Prepared in cooperation with the Napa County Department of Public Works

Ground-Water Resources in the Lower Milliken–Sarco–Tulucay Creeks Area, Southeastern Napa County, California, 2000–2002

Water-Resources Investigations Report 03-4229

U.S. Department of the Interior
U.S. Geological Survey

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By Christopher D. Farrar *and* Loren F. Metzger

U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1	meter per meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	259.0	hectare
	Volume	
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per acre (acre-ft/acre)	0.0000003	cubic hectometer per square meter
gallons (gal)	3.785	liter
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	meter per day
acre foot per day per mile [(acre-ft/d)/mi]	0.000766	cubic hectometer per second
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot per second (ft/s)	0.3048	meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.3048	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per minute
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day

Temperature in degrees Celsius (^oC) may be converted to degrees Fahrenheit (^oF) as follows:

$$^oF=1.8\ ^oC+32.$$

Specific conductance is given microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25^{o}C).

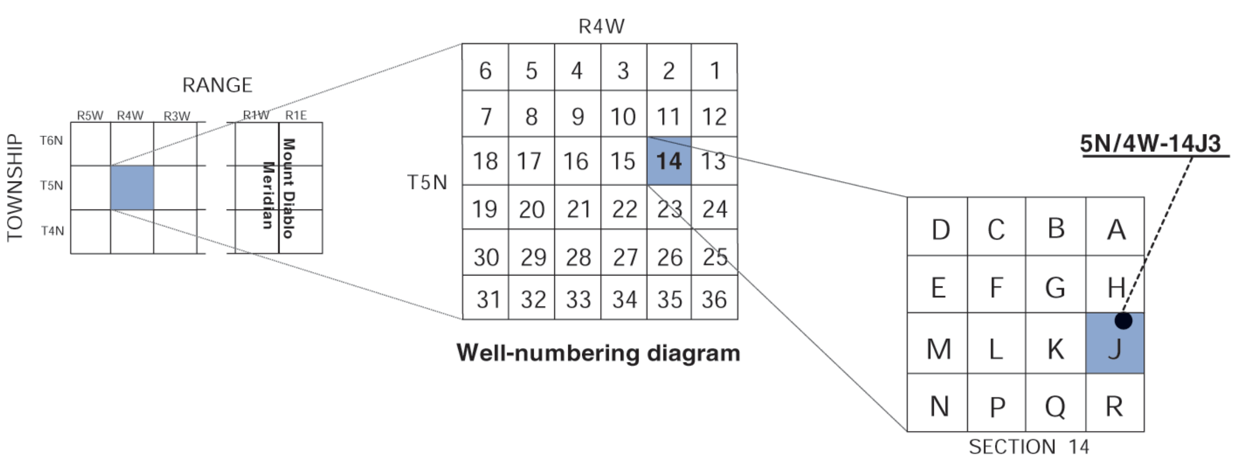
Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

cm^3/L	cubic centimeters per liter
hr/d	hour per day
kg	kilogram
L	liter
mg/L	milligrams per liter
mL	milliliter
pg/kg	picogram per kilogram
μg/L	micrograms per liter
μS/cm	microsiemens per centimeter
AL	action level
bls	below land surface
DWR	Department of Water Resources
GIS	geographic information system
GPS	global positioning system
GULP	Groundwater Under Local Protection
MCL	maximum contaminant level
NWIS	National Water Information System
pptv	part per trillion by volume
STP	standard temperature and pressure
USGS	U.S. Geological Survey
V-SMOW	Vienna Standard Mean Ocean Water
Ar	argon
$CaCO_3$	calcium carbonate
CFC	chloroflurocarbons
CH_4	methane
CO_2	carbon dioxide
H_2	hydrogen gas
^1H	hydrogen isotope
^2H	deuterium
^3H	tritium
He	helium
^3He	helium-3
^4He	helium-4
H_2S	hydrogen sulfide
N_2	nitrogen
Ne	neon
O_2	oxygen
^{16}O	oxygen-16
^{18}O	oxygen-18
TU	tritium units
δ	delta notation
‰	parts per thousand

WELL-NUMBERING SYSTEM

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a boustrophedonic manner to "R" in the southeast corner. Within the 40-acre tract, wells are numbered sequentially in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humbolt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referred to the Mount Diablo base line and meridian (M). Well numbers consist of 15 characters and follow the format 005N004W14J003M. In this report, well numbers are abbreviated and written 5N/4W-14J3. The following diagram shows how the number for well 5N/4W-14J3 is derived.



Well-numbering diagram

Ground-Water Resources in the Lower Milliken–Sarco–Tulucay Creeks Area, Southeastern Napa County, California, 2000–2002

By Christopher D. Farrar and Loren F. Metzger

ABSTRACT

Ground water obtained from individual private wells is the sole source of water for about 4,800 residents living in the lower Milliken–Sarco–Tulucay Creeks area of southeastern Napa County. Increases in population and in irrigated vineyards during the past few decades have increased water demand. Estimated ground-water pumpage in 2000 was 5,350 acre-feet per year, an increase of about 80 percent since 1975. Water for agricultural irrigation is the dominant use, accounting for about 45 percent of the total. This increase in ground-water extraction has resulted in the general decline of ground-water levels. The purpose of this report is to present selected hydrologic data collected from 1975 to 2002 and to quantify changes in the ground-water system during the past 25 years.

The study area lies in one of several prominent northwest-trending structural valleys in the North Coast Ranges. The area is underlain by alluvial deposits and volcanic rocks that exceed 1,000 feet in thickness in some places. Alluvial deposits and tuff beds in the volcanic sequence are the principal source of water to wells.

The ground-water system is recharged by precipitation that infiltrates, in minor amounts, directly on the valley floor but mostly by infiltration in the Howell Mountains. Ground water moves laterally from the Howell Mountains into the study area. Although the area receives abundant winter precipitation in most years, nearly half of the precipitation is lost as surface runoff to the Napa River. Evapotranspiration also is high, accounting for nearly one-half of the total precipitation received. Because of the uncertainties in the estimates of precipitation, runoff, and evapotranspiration, a precise estimate of potential ground-water recharge cannot be made.

Large changes in ground-water levels occurred between 1975 and 2001. In much of the western part of the area, water levels increased; but in the central and eastern parts, water levels declined by 25 to 125 feet. Ground-water extraction produced three large pumping depressions in the northern and east-central parts of the area. The general decline in ground-water levels is a result of increases in ground-water pumpage and possibly changes in infiltration capacity caused by changes in land use.

Ground-water-level declines during 1960–2002 are evident in the records for 9 of 10 key monitoring wells. In five of these wells, water levels dropped by greater than 20 feet since the 1980s. The largest water-level declines have occurred since the mid 1970s, corresponding with a period of accelerated well construction and ground-water extraction.

Analysis of samples from 15 wells indicates that the chemical quality of ground water in the study generally is acceptable. However, arsenic concentrations in samples from five wells exceed the U.S. Environmental Protection Agency primary drinking-water standard of 10 micrograms per liter, and iron concentrations in samples from five wells exceed the U.S. Environmental Protection Agency and the California Department of Health Services secondary drinking-water

standard of 300 micrograms per liter. Water from 12 of 15 wells sampled contained concentrations of manganese that exceed the U.S. Environmental Protection Agency and the California Department of Health Services secondary drinking-water standard of 50 micrograms per liter. Two wells produced water that had boron in excess of the California Department of Health Services action level of 1 milligram per liter.

Stable isotope, chlorofluorocarbon, and tritium data indicate that ground water in the area is a mixture of waters that recharged the aquifer system at different times. The presence of chlorofluorocarbons and tritium in water from the study area is evidence that modern recharge (post 1950) does take place. Water-temperature logs indicate that ground-water temperatures throughout the study area exceed 30°C at depths in excess of 600 feet. Further, water at depths greater than 600 feet in parts of the study area may contain objectionable concentrations of some constituents that may limit the use of the ground water.

INTRODUCTION

The Milliken–Sarco–Tulucay Creeks area, in southeastern Napa County, California, lies adjacent to the city of Napa and extends eastward into the Howell Mountains. This part of Napa County is approximately 40 mi northeast of San Francisco. The Milliken, Sarco, and Tulucay Creeks are the main streams that drain the Howell Mountains between 38° 25´ and 38° 17´ north latitude; the creeks have a combined drainage area of 42 mi^2. Land-surface altitudes range from about 10 ft above sea level at the Napa River, in the southwest part of the area, to 1,877 ft above sea level on the summit of Mt. George in the Howell Mountains. The lower parts of the three drainage basins, which cover about 15 mi^2 of rolling hills that extend westward from the mountain front to the Napa River, were the focus of this study (fig. 1). The study area has been extensively developed into agricultural land and rural home sites. Most home sites are on parcels larger than 1 acre.

Ground water is the only source of water in much of the lower Milliken–Sarco–Tulucay Creeks area. The city of Napa supplies part of this area with surface water delivered through a pipeline distribution system. For most of the area, however, each developed land parcel has an individual water system supplied by one or more wells. Single-family dwelling units, irrigated agriculture, and golf courses are the main users of the local ground water. An increase in ground-water extraction since the 1950s has resulted in the general decline of ground-water levels throughout the area. Declining ground-water levels are evidence of a ground-water system under stress.

Purpose and Scope

The U.S. Geological Survey (USGS) in cooperation with the Napa County Department of Public Works undertook this study to evaluate possible strategies for reducing water-level declines in the Milliken–Sarco–Tulucay Creeks area. A previous hydrologic assessment of the area was completed more than 25 years ago (Johnson, 1977). Many wells have been completed and significant hydrologic data have been collected since Johnson's study. These more recent data were used in this study to increase the level of knowledge of the local geohydrology of the area and to describe changes in land use, water use, and ground-water levels since 1975.

The purpose of this report is to present selected hydrologic data collected from 1975 to 2002 and to quantify changes in the ground-water system that occurred during the past 25 years. This information is essential for the future management of the ground-water system, which is the primary source of water supply for a rapidly developing area of the county. Specific objectives of the study were to refine the conceptual model of the geohydrologic framework, quantify changes in water use, describe present day ground-water conditions, identify the locations with the largest changes in ground-water storage, provide a more complete description of ground-water quality, and update the hydrologic budget of the lower Milliken–Sarco–Tulucay Creeks area. The emphasis of this study was on documenting changes in ground-water levels within the study area and identifying the principal causes of the ground-water level declines. An additional objective was to determine the source and movement of ground water in the different drainage basins.

