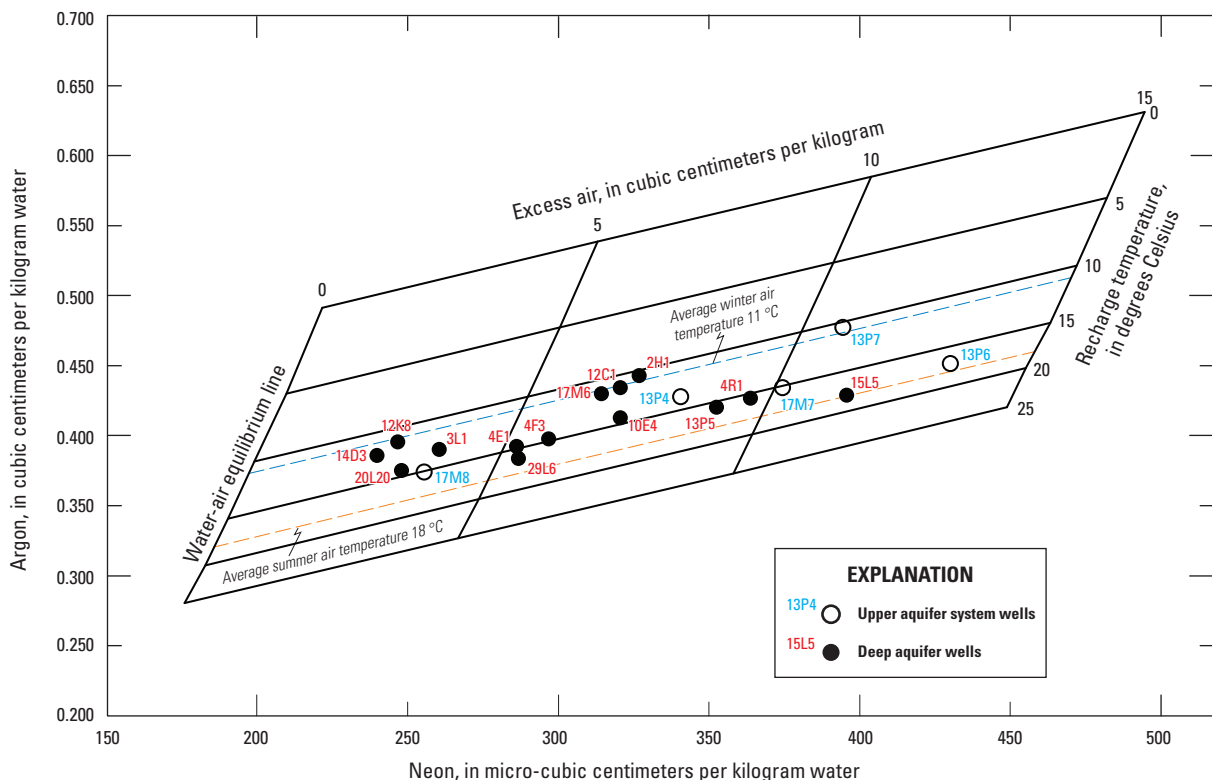
The magnitude of the excess air component and NGT can be used as a proxy for relative infiltration conditions, as periods of recharge may be seasonal, and periods of greater recharge may result in the entrainment of larger amounts of excess air in groundwater (Heaton and Vogel, 1981; Heaton and others, 1986; Kulongoski and others, 2003). For the purpose of this study, groundwater NGT cooler than about 11 °C and excess-air concentrations greater than 10 cubic centimeters per kilogram ( $\text{cm}^3/\text{kg}$ ) are interpreted to be consistent with focused recharge from winter stormflows that infiltrated rapidly through the unsaturated zone (trapping air). In contrast, groundwater NGT warmer than 11 °C and excess-air concentrations lower than 10  $\text{cm}^3/\text{kg}$  are consistent with recharge from sustained streamflows along losing stream reaches downstream from the mountain front, with areal recharge from precipitation, or irrigation return flows that infiltrated slowly through the unsaturated zone prior to recharge (Stute and Schlosser, 2000).

The noble gas concentrations measured in groundwater from the Niles Cone and southern East Bay Plain groundwater subbasins are presented in appendix 6, along with salinity,  $\Delta N_e$ , the calculated NGTs, helium-4 ages, tritium, and tritium/ $^3\text{He}$  ages. The observed excess-air component,  $\Delta N_e$ , ranges from 22.2 to 126.1 percent (appendix 6). The median  $\Delta N_e$  values for the upper aquifer system and the Deep aquifer were 94.9 and 56.6 percent, respectively. Although the medians suggest that the excess air component is greater in the upper aquifer system than in the Deep aquifer, this difference was not significant ( $P$ -value = 0.06). Values of NGTs in both the upper aquifer system and Deep aquifer range from near the average winter temperature of 11 °C to slightly greater than the average summer temperature of 18 °C. The median NGT of 15.4 °C was close to the average annual temperature of the area of 15 °C. Calculated NGTs derived from samples from wells in the upper aquifer system ranged from  $10.6 \pm 0.7$  to  $19.2 \pm 0.8$  °C (fig. 12 and appendix 6). Calculated NGTs derived from samples from wells in the Deep aquifer ranged from  $10.1 \pm 0.7$  to  $18.1 \pm 0.8$  °C.

Differences in excess air values and NGTs in upper aquifer system wells and Deep aquifer wells in the southeastern part of the study area suggest that recharge processes were different before the introduction of managed aquifer recharge. Presently, the Deep aquifer wells near Quarry Lakes are recharged from the shallow aquifer; therefore, similar excess air and NGT values for the upper aquifer system and the Deep aquifer would be expected

following propagation of managed aquifer recharge through the entire aquifer system. However, the range in NGTs was greatest in the upper aquifer system and the Deep aquifer wells near recharge areas adjacent to Quarry Lakes and along Alameda Creek. Historically, recharge may have occurred during seasonal flow in Alameda and Dry Creeks. Well 17M6, and also wells 12C1 and 2H1, has a slightly cooler NGT, and lower excess air value, than upper aquifer system well 17M7 and likely represents water that was recharged during sustained winter streamflow in Dry Creek. Well 13P5 has a slightly warmer NGT, and lower excess air value, than upper-aquifer-system well 13P7 and likely represents water that was recharged during summer streamflows in Alameda Creek. The data also suggest that water in wells 15L5 and 4R1 may have been recharged from a source similar to that of well 13P5.

The relative increase in excess air from the Deep aquifer wells 13P5 and 17M6 to their respective upper aquifer system wells 13P6 and 13P7, and 17M7 (fig. 12), is likely a result of rapid fluctuation of the water table, and resulting bubble entrapment and dissolution, possibly associated with managed aquifer recharge or rapid groundwater recharge along the mountain front. The shallowest wells near the recharge areas (17M8 and 13P4) have excess-air values less than the deeper wells in the area, suggesting that these wells may receive water that is diffusely recharged from precipitation or as water lost to the unsaturated zone surrounding the areas of managed aquifer recharge.



**Figure 12.** Selected noble-gas concentrations in water from selected wells in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.



The excess-air values and NGTs for wells in the transition zone and the southern East Bay Plain groundwater subbasin suggest areal recharge from precipitation. Most of the wells in the transition zone (10E4, 3L1, 4F3, and 4E1) have excess-air values less than those of wells near Dry Creek and NGTs near the average annual temperature of 15 °C. Wells located north of the transition zone, in the southern East Bay Plain groundwater subbasin (29L6 and 20L20), have low excess-air values and NGTs near the average annual temperature of 15 °C. The NGTs for wells 29L6 and 20L20 were warmer than those estimated for groundwater recharged from San Lorenzo and San Leandro Creeks in the southern East Bay Plain groundwater subbasin to the north of the study area (Izbicki and others, 2003), suggesting that recharge in the area south of San Lorenzo Creek is from areal recharge from precipitation.

## Tritium and Helium

Tritium ( $^3\text{H}$ ) was used to indicate the presence of recent (post-1950s) water. Tritium is a naturally occurring radioactive isotope of hydrogen that has a half-life of 12.43 years. In this study, tritium concentrations are reported in tritium units (TU); 1 tritium unit is equivalent to 1 tritium atom in  $10^{18}$  atoms of hydrogen (Taylor and Roether, 1982). Prior to 1952, the tritium concentration in precipitation in coastal California was about 2 TU. About 800 kilograms (kg) of tritium was released to the atmosphere as a result of the atmospheric testing of nuclear weapons during 1952–62 (Michel, 1976), and the tritium concentration of precipitation increased to a maximum of about 1,200 TU. After the cessation of atmospheric testing of nuclear weapons in 1962, the tritium concentration of precipitation decreased and present-day tritium levels in precipitation are near the pre-1952 levels. Because tritium is part of the water molecule, tritium is not affected by reactions other than radioactive decay, and—neglecting the effects of dispersion—tritium is an excellent tracer of the movement of groundwater recharged less than 50 years before present.

Helium has two stable isotopes, helium-3 ( $^3\text{He}$ ) and helium-4 ( $^4\text{He}$ ). Most helium in the natural environment (atmospheric) is helium-4;  $^3\text{He}$  concentrations are orders of magnitude smaller than  $^4\text{He}$  concentrations. As with many isotopes, the ratio of  $^3\text{He}$  to the more abundant isotope  $^4\text{He}$  can be measured more precisely than can the absolute abundance of a single isotope, and  $^3\text{He}$  data are reported as delta helium-3 ( $\delta^3\text{He}$ ). Helium concentrations in groundwater originate from several sources; these sources must be accounted for in order to estimate tritium/helium-3 apparent ages.

Water in contact with the atmosphere contains gases, including helium, as a result of equilibrium (Henry's law) partitioning between atmosphere and water. In groundwater, final solubility equilibration between water and air occurs as water reaches the water table. Concentrations of gasses in the groundwater are a function of recharge temperature. For example,  $^3\text{He}$  is naturally present in the atmosphere, and water at 10 °C in equilibrium with the atmosphere will have a  $^3\text{He}$

concentration of 63.7  $\text{cm}^3/\text{kg}$  at 10 °C (Solomon and Cook, 2000).

Another source of gases to ground water is known as excess air (Heaton and Vogel, 1981; Busenberg and Plummer, 2000; Stute and Schlosser, 2000). Excess air is thought to result from dissolution of air bubbles entrained by a fluctuating water table or trapped near the water table by recharging water. Gases, including helium and neon, in excess air are assumed to be added to groundwater in the proportions in which they exist in the atmosphere (unfractionated air; Heaton and Vogel, 1981; Schlosser and others, 1989). Unlike helium, neon does not have significant subsurface sources, so  $^3\text{He}$  and  $^4\text{He}$  from excess air are assumed to be proportional to the neon from excess air. Excess air trapped during groundwater recharge will increase the  $^3\text{He}$  contribution from atmospheric sources. Cook and Solomon (1997) estimated that the sensitivity of tritium/helium-3 ages to excess air ranges from –5.0 years per cubic centimeter per kilogram ( $\text{cm}^3/\text{kg}$ ) of excess air for very young groundwater to –0.25 year per  $\text{cm}^3/\text{kg}$  of excess air for groundwater recharged 25 years before present.

Helium is also added to groundwater from uranium- and thorium-series decay reactions in the Earth's crust (radiogenic). Radiogenic  $^3\text{He}$  produced in the subsurface through the decay of lithium-6 is small and does not affect the tritium/helium-3 age in most groundwater systems (Solomon and Cook, 2000). Production of  $^4\text{He}$  is the result of the decay of elements in the uranium-thorium radioactive decay series, other than  $^6\text{Li}$ . The  $^3\text{He}/^4\text{He}$  ratio of radiogenic helium in deep crustal material is about  $3 \times 10^{-8}$  (Mamyrin and Tolstikhin, 1984).

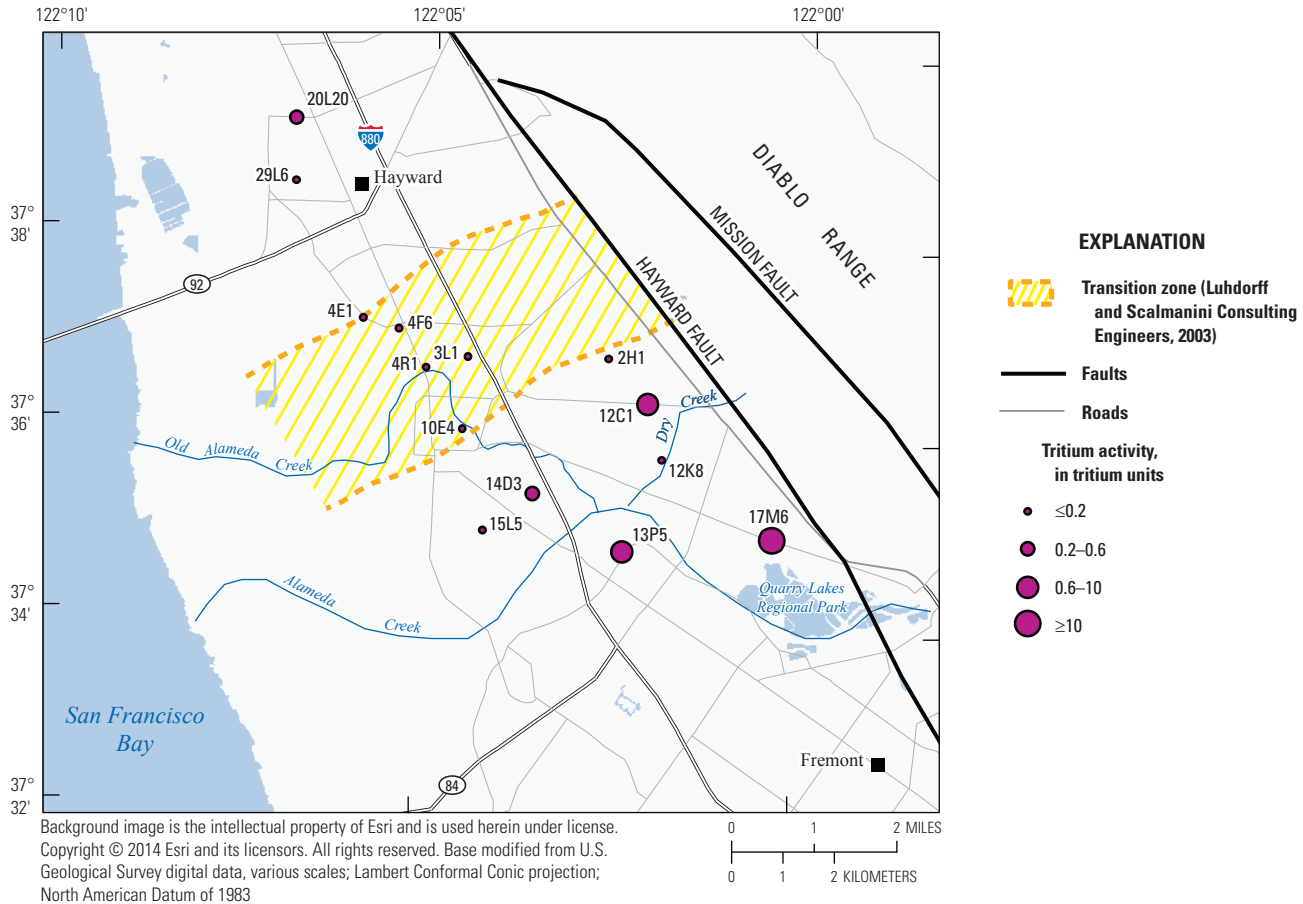
Because the  $^3\text{He}$  term is small for most groundwater and the  $^4\text{He}$  from radioactive decay is usually small for young ground water, the radiogenic  $^3\text{He}$  and  $^4\text{He}$  terms are combined with the helium terms from mantle degassing. The ratio of  $^3\text{He}$  to  $^4\text{He}$  in mantle gases is between  $1 \times 10^{-5}$  and  $1.4 \times 10^{-5}$  (Torgersen and Clarke, 1987).

Finally,  $^3\text{He}$  is produced by the radioactive decay of tritium (tritogenic helium). Solomon and Cook (2000) published a simultaneous solution to the  $^3\text{He}$  and  $^4\text{He}$  mass-balance equations that uses measured  $^4\text{He}$  concentrations,  $\delta^3\text{He}$  values, and neon concentrations (to constrain recharge temperatures and excess-air values) to calculate the concentration of  $^3\text{He}$  from the radioactive decay of tritium. Ground-water ages are then calculated on the basis of the radioactive decay of tritium.

## Tritium-Helium-3 Ages

Tritium in water from sampled wells in the upper aquifer system and Deep aquifer ranged from 7.2 to 46.6 TU and from less than the reporting limit of 0.2 to 16.6 TU, respectively (table 6–1). Tritium was present in water from wells in the Deep aquifer near Quarry Lakes and Alameda Creek and concentration decreased with distance from the recharge area to values below the reporting level of 0.2 TU (fig. 13).





**Figure 13.** Spatial distribution of tritium concentrations in groundwater from selected Deep aquifer wells in the Niles cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.

Detections of tritium in Deep aquifer wells near recharge areas suggest a primary contribution of water recharged at the surface. Groundwater samples from Deep aquifer wells to the northwest have tritium levels less than the reporting limit of 0.2 TU and are considered “tritium dead.” These waters have been isolated from surface recharge for more than 50 years.

Tritium/helium-3 ages for groundwater range from 6 to >50 years (appendix 6). The tritium/helium-3 ages reflect the age of young fractions of groundwater recharged in the last 60 years. Water from Deep aquifer wells has less tritium and higher concentrations of helium, providing evidence that these groundwater samples are older than water from the upper-aquifer-system wells (appendix 6). Combined with lower recharge temperatures, this suggests that the Deep aquifer was mostly recharged under cooler, natural conditions (managed aquifer recharge leads to high  $\Delta N_e$ ), occurring more than 50 years before the sample analyses year (2002). In the study area, none of the noble gas and tritium samples showed substantial mixing of young and old waters. Rather, there was a clear areal delineation between wells containing modern and pre-modern waters. In monitoring well nests 17M6–8 and 13P5–7, groundwater ages were younger at shallower depths and older at greater depths (appendix 6).

## Helium-4 Ages

A naturally occurring isotope of helium present within the Earth’s crust,  $^4\text{He}$ , was used to estimate time since recharge for groundwater that does not contain measurable tritium and is older than the range of tritium/helium-3 dating techniques. The  $^4\text{He}$  ages are calculated from the accumulation of produced radiogenic  $^4\text{He}$  in groundwater. Contributions to the  $^4\text{He}$  inventory include two components: in situ production within the aquifer and a deep crustal flux ( $J_0$ ). Assuming that the deep crustal flux may be quantified (or neglected), the former component has chronological significance for the groundwater age. Stute and others (1992) proposed an approach by which the different helium sources may be separated, enabling either groundwater ages or crustal helium fluxes to be estimated. The relationship between apparent (corrected) groundwater age ( $\tau_{\text{corr}}$ , in years) and deep crustal flux entering the aquifer ( $J_0$ ,  $^4\text{He}$  in  $\text{cm}^3 \cdot \text{STP} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$ ) is given by equation 1 (Stute and others, 1992):

$$\tau_{corr} = \frac{{}^4He_{ex}}{\left( \frac{J_0}{\phi z_o \rho_w} + {}^4He_{sol} \right)} \quad (1)$$

where

- ${}^4He_{ex}$  is the excess  ${}^4He$  (above concentrations expected from air equilibration and air bubble contamination),
- $\phi$  is the effective porosity of the aquifer,
- $z_o$  is the depth (m) at which the deep crustal flux enters the aquifer, and
- $\rho_w$  is the density of water ( $\sim 1$  g/cm<sup>3</sup>).

The  ${}^4He$  solution or accumulation rate ( ${}^4He_{sol}$  in cm<sup>3</sup>•STP•g<sup>-1</sup> H<sub>2</sub>O•yr<sup>-1</sup>) is given by equation 2, which combines the radioelement content of the aquifer {in brackets} with its physical properties (Andrews and Lee, 1979):

$${}^4He_{sol} = \rho \times \Lambda \times \left\{ 1.19 \times 10^{-13} [U] + 2.88 \times 10^{-14} [Th] \right\} \times \frac{1-\phi}{\phi} \quad (2)$$

where

- [U] and [Th] are the uranium and thorium concentrations in the aquifer rock in parts per million (ppm),
- $\rho$  is the bulk density of the aquifer rock (g/cm<sup>3</sup>),
- $\Lambda$  is the fraction of helium produced in the rock that is released into the water, assumed to be unity, and
- $\phi$  is the fractional effective porosity of the aquifer rock.

Assuming aquifer properties for the Deep aquifer of porosity ( $\phi$ ) of 35 percent, and bulk density ( $\rho$ ) of 1.76 g/cm<sup>3</sup>, with average uranium and thorium concentrations of 1.4 and 5.2 milligrams per kilogram of alluvium (ppm; appendix 3), then the groundwater accumulation rate for  ${}^4He$  in the study area would be  $\sim 1.04 \times 10^{-12}$  cm<sup>3</sup>•STP•g<sup>-1</sup> H<sub>2</sub>O•yr<sup>-1</sup>, which yields  ${}^4He$  groundwater ages uncorrected for crustal He flux ranging from 0.0007 to >3.8 million years (Myr; eq. 2). These ages are many orders of magnitude greater than ages determined by  ${}^{14}C$  (see “Carbon-14 and Carbon-13” section). These results imply the presence of a significant deep crustal contribution of helium to the study area. Adopting a crustal flux ( $J_0$ ) of  $3 \times 10^{-6}$  cm<sup>3</sup>•STP•cm<sup>-2</sup>•yr<sup>-1</sup> provides the best agreement between  ${}^4He$  and  ${}^{14}C$  ages and yields  ${}^4He$  ages between <1 to >11,000 years (appendix 6).

The distribution of  ${}^4He$  ages for Deep aquifer wells plotted on a map of the study area is presented in figure 14. Apparent  ${}^4He$ -derived ages are significantly younger for wells located near Quarry Lakes, with ages between <1 to 26 years, whereas the ages of groundwater in wells to the west/northwest are greater, as much as >11,000 years. The old

apparent  ${}^4He$ -derived ages for wells 15L5 and 14D3 could be influenced by a pocket of old water in the areas surrounding those wells.

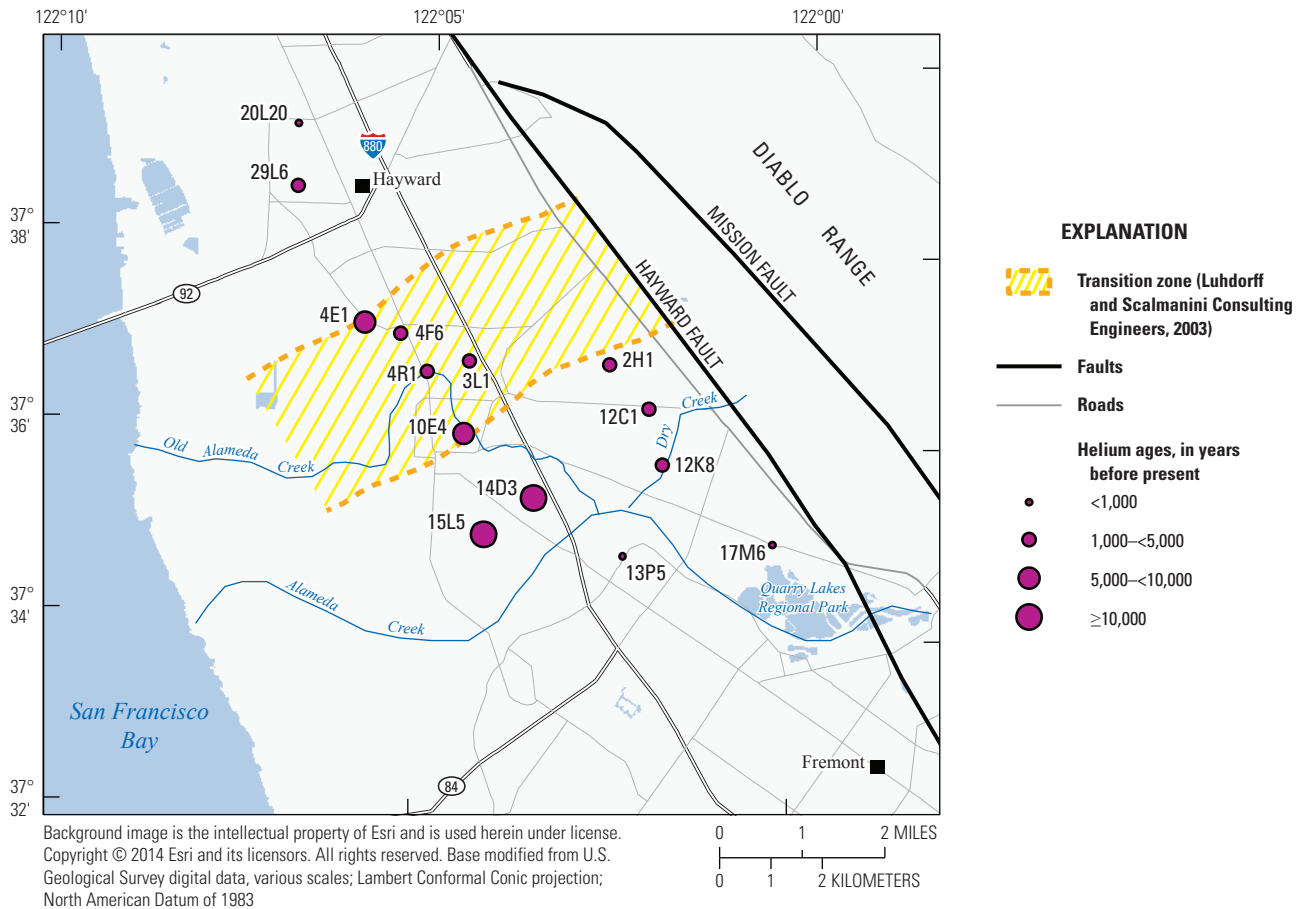
## Isotopic Composition of Groundwater

### Oxygen-18 and Deuterium

The proportion of the heavy stable isotopes of oxygen ( ${}^{18}O$ ) and hydrogen ( ${}^2H$ , deuterium) in water molecules can be used to infer the source and evaporative history of water. Atoms of oxygen-18 ( ${}^{18}O$ ) and deuterium ( ${}^2H$ ) have more neutrons and a greater atomic mass than do atoms of the more common isotopes, oxygen-16 and hydrogen. The difference in weight results in differences in the physical and chemical behavior of the heavier, less abundant isotopes.

Oxygen-18 and deuterium abundances are expressed as ratios of the heavy isotope to the light isotope, in delta notation ( $\delta$ ), as per mil (parts per thousand) differences, relative to Vienna Standard Mean Ocean Water (VSMOW; Gonfiantini, 1978). By convention, the value of both oxygen-18 and deuterium abundance ratios in VSMOW is 0 per mil. Oxygen-18 ( $\delta^{18}O$ ) and deuterium ( $\delta D$ ) ratios relative to VSMOW can be measured more precisely than absolute abundances, and these ratios are useful in hydrologic studies (International Atomic Energy Agency, 1981). Based on duplicate analyses presented elsewhere (Coplen, 1994; Izubicki, 1996), we have assumed a similar analytical precision of  $\pm 0.05$  per mil for  $\delta^{18}O$  and  $\pm 1.5$  per mil for  $\delta D$  for the results presented here.

The  $\delta^{18}O$  and  $\delta D$  composition of a water sample can provide a record of the source and evaporative history of the water, and differences in isotopic composition can be used to trace the water as it moves through the aquifer. Most precipitation originates from the evaporation of seawater, resulting in a linear correlation of  $\delta^{18}O$  and  $\delta D$  (fig. 15) that plots along a line known as the global meteoric water line (GMWL; Craig, 1961). Deviations from the GMWL are caused by differences in isotopic composition of precipitation if water vapor originated from evaporation of cooler or warmer water, and heavier isotopes are preferentially removed by precipitation as moist air masses move across continents. At a given location, the isotopic composition of precipitation tends to be an average value and is ultimately determined by local differences in the temperature of condensation and evaporative sources. Water that condensed at cooler temperatures (associated with higher altitudes, cooler climatic regimes, or higher latitudes) is lighter (more negative  $\delta$  values) than water that condensed at warmer temperatures (associated with lower altitudes, warmer climatic regimes, and lower latitudes). Also, water that has been partially evaporated becomes enriched in heavier isotopes relative to its original composition and plots to the right of the GMWL, along an evaporative-trend line.

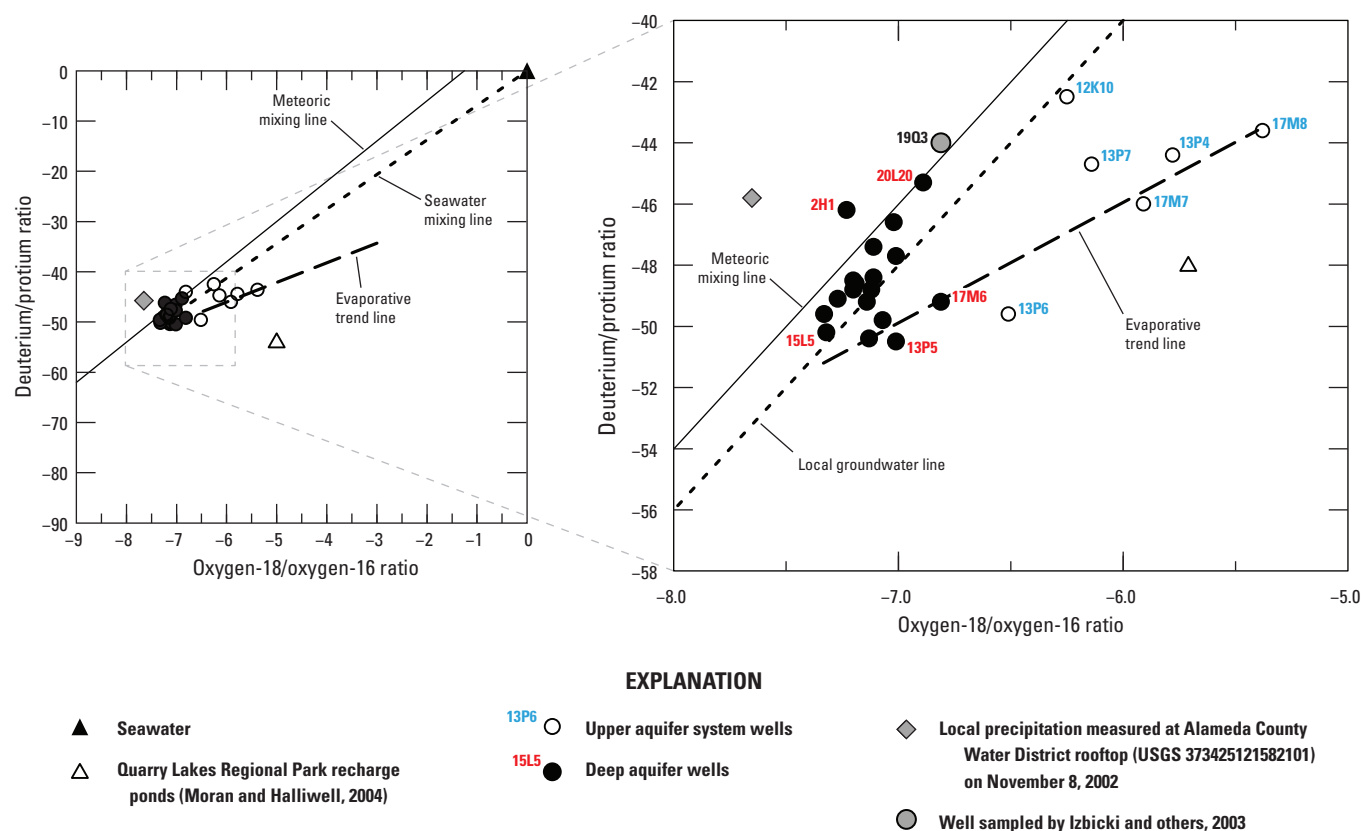


**Figure 14.** Spatial distribution of  $^4\text{He}$  ages from selected wells in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.