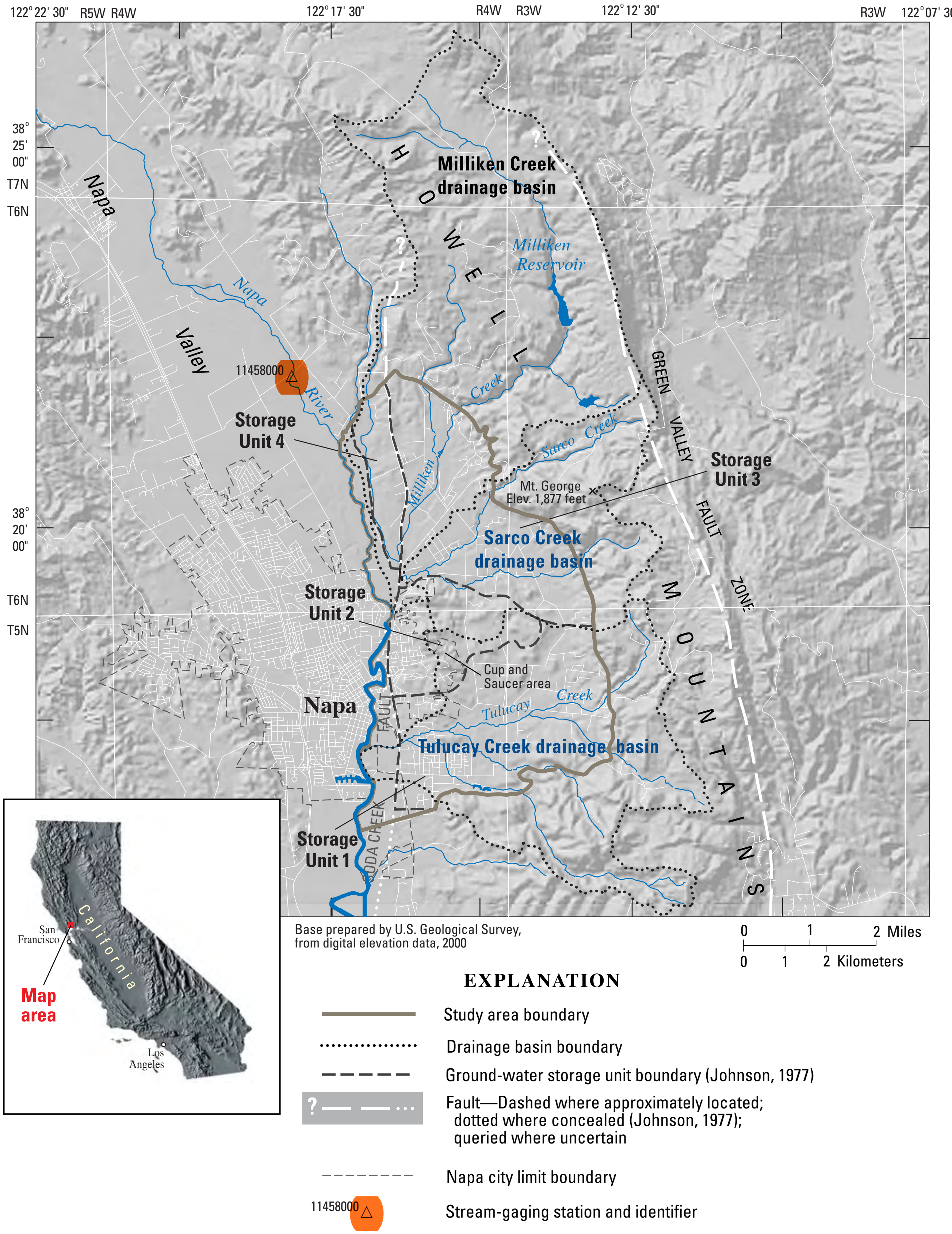


Figure 1. Location of study area, southeastern Napa County, California.

To meet the objectives of this study, four principal tasks were identified: (1) evaluation of existing geohydrologic and geochemical data, (2) collection and analysis of new geohydrologic data including subsurface lithologic data, ground-water levels, and streamflow gains and losses, (3) collection and analysis of new water chemistry and isotopic data, and (4) updating estimates of water use and changes in ground-water storage and movement.

New hydrologic data presented in this report were collected between April 2000 and November 2002. These data include ground-water levels, surface-water discharge measurements, water chemistry including isotopic composition, and temperature logs in wells.

Description of Study Area

The study area, which is a topographic depression underlain by lava flows, tuff beds, and volcanic debris, is enclosed on the north, east, and south by the Howell Mountains and is bounded on the west by the Napa River (fig. 1). Johnson (1977) divided most of the study area into four storage units on the basis of geologic structure and surface-water drainage basins. However, parts of the study area near the western boundary are not included in these storage units. Storage unit 1 consists of 3,873 acres in the southern part of the study area and includes most of the lower reach of Tulucay Creek and several tributary streams. Storage unit 2 consists of about 1,638 acres of hilly land along the western side of the central part of the study area and is drained only by a few minor unnamed ephemeral streams. This area is known as The Cup and Saucer area in reference to the somewhat cup-shaped topography. Storage unit 3 consists of about 3,584 acres in the northern and eastern parts of the study area and is drained by Milliken and Sarco Creeks. Storage unit 4 comprises about 815 acres in a narrow area west of the Soda Creek Fault.

Ground-water level and geochemical data collected during this study do not support the notion that these storage units are hydraulically separate. The storage unit designations, nevertheless, are useful because they are used by local governmental agencies and residents as names for partitions of the study area. For this reason the storage units are referred to in the text and the boundaries are shown in several figures in this report.

The study area consists of predominantly unincorporated land within the county of Napa, but it also includes a part of the city of Napa on the western side of the area. Land use is a combination of urban, agriculture, and unimproved open space (fig. 2). Land-use mapping by the California Department of Conservation in 2000 (Sherron Muma, California Department of Conservation, written commun., 2002) showed that unimproved open space with mixed residential use predominates, amounting to about 40 percent of the total area, followed by urban use of 31 percent, and irrigated agriculture mixed with residential use of 21 percent (table 1, at back of report). Major changes in land use have taken place in the study area over the past 40 years. On the basis of land-use analysis completed as a part of this study using the earliest available aerial photographs, land use for unimproved open space with mixed residential use decreased by 35 percent, urban use increased by 58 percent, and irrigated agriculture with residential use increased by 304 percent since 1958. The dramatic increase in irrigated agriculture is attributable to the emergence of drip-irrigated vineyards for the production of wine grapes. Other agricultural uses, such as orchards, row crops, and non-irrigated grass and pasture lands, have been almost completely replaced by vineyards in the study area.

Census data for the year 2000 indicate that about 16,500 people live in the study area (Association of Bay Area Governments, 2002), an increase of about 21 percent since Johnson's study in the early 1970s . The population in the unincorporated county part of the study area is about 8,000. However, a direct comparison of the present day population in the county area with Johnson's data cannot be made because some previously unincorporated areas are now part of the city.

The climate of the study area is mediterranean, with distinct wet and dry seasons. About 90 percent of the area's yearly precipitation occurs from November through April. Mean annual precipitation at Napa State Hospital averaged about 24.5 inches from water years 1918 through 2002 (fig. 3*A*) (National Oceanic and Atmospheric Administration, 2002). Figure 3*A* shows that annual precipitation in any given year can deviate as much as 200 percent from the 85-year average. During the study period, water years 2000 through 2002, rainfall at Napa State Hospital ranged from about 6 inches below average in 2001 to about 1.5 inches above average in 2000 and 2002 (fig. 3*B*).

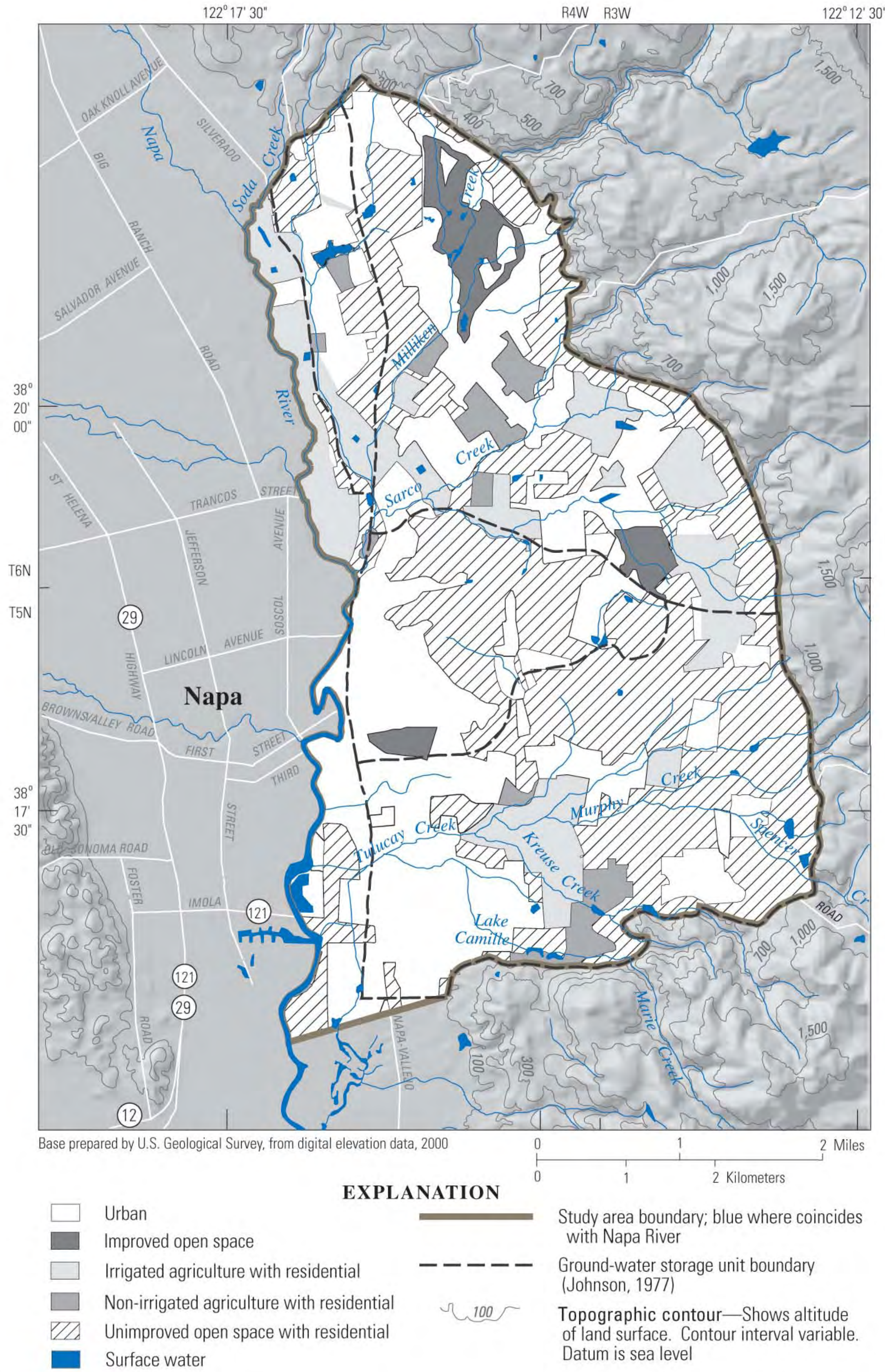


Figure 2. Land use in 2000 in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

(Modified from Important Farmland Data, Napa County, California, 2000, 1:24,000 enlargement, Sherron Muma, California Department of Conservation, Farmland Mapping and Monitoring Program, written commun., 2000)

The areal distribution of mean annual precipitation for 1961–90 in the study area is shown in figure 4. Isohyetal contours show that precipitation generally increases from south to north and with increasing altitude. Average annual precipitation is as much as 40 inches in the highest altitudes of the Howell Mountains. This is about 65 percent more precipitation than the amount received at the lower altitudes (Daly and Taylor, 1998).