Because of the temporal and spatial variability of  $\delta^{18}\text{O}$  and  $\delta\text{D}$ , and because precipitation is often not representative of groundwater, owing to runoff and recharge processes, shallow groundwater samples often are collected to characterize the stable isotopic composition of recharge (Kendall and Coplen, 2001). Izbicki and others (2003) defined a local groundwater meteoric line by characterizing the stable isotopic composition of groundwater in the southern East Bay Plain groundwater subbasin. This local groundwater line is shown in figure 15 and is useful for discussing the evaporative history of groundwater sampled during this study.

Sources of recharge in the study area include diffuse infiltration from precipitation, infiltration from stream channels, and water artificially infiltrated at Quarry Lakes and behind seasonally inflated rubber dams in parts of Alameda Creek. Precipitation collected at a station near Quarry Lakes had  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values of  $-7.7$  and  $-45.8$ , respectively; for reasons stated in the “Methods” section, this single sample is not representative of annually weighted values (fig. 15). Some runoff in the Alameda Creek watershed is stored at reservoirs upstream from the study area where it may fractionate during evaporation before release downstream. Water in ACWD recharge ponds has a variable stable isotopic composition because it is derived from both local runoff in the Alameda Creek basin and water imported from the Sacramento–San

Joaquin River Delta. Water imported from the Sacramento–San Joaquin River Delta may be mixed with local runoff stored in reservoirs in the Alameda Creek watershed or may be discharged directly to a tributary of Alameda Creek upstream from the study area. Water imported from the South Bay Aqueduct has a  $\delta^{18}\text{O}$  value of  $-9$  to  $-10$  per mil (Moran and Halliwell, 2004). Imported water deliveries began in the early 1960s partly to dilute effluent from wastewater treatment plants that was discharged to streams in the Alameda Creek watershed (Lopp, 1981). Although most wastewater has been exported via pipeline to the San Francisco Bay since 1980, the stable isotopic composition of groundwater near Alameda Creek that was recharged before 1980 may be partly influenced by wastewater. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  composition of the wastewater has not been characterized. During late summer, much of the water in Alameda Creek is derived from groundwater originating from Quarry Lakes. The stable isotopic composition of water in the recharge ponds ( $\delta^{18}\text{O} = -5.71$ ;  $\delta\text{D} = -48$ ), sampled in December 1997 (Moran and Halliwell, 2004), indicates that recharge water infiltrating from the ponds was evaporated (fig. 15). The relative volume of imported water and local Alameda Creek sources used for managed aquifer recharge at the ACWD recharge ponds varies considerably from year to year.



**Figure 15.** Relations of delta oxygen-18 ( $\delta^{18}\text{O}$ ) with delta deuterium ( $\delta\text{D}$ ) in water from wells, Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.

The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  composition of water from sampled wells in the study area ranged from  $-5.4$  to  $-7.3$  per mil and  $-42.5$  to  $-50.5$  per mil, respectively (table 5–1). The range in  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values is small given the many sources of water having different isotopic compositions. Water from wells in the upper aquifer system and the Deep aquifer near Alameda Creek and Quarry Lakes (4S/2W-13P4–7 and 4S/1W-17M6–8) shows signs of evaporation and plot along an evaporation trend line (fig. 15). The evaporative signal apparent from wells near (within 2 miles) the Quarry Lakes recharge ponds is likely a result of isotopically depleted water (less negative values) recharging from the ponds. Wells screened in the upper aquifer system show heavier isotopic ratios, and plot further right along the evaporative trend line, than the Deep aquifer wells because of mixing of the managed recharge source with other water farther from the source. Most samples plot slightly below the meteoric water line along the local groundwater line of Izbicki and others (2003). Isotopic data from wells 20L20 and 19Q3 suggest that groundwater in the southern East Bay Plain groundwater subbasin is derived from a different source, likely areal recharge. The isotopic composition of water in well 4S/2W-2H1 has a  $\delta\text{D}$  value greater than the other Deep aquifer wells in the Niles Cone subbasin and is similar to local precipitation measured at USGS site 373425121582101, indicating that the source of water in this well is predominantly infiltration of precipitation.

## Carbon-14 and Carbon-13

Carbon-14 ( $^{14}\text{C}$ ) is a naturally occurring radioactive isotope of carbon having a half-life of 5,730 years (Manov and Curtiss, 1951). Carbon-14 is formed in the atmosphere by the interaction of cosmogenic radiation with nitrogen (Clark and Fritz, 1997). Atmospheric carbon-14 is present as carbon dioxide ( $\text{CO}_2$ ), which can then be incorporated into various hydrospheric (oceans, lakes, and groundwater) and biospheric (plants and animals) reservoirs. Whether through infiltration of water or the decay and release of biomass into the soil zone, once these intermediate sources of carbon are isolated from the atmosphere, the carbon-14 content in the dissolved carbon steadily decreases.

Carbon-14 that has been isolated from the atmosphere is seldom only affected by radioactive decay. Chemical reactions can dilute carbon-14 by either the addition of dissolved inorganic carbon (DIC) that lacks carbon-14 or by the removal of DIC that contains carbon-14 (Clark and Fritz, 1997). Carbon-14 concentrations can be decreased when carbon is added to groundwater by the dissolution of calcite or dolomite, which are devoid of carbon-14 and are often said to contain “dead” carbon (Freeze and Cherry, 1979). The addition of DIC from these sources dilutes the original carbon-14 content to give the appearance of older water, as does the production of DIC from oxidation of organic matter that is devoid of carbon-14. Above ground nuclear testing increased the amount of carbon-14 in the atmosphere, similar to tritium, within the last 50 years. Groundwater recharged within this period likely contains  $^{14}\text{C}$  above natural background concentrations of 100 pmC.



Because of its long half-life, carbon-14 can be used to estimate groundwater ages ranging from 1,000 to less than 30,000 years before present (Clark and Fritz, 1997). Radiocarbon dating is based on measuring the loss of the parent radionuclide carbon-14 in a given sample, assuming the initial carbon-14 concentration is known and that losses or gains of carbon-14 are minimal or can be quantified (Clark and Fritz, 1997). The activity of carbon-14 in a sample is reported in percent modern carbon, which indicates the carbon-14 activity of the sample relative to that of modern carbon, defined as 95 percent of the carbon-14 activity of the National Bureau of Standards oxalic acid in 1950 (Clark and Fritz, 1997).

Ratios of the stable isotopes carbon-13 to the far more abundant carbon-12 (delta carbon-13,  $\delta^{13}\text{C}$ ) were used in this study as indicators of biogeochemical and carbon-exchange processes that can affect estimates of carbon-14 ages. Because carbonate minerals and DIC exchange carbon isotopes (equilibration), groundwater can acquire a less negative delta  $\delta^{13}\text{C}$  value as it moves through the aquifer. Values of  $\delta^{13}\text{C}$  can also be affected by decomposition (oxidation or mineralization) of organic matter buried in the aquifer because organic material has a more negative  $\delta^{13}\text{C}$  composition than does inorganic carbon so that carbon isotopes would become lighter. Values of  $\delta^{13}\text{C}$  were used to make qualitative inferences about the extent to which these processes have caused the carbon-14 age to overestimate the actual time elapsed since recharge in this study.

Carbon-14 activities in DIC in the Deep aquifer ranged from 16 to 86 pmC and had a median of 50 pmC (table 5-1). These carbon-14 activities correspond to uncorrected ages ranging from 1,300 to 15,000 years before present (ybp), with a median uncorrected age of 5,700 ybp. Dissolved inorganic carbon delta carbon-13 values ranged from -13.3 to -15.3 per mil. Carbon-13 values became lighter with increasing distance along the groundwater flowpath, north from Quarry Lakes. Additionally,  $\delta^{13}\text{C}$  measured in water from wells within the Niles Cone groundwater subbasin (table 5-1) are generally less negative than in water from wells within the southern East Bay Plain groundwater subbasin (represented by wells 20L20 and 29L6), including wells sampled by Izbicki and others (2003).

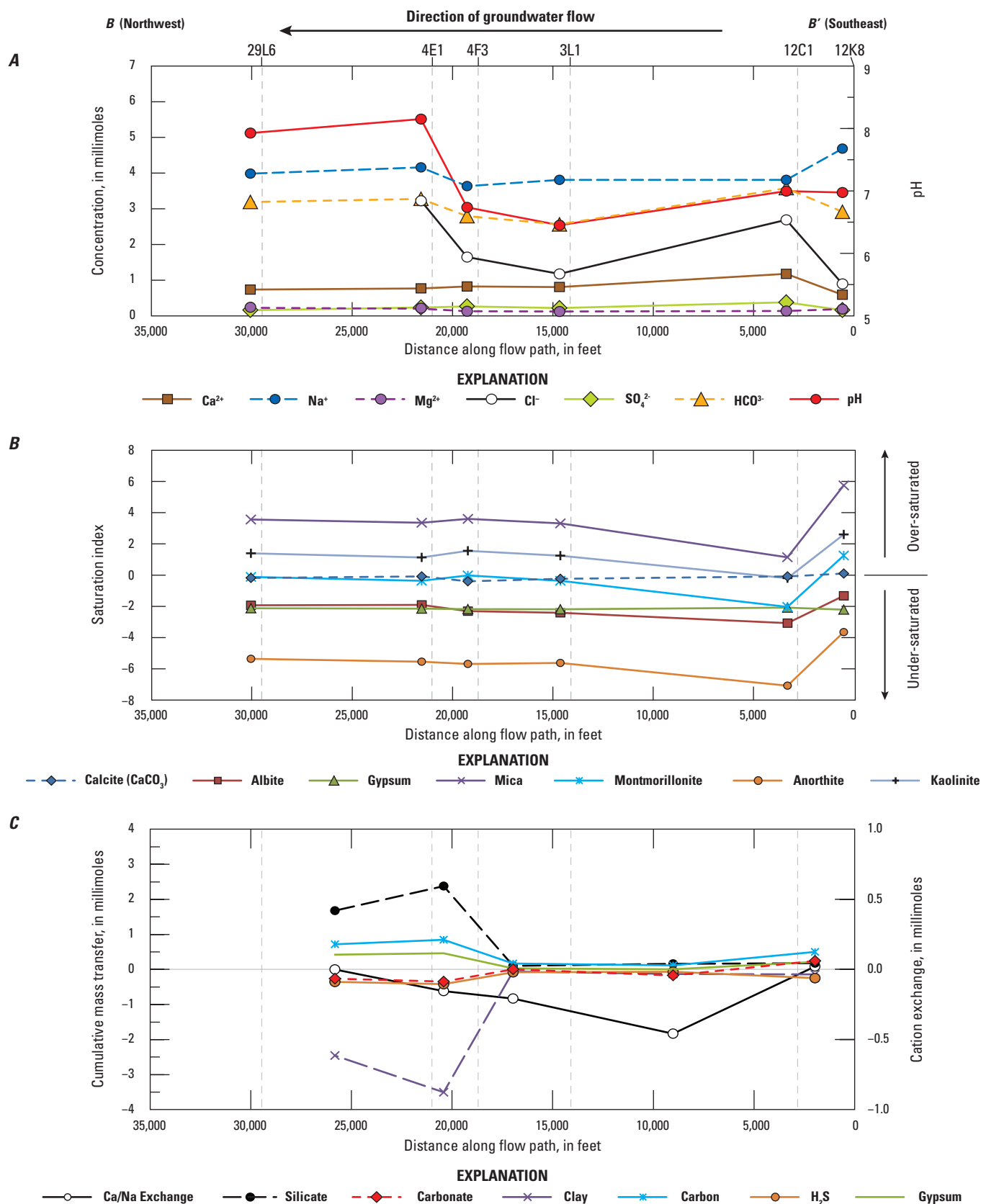
### Interpretation of Carbon-14 Data

The computer program NETPATH (Plummer and others, 1991) was used to account for reactions that affect DIC and adjust the measured carbon-14 activities to estimate the age (time since recharge) of groundwater along a flowpath extending from recharge areas along Alameda Creek near Quarry Lakes, through the transition zone within the Deep aquifer, into the East Bay Plain groundwater subbasin (flowpath B-B'; fig. 4). Restriction of groundwater flow near the transition zone that was not discernible from water-level data can be detected using groundwater ages of water from wells across the area (Izbicki and Martin, 1997).

Inputs to NETPATH model calculations include changes in groundwater chemistry and isotopic composition along the study flowpath (fig. 16; appendix 7) and aquifer mineralogy (table 3-1). Chemical data are used to calculate saturation indexes (SI; fig. 16) that indicate if a mineral will tend to dissolve if present in the aquifer (negative values) or, in the absence of thermodynamic constraints, precipitate (positive values) from groundwater onto aquifer materials. Large magnitude values (either positive or negative) may indicate the presence of constraints on these processes. For example, primary minerals such as albite or mica cannot precipitate in comparatively low-temperature/low-pressure groundwater environments; similarly, there may be kinetic constraints on clay-mineral formation that limit their precipitation from groundwater. Chemical data and the mass-balance of the various elements in groundwater and minerals also constrain NETPATH model calculations representing the dissolution and precipitation and the mass-transfer of dissolved constituents along the flowpath (Plummer and others, 1991). The carbon-13 composition of organic material in the aquifer was assumed to be -25 per mil, consistent with carbon from a mixture of plants having C3 and C4 photosynthetic pathways and similar to the value used in NETPATH calculations used to estimate groundwater age in the East Bay Plain groundwater subbasin (Izbicki and others, 2003).

For the purpose of model calculations, carbon-14 activity ( $A_0$ ) of groundwater at the beginning of the flowpath through the aquifer was estimated using an approach described by Verhagen and others (1991; fig. 17). This approach, based on field data, is applicable in systems where groundwater may contain modern groundwater recharged after the atmospheric testing of nuclear weapons beginning in the early 1950s. Carbon-14 data are shown in rank order, expressed as percent greater than or equal to, from largest to smallest. Carbon-14 activities generally exceeded 69.37 pmC in water samples from wells containing tritium. This value was selected as the initial carbon activity,  $A_0$ , for modeling purposes and was also used to calculate uncorrected carbon-14 ages from the measured percent modern carbon values. Water from three wells having lower carbon-14 activities contain measurable tritium, suggesting that the water from these wells (1) is a mixture of modern water containing tritium and older water that does not contain tritium or (2) chemical reactions have occurred in water from these wells that has resulted in the addition of carbon from aquifer materials that does not contain carbon-14, resulting in a lower than expected carbon-14 activity. Water from one of these wells, 12C1 near Dry Creek, has comparatively high tritium activity of 7.8 TU, and the water likely contains a high fraction of modern groundwater. Water from well 14D3 near Alameda Creek has a tritium activity of 0.4 TU, indicating a smaller but measurable fraction of modern groundwater. Tritium also was detected in water from well 20L20 at an activity of 0.6 TU near the downgradient end of the study flowpath, suggesting a small amount of modern water consistent with recent recharge in that area. Carbon-14 ages for these wells were not adjusted for the presence of modern water, and actual ages of the older groundwater in these wells are likely older than the ages calculated by NETPATH.





**Figure 16.** Selected changes in chemical and isotopic composition of water from wells used to interpret carbon-14 data along section B–B', Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03.

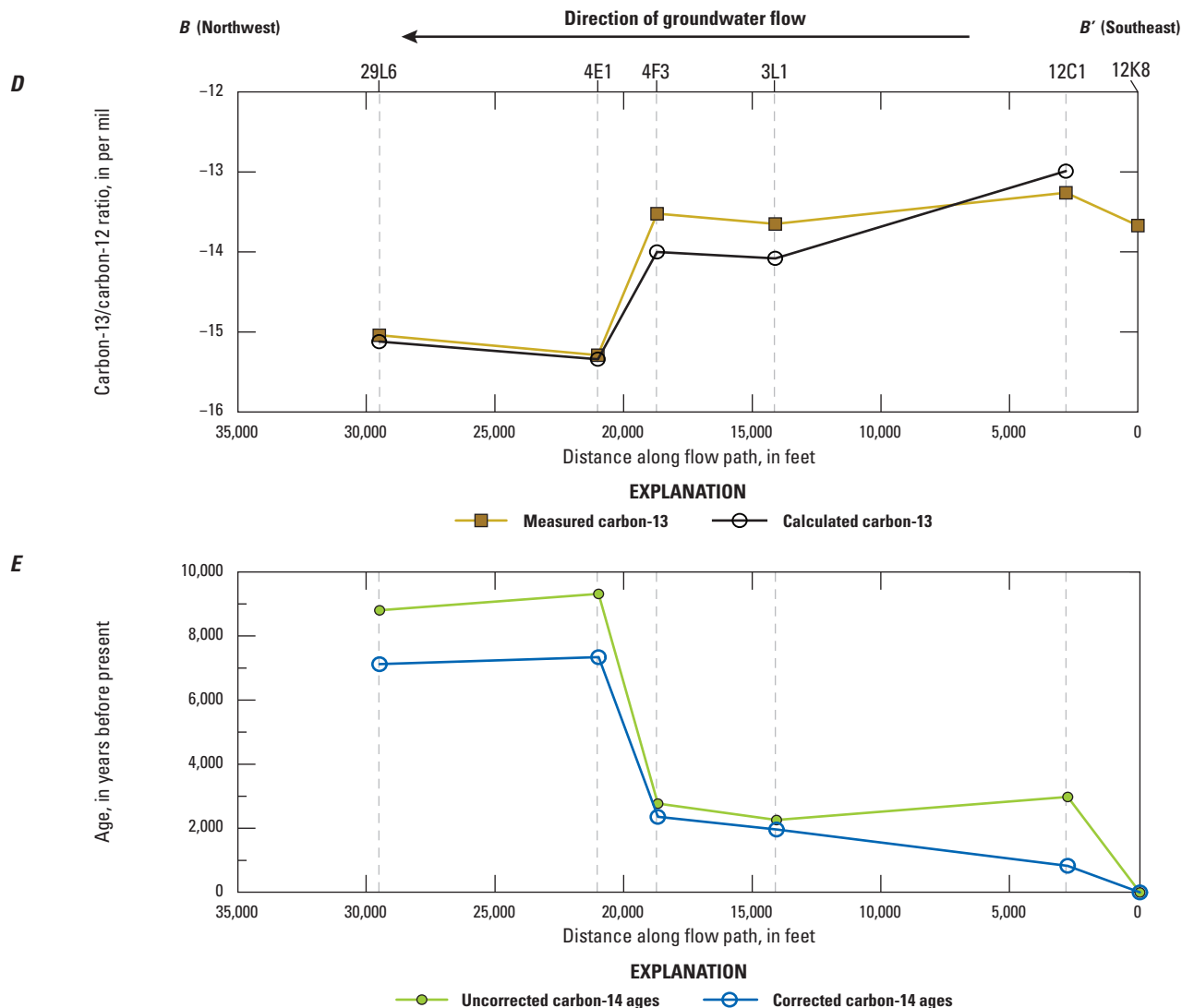
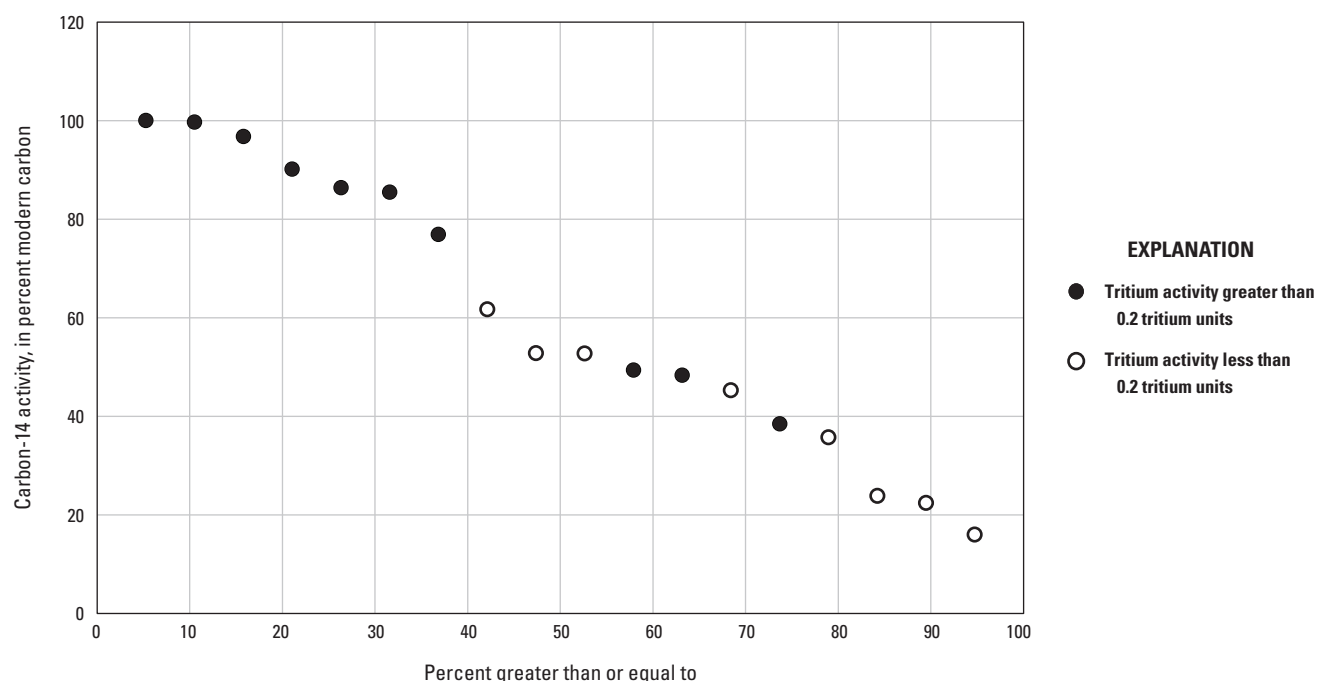


Figure 16. —Continued

Major-ion composition of groundwater along flowpath B–B' gradually changes from a mixed composition to a more sodium-type water downgradient (fig. 10), consistent with cation exchange previously identified as important reactions in the East Bay Plain groundwater subbasin (Izbicki and others, 2003). The largest changes in major-ion composition, accompanied by increases in pH, occur between wells 4F3 and 4E1 near the downgradient end of the transition zone between the Niles Cone and East Bay Plain groundwater subbasins within the Deep aquifer. NETPATH calculations provide estimates of (1) saturation indices for selected minerals at each well along the flowpath, (2) mass transfer of major cations and anions, and (3) cation exchange between each well. Positive mass transfer values indicate that the constituent is increasing in concentration, and negative values indicate that the constituent is decreasing in concentration. Positive cation exchange values indicate that calcium is exchanging for sodium on clay minerals, and negative values indicate

that sodium is exchanging for calcium on clay minerals. The NETPATH calculations indicate saturation of groundwater with respect to calcite and exchange of sodium for calcium on clay minerals along flowpath B–B' (fig. 16). Because calcium is a divalent cation, it is preferentially absorbed by exchange sites on clay minerals; however, in environments where the equilibrium is shifted to an oversaturation of sodium, such as aquifers influenced by seawater intrusion, sodium ions may replace calcium ions on exchange sites (Izbicki, 1991).

NETPATH calculations also indicate consumption of organic carbon within the aquifer, likely through biological processes. Consistent with consumption of organic carbon from aquifer materials by microbiological processes, alkalinity increases and  $\delta^{13}\text{C}$  values become increasingly negative with distance downgradient along flowpath B–B' (fig. 16). Measured and model-calculated  $\delta^{13}\text{C}$  values generally agree within 0.5 per mil.



**Figure 17.** Plot of rank order carbon-14 data, expressed as cumulative exceedance percentage, in water from sampled wells in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, 2002–03. Tritium concentrations are shown using filled and open circle symbols.

Field data and NETPATH results show a decrease in carbon-14 activity with distance downgradient along flowpath *B–B'* (fig. 16). Uncorrected carbon-14 ages range from near modern near the recharge areas to as much as 9,000 years before present (ybp) downgradient. Interpreted carbon-14 ages are slightly less, ranging from modern to about 7,340 ybp (table 7–1). The difference between uncorrected and interpreted ages results from addition of carbon that does not contain carbon-14 from microbiological respiration of organic carbon within aquifer materials along the flowpath. Both uncorrected and interpreted ages indicate large changes in groundwater age near the downgradient end of the transition zone, whereas stable water isotope data ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ; fig. 15) suggest the source of groundwater recharge in this area is relatively unchanged. The slight decrease in groundwater age in water from well 4E1 to 29L6 suggests that well 29L6 is not at the end of the *B–B'* flowpath. Uncorrected carbon-14 age data from well 20L20 suggest that groundwater age increases from north to south in the East Bay Plain groundwater subbasin and that flowpaths may be converging at the transition zone between the Niles Cone and the East Bay Plain groundwater subbasins. Groundwater velocities calculated from interpreted carbon-14 ages range from 3 to 12 ft/yr in the Deep aquifer of the Niles Cone groundwater subbasin and decrease to as little as 0.5 ft/yr near the transition to the southern East Bay Plain groundwater subbasin. Groundwater flow rates within the Deep aquifer, calculated on the basis of groundwater  $^{14}\text{C}$  ages and distance along the flowpath, decrease by an order of magnitude from 11.6 ft/yr between wells 4S/2W-3L1 and 4S/2W-4F3 to 0.5 ft/yr between wells 4S/2W-4F3 and 4S/2W-4E1 just

south of the southern East Bay Plain groundwater subbasin transition zone boundary (table 7–1). These results are consistent with lithologic changes (Luhdorff and Scalmanini Consulting Engineers, 2003) within the transition zone that separates the two groundwater subbasins and acts to limit flow between the Niles Cone and southern East Bay Plain groundwater subbasins. Because the converging flowpaths and lithologic changes at the transition zone restrict movement of groundwater from the Niles Cone groundwater subbasin into the East Bay Plain groundwater subbasin, water recharged at the Quarry Lakes likely remains within the Niles Cone groundwater subbasin.

### Limitations of Carbon-14 Interpretations

Carbon-14 ages calculated using NETPATH are interpretive and subject to uncertainty. For aquifers for which the chemistry is well understood, interpreted carbon-14 ages are within  $\pm 20$  percent of the actual value (Davis and Bentley, 1982). In areas where present-day recharge may not reflect the composition of recharge for older groundwater, the greatest source of uncertainty in interpreting carbon-14 data is in determining the initial chemistry, carbon-14 activity, and  $\delta^{13}\text{C}$  composition of the recharge water.

In this study, the carbon-14 age calculated for water from well 12C1, which is a mixture of modern and older groundwater (samples with tritium detections greater than or equal to 0.8 TU and carbon-14 activities less than or equal to 95 pmC), is an average age. The age of the older fraction of groundwater composing this mixture was not calculated. It is likely that the age of the older fraction of water is greater than the age shown in table 7–1 and on figure 16.

## Summary

The principal water-bearing units in the Niles Cone and southern East Bay Plain groundwater subbasins are located west of the Hayward Fault. The aquifers (from shallowest to deepest) are the Newark, Centerville, Fremont, and Deep aquifers; these were originally defined in the Niles Cone groundwater subbasin and projected to the southern East Bay Plain groundwater subbasin. The Newark, Centerville, and Fremont aquifers are thickest and most continuous in the Niles Cone groundwater subbasin. Unlike the Niles Cone groundwater subbasin to the south, alluvial fans in the southern East Bay Plain groundwater subbasin were not deposited by large streams, and as a result, sediments in shallow aquifers are finer grained and more discontinuous than in the Niles Cone groundwater subbasin. Fine-grained sediments deposited between the alluvial fans of the Niles Cone and southern East Bay Plain groundwater subbasins interrupt lateral continuity of coarse-grained layers and may restrict interbasin flow of groundwater.

Beginning in 1974, ACWD imported water to supplement natural recharge to the aquifer system in the Niles Cone groundwater subbasin by recharging water through ponds at Quarry Lakes Regional Park. This recharged water was intended to increase hydraulic heads in the area and halt intrusion of water from San Francisco Bay into the aquifer systems, and along with other projects in the area, to improve groundwater quality. Although water levels in wells in the region increased, the effect of managed aquifer recharge was not otherwise quantified. Hydrologic, InSAR, and geochemical data for 2002 and 2003 were collected and analyzed to evaluate the geologic and hydrologic controls on groundwater movement through aquifers between the Niles Cone and southern East Bay Plain groundwater subbasins on the east side of San Francisco Bay, California, in cooperation with the East Bay Municipal Utility District, City of Hayward, and Alameda County Water District.

Groundwater in the upper aquifer system and Deep aquifer flows to the west and north from recharge areas near Quarry Lakes and along Alameda Creek. Water levels were about 20 ft lower in the Deep aquifer than in the upper aquifer system. Water levels in the Deep aquifer were as much as 9 ft below sea level during this study. Steep water-level gradients to the south of the recharge areas are likely the result of pumping at the Mowry well field and Aquifer Reclamation Program (ARP) wells. To the north, fewer wells completed solely in the upper aquifer system were available to measure water levels because of the finer-grained nature of the aquifer deposits in this area. Water-level data show groundwater in the Deep aquifer flows to the north toward the southern East Bay Plain groundwater subbasin. Changes in the slope of the water-level contours near the transition zone between the Niles Cone and southern East Bay Plain groundwater subbasins are consistent with changes in lithology, or could indicate structural features such as faults or folds, that restrict groundwater flow.

Water recharged at Quarry Lakes affects the hydraulic heads in nearby wells in which both the upper aquifer system and Deep aquifer respond rapidly and with little lag between recharge and the measured responses to recharge (fig. 5). InSAR data show land surface deformation in response to aquifer recharge of about 0.8 in. (20 mm). Measured deformation is greater to the west and northwest (fig. 6), downgradient from groundwater recharge areas where aquifers are finer-grained and elastic, and less near recharge areas where aquifers are coarser-grained. The extent of the uplift shown on interferograms may not represent the extent of the movement of water from managed aquifer recharge, but instead results from a pressure response. InSAR data also show land surface deformation in response to pumping, suggesting land surface deformation is elastic and occurs rapidly.