The average total amount of precipitation received in the Milliken, Sarco, and Tulucay Creeks drainage basins is about 69,000 acre-ft/yr based on the isohyetal map (fig. 4). Of this amount, about 29,000 acre-ft/yr leaves the watershed as runoff in local streams to the Napa River. This estimate is based on streamflow records for stations on the Napa River and Tulucay Creek and is consistent with estimated unit-runoff for this area given in Rantz (1968). Johnson (1977) estimated that evapotranspiration in the basins consumes about 30,500 acre-ft/yr. An estimate of about 34,000 acre-ft/yr is obtained when Johnson's estimate is adjusted for the slightly larger area mapped for this study. Using these estimates, it is clear that most of the water entering the basins leaves as runoff or evapotranspiration. Potential ground-water recharge can be calculated as the residual of total precipitation minus runoff and evapotranspiration, assuming no other inflows or outflows. Using this method, a residual of 6,000 acre-ft/yr is calculated based on the estimates made in this study. However, because of the uncertainty in the estimates of precipitation, runoff, and evapotranspiration, this value is not a precise estimate of potential ground-water recharge and should not be construed as the safe yield for the study area.

Residential water supplies in the study area are a combination of municipal and private sources. The City of Napa Municipal Water Department supplies almost 79,000 people within the city limits of Napa and in several unincorporated parts of Napa County (Don Ridenhour, City of Napa Municipal Water Department, written commun., 2002). The water supplied by the city of Napa primarily is obtained from Lake Hennessey and the Milliken Reservoir (fig. 1) and imported surface water obtained from the North Bay Aqueduct through a contract with the State Water Project. County areas served by public water supply include residences in an area bounded by Monticello Road, Sarco Creek, and Vichy Avenue, and the Silverado Country Club east of Atlas Peak Road and north of Monticello Road (fig. 5). An estimated 3,200 people are served by about 1,000 metered public-supply connections. The remaining estimated 4,800 residents of the county part of the study area rely on private water systems. Ground water is the predominant source of water for both domestic and irrigation use.

Previous Investigations

Weaver (1949) carried out one of the earliest published geologic investigations that included the study area. His work defined the basic geology of the area in terms of stratigraphy and structure. Studies by Fox and others (1973) and Sims and others (1973) provide the most detailed geologic maps for the study area to date.

Hydrologic data have been collected in the study area since the late 1940s but some earlier sources of information also are available. Water levels have been measured in the study area since about the late 1910s as part of local or special studies and through cooperative efforts by various government entities [California Department of Water Resources (DWR), 1995]. Intermittent water-level measurements through the 1940s were made primarily by the USGS. Regular long-term regional water-level monitoring by the USGS, DWR, and the Napa County Agricultural Advisor began in the late 1950s. Since 1973, Napa County in cooperation with DWR has collected water-level data semiannually for a network of about 10 wells. These data were reviewed for this study and provided a basis for documenting long-term trends in ground-water levels throughout the study area. The study area also was included in a comprehensive hydrogeologic investigation of Napa and Sonoma Counties by the U.S. Geological Survey (Kunkel and Upson, 1960). Their data and interpretation provided the foundation for later hydrologic studies. In the mid-1970s, the USGS carried out a more detailed study focused solely on the Milliken–Sarco–Tulucay Creek area (Johnson, 1977).

The Regional Water Quality Control Board has developed a geographic information system (GIS) for Napa Valley (Jeff Kapellas, California Regional Water Quality Control Board, written commun., 2000) that includes surficial geology, soils, ground-water basins, well yield, depth to ground water, recharge areas, well data, Napa County septic systems, hazardous material storage sites, landfills, and land use.

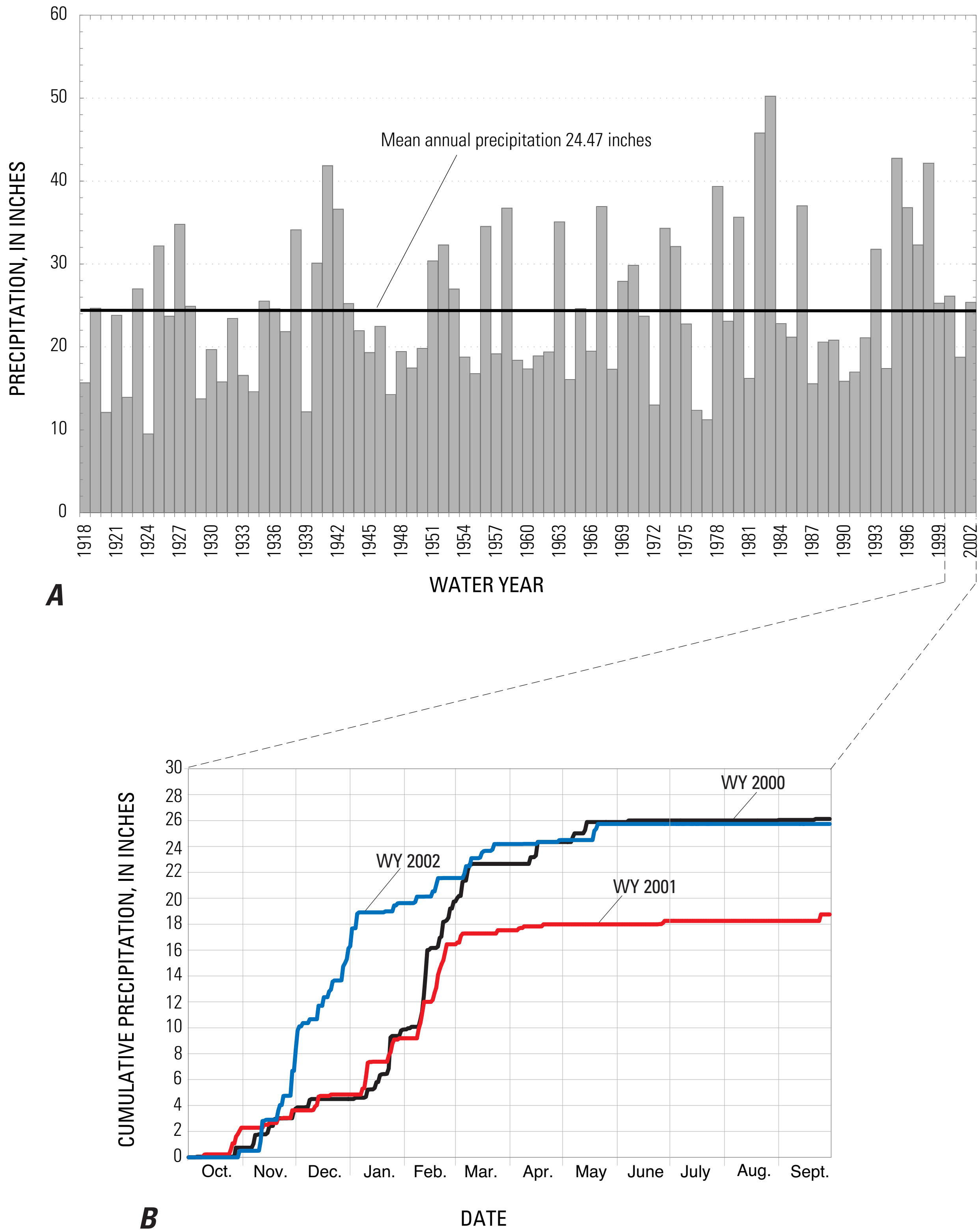


Figure 3. (A) Annual precipitation for water years 1918–2002, and (B) distribution of cumulative precipitation for water years (WY) 2000–2002 at Napa State Hospital, southeastern Napa County, California.

(See figure 4 for areal distribution.)

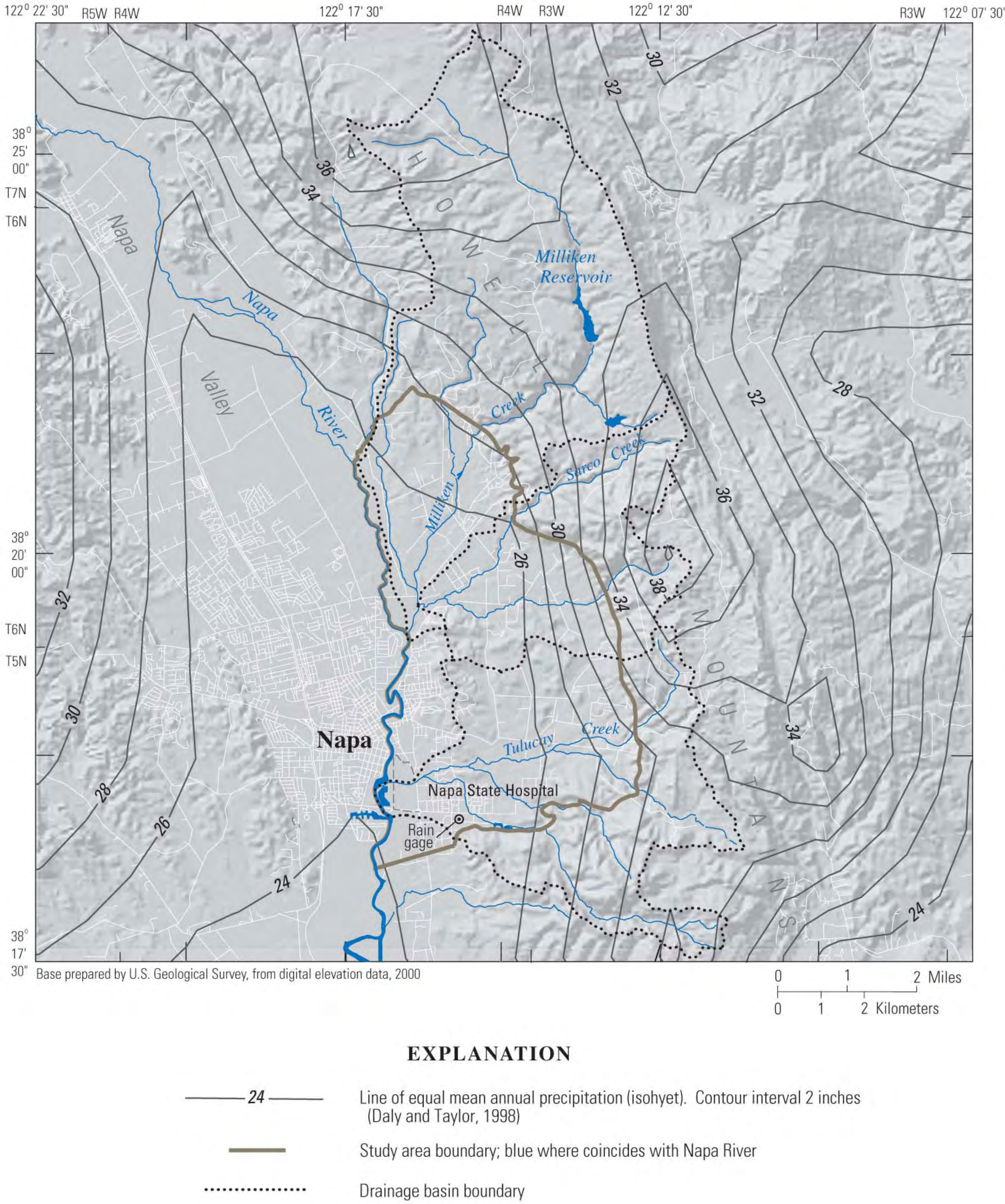


Figure 4. Mean annual precipitation in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, 1961-90. (Modified from Daly and Taylor, 1998)

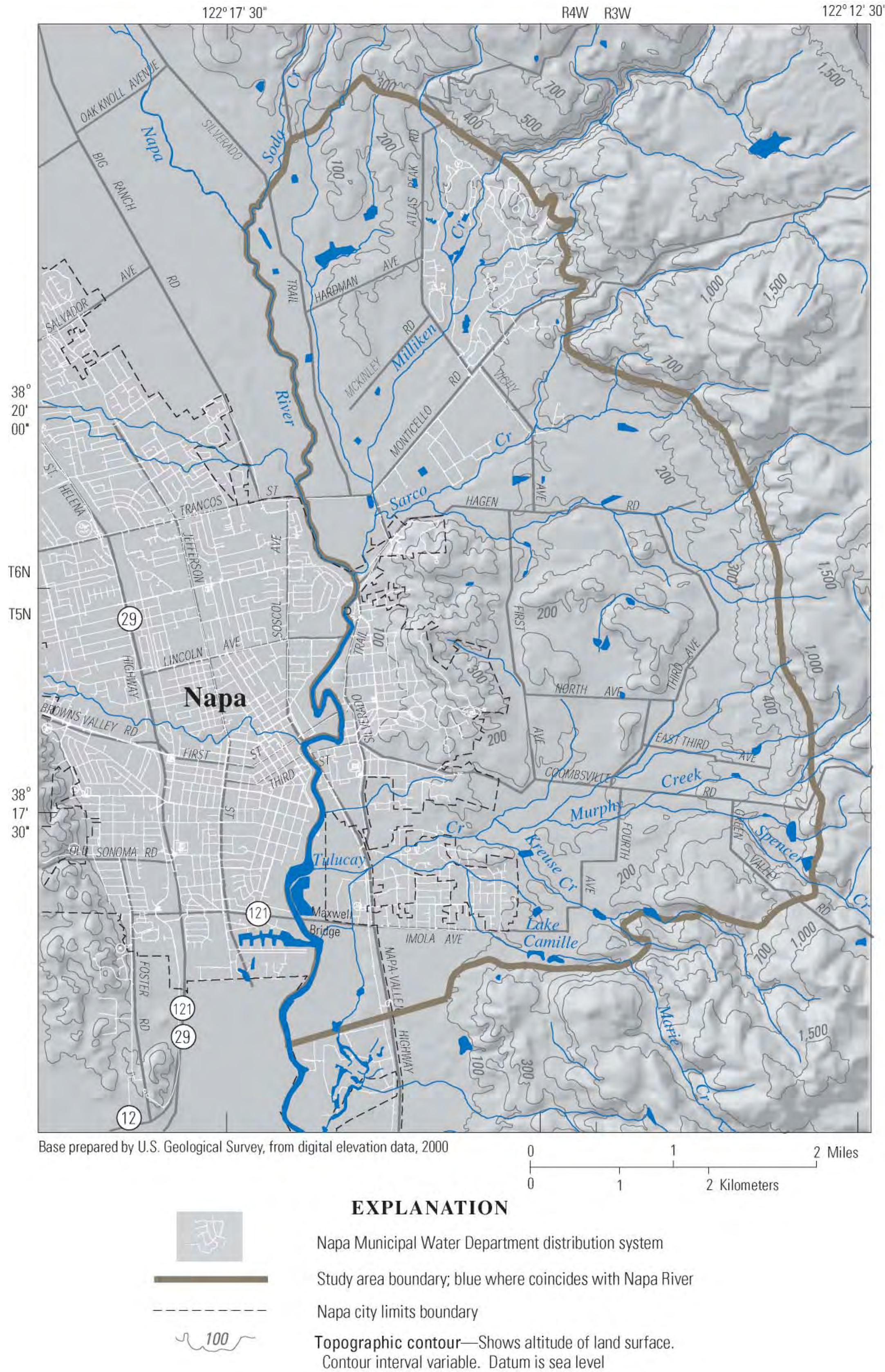


Figure 5. City of Napa Municipal Water Department distribution system, in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

Acknowledgments

The authors acknowledge the assistance of the staffs of the Napa County Departments of Public Works and Environmental Management, Napa County GIS Services, the City of Napa Municipal Water Department, the Central District of the Department of Water Resources, the California Department of Conservation, Farmland Mapping and Monitoring Program, and the resident volunteers of the Groundwater Under Local Protection (GULP) committee. Special thanks are extended to the more than 100 private property owners for allowing access to wells.

GEOLOGY

The study area lies in the southeastern part of Napa Valley, one of several prominent northwest-trending structural valleys in the North Coast Ranges. Napa Valley was formed between 1 and 2 million years ago by faulting and downwarping in the crust, processes that are related to plate tectonics and the transformation of a subduction zone into the strike-slip movement on the San Andreas and related faults (Howell and Swinchatt, 2000). Most of the study area is bounded on the west by the Soda Creek Fault and on the east by the steep west-facing slope of the Howell Mountains. The Green Valley Fault strikes north-northwest through the Howell Mountains east of the study area (fig. 1).

Stratigraphy

Geologic formations exposed at the surface include the Sonoma Volcanics and younger, thin, unconsolidated Quaternary alluvial deposits (fig. 6). Drillers' logs of a few wells drilled greater than 1,000 ft deep indicate that the thickness of the Sonoma Volcanics exceeds 1,000 ft in some parts of the study area. The Sonoma Volcanics unconformably overlie much older rocks—either of the Lower Cretaceous age Great Valley sequence, which mostly consist of highly indurated marine siltstones, sandstones, and conglomerates, or possibly of the Jurassic-Cretaceous age Franciscan Complex (Wagner and Bortugno, 1982). Rocks in the Great Valley sequence and Franciscan Complex are highly lithified and generally of low permeability. In other areas of northern California, these geologic assemblages generally provide only small quantities of water to wells. The Great Valley sequence or Franciscan Complex form the bottom boundary of the ground-water basin in the study area because the rocks in these assemblages are relatively impermeable compared with the rocks of the Sonoma Volcanics and sediments in the Quaternary alluvial deposits.

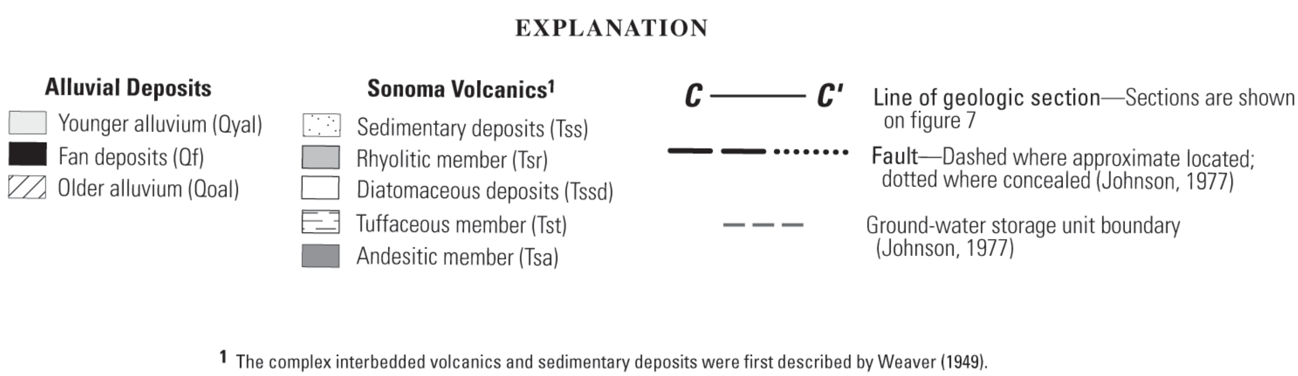


Figure 6. Explanation.