Streamflow data show that during the period of the study, the section of Alameda Creek nearest Quarry Lakes was a losing section, and the reach of Alameda Creek as much as 1.5 miles (fig. 3) upstream from the tidally affected section was a gaining reach. Water from the losing reach of Alameda Creek likely recharges the upper aquifer system and the Deep aquifer. Large streamflows during winter months could cause losing conditions along the entire nontidally affected reach of Alameda Creek. Under predevelopment conditions, sustained flow in Alameda Creek may have been great enough to provide a consistent source of recharge to the local aquifers.

Groundwater in the study area was fresh, with dissolved solids concentrations in sampled wells less than 1,080 mg/L. Values of pH were near neutral to alkaline, with increasing pH with depth and distance from groundwater recharge areas. Water from sampled wells in the upper aquifer system had varied dissolved oxygen concentrations ranging from oxic (2.9 mg/L) to reduced (<0.2 mg/L). Water from sampled wells in the Deep aquifer was generally reducing. Water from upper-aquifer-system wells located near Quarry Lakes is marked by higher calcium and magnesium percentages than water from most wells in the Deep aquifer, indicating influence by water recharged at Quarry Lakes and from the ponded areas behind the inflatable dams in Alameda Creek. The effect of past intrusion of water from San Francisco Bay and high-chloride water from partly consolidated marine rock underlying the study area can be seen in water from some wells in the Deep aquifer that have chloride concentrations as high as 350 mg/L. Water from some Deep aquifer wells has elevated chloride concentrations and major-ion concentrations indicative of exchange of sodium for calcium and magnesium on clay in aquifer deposits. Water from well 4S/2W-15L5 has major-ion proportions suggesting the source of high-chloride water to well 15L5 is likely from partly consolidated marine rock.

Groundwater recharge temperatures estimated using noble-gas data ranged from  $10.1 \pm 0.7$  to  $19.2 \pm 0.8$  °C, warmer than those estimated for focused recharge along San Lorenzo and San Leandro Creeks in the southern East Bay Plain groundwater subbasin, north of the study area (Izbicki and others, 2003). The warmer recharge temperatures in the study area may reflect year-round recharge from Quarry Lakes and Alameda Creek rather than winter recharge from infiltration of winter stormflows in the smaller, unmanaged streams that recharge the East Bay Plain groundwater subbasin. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  data in shallow wells near the recharge area indicate evaporative modification of water stored in the recharge ponds, or behind the rubber dams, prior to infiltration. In contrast, isotopic data from a few wells suggest that groundwater in the southern East Bay Plain groundwater subbasin is derived from a different source, likely areal recharge or infiltration of precipitation.

Tritium/helium-3 age data show that upper aquifer system and Deep aquifer wells near Quarry Lakes contain water that has been recently recharged. Tritium/helium-3 ages for groundwater range from 6 to 50 years for these wells and were greater than 50 years for the rest of the wells in the study area. Tritium/helium-3 ages and tritium activities decreased away from Quarry Lakes with distance from the recharge area to values below the reporting level. Although  $^4\text{He}$  ages and uncorrected  $^{14}\text{C}$  ages differed, generally they both increased downgradient.

NETPATH analyses of water-chemistry data show that as water flows through the aquifer systems, concentrations of sodium (plus potassium relative to calcium plus magnesium) increase owing to primary silicate weathering and (or) exchange of calcium and magnesium for sodium on clay within aquifer deposits (Izbicki and others, 1992; Izbicki and others 2003). Carbon-14 groundwater ages in the Deep aquifer, corrected for reactions that occur between groundwater and aquifer materials, range from 830 to 7,340 years before present. Ages increase northward along the flowpath from the Niles Cone groundwater subbasin toward the southern East Bay Plain groundwater subbasin, with large changes in groundwater age within the transition zone separating the Niles Cone from the southern East Bay Plain groundwater subbasins. Groundwater flow rates within the Deep aquifer decrease by an order of magnitude from 11.6 ft/yr between wells 4S/2W-3L1 and 4S/2W-4F3 to 0.5 ft/yr between wells 4S/2W-4F3 and 4S/2W-4E1 just south of the southern East Bay Plain groundwater subbasin transition zone boundary. These results are consistent with restricted groundwater flow between the two groundwater subbasins and consistent with the result of lithologic changes within the transition zone and converging groundwater flowpaths north of the transition zone. Additionally, converging groundwater flowpaths north of the transition zone from different recharge areas within the two subbasins may restrict transfer of water between the two subbasins. As a consequence, water recharged at Quarry Lakes directly affects water levels and water quality in wells in the vicinity of the recharge facility, and that water likely remains within the subbasin.

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# Appendix 1. Location and Construction Data and Water-Level Measurements Collected by the U.S. Geological Survey During 2002 for Wells Drilled in the Niles Cone and Southern East Bay Plain Groundwater Subbasins

**Table 1–1.** Location and construction data and water-level measurements collected by the U.S. Geological Survey during fall 2002 for wells drilled in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California.

[Water-level data shown in **bold** are used in [figures 3](#) and [4](#). **Abbreviations:** bls, below land surface; bmsl, below mean sea level; F, flowing; ft, foot; mm/dd/yyyy, month/day/year; NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey; \*, mean sea level is 6.75 ft above the station datum for Station 9414750, Alameda, Calif., of 3.56 ft (NAVD 88); —, no data; >, greater than]

State well number	USGS identification number	Well type	Primary aquifer contributing water to well	Land-surface altitude, NAVD 88 (ft)	Depth to upper-most perforation interval (ft)	Depth to bottom-most perforation interval (ft)	Well depth (ft bls)	Depth to water (ft bls)	Water-level altitude NAVD 88 (ft)	Date of water-level measurement (mm/dd/yyyy)	Water-level (ft bmsl)*
Upper aquifer system											
4S/1W-17M7	373457122002102	Observation	Centerville-Fremont	52.7	215	255	260	42.4	10.3	03/19/2002	0.0
4S/1W-17M7	373457122002102	Observation	Centerville-Fremont	52.7	215	255	260	47.2	5.5	10/28/2002	–4.8
4S/1W-17M8	373457122002103	Observation	Newark	52.4	80	120	125	28.6	<b>23.8</b>	03/22/2002	13.5
4S/1W-17M8	373457122002103	Observation	Newark	52.4	80	120	125	35.5	16.9	10/28/2002	6.6
4S/1W-18R1	373313122002401	Observation	Newark	51.1	—	—	150	28.7	<b>22.4</b>	04/16/2002	12.1
4S/1W-19E2	373418122011901	Observation	Newark	40.6	—	—	147	19.9	<b>20.7</b>	05/01/2002	10.4
4S/1W-19J6	373409122003601	Observation	Newark	53.1	—	—	145	31.0	<b>22.2</b>	05/01/2002	11.8
4S/1W-19N14	373349122011803	Observation	Newark	43.1	—	—	100	23.2	<b>19.9</b>	05/06/2002	9.6
4S/1W-20H3	373422121592201	Observation	Newark	70.2	—	—	65	40.8	<b>29.4</b>	04/16/2002	19.1
4S/1W-20J6	373404121591901	Observation	Newark	61.8	—	—	80	33.4	<b>28.4</b>	05/06/2002	18.1
4S/1W-20R1	373356121593302	Observation	Newark	61.9	—	—	85	38.2	<b>23.7</b>	06/06/2002	13.4
4S/1W-28D12	373348121590401	Observation	Newark	65.6	—	—	160	48.9	<b>16.7</b>	05/03/2002	6.4
4S/1W-29A6	373345121591701	Observation	Newark	63.9	—	—	127	42.9	<b>21.0</b>	05/03/2002	10.7
4S/1W-29C7	373543121595901	Observation	Newark	58.0	—	—	61	37.0	21.0	05/06/2002	10.7
4S/1W-29C8	373345121595101	Observation	Newark	60.1	—	—	59	38.9	<b>21.3</b>	05/06/2002	10.9
4S/1W-30A5	373341122003703	Observation	Newark	54.9	—	—	150	34.8	<b>20.1</b>	05/02/2002	9.8
4S/1W-30E4	373329122011802	Observation	Newark	44.2	—	—	155	25.6	<b>18.6</b>	05/02/2002	8.3
4S/2W-12K9	373545122015002	Observation	Fremont	56.1	300	310	310	56.1	0.0	11/05/2002	–10.3
4S/2W-12K10	373545122015003	Observation	Centerville	56.1	210	240	240	54.8	1.3	11/05/2002	–9.0
4S/2W-12K11	373545122015004	Observation	Newark	56.4	110	150	150	40.5	<b>15.9</b>	11/05/2002	5.6

**Table 1-1.** Location and construction data and water-level measurements collected by the U.S. Geological Survey during fall 2002 for wells drilled in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California. Water—Continued

[Water-level data shown in **bold** are used in figures 3 and 4. **Abbreviations:** bls, below land surface; bmsl, below mean sea level; F, flowing; ft, foot; mm/dd/yyyy, month/day/year; NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey; \*, mean sea level is 6.75 ft above the station datum for Station 9414750, Alameda, Calif., of 3.56 ft (NAVD 88); —, no data; >, greater than]

State well number	USGS identification number	Well type	Primary aquifer contributing water to well	Land-surface altitude, NAVD 88 (ft)	Depth to upper-most perforation interval (ft)	Depth to bottom-most perforation interval (ft)	Well depth (ft bls)	Depth to water (ft bls)	Water-level altitude NAVD 88 (ft)	Date of water-level measurement (mm/dd/yyyy)	Water-level (ft bmsl)*
Upper aquifer system—Continued											
4S/2W-13E3	373514122022101	Observation	Newark	30.6	—	—	144	12.3	<b>18.3</b>	04/25/2002	8.0
4S/2W-13P4	373447122021904	Observation	Newark	28.6	48	78	145	9.2	<b>19.4</b>	03/27/2002	9.1
4S/2W-13P4	373447122021904	Observation	Newark	28.6	48	78	145	13.6	15.0	10/28/2002	4.7
4S/2W-13P6	373447122021902	Observation	Fremont	28.9	340	360	360	19.6	9.3	03/26/2002	-1.0
4S/2W-13P6	373447122021902	Observation	Fremont	28.9	340	360	360	26.0	2.9	10/28/2002	-7.4
4S/2W-13P7	373447122021903	Observation	Centerville	28.7	190	280	280	19.0	9.8	03/26/2002	-0.6
4S/2W-13P7	373447122021903	Observation	Centerville	28.7	190	280	280	25.4	3.4	10/28/2002	-7.0
4S/2W-14D5	373521122033103	Observation	Fremont	16.7	260	280	280	16.5	0.3	11/06/2002	-10.1
4S/2W-14D6	373521122033104	Observation	Centerville	16.9	180	220	220	16.5	0.4	11/06/2002	-9.9
4S/2W-14D7	373521122033105	Observation	Newark	16.8	70	110	110	5.1	<b>11.7</b>	11/06/2002	1.4
4S/2W-14H3	373517122024301	Observation	Newark	27.7	—	—	125	10.4	<b>17.3</b>	05/02/2002	7.0
4S/2W-14L6	373507122031901	Observation	Newark	17.6	—	—	120	3.4	<b>14.2</b>	04/17/2002	3.9
4S/2W-14R3	373441122024101	Observation	Newark	28.6	—	—	110	11.1	<b>17.5</b>	04/16/2002	7.2
4S/2W-23J2	373403122024501	Observation	Newark	26.8	—	—	122	9.2	<b>17.6</b>	05/06/2002	7.3
4S/2W-24F11	373421122021301	Observation	Newark	31.9	—	—	70	12.9	<b>19.0</b>	04/16/2002	8.7
4S/2W-25D3	373343122022602	Observation	Newark	25.7	—	—	154	8.1	<b>17.6</b>	04/26/2002	7.3
4S/2W-26K6	373321122025002	Observation	Newark	22.5	—	—	145	7.3	<b>15.2</b>	05/01/2002	4.9
Deep aquifer											
3S/2W-20L20	373912122065001	Public production	Deep	49.8	500	585	600	36.4	13.4	03/07/2002	3.1
3S/2W-29L6	373832122064801	Public production	Deep	43.0	480	580	600	42.4	<b>0.6</b>	10/30/2002	-9.8
3S/2W-32D2	373759122064901	Observation	Deep	23.8	—	—	550	29.5	-5.7	11/08/2002	-16.0
3S/2W-35J11	373733122025901	Observation	Deep	16.0	—	—	580	20.5	-4.5	11/13/2002	-14.8
4S/1W-7P4	373543122010101	Observation	Deep	69.2	—	—	476	69.3	-0.1	11/13/2002	-10.4
4S/1W-17M6	373457122002101	Observation	Deep	52.6	420	460	460	46.1	6.5	03/19/2002	-3.8
4S/1W-17M6	373457122002101	Observation	Deep	52.6	420	460	460	50.5	<b>2.1</b>	10/28/2002	-8.2
4S/1W-28D1	373348121590503	Observation	Deep	65.7	—	—	445	67.0	-1.3	11/08/2002	-11.6

**Table 1-1.** Location and construction data and water-level measurements collected by the U.S. Geological Survey during fall 2002 for wells drilled in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California. —Continued

[Water-level data shown in **bold** are used in figures 3 and 4. **Abbreviations:** bls, below land surface; bmsl, below mean sea level; F, flowing; ft, foot; mm/dd/yyyy, month/day/year; NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey; \*, mean sea level is 6.75 ft above the station datum for Station 9414750, Alameda, Calif., of 3.56 ft (NAVD 88); —, no data; >, greater than]

State well number	USGS identification number	Well type	Primary aquifer contributing water to well	Land-surface altitude, NAVD 88 (ft)	Depth to upper-most perforation interval (ft)	Depth to bottom-most perforation interval (ft)	Well depth (ft bls)	Depth to water (ft bls)	Water-level altitude NAVD 88 (ft)	Date of water-level measurement (mm/dd/yyyy)	Water-level (ft bmsl)*
Deep aquifer—Continued											
4S/1W-30A2	373341122003701	Observation	Deep	54.5	—	—	400	54.9	<b>-0.4</b>	11/08/2002	-10.7
4S/1W-30E3	373329122011801	Observation	Deep	44.8	—	—	593	45.0	<b>-0.2</b>	11/08/2002	-10.5
4S/2W-2H1	373648122023601	Private production	Deep	39.0	429	459	472	34.4	4.6	03/20/2002	-5.7
4S/2W-3L1	373646122042701	Private production	Deep	13.5	367	442	452	22.6	<b>-9.1</b>	11/07/2002	-19.4
4S/2W-4E1	373708122055101	Public production	Deep	12.4	470	525	535	10.5	1.9	03/07/2002	-8.4
4S/2W-4F3	373702122052201	Observation	Deep	12.7	440	525	550	9.8	3.0	03/21/2002	-7.4
4S/2W-4F6	373700122052301	Public production	Deep	13.0	358	524	534	8.8	4.2	03/07/2002	-6.1
4S/2W-4R1	373638122045901	Public production	Deep	12.5	370	456	466	14.9	<b>-2.4</b>	10/29/2002	-12.7
4S/2W-10E4	373601122042901	Observation	Deep	17.2	400	440	440	18.6	<b>-1.4</b>	11/04/2002	-11.7
4S/2W-12C1	373620122015901	Public production	Deep	68.9	410	487	512	64.1	4.8	03/20/2002	-5.5
4S/2W-12K8	373545122015001	Observation	Deep	55.8	470	510	510	56.7	<b>-0.9</b>	11/05/2002	-11.2
4S/2W-13P5	373447122021901	Observation	Deep	28.7	400	420	420	20.7	8.1	03/26/2002	-2.3
4S/2W-13P5	373447122021901	Observation	Deep	28.7	400	420	420	27.3	<b>1.5</b>	10/28/2002	-8.9
4S/2W-14D3	373521122033101	Observation	Deep	16.7	400	450	450	18.9	-2.2	11/06/2002	-12.5
4S/2W-14D4	373521122033102	Observation	Deep	16.6	520	540	540	18.1	<b>-1.5</b>	11/06/2002	-11.8
4S/2W-15L5	373457122041001	Observation	Deep	10.3	430	470	470	11.7	<b>-1.4</b>	10/29/2002	-11.7
4S/2W-25D1	373343122022601	Observation	Deep	24.9	—	—	517	24.9	<b>0.0</b>	11/13/2002	-10.3
4S/2W-26K4	373321122024901	Observation	Deep	23.0	—	—	501	22.6	<b>0.4</b>	11/13/2002	-9.9



## Appendix 2. U.S. Geological Survey National Water-Quality Laboratory Analytical Methods and Reporting Levels for Analysis of Groundwater and Surface-Water Samples

Samples were collected by the U.S. Geological Survey during 2002–03. Samples from domestic and public production wells were collected using existing pumping systems; samples from unused wells and monitoring wells were collected using a small diameter, stainless steel, submersible pump (Wilde, 1999a). The surface-water sample from Dry Creek was collected using the pump-sampling method described in Wilde (1999a).