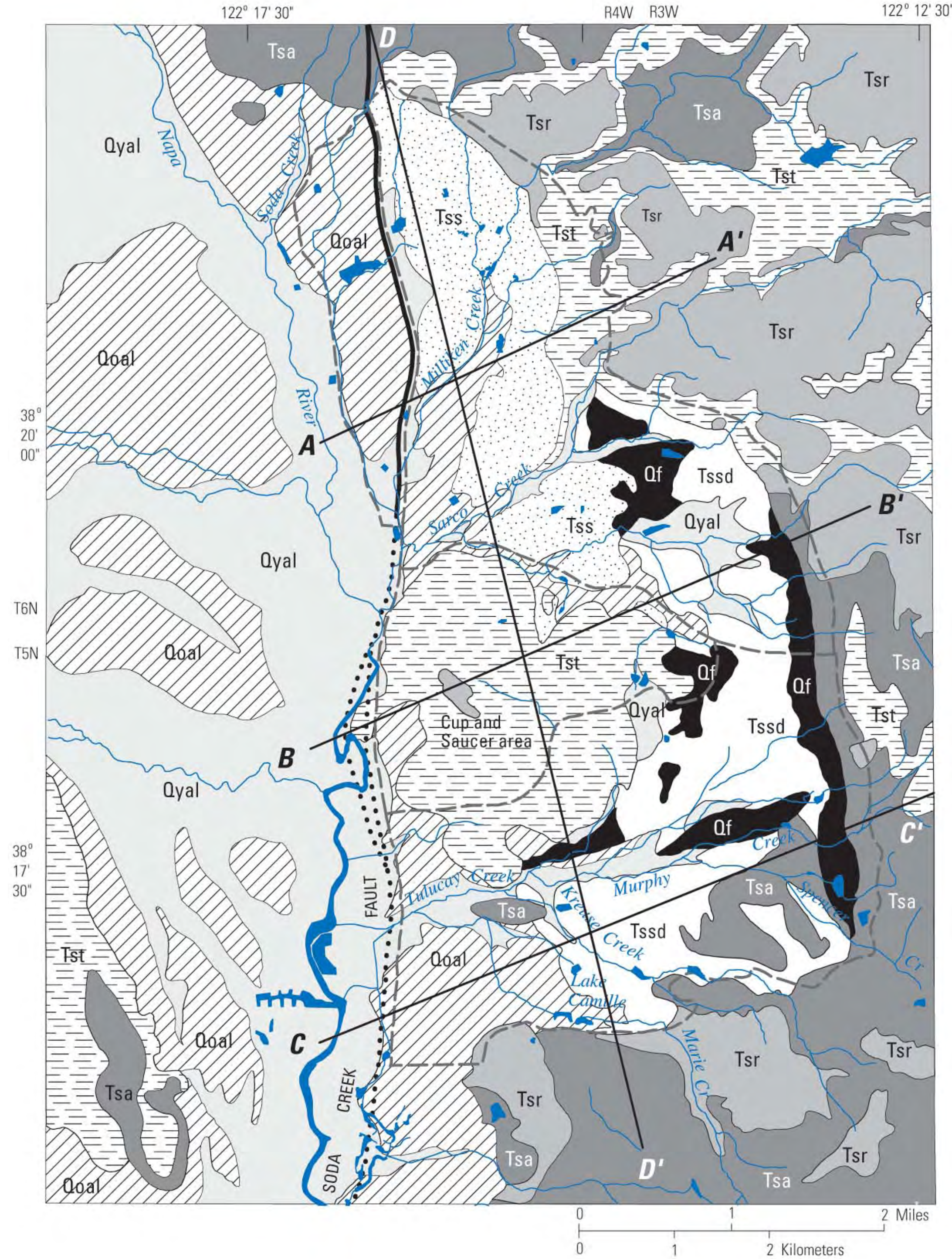


Figure 6. Geology of, and cross section locations in, the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California. (Modified from Johnson, 1977)

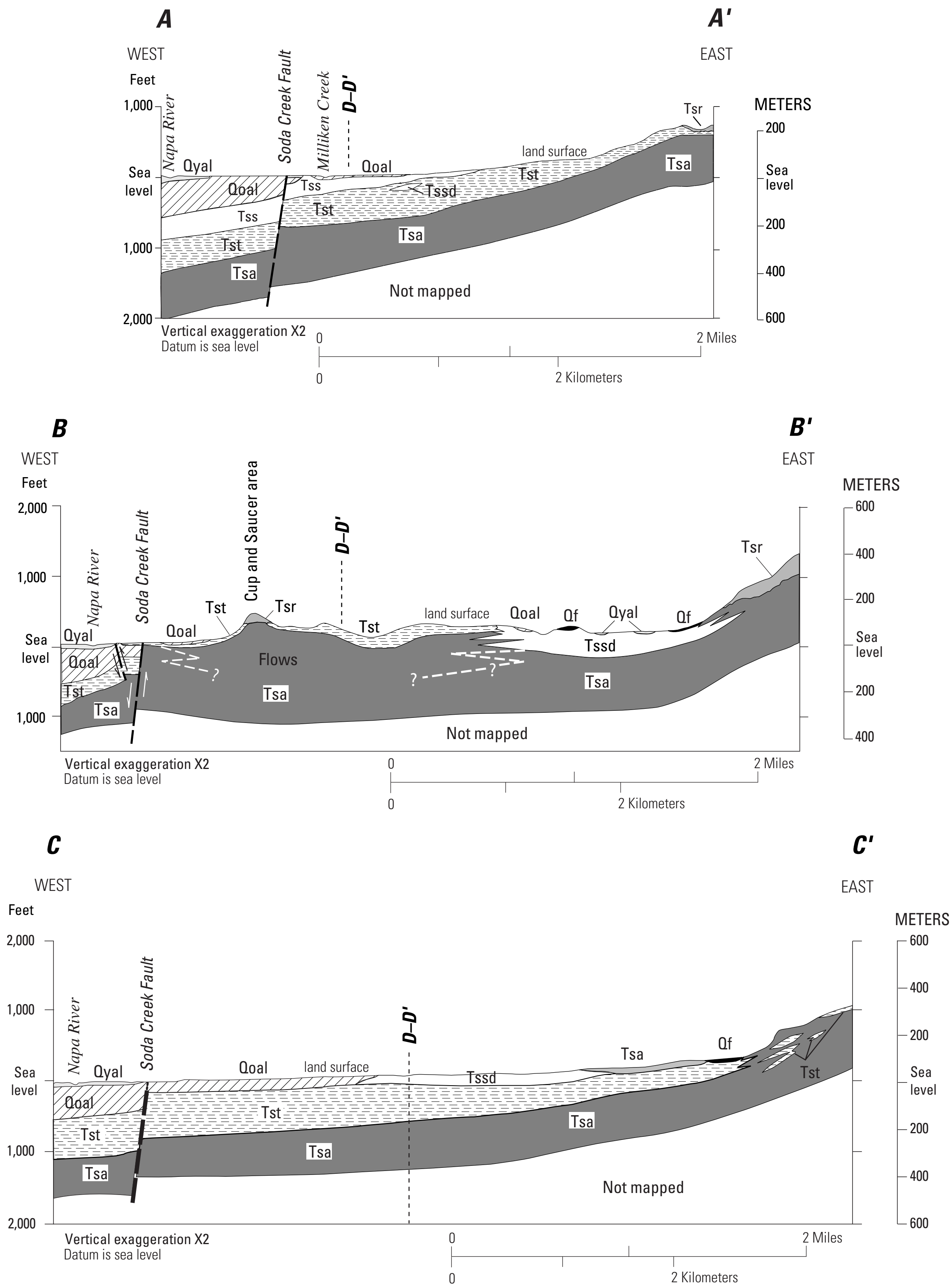


Figure 7. Generalized geologic cross sections in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California. (Modified from Johnson, 1977)

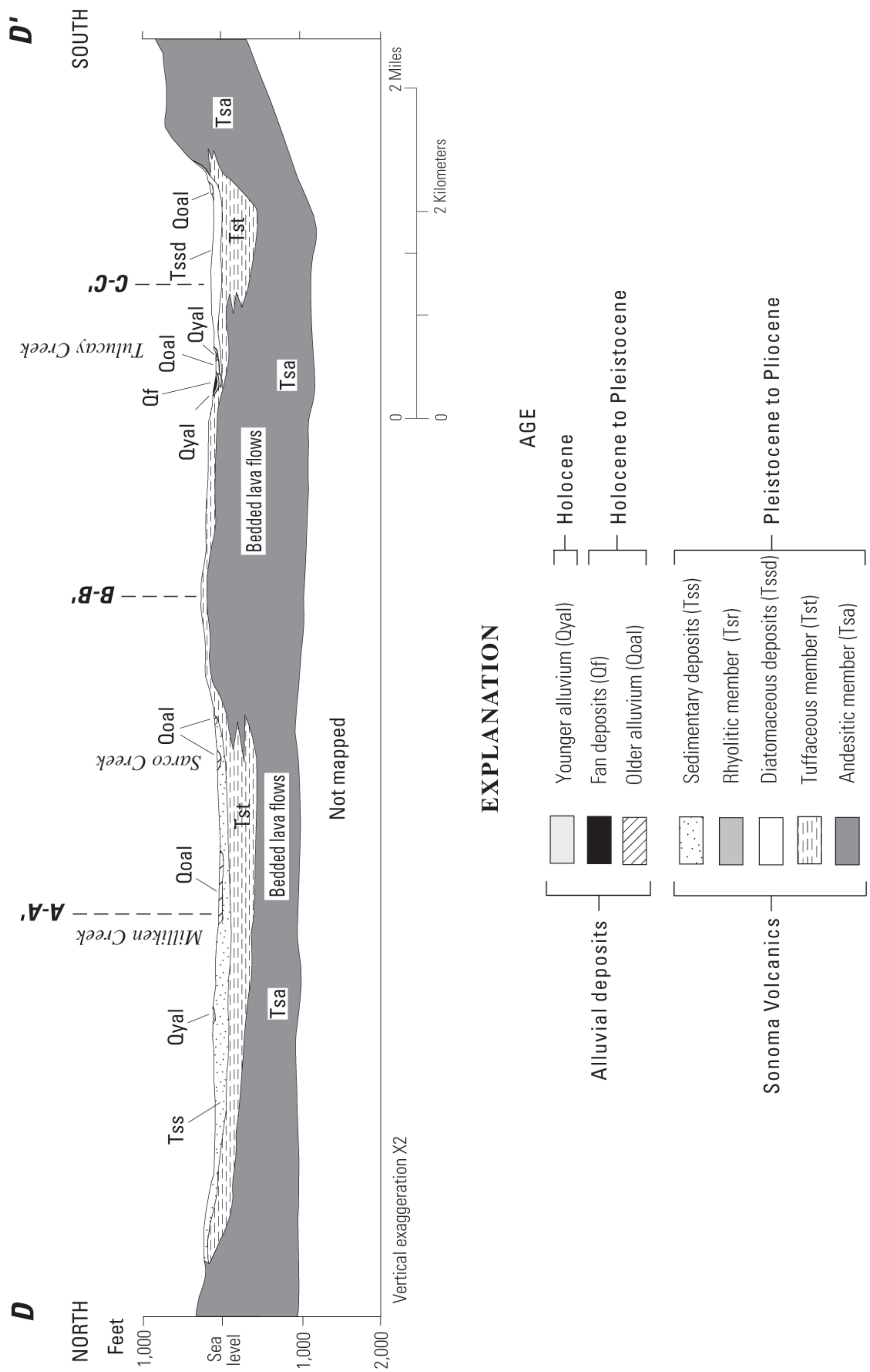


Figure 7.—Continued.