Field parameters (pH, specific conductance, temperature, and alkalinity) were measured for each sample collected by the U.S. Geological Survey as described in Wilde (1999a). Dissolved oxygen was measured in the field by the U.S. Geological Survey using colorimetric methods (CHEMets Kit K-7512 or K7501). Selected samples were processed in the field and sent to the U.S. Geological Survey's National Water-Quality Laboratory (NWQL) for inorganic analysis. Samples for inorganic analysis of dissolved constituents were filtered in the field using a capsule filter having a pore size of 0.45 mm (Wilde, 1999b). Nutrients were preserved by chilling at 4 °C and were analyzed within seven days. Trace elements were preserved by acidification to pH <2.0. Stable isotope samples were sent to the USGS Reston Stable Isotope Laboratory. Carbon isotope samples were sent to the University of Waterloo Environmental Isotope Laboratory. Dissolved gas samples and tritium samples were sent to the University of Rochester Rare Gas Facility. Analytical methods and associated reporting limits are listed in table 2–1.

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**Table 2–1.** U.S. Geological Survey National Water-Quality Laboratory analytical methods and reporting levels for analysis of groundwater samples.

[ASF, automated-segmented flow; mg/L, milligram per liter; pCi/L, picocurie per mil; std, standard; °C, degrees Celsius; µS/cm, microsiemen per centimeter at 25 °C; µg/L, microgram per liter]

Constituent	Methodology	Reporting limit	Reference
Field parameters			
pH	pH electrode	0.1 std units	Fishman and Friedman, 1989
Specific conductance	Wheatstone bridge	1.0 µS/cm	Fishman and Friedman, 1989
Alkalinity	Titrimetry with sulfuric acid	1.0 mg/L	Fishman and Friedman, 1989
Dissolved oxygen	Colorimetric indigo-carmin	0.006 mg/L	White and others, 1990
Major ions			
Calcium, dissolved	Inductively coupled plasma	0.011 mg/L	Fishman, 1993
Chloride, dissolved	Ion chromatography	0.08 mg/L	Fishman and Friedman, 1989
Dissolved solids	Gravimetric, residue on evaporation at 180 °C	10.0 mg/L	Fishman and Friedman, 1989
Magnesium, dissolved	Inductively coupled plasma	0.008 mg/L	Fishman, 1993
Potassium, dissolved	Atomic adsorption, flame	0.09 mg/L	Fishman and Friedman, 1989
Silica, dissolved	Colorimetry, ASF	0.48 mg/L	Fishman and Friedman, 1989
Sodium, dissolved	Inductively coupled plasma	0.06 mg/L	Fishman, 1993
Sulfate, dissolved	Ion chromatography	0.11 mg/L	Fishman and Friedman, 1989
Nutrients			
Nitrite, dissolved	Colorimetry, ASF	0.006 mg/L	Fishman, 1993
Nitrite + nitrate, dissolved	Colorimetry, ASF, cadmium reduction-diazotization	0.047 mg/L	Fishman, 1993
Ammonia, dissolved	Colorimetry, ASF, salicylate-hypochlorite	0.041 mg/L	Fishman, 1993
Ammonia + organic nitrogen, dissolved	Colorimetry, ASF, microkjeldahl digestion	0.10 mg/L	Patton and Truitt, 1992
Phosphorus, dissolved	Colorimetry, ASF, microkjeldahl digestion	0.05 mg/L	Patton and Truitt, 1992
Orthophosphate, dissolved	Colorimetry, ASF, phosphomolybdate	0.018 mg/L	Fishman, 1993
Trace elements			
Arsenic, dissolved	Graphite furnace atomic adsorption	2.0 µg/L	Jones and Garbarino, 1999
Barium, dissolved	Inductively coupled plasma	0.9 µg/L	Fishman, 1993
Boron, dissolved	Inductively coupled plasma	13.0 µg/L	Struzeski and others, 1996
Bromide, dissolved	Colorimetry, ASF	0.01 mg/L	Fishman and Friedman, 1989
Fluoride, dissolved	ASF, ion-selective electrode	0.16 mg/L	Fishman and Friedman, 1989
Iodide, dissolved	Colorimetry, ASF, ceric-arsenous	0.001 mg/L	Fishman and Friedman, 1989
Iron, dissolved	Inductively coupled plasma	10.0 µg/L	Fishman, 1993
Manganese, dissolved	Inductively coupled plasma	3.2 µg/L	Fishman, 1993
Isotopes			
Carbon-14	Accelerator mass spectrometry	0.3 percent	Beukens, R.P., 1992
Carbon-13/carbon-12	Mass spectrometry	0.15 per mil	Gleason and others, 1969
Deuterium/protium	Mass spectrometry	2.0 per mil	Coplen and others, 1991
Oxygen-18/oxygen-16	Mass spectrometry	0.2 per mil	Epstein and Mayeda, 1953
Tritium	Electrolytic enrichment and liquid scintillation	1.0 pCi/L	Thatcher and others, 1977

## Appendix 3. Aquifer Mineralogy, Niles Cone Groundwater Subbasin, Alameda County, California

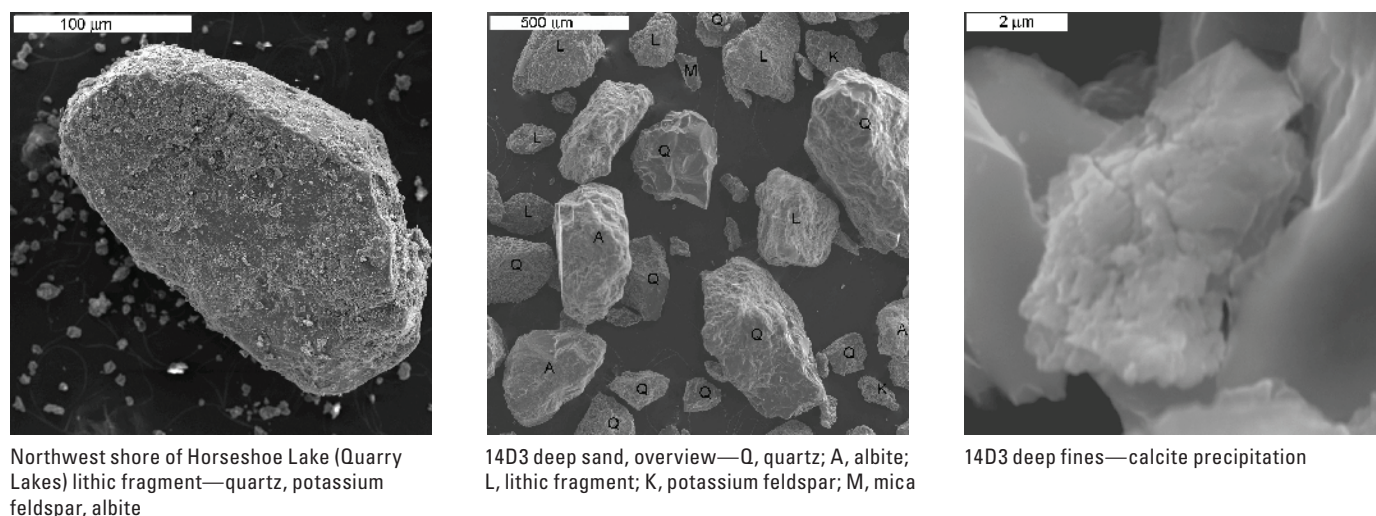
The elemental composition of cores and cuttings was determined by inductively coupled plasma–mass spectrometry (table 3–1; Briggs and Meier, 2002). The mineralogy of selected cores and cuttings was determined by X-ray diffraction (table 3–2; Amonette and Zelazny, 1994). Images of selected materials were obtained using a scanning electron microscope equipped with a spectral analyzer (Amonette and Zelazny, 1994). Mineralogic analyses were done on cuttings and core material from the Deep aquifer at a depth of 517 ft below land surface at well 14D3 and on a composite of coarse-grained outcrop material at Horseshoe Lake recharge pond (old gravel quarry) sampled from 2 ft and 20 ft below land surface, on the northwest shore (table 3–1). Mineralogic data were used as inputs to the computer program NETPATH for interpretation of carbon-14 data discussed in this report. Analysis of the uranium (U) and thorium (Th) content of coarse-grained sediments in both the Deep aquifer and surface deposits were used as a basis for estimating the magnitude of in situ generation of He and He isotopic composition.

Results are similar to previous analyses of core material from the East Bay Plain groundwater subbasin (Izbicki and others, 2003) in that quartz is the dominant mineral and a smaller amount of feldspar minerals are present. Primary and secondary minerals are listed in table 3–1. Scanning electron microscope images show little evidence of weathering or dissolution of mineral grains in cores and cuttings (fig. 3–1). Grain morphology and spectral analysis suggest that the bulk of the aquifer is composed of relatively nonreactive quartz. This is consistent with X-ray diffraction data in table 3–1. Scanning electron microscope images collected as part of this study show evidence of secondary precipitation of calcite

(fig. 3–1), suggesting that this may be an important reaction between groundwater and aquifer materials. On the basis of scanning electron microscopy with spectral analysis, small amounts of chlorite were present in aquifer deposits. Highly soluble chloride minerals are not likely to be present within freshwater aquifers underlying the Niles Cone groundwater subbasin. Dissolution of chlorapatite, or recrystallization into the more common form apatite, may explain small increases in chloride concentrations that alter chloride-to-bromide and chloride-to-iodide ratios (fig. 11) as groundwater flows through aquifer deposits. These increases are not nearly as large as chloride concentrations measured in water from underlying aquifers or increases resulting from seawater intrusion.

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**Figure 3–1.** Scanning electron microscopy (SEM) images of typical mineral grains from core material from selected sites in the Niles Cone groundwater subbasin, Alameda County, California [µm, micrometers].

**Table 3-1.** Elemental composition of samples from Lake Chad well (4S/2W-14D3) at 517 feet deep and outcrop on northwest shore of Quarry Lakes, Niles Cone groundwater subbasin, Alameda County, California.

[ft, foot; kg, kilogram; mg, milligram; NW, northwest; w/o, without; x, present; <, less than; ?, uncertain; —, not present]

Sample identifier			4S/2W-14D3 (bulk)	NW Quarry Lakes composite	4S/2W-14D3 (deep sand w/o fines)	4S/2W-14D3 (deep fines)
Sample description	Detection limit		Drilling mud impregnated core, 517 ft deep	Outcrop— sandy gravel near recharge ponds	Washed and sieved core, 517 ft	Hydrometer fines— native formation plus drilling mud from core, 517 ft deep
Elements (mg/kg)						
Gold	Ag	2	5.3	2.3	<2	<2
Arsenic	As	1	5.8	6.7	1.8	4.7
Barium	Ba	0.2	398	502	295	549
Beryllium	Be	0.03	0.82	0.92	0.62	1.1
Bismuth	Bi	0.06	0.14	0.12	<0.06	0.13
Calcium	Ca	100	8,280	13,400	6,620	11,700
Cadmium	Cd	0.007	0.34	0.13	0.16	0.26
Cerium	Ce	0.1	28.9	39.9	22.7	47.4
Cobalt	Co	0.03	11.9	13.0	8.4	17.0
Chromium	Cr	0.5	135	158	98.2	196
Ceasium	Cs	0.003	1.6	2.0	1.0	2.8
Copper	Cu	2	22.3	25.7	41.2	65.9
Iron	Fe	50	27,200	31,500	18,700	41,200
Gallium	Ga	0.02	9.3	10.9	7.1	14.1
Potassium	K	20	8,810	11,100	7,540	14,400
Lanthanum	La	0.05	15.0	21.6	13.0	24.2
Lithium	Li	0.3	23.8	25.2	17.9	33.5
Magnesium	Mg	6	13,000	15,600	9,840	19,400
Manganese	Mn	0.7	403	608	293	511
Molybdenum	Mo	0.05	0.95	0.52	0.23	0.67
Sodium	Na	20	14,200	16,900	16,200	38,100
Niobium	Nb	0.1	4.5	6.6	3.2	9.4
Nickel	Ni	0.3	77.3	93.1	58.6	122
Phosphorus	P	5	543	566	538	27,000
Lead	Pb	0.4	8.74	20.0	4.21	10.8
Rubidium	Rb	0.01	34.6	43.5	27.3	56.2
Antimony	Sb	0.04	0.51	0.94	0.24	0.50
Scandium	Sc	0.04	9.5	11.9	6.6	14.2
Strontium	Sr	0.8	108	134	87.1	154
Tantalum	Ta	0.02	0.44	0.61	0.24	0.97
Thorium	Th	0.1	4.52	6.05	3.11	7.27
Titanium	Ti	40	2,450	3,210	1,990	3,120
Thallium	Tl	0.08	0.20	0.26	0.15	0.34
Uranium	U	0.02	1.30	1.48	1.01	1.98
Vanadium	V	0.2	72.4	90.0	47.0	110
Tungsten	W	0.1	2.4	1.3	0.8	1.4
Yttrium	Y	0.05	14.4	16.4	14.2	21.5
Zinc	Zn	3	54.5	63.8	45.9	92.9

**Table 3-2.** Mineralogical composition and optical observations of samples from Lake Chad well (4S/2W-14D3) at 517 feet deep and outcrop on northwest shore of Quarry Lakes, Niles Cone groundwater subbasin, Alameda County, California.

[ft, foot; kg, kilogram; mg, milligram; NW, northwest; w/o, without; x, present; &lt;, less than; ?, uncertain; —, not present]

Sample identifier		4S/2W-14D3 (bulk)	NW Quarry Lakes composite	4S/2W-14D3 (deep sand w/o fines)	4S/2W-14D3 (deep fines)
Sample description	Detection limit	Drilling mud impregnated core, 517 ft deep	Outcrop— sandy gravel near recharge ponds	Washed and sieved core, 517 ft	Hydrometer fines— native formation plus drilling mud from core, 517 ft deep
Minerals (percent abundance)					
Quartz	—	54.0	46.0	63.0	36.0
Potassium feldspar	—	3.0	—	7.0	6.0
Chlorite	—	5.0	4.0	2.0	5.0
Muscovite	—	4.0	8.0	4.0	12.0
Kaolinite	—	<2	?	—	—
Monmorillonite	—	?	<2?	—	—
Kao-mont mixed	—	10.0	12	5.0	17.0
Plagioclase feldspar	—	23.0	27	19.0	23.0
Hematite	—	?	?	—	—
Calcite	—	—	1	—	—
Optical observations	—	Gravel—rounded rock fragments with some clay and iron coatings; fine-grained material—quartz sand, sandstone fragments.	Gravel—rounded rock fragments with some large quartz and feldspar blocky fragments; fine-grained material—rock fragments, quartz, clay coatings.	Angular to semi-rounded quartz.	Fine-grained quartz, large sheets of material.
Minerals from X-ray diffraction					
Quartz	—	x	x	x	x
Albite	—	x	x	x	x
Kaolinite/montmorillonite	—	x	x	x	x
Orthoclase, barian	—	—	—	x	x
Orthoclase	—	x	—	—	—
Clinocllore	—	x	x	x	x
Muscovite	—	x	x	x	x
Calcite	—	—	—	—	—
Kaolinite	—	x	?	—	—
Montmorillonite	—	x	x	—	—
Hematite	—	?	?	—	—
Minerals from scanning electron microscope (major or minor component)					
Organics	—	None	None	None	None
Lithics	—	—	Major	—	—
Quartz	—	Major	Major	Major	Major
Albite	—	Major	Minor	Major	—
Mica	—	Major	—	Major	Minor
Sodium phosphate	—	—	—	—	Major
Potassium feldspar	—	—	—	—	Minor
Andalusite barite	—	Minor	—	—	—
Ilmenite	—	Minor	Minor	Minor	—
Iron oxide	—	Minor	Minor	Minor	—
Rutile	—	Minor	—	—	Minor
Apatite	—	Minor	—	—	—
Clays	—	Minor	Minor	Minor	—
Mica	—	Major	Minor	Major	—
Calcite	—	—	—	—	Minor
Anorthite	—	—	Major	—	—





## Appendix 4. Streamflow Data Collected by the U.S. Geological Survey during April 2002

**Table 4–1.** Streamflow data collected by the U.S. Geological Survey during April 2002, Alameda Creek, California.

[ft<sup>3</sup>/s, cubic foot per second; N, North; W, West; °, degrees; ', minutes; ", seconds; —, no data]

Site number (as shown in figure 3)	Distance downstream from site 1, in miles	April 24, 2002, morning			April 24, 2002, afternoon			April 25, 2002, midday			
		Discharge, in ft <sup>3</sup> /s	Gage height, in feet	Rating	Discharge, in ft <sup>3</sup> /s	Gage height, in feet	Rating	Discharge, in ft <sup>3</sup> /s	Gage height, in feet	Rating	Temperature, in degrees Celsius
1*	0	2.84	0.87	Good	0.48	0.78	Poor	0.41	0.72	Poor	19.0
2	0.4	2.94	0.68	Good	0.58	0.485	Fair	—	—	—	20.5
3	0.8	—	—	—	—	—	—	0	5.07	Estimated	—
4	1.1	1.18	5.63	Fair	—	—	—	0.01	5.39	Poor	21.5
5	1.3	1.16	—	Good	0.42	7.325	Poor	—	—	—	23.0
6	1.9	1.43	8.13	Poor	0.602	8.08	Fair	0.21	8.02	Poor	20.5
7	2.5	1.28	11.16	Fair	1.79	11.66	Fair	—	—	—	22.5
8	3.0	2.86	12.39	Good	—	—	—	1.9	12.31	Fair	22.5
9	3.6	3.61	—	Good	3.96	—	Good	3.37	—	Good	21.0

\*Site 1 is located at 37°33'57.13052" N., 121°59'50.33553" W.





**Table 5-1.** Physical property, major-ion, selected trace-element, and isotopic data for groundwater, stream-water, and precipitation samples collected and analyzed by the U.S. Geological Survey, southern East Bay Plain and Niles Cone groundwater subbasins, Alameda County, California, 2002–03.—Continued

[Data analyzed by U.S. Geological Survey (USGS). Location of sites shown in figure 1. Abbreviations: A, at; ACWD, Alameda County Water District; BLDG, building; CaCO<sub>3</sub>, calcium carbonate; E, approximate value; h:mm, 24-hour time format in hours and minutes; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; N, nitrogen; PO<sub>4</sub>, phosphate; SiO<sub>2</sub>, silicon dioxide; °C, degrees Celsius; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 °C; <, actual value less than value shown; —, no data]

State well number	Date (mm/dd/yyyy)	Hardness, total (mg/L as CaCO <sub>3</sub> )	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	Alkalinity, dissolved (Gran titration) (mg/L as CaCO <sub>3</sub> )	Chloride, dissolved (mg/L as Cl)
4S/1W-17M7	03/19/2002	330	76.1	32.7	1.94	58.8	1260	82.8
4S/1W-17M8	03/22/2002	230	53	23.7	1.59	59.3	1162	74.1
4S/2W-12K10	11/05/2002	350	96.3	26.4	2.11	61.1	273	77.8
4S/2W-13P4	03/27/2002	370	86.3	38.5	2.11	68.8	1243	121
4S/2W-13P6	03/26/2002	530	141	42.3	2.71	46.3	1232	233
4S/2W-13P7	03/27/2002	510	138	40.3	2.63	46.1	1228	151
3S/2W-20L20	10/29/2002	180	46.4	15.4	1.76	67.8	205	46
3S/2W-29L6	10/30/2002	140	40.9	9.82	1.94	123	212	98.5
4S/1W-17M6	03/19/2002	390	103	31.4	2.39	42.7	1220	131
4S/2W-2H1	03/20/2002	160	45	10.5	1.99	87	1207	62.3
4S/2W-3L1	03/27/2002	160	43.4	11.2	1.95	63.5	1173	49.3
4S/2W-4E1	10/30/2002	150	42.2	11.7	2.47	132	218	122
4S/2W-4F3	03/21/2002	160	44.1	12.4	2.03	75	1187	66.2
4S/2W-4R1	10/29/2002	240	66.6	17.6	2.34	92.8	199	133
4S/2W-10E4	11/04/2002	290	82.3	19.3	2.84	57.6	174	118
4S/2W-12C1	03/20/2002	210	59.4	15.4	2.35	85.5	1237	103
4S/2W-12K8	11/05/2002	130	34.7	9.81	1.98	84.6	196	39.4
4S/2W-13P5	03/26/2002	570	156	42.2	2.58	48.8	1173	315
4S/2W-14D3	04/16/2003	66	19.7	4.05	2.06	110	180	45.8
4S/2W-14D4	11/06/2002	140	39.8	10.8	2.57	144	211	136
4S/2W-15L5	10/29/2002	220	63.5	13.6	2.9	236	166	346
Dry Creek near Union City	04/17/2003	230	54.3	23.6	1.34	44	218	27.8
USGS 373425121582101 PRECIP SAMPLER ACWD ROOFTOP INFLATION BLDG A NILES	11/08/2002	—	—	—	—	—	—	—

**Table 5-1.** Physical property, major-ion, selected trace-element, and isotopic data for groundwater, stream-water, and precipitation samples collected and analyzed by the U.S. Geological Survey, southern East Bay Plain and Niles Cone groundwater subbasins, Alameda County, California, 2002–03.—Continued

[Data analyzed by U.S. Geological Survey (USGS). Location of sites shown in figure 1. **Abbreviations:** A, at; ACWD, Alameda County Water District; BLDG, building; CaCO<sub>3</sub>, calcium carbonate; E, approximate value; hmmm, 24-hour time format in hours and minutes; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; N, nitrogen; PO<sub>4</sub>, phosphate; SiO<sub>2</sub>, silicon dioxide; °C, degrees Celsius; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 °C; <, actual value less than value shown; —, no data]

State well number	Date (mm/dd/yyyy)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO <sub>2</sub> )	Sulfate, dissolved (mg/L as SO <sub>4</sub> )	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Nitrogen, nitrate + nitrite, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)
4S/1W-17M7	03/19/2002	0.1	18.3	86.2	<0.04	<0.1	1.63	<0.008
4S/1W-17M8	03/22/2002	0.2	15.6	81.8	<0.04	<0.1	0.2	<0.008
4S/2W-12K10	11/05/2002	<0.17	24.7	62.4	<0.04	<0.1	8.13	0.059
4S/2W-13P4	03/27/2002	0.2	16.6	88.8	<0.04	<0.1	2.38	<0.008
4S/2W-13P6	03/26/2002	0.1	20.3	65	<0.04	<0.1	3.75	<0.008
4S/2W-13P7	03/27/2002	0.1	20.7	85.2	<0.04	<0.1	9.5	<0.008
3S/2W-20L20	10/29/2002	0.31	21.4	42.2	0.06	E0.08	<0.06	<0.008
3S/2W-29L6	10/30/2002	<0.17	24.8	50	<0.04	<0.1	0.11	<0.008
4S/1W-17M6	03/19/2002	0.1	20.6	59.9	<0.04	E0.07	3.54	0.024
4S/2W-2H1	03/20/2002	0.2	21.9	39.6	<0.04	<0.1	0.66	E0.004
4S/2W-3L1	03/27/2002	0.2	21.5	37.4	<0.04	<0.1	0.91	<0.008
4S/2W-4E1	10/30/2002	0.2	25.3	47.5	0.1	0.1	<0.06	<0.008
4S/2W-4F3	03/21/2002	0.2	23.3	38.6	<0.04	<0.1	0.31	<0.008
4S/2W-4R1	10/29/2002	<0.17	22.3	47.1	<0.04	<0.1	2.09	E0.006
4S/2W-10E4	11/04/2002	<0.17	22.5	63.9	0.06	E0.08	0.11	<0.008
4S/2W-12C1	03/20/2002	0.1	22.2	40.3	<0.04	<0.1	1.37	<0.008
4S/2W-12K8	11/05/2002	<0.17	18.7	44	<0.04	<0.1	0.35	E0.004
4S/2W-13P5	03/26/2002	E0.1	19.6	47	<0.04	<0.1	2.53	E0.005
4S/2W-14D3	04/16/2003	0.18	21	50.8	0.07	E0.08	0.1	<0.008
4S/2W-14D4	11/06/2002	0.18	21.1	54.2	<0.04	<0.1	<0.06	<0.008
4S/2W-15L5	10/29/2002	<0.17	20.3	75.3	0.08	0.1	<0.06	<0.008
Dry Creek near Union City	04/17/2003	0.32	14.8	53.4	<0.04	0.21	0.11	<0.008
USGS 373425121582101 PRECIP SAMPLER ACWD ROOFTOP INFLATION BLDG A NILES	11/08/2002	—	—	—	—	—	—	—



**Table 5-1.** Physical property, major-ion, selected trace-element, and isotopic data for groundwater, stream-water, and precipitation samples collected and analyzed by the U.S. Geological Survey, southern East Bay Plain and Niles Cone groundwater subbasins, Alameda County, California, 2002–03.—Continued

[Data analyzed by U.S. Geological Survey (USGS). Location of sites shown in figure 1. Abbreviations: A, at; ACWD, Alameda County Water District; BLDG, building; CaCO<sub>3</sub>, calcium carbonate; E, approximate value; hmmm, 24-hour time format in hours and minutes; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; N, nitrogen; PO<sub>4</sub>, phosphate; SiO<sub>2</sub>, silicon dioxide; °C, degrees Celsius; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 °C; <, actual value less than value shown; —, no data]

State well number	Date (mm/dd/yyyy)	Phosphorous, total, dissolved (mg/L as P)	Phosphorous, ortho, dissolved (mg/L as PO <sub>4</sub> )	Solids, residue at 180 °C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Bromide, dissolved (mg/L as Br)
4S/1W-17M7	03/19/2002	<0.06	0.02	532	522	0.5	106	455	0.29
4S/1W-17M8	03/22/2002	<0.06	<0.02	422	409	0.3	83	470	0.25
4S/2W-12K10	11/05/2002	E0.03	0.04	566	553	0.5	165	232	0.36
4S/2W-13P4	03/27/2002	<0.06	E0.02	617	580	0.4	56	508	0.47
4S/2W-13P6	03/26/2002	E0.03	0.03	883	709	1.1	268	315	1.14
4S/2W-13P7	03/27/2002	E0.04	0.04	725	667	1	265	383	1.43
3S/2W-20L20	10/29/2002	0.04	0.04	379	366	1.2	63	320	0.18
3S/2W-29L6	10/30/2002	0.08	0.09	483	479	0.5	90	461	0.4
4S/1W-17M6	03/19/2002	0.1	0.12	561	541	1.3	173	314	0.63
4S/2W-2H1	03/20/2002	E0.05	0.04	403	398	0.7	115	546	0.24
4S/2W-3L1	03/27/2002	E0.05	0.05	352	338	0.4	99	367	0.19
4S/2W-4E1	10/30/2002	0.12	0.12	523	517	0.8	97	430	0.51
4S/2W-4F3	03/21/2002	E0.04	0.06	386	377	1	96	309	0.27
4S/2W-4R1	10/29/2002	E0.04	0.04	528	513	0.8	147	323	0.48
4S/2W-10E4	11/04/2002	E0.03	0.03	491	474	1.6	165	279	0.51
4S/2W-12C1	03/20/2002	E0.05	0.05	475	479	0.8	136	379	0.41
4S/2W-12K8	11/05/2002	0.04	0.05	358	354	1.9	98	314	0.18
4S/2W-13P5	03/26/2002	<0.06	0.03	1,080	750	0.8	367	299	1.23
4S/2W-14D3	04/16/2003	0.07	0.07	368	364	4.3	48	341	0.18
4S/2W-14D4	11/06/2002	0.06	0.06	550	537	2.1	119	401	0.56
4S/2W-15L5	10/29/2002	0.05	0.05	882	861	2.1	105	545	1.33
Dry Creek near Union City	04/17/2003	E0.03	0.02	373	352	0.7	55	218	0.03
USGS 373425121582101 PRECIP SAMPLER ACWD ROOFTOP INFLATION BLDG A NILES	11/08/2002	—	—	—	—	—	—	—	—

**Table 5-1.** Physical property, major-ion, selected trace-element, and isotopic data for groundwater, stream-water, and precipitation samples collected and analyzed by the U.S. Geological Survey, southern East Bay Plain and Niles Cone groundwater subbasins, Alameda County, California, 2002–03.—Continued

[Data analyzed by U.S. Geological Survey (USGS). Location of sites shown in figure 1. **Abbreviations:** A, at; ACWD, Alameda County Water District; BLDG, building; CaCO<sub>3</sub>, calcium carbonate; E, approximate value; h:mm, 24-hour time format in hours and minutes; mg/L, milligram per liter; mm/dd/yyyy, month/day/year; N, nitrogen; PO<sub>4</sub>, phosphate; SiO<sub>2</sub>, silicon dioxide; °C, degrees Celsius; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 °C; <, actual value less than value shown; —, no data]