Sonoma Volcanics

The Sonoma Volcanics range in age from about 6 to 3 million years old (A. Sarna-Wojcick, U.S. Geological Survey, oral commun., 2002) and are distributed over hundreds of square miles in Napa and Sonoma Counties. Within the study area, they are exposed in road cuts along Monticello Road through the Howell Mountain block, where a stratigraphic section 1,290 ft thick can be observed. First described by Weaver (1949), the Sonoma Volcanics consist of a complex variety of lithologies and compositions including basalt, andesite, and rhyolite lavas; tuffs; debris flows; diatomaceous lacustrine sediments; and sedimentary volcanic rocks. A detailed description of the Sonoma Volcanics is given in Kunkel and Upson (1960). For regional geologic mapping, the Sonoma Volcanics have been subdivided into five members (Sims and others, 1973; Fox and others, 1973). Johnson (1977) followed this stratigraphic nomenclature and described the Sonoma Volcanics as consisting of three volcanic members: the lower andesitic member (Tsa), the middle tuffaceous member (Tst), and the upper rhyolitic member (Tsr), separated by two subaqueous deposits: diatomaceous deposits (Tssd) and sedimentary deposits (Tss), interbedded between the volcanic units (fig. 7). This "layer-cake" model of the five members is a useful simplification for some purposes, but it ignores the true complexity in the distribution of the various lithologies found in the Sonoma Volcanics. Many lithologic units in the Sonoma Volcanics lack wide areal continuity and some units have a lenticular geometry or have interfingering contacts with adjacent lithologic units.

Erosion during the past 3 million years has modified the landscape and obscured the locations of volcanic centers and the relations between the various lithologic units. On the basis of studies of active volcanic systems elsewhere and the sequence of rocks derived from them, it is clear that the distribution of the different rock types in the study area is equally complex. It is likely that several volcanic vents were sources for the Sonoma Volcanics in the study area. Volcanic materials ejected from any one vent changed as the eruptions progressed from vent clearing to tephra (pumice and ash) eruptions to lava flows. Such sequences of volcanic activity from individual vents probably occurred repeatedly over periods of thousands of years. The volcanic activity produced a variety of rock types and chemical compositions, emplaced as lava flows, dikes, plugs, breccias, pumice beds, and avalanche deposits. The volcanic vents in proximity to each other may have been in different phases of eruptive evolution so that lava was being extruded in one location while tephra was being explosively ejected from a nearby vent. This type of activity results in a very heterogeneous sequence of rock types and compositions with depth and over distances of miles or less.

Quaternary Alluvial Deposits

Thin unconsolidated, uncemented alluvial deposits blanket about 6 mi^2 of the study area and directly overlie the Sonoma Volcanics. During previous studies (Kunkel and Upson, 1960; Sims and others, 1973; Johnson, 1977), these alluvial deposits were subdivided into alluvial fan deposits, older alluvium, and younger alluvium on the basis of age and depositional environment. The alluvial fan deposits crop out mostly at the foot of the Howell Mountain block in the eastern part of the study area (fig. 6). The alluvial fan deposits are wedge-shaped bodies that are thickest near the mountain front; they are formed by colluvium, landslide debris, and alluvial material carried by ephemeral streams that discharged from steep canyons eroded into the mountain front. The deposits are composed of boulders, cobbles, gravel, sand, and finer-grained material. Generally the coarsest, more angular, and poorly sorted material occurs near the mountain front and the finer, more rounded, and better-sorted material occurs toward the central part of the basin.

The largest outcrops of older alluvium are in the southwestern and northwestern parts of the study area. The younger alluvium primarily crops out along present-day stream channels and associated flood plains. Both the older and younger alluvium consist of boulders, cobbles, gravel, sand, and fine-grained material that were deposited by streams over the past few thousand years. These deposits are better sorted and include more rounded clasts than the fan deposits and thus potentially are more permeable.

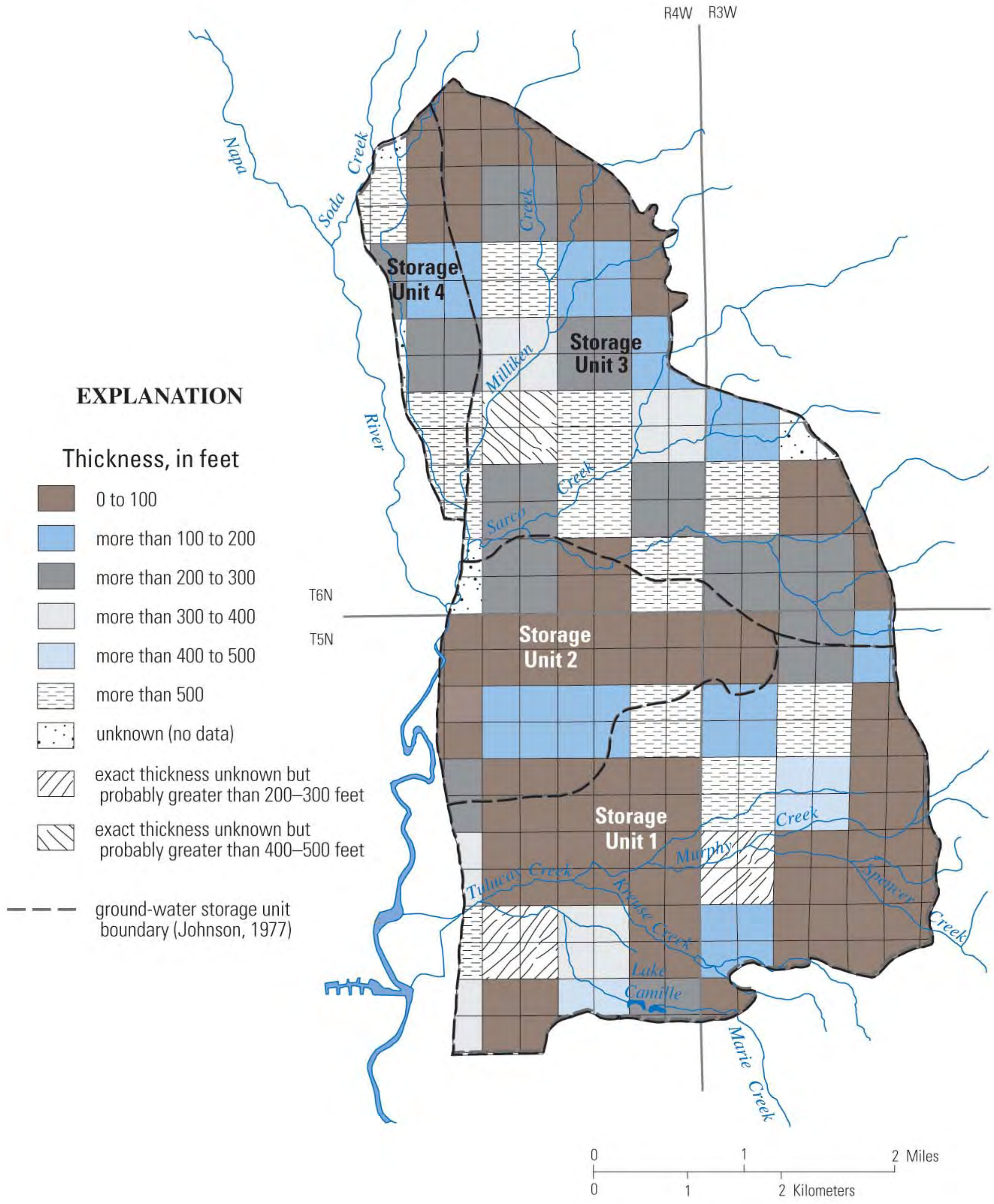


Figure 8. Generalized thickness of unconsolidated deposits in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