State well number	Date (mm/dd/yyyy)	Iodide, dissolved (mg/L as I)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Delta deuterium (per mil)	Delta oxygen-18 (per mil)	Carbon-14 (percent modern)	Carbon-13/Carbon-12 ratio (per mil)	Radiocarbon-age (years before present)
4S/1W-17M7	03/19/2002	0.004	<10	0.2	850	-46	-5.91	99.78	-15.31	18
4S/1W-17M8	03/22/2002	0.035	<10	0.7	585	-43.6	-5.38	100.1	-12.04	0
4S/2W-12K10	11/05/2002	0.004	<10	21.6	1,140	-42.5	-6.25	83.27	-16.21	1,500
4S/2W-13P4	03/27/2002	0.019	<10	4.2	879	-44.4	-5.78	96.8	-16.2	260
4S/2W-13P6	03/26/2002	0.002	<10	12	1,800	-49.6	-6.51	86.42	-14.85	1,200
4S/2W-13P7	03/27/2002	0.004	<10	0.3	1,690	-44.7	-6.14	90.18	-15.09	830
3S/2W-20L20	10/29/2002	0.154	331	189	567	-45.3	-6.89	38.53	-15.01	7,700
3S/2W-29L6	10/30/2002	0.465	17	86.3	512	-48.5	-7.2	23.92	-15.04	12,000
4S/1W-17M6	03/19/2002	0.004	<10	25.7	1,330	-49.2	-6.81	76.98	-14.47	2,100
4S/2W-2H1	03/20/2002	0.193	143	164	562	-46.2	-7.23	35.78	-14.52	8,300
4S/2W-3L1	03/27/2002	0.148	<10	194	527	-49.8	-7.07	52.78	-13.65	5,100
4S/2W-4E1	10/30/2002	0.539	45	49.5	585	-49.1	-7.27	22.48	-15.29	12,000
4S/2W-4F3	03/21/2002	0.236	<10	141	527	-50.4	-7.13	49.6	-13.52	5,600
4S/2W-4R1	10/29/2002	0.096	15	204	853	-46.6	-7.02	61.76	-13.64	3,900
4S/2W-10E4	11/04/2002	0.483	E6	139	1,100	-48.8	-7.2	52.86	-14.04	5,100
4S/2W-12C1	03/20/2002	0.255	48	217	735	-48.4	-7.11	48.38	-13.26	5,800
4S/2W-12K8	11/05/2002	0.178	<10	74.5	457	-48.8	-7.12	45.35	-13.67	6,400
4S/2W-13P5	03/26/2002	0.002	<10	21.6	2,100	-50.5	-7.01	85.54	-15.11	1,300
4S/2W-14D3	04/16/2003	0.175	<10	24	318	-49.2	-7.14	49.43	-13.85	5,700
4S/2W-14D4	11/06/2002	0.577	<10	75.5	552	-49.6	-7.33	20.55	-15.1	13,000
4S/2W-15L5	10/29/2002	0.632	E10	82.9	972	-50.2	-7.32	16.04	-15.08	15,000
Dry Creek near Union City	04/17/2003	0.004	<10	3.6	407	—	—	—	—	—
USGS 373425121582101 PRECIP SAMPLER ACWD ROOFTOP INFLATION BLDG A NILES	11/08/2002	—	—	—	—	-45.8	-7.65	—	—	—

<sup>1</sup>Alkalinity calculated using incremental titration, as milligrams per liter.



## Appendix 6. Noble Gas and Tritium Data for Groundwater Samples Collected and Analyzed by the U.S. Geological Survey

**Table 6–1.** Noble gas and tritium data for groundwater samples collected from selected wells in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, March–October, 2002–03.

[cm<sup>3</sup>/kg, cubic centimeter per kilogram; ID, identification; mm/dd/yyyy, month/day/year; nd, not determined;  $R_A$ , <sup>3</sup>He/<sup>4</sup>He ratio of air ( $1.84 \times 10^{-6}$ );  $R_s$ , <sup>3</sup>He/<sup>4</sup>He ratio of sample; USGS, U.S. Geological Survey;  $\mu\text{cm}^3/\text{kg}$ , micro-cubic centimeter per kilogram; +/–, plus or minus; <, less than; >, greater than; \*, helium-4 age calculated with crustal flux ( $J_0$ ) =  $3.0 \times 10^{-6}$ ;  $\Delta$  Ne, excess air (neon oversaturation); —, no data]

State well number	USGS site ID	Sample date (mm/dd/yyyy)	Noble gas recharge temperature, in degrees Celsius	Salinity, in grams per kilograms	RS/RA	Helium-3 ( <sup>3</sup> He), in $\times 10^{-8} \mu\text{cm}^3/\text{kg}$	Helium-4 ( <sup>4</sup> He) in $\mu\text{cm}^3/\text{kg}$	Neon (Ne), in $\mu\text{cm}^3/\text{kg}$
Upper aquifer system								
4S/1W-17M7	373457122002102	03/19/2002	15.4 +/– 0.8	0.51	1.30	17.8	98.7	374.4
4S/1W-17M8	373457122002103	03/22/2002	19.2 +/– 0.8	0.42	1.03	8.9	62.5	255.7
4S/2W-13P4	373447122021904	03/27/2002	11.4 +/– 0.7	0.61	1.68	20.8	89.2	340.4
4S/2W-13P6	373447122021902	03/26/2002	16.6 +/– 0.9	0.76	2.22	37.9	123.1	430.1
4S/2W-13P7	373447122021903	03/27/2002	10.6 +/– 0.7	0.72	1.97	27.1	99.3	394.7
Deep aquifer								
3S/2W-20L20	373912122065001	10/29/2002	15.5 +/– 0.7	0.38	0.91	8.3	66.0	248.0
3S/2W-29L6	373832122064801	10/30/2002	18.1 +/– 0.8	0.50	3.80	841.1	1599.9	286.6
4S/1W-17M6	373457122002101	03/19/2002	12.0 +/– 0.7	0.56	2.16	23.8	79.4	314.4
4S/2W-10E4	373601122042901	11/04/2002	14.3 +/– 0.8	0.48	4.16	1,494.6	2595.3	320.5
4S/2W-12C1	373620122015901	03/20/2002	10.1 +/– 0.7	0.48	4.05	480.7	857.8	320.4
4S/2W-12K8	373545122015001	11/05/2002	13.1 +/– 0.7	0.36	4.05	889.6	1586.6	246.9
4S/2W-13P5	373447122021901	03/26/2002	15.9 +/– 0.8	0.85	2.33	31.9	98.9	352.6
4S/2W-15L5	373457122041001	10/29/2002	10.5 +/– 0.9	0.93	4.21	2,396.4	4108.9	395.5
4S/2W-02H1	373648122023601	03/20/2002	14.1 +/– 0.7	0.41	3.83	436.9	824.6	327.2
4S/2W-03L1	373646122042701	03/27/2002	13.5 +/– 0.7	0.35	3.89	437.1	811.7	260.9
4S/2W-04E1	373708122055101	10/30/2002	16.7 +/– 0.8	0.53	4.00	1,130.1	2042.8	286.0
4S/2W-04F6	—	10/31/2002	15.1 +/– 0.8	0.33	3.39	254.9	544.1	297.2
4S/2W-04R1	373638122045901	10/29/2002	15.4 +/– 0.8	0.54	4.08	292.6	518.2	364.1
4S/2W-14D3	373521122033101	04/16/2003	13.4 +/– 0.7	0.36	4.25	2,274.9	386.0	240.0

**Table 6-1.** Noble gas and tritium data for groundwater samples collected from selected wells in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, March–October, 2002–03.—Continued

[cm<sup>3</sup>/kg, cubic centimeter per kilogram; ID, identification; mm/dd/yyyy, month/day/year; nd, not determined; R<sub>A</sub>, <sup>3</sup>He/<sup>4</sup>He ratio of air (1.84×10<sup>-6</sup>); R<sub>s</sub>, <sup>3</sup>He/<sup>4</sup>He ratio of sample; USGS, U.S. Geological Survey; μcm<sup>3</sup>/kg, micro-cubic centimeter per kilogram; +/-, plus or minus; <, less than; >, greater than; \*, helium-4 age calculated with crustal flux (J<sub>0</sub>) = 3.0×10<sup>-6</sup>; Δ Ne, excess air (neon oversaturation); —, no data]

State well number	USGS Site ID	Sample date (mm/dd/yyyy)	Krypton (Kr), in μcm <sup>3</sup> /kg	Argon (Ar), in cm <sup>3</sup> /kg	Δ Ne (percent)	Helium-4 ( <sup>4</sup> He) Age*, in years before present	Tritium, in tritium units	Tritium/Helium-3 residence times, in years before present
Upper aquifer system—Continued								
4S/1W-17M7	373457122002102	03/19/2002	90.1	0.434	94.9	2	22.9	22
4S/1W-17M8	373457122002103	03/22/2002	80.8	0.374	37.3	<1	7.2	6
4S/2W-13P4	373447122021904	03/27/2002	99.0	0.428	71.0	9	32.5	27
4S/2W-13P6	373447122021902	03/26/2002	91.6	0.452	126.1	26	22.1	47
4S/2W-13P7	373447122021903	03/27/2002	102.0	0.478	96.7	<1	46.6	27
Deep aquifer—Continued								
3S/2W-20L20	373912122065001	10/29/2002	80.9	0.375	29.2	12	0.6	nd
3S/2W-29L6	373832122064801	10/30/2002	78.3	0.384	52.5	4425	<0.2	>50
4S/1W-17M6	373457122002101	03/19/2002	93.1	0.430	58.8	<1	16.6	43
4S/2W-10E4	373601122042901	11/04/2002	89.1	0.413	65.2	7287	<0.2	>50
4S/2W-12C1	373620122015901	03/20/2002	100.2	0.434	58.9	2255	7.8	>50
4S/2W-12K8	373545122015001	11/05/2002	85.4	0.396	25.9	4425	<0.2	>50
4S/2W-13P5	373447122021901	03/26/2002	87.9	0.420	84.2	21	10.0	58
4S/2W-15L5	373457122041001	10/29/2002	87.8	0.429	109.4	11612	<0.2	>50
4S/2W-02H1	373648122023601	03/20/2002	87.2	0.443	68.5	2145	<0.2	>50
4S/2W-03L1	373646122042701	03/27/2002	86.6	0.390	33.6	2166	<0.2	nd
4S/2W-04E1	373708122055101	10/30/2002	80.8	0.392	50.4	5711	<0.2	>50
4S/2W-04F6	—	10/31/2002	85.8	0.398	54.3	1358	<0.2	>50
4S/2W-04R1	373638122045901	10/29/2002	89.6	0.427	89.5	1228	<0.2	>50
4S/2W-14D3	373521122033101	04/16/2003	84.4	0.386	22.2	11034	0.4	>50



## Appendix 7. Measured and Interpreted Carbon-13 and Carbon-14 Data for Groundwater Samples Collected and Analyzed by the U.S. Geological Survey

**Table 7-1.** Measured and interpreted carbon-13 and carbon-14 data for groundwater samples collected from selected wells in the Niles Cone and southern East Bay Plain groundwater subbasins, Alameda County, California, March–October, 2002.

[m, meter; pmC, percent modern carbon; \*, data interpreted using the NETPATH computer program (Plummer and others, 1991); \*\*, uncorrected ages calculated using the calculated  $\Delta a$  value of 69.37 pmC]

State well number	Local name	Distance along flow path, in feet	Well construction		Carbon-13/carbon-12, in per mil		Carbon-14			
			Top of screened interval, in feet below land surface	Bottom of screened interval, in feet below land surface	Measured	Interpreted*	Measured, in percent in modern carbon	Uncorrected age**, in years before present	Interpreted age*, in years before present	Interpreted groundwater flow rate, in feet per year
4S/2W-12K8	Pacific	0	470	510	-13.67	—	45.35	—	0	—
4S/2W-12C1	Whipple	2,800	410	487	-13.26	-12.99	48.38	2,979	830	3.37
4S/2W-3L1	Danone	14,100	367	442	-13.65	-14.08	52.78	2,259	1,963	9.97
4S/2W-4F3	Well B	18,700	440	525	-13.52	-14.00	49.60	2,773	2,358	11.6
4S/2W-4E1	Well E	21,000	470	525	-15.29	-15.34	22.48	9,315	7,340	0.46
3S/2W-29L6	Mt. Eden	29,500	480	580	-15.04	-15.12	23.92	8,802	7,121	38.8

Mass transfer and cation exchange, in millimoles						
State well number	Silicates	Carbonates	Cation exchange	Clay precipitation	Carbon	Gypsum
4S/2W-12K8	—	—	—	—	—	—
4S/2W-12C1	0.17433	0.24003	0.01984	-0.14517	0.49844	0.2123
4S/2W-3L1	0.15806	-0.17239	-0.45914	-0.13475	0.11315	0.00189
4S/2W-4F3	0.09995	0.00217	-0.20884	-0.06165	0.16557	0.02812
4S/2W-4E1	2.37506	-0.34908	-0.1557	-3.50761	0.84418	0.45862
3S/2W-29L6	1.67357	-0.26514	-0.00092	-2.45955	0.71404	0.41957

**Table 7–2.** Chemical reactions used to interpret carbon-14 data.

Process	Representative chemical equation	Comments
Cation exchange	$(\text{Ca}, \text{Mg})^{+2} + \text{Na}_2 \bullet \text{clay} \leftrightarrow 2\text{Na}^+ + (\text{Ca}, \text{Mg}) \bullet \text{clay}$	Simulated as exchange of equal parts dissolved $\text{Ca}^{+2}$ and $\text{Mg}^{+2}$ for each part $\text{Na}^+$ on the clay-exchange sites.
Carbonate precipitation	$\text{HCO}_3^- + \text{Ca}^{+2} \leftrightarrow \text{CaCO}_3 + \text{H}^+$ and $\text{HCO}_3^- + \text{Mg}^{+2} \leftrightarrow \text{MgCO}_3 + \text{H}^+$	Simulated as separate phases. Precipitation of only small amounts of $\text{MgCO}_3$ were needed to balance the mass-balance model. In the environment, $\text{Mg}^{+2}$ probably substitutes for $\text{Ca}^{+2}$ in variable amounts within carbonate minerals.
Silicate weathering	$\text{CaAl}_2\text{Si}_2\text{O}_8 + 8\text{H}^+ \rightarrow \text{Ca}^{+2} + 2\text{Al}^{+3} + 2\text{H}_4\text{SiO}_{40}$ and $\text{NaAlSi}_3\text{O}_8 + 4\text{H}_2\text{O} + 4\text{H}^+ \rightarrow \text{Al}^{3+} + 3\text{H}_4\text{SiO}_{40} + \text{Na}^+$ and $\text{KAlSi}_3\text{O}_8 + 4\text{H}_2\text{O} + 4\text{H}^+ \rightarrow \text{Al}^{+3} + 3\text{H}_4\text{SiO}_{40} + \text{K}^+$	Simulated as dissolution of anorthite with smaller amounts of albite and potassium feldspar included to satisfy mass-balance constraints. In some settings, dissolution of chlorite or sepiolite also may occur. Although other primary silicates also may dissolve, thermodynamic data show that the system is supersaturated with respect to biotite (mica) and that dissolution of this mineral will not occur.
Sulfate reduction	$2\text{CH}_2\text{O} + \text{SO}_4^{-2} \rightarrow \text{HS}^- + 2\text{HCO}_3^- + \text{H}^+$	Simulated as oxidation of organic matter having a $\delta^{13}\text{C}$ of –21 per mil.
Clay precipitation	$0.33\text{Na}^+ + 2.33\text{Al}(\text{OH}) + 3.67\text{H}_4\text{SiO}_{40} + 2\text{H}^+ \rightarrow \text{Na}_{0.33}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2 + 12\text{H}_2\text{O}$ or $2\text{Al}^{+3} + \text{H}_2\text{O} + 2\text{H}_4\text{SiO}_{40} \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 6\text{H}^+$	Only small differences in mass transfer result from simulation of clay precipitation as montmorillonite or as kaolinite. Both minerals detected by X-ray diffraction.

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