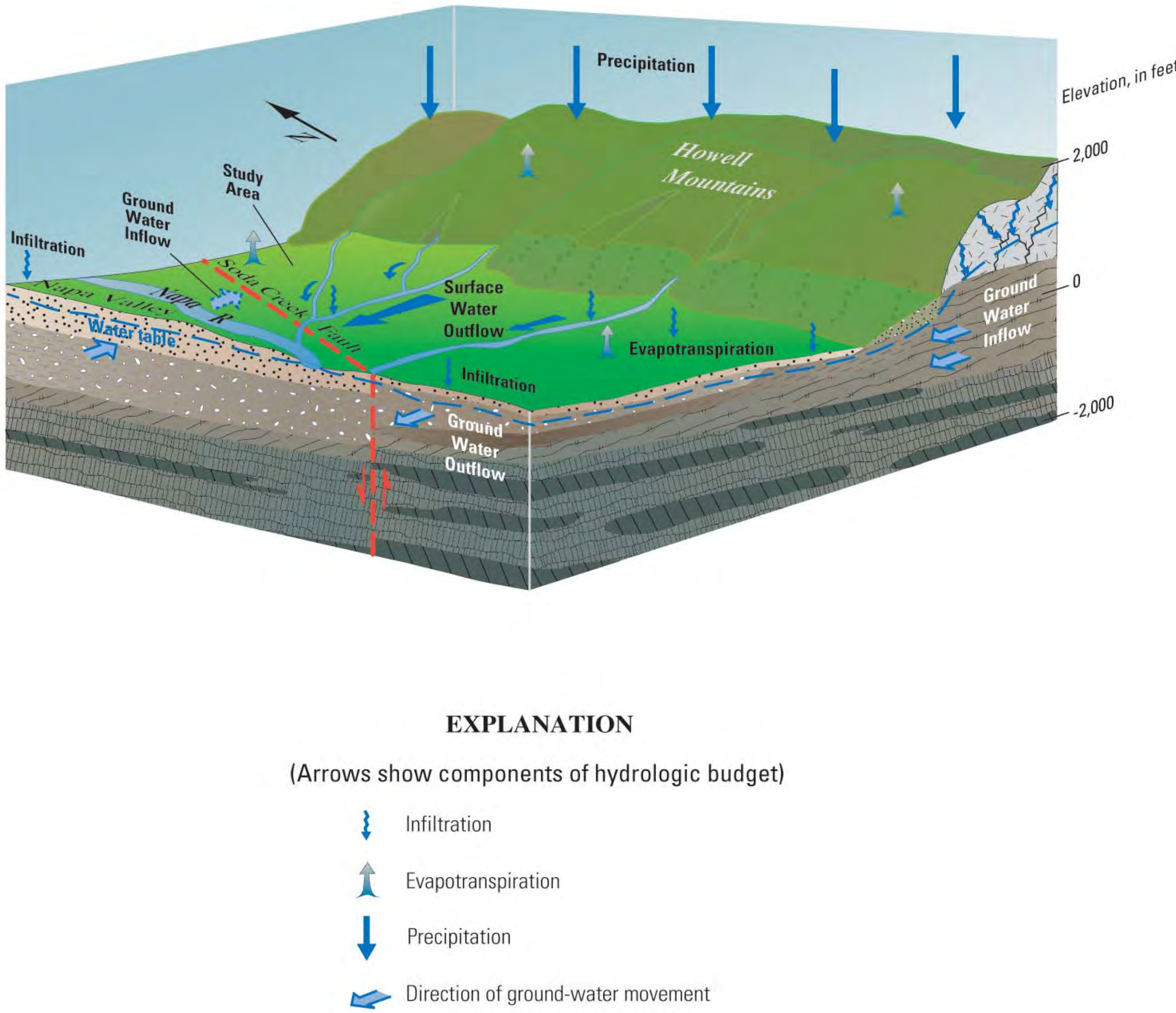


Figure 9. Conceptual model of the ground-water flow system in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

GROUND-WATER HYDROLOGY

The principal water-bearing units in the study area are alluvial deposits west of the Soda Creek Fault and the tuffaceous member of the Sonoma Volcanics east of the fault. Alluvial deposits overlie the Sonoma Volcanics throughout much of the study area. The alluvial deposits are not highly productive aquifers in parts of the study area to the east of the Soda Creek Fault (storage units 1, 2, and 3) because they are fairly thin and generally are above the water table. West of the Soda Creek Fault (storage unit 4), the alluvial deposits are an important source of water because the deposits are considerably thicker and largely saturated. Throughout much of Napa Valley west of the study area, alluvial deposits constitute the major aquifer (Faye, 1973). Several tens to a few hundred gallons per minute of water can be pumped from wells completed in clean sand and gravel lenses in the younger alluvial deposits (Kunkel and Upson, 1960). Older alluvial deposits contain large fractions of clay and silt or are poorly sorted coarse- and fine-grained materials and in some beds are highly compacted or slightly cemented. The presence of large percentages of fine-grained materials, poor sorting, compaction, or cementation greatly reduces the permeability in many areas underlain by older alluvial deposits. Wells tapping such deposits generally produce less than 50 gal/min.

Alluvial fan deposits crop out over an extensive area at the base of the Howell Mountains. Although these deposits contain large percentages of boulders, cobbles, and gravel, the sorting generally is poor and some beds or lenses are cemented, greatly limiting the permeability. The topographic occurrence of the fan deposits places them above the zone of saturation in most of the area; therefore, these deposits are not an important source of water to wells.

East of the Soda Creek Fault, ground water is pumped almost exclusively from the Sonoma Volcanics. The andesitic member is the basal member of the Sonoma Volcanics and underlies the entire study area (fig. 7). This member consists of andesitic and basaltic lavas that have little primary permeability except in the interflow zones. Fracture zones produced by faulting and folding provide some secondary permeability to this member and yield small amounts of water to wells. In storage unit 2, the andesitic member lies within 100 ft of the surface and is essentially the only source of water to wells.

The tuffaceous member overlies the lower andesitic member throughout most of the area and is the principal water-bearing unit within the study area. This unit is about 500 ft thick in storage units 1, 3, and 4. Thick sections of uncemented and non-welded tuff or pumice beds can provide moderate to large quantities of water to wells. Well yields of 500 gal/min or more have been reported for wells open to the non-welded tuff.

The upper rhyolite member overlies the tuffaceous member in the eastern parts of the study area and consists of low-permeability, banded rhyolitic lava with intercalated rhyolitic tuff. Many of the tuff beds in the rhyolite member are slightly to densely welded, which reduces intergranular permeability. In some areas, lava beds or welded tuffs in the rhyolite member confine ground water in the underlying tuffaceous member.

The low permeability of the diatomaceous and sedimentary members of the Sonoma Volcanics restricts the downward movement of recharge water throughout much of the study area. The diatomaceous deposits are mostly in the eastern part of storage units 1 and 3 and consist of diatomaceous clay and silt deposited in a lacustrine or paludal environment (Kunkel and Upson, 1960). The sedimentary deposits mostly are in storage unit 3 where they reach a maximum thickness of 250 ft. The diatomaceous and sedimentary members have low permeability and confine ground water in underlying geologic units.

Within the study area, the largest amount of ground water per unit volume of material is contained in the uncemented, poorly consolidated, coarse clastic materials (either volcanic or sedimentary in origin), referred to in this report as unconsolidated material. The greatest potential for ground-water production is in the coarse clastic materials (sand, gravel, cobbles, pumice, and volcanic tephra). The least amount of ground water is contained in the well-lithified volcanic rocks (andesite, basalt, rhyolite, and welded tuff).

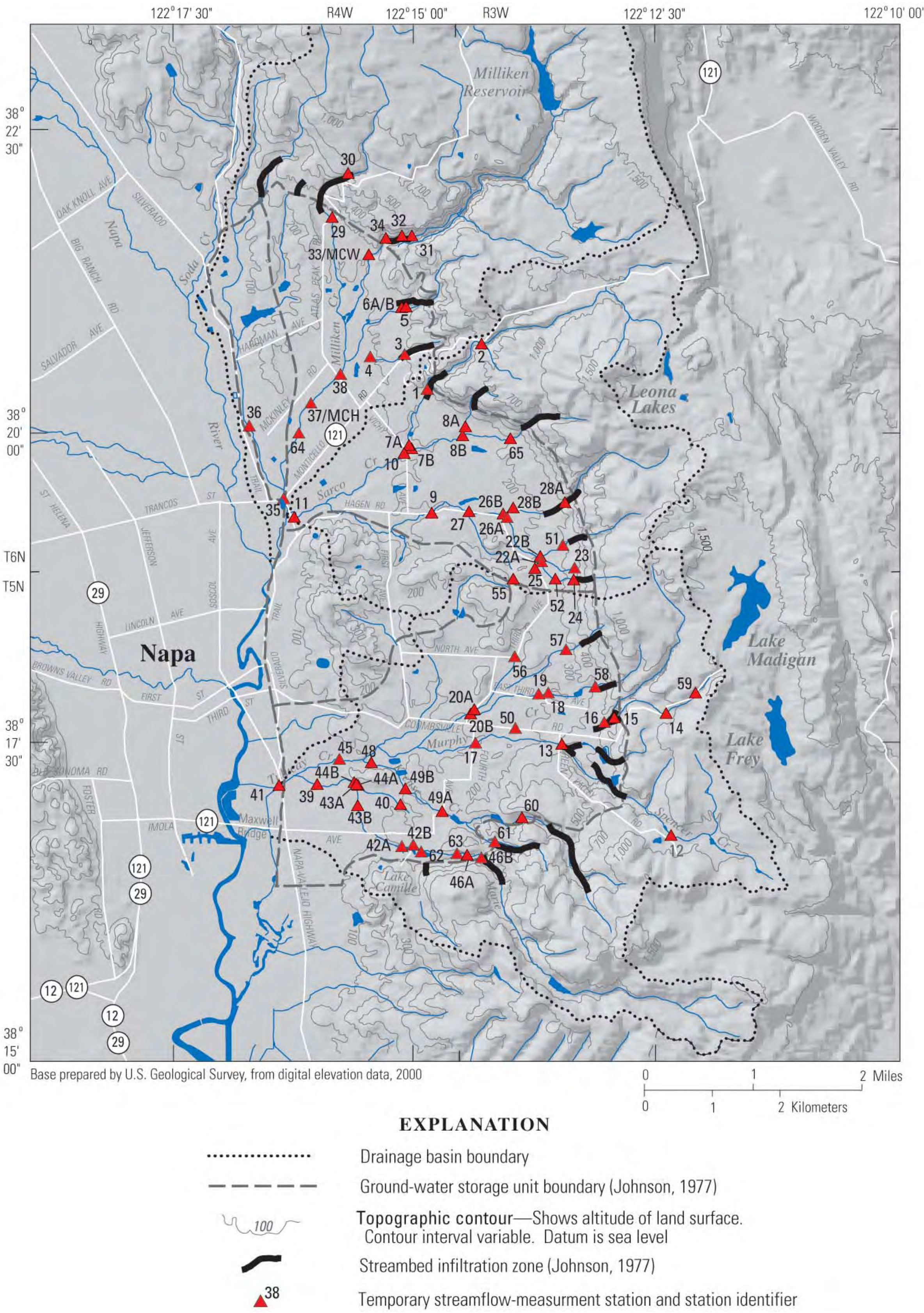


Figure 10. Locations of streamflow-measurement stations and streambed infiltration zones in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

The thickness of the unconsolidated deposits and the percentage of coarse clastic materials within these deposits were determined by inspection of drillers' logs. Drillers' logs for the deepest well in each quarter section of land (160 acres) were examined: this included 69 wells that range in depth from 150 to 1,554 ft. The term *rock* generally is used in the drillers' logs to describe well-lithified volcanic rocks. For this report, the thickness of the unconsolidated deposits included all material above the depth where materials were described predominantly as rock.

The thicknesses of the unconsolidated deposits within the study area are shown by 100-foot depth intervals in figure 8. Because of the complexity in the distribution of the lithologies in the study area, this generalized summary cannot be used to accurately determine the thickness of unconsolidated deposits at any particular well site. In general, the thickness of unconsolidated deposits is less than 100 ft at the northern, eastern, and southern perimeters of the study area and is as much as 500 ft or greater along the western perimeter. The thickness of the unconsolidated deposits generally is less than 200 ft in storage units 1 and 2 and greater than 200 ft in storage unit 3. The thickness of the deposits is greater than 300 ft over about one-third of the area of storage unit 3. In storage unit 4, the thicknesses of the unconsolidated deposits range from less than 100 to more than 500 ft. The greater thicknesses of the unconsolidated deposits in storage unit 4 probably are related to the downward displacement of Sonoma Volcanics along the west side of the Soda Creek Fault and the contemporaneous deposition of sediments.

The thickness of unconsolidated deposits (fig. 8) is consistent with the results of a regional gravity survey (Youngs and others, 1989), which shows that the lowest gravity values occur along the western edge of the study area, corresponding with the areas underlain by thick sections of unconsolidated deposits. A gravity high occurs in a large part of the southern half of the study area where the unconsolidated deposits generally are less than 100 ft thick.

Drillers' logs also were examined to determine the percentage of uncemented coarse-grained materials contained in the upper 300 ft of unconsolidated deposits. Uncemented coarse-grained materials include boulders, cobbles, gravel, sand, pumice, or any combination of these not specifically described as cemented or imbedded in clay. The most productive wells generally are located in areas underlain by large amounts of uncemented coarse grained-material in the zone of saturation. Nearly one-third of the study area is underlain by deposits made up of greater than 10 percent uncemented coarse-grained material. This includes a large part of storage unit 3 and the southern half of storage unit 4. More than half the study area is underlain by deposits having 5 percent or less uncemented coarse-grained material. This includes the eastern part of the study area overlying the syncline mapped by Fox and others (1973) and most of the southwest perimeter of the study area. Less than 20 percent of storage unit 2 is underlain by deposits containing greater than 5 percent uncemented coarse-grained material.

Recharge

The principal source of recharge to the ground-water system in the Milliken–Sarco–Tulucay Creeks drainage basin is precipitation within the basin; this recharge occurs as seepage from creeks, lakes, and man-made ponds, and areally as direct infiltration. Other significant sources of recharge are ground-water inflow from the Howell Mountains and, in the northern part of the area, ground-water inflow from the west. Minor sources of recharge include infiltration from septic tanks, leaking water-supply pipes, irrigation water in excess of crop requirements, and crop frost-protection applications. Although recharge from excess irrigation sometimes can be a significant part of total recharge within some basins, within this study area it is considered minor because the predominant crop is wine grapes and local growers use highly efficient drip systems.

A schematic of the conceptual model of the ground-water system is shown in figure 9. The block diagram shows the geologic framework of the study area and the main components of the hydrologic budget, including direct recharge from precipitation, ground-water underflow into and out of the study area, streambed infiltration, surface-water outflow, and evapotranspiration.

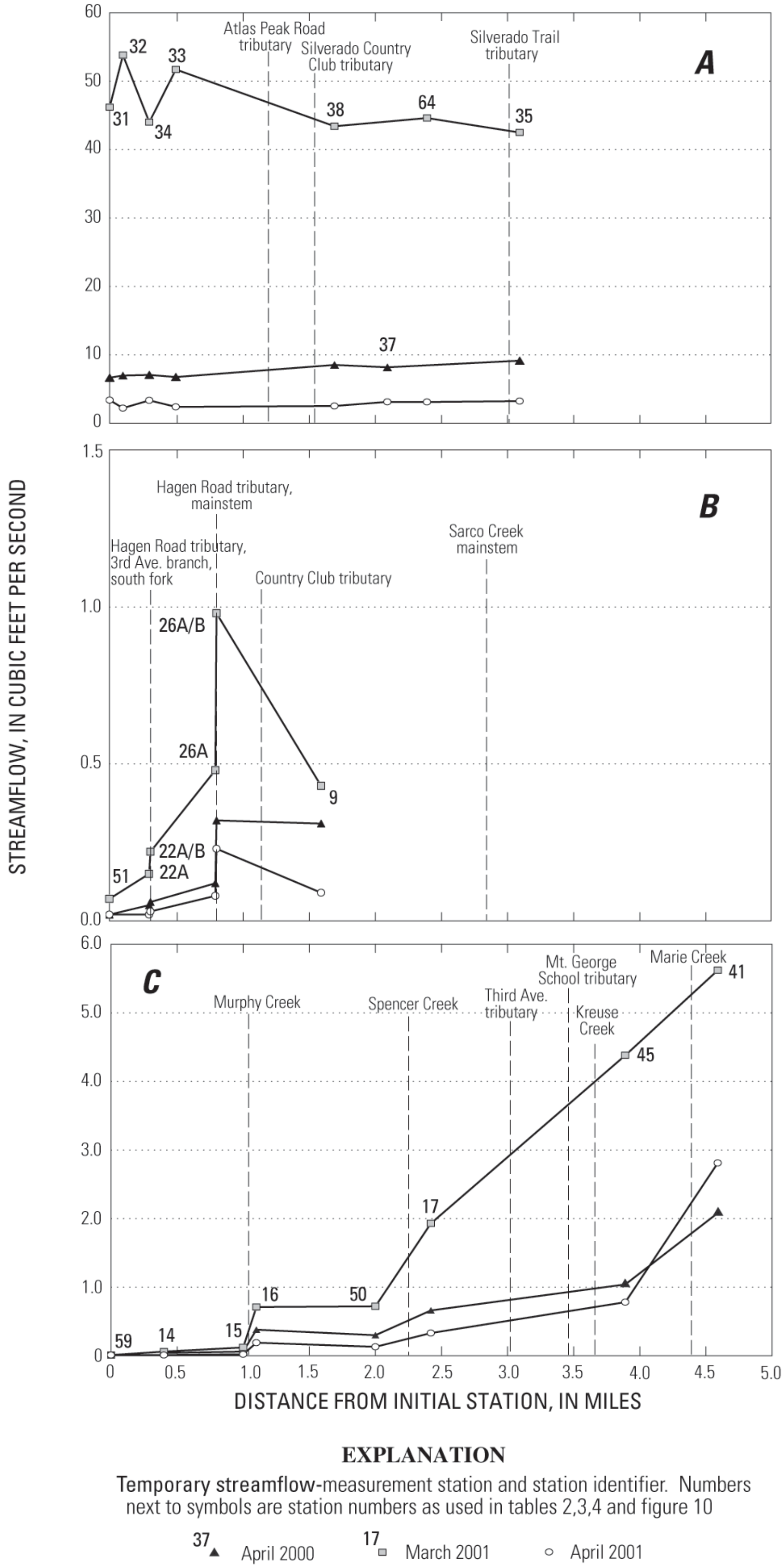


Figure 11. Streamflow measurements for the three seepage runs for selected parts of the (A) Milliken, (B) Sarco, and (C) Tulucay Creeks and their tributaries, southeastern Napa County, California.

Johnson (1977) estimated that the average annual recharge in the area of this study in 1975 was 5,400 acre-ft/yr: 3,050 acre-ft/yr from streamflow infiltration; 2,100 acre-ft/yr from subsurface inflow from the Howell Mountain block; and about 250 acre-ft/yr from direct infiltration of precipitation. According to Johnson (1977), most of the streamflow infiltration was restricted to 22 areas, defined as streambed-infiltration zones, along the eastern margin of the study area. Johnson's conclusions were based on measured streamflow losses in Milliken Creek, Sarco Creek, and a few unnamed streams along reaches that cross tuffaceous materials near the base of the Howell Mountain block. Streamflow measurements were collected along Milliken, Sarco and Tulucay Creeks and their tributaries as part of this study to help identify streambed infiltration.

Streamflow Gains and Losses

Streamflow gains and losses along Milliken, Sarco, and Tulucay Creeks and their tributaries were determined from streamflow measurements made during three seepage runs between April 2000 and April 2001. A seepage run consists of a series of streamflow measurements made at several sites along a stream to quantify streamflow gains and losses (Riggs, 1972). A gaining reach is defined as one in which streamflow increases in the downstream direction due to ground-water inflow, tributary inflow, or precipitation (Blodgett and others, 1992). If ground-water inflow is the only source of streamflow gain, it may be referred to as a seepage gain. In contrast, a losing reach is defined as one in which streamflow decreases by infiltration to the subsurface or by evapotranspiration. A seepage loss is a decrease in streamflow attributable to infiltration only.

Methods of Data Collection and Analysis

Streamflow was measured or observed at 16 stations in the Milliken Creek drainage basin, at 23 stations in the Sarco Creek drainage basin, and at 33 stations in the Tulucay Creek drainage basin (fig. 10). These stations were assigned numbers sequentially at the time of the initial measurement.

No-flow conditions were observed at some of the stations for all three seepage runs during 2000 and 2001 (April 17–26, 2000; March 13–16, 2001; and April 10–12, 2001). Flow was estimated when it was too low for direct measurement. The seepage runs were scheduled to avoid peak-flow conditions and periods of significant changes in stage, such as receding storm flows.

Most of the streamflow measurements were made using velocity-area methods [for a description of these methods see Rantz and others (1982)]. During low-flow conditions at stations where velocities were less than 0.2 ft/s and stream depths were less than 0.3 ft, streamflow was measured using a modified 3-inch Parshall flume (Rantz and others, 1982). At stations where flows were too low and channel configurations unsuitable for conventional measurement techniques, miscellaneous methods including floats, volumetric, or visual estimates were used to estimate streamflow (Rantz and others, 1982).

The accuracy of streamflow measurements is largely dependent on flow conditions and measurement technique (Rantz and others, 1982). For this study, the accuracy of streamflow measurements was determined using a computer program (Sauer and Meyer, 1992) that determines the uncertainty or error of individual streamflow measurements. This program assigns a corresponding qualitative rating (excellent, good, fair, or poor) for each streamflow measurement. The streamflow-measurement rating ranged from good (2 to less than 5 percent error) to poor (greater than 8 percent error) for the individual pygmy meter measurements. In contrast, the measurements made using the modified 3-inch Parshall flume generally were rated good (within 2 to 3 percent error). The miscellaneous discharge measurement methods (floats, volumetric, and visual estimates) generally had an accuracy of plus or minus 10 percent or more and were assigned a measurement rating of poor.

Streamflow Measurements and Estimated Gains and Losses

Streamflow gains and losses were calculated for each reach using streamflow measurements from successive stations. Duplicate measurements made during the same seepage run for individual sites were averaged prior to calculating gains and losses. Streamflow measurements, gains or losses between stations, flow distances, and rates of gain or loss of flow are shown in tables 2, 3, and 4 (at back of report) for the three seepage runs. The measurements indicate that few reaches have significant streamflow losses, and those that do are not consistently losing reaches. These data indicate that most winter runoff leaves the study area as streamflow to the Napa River and that only a small amount infiltrates beneath the streambeds.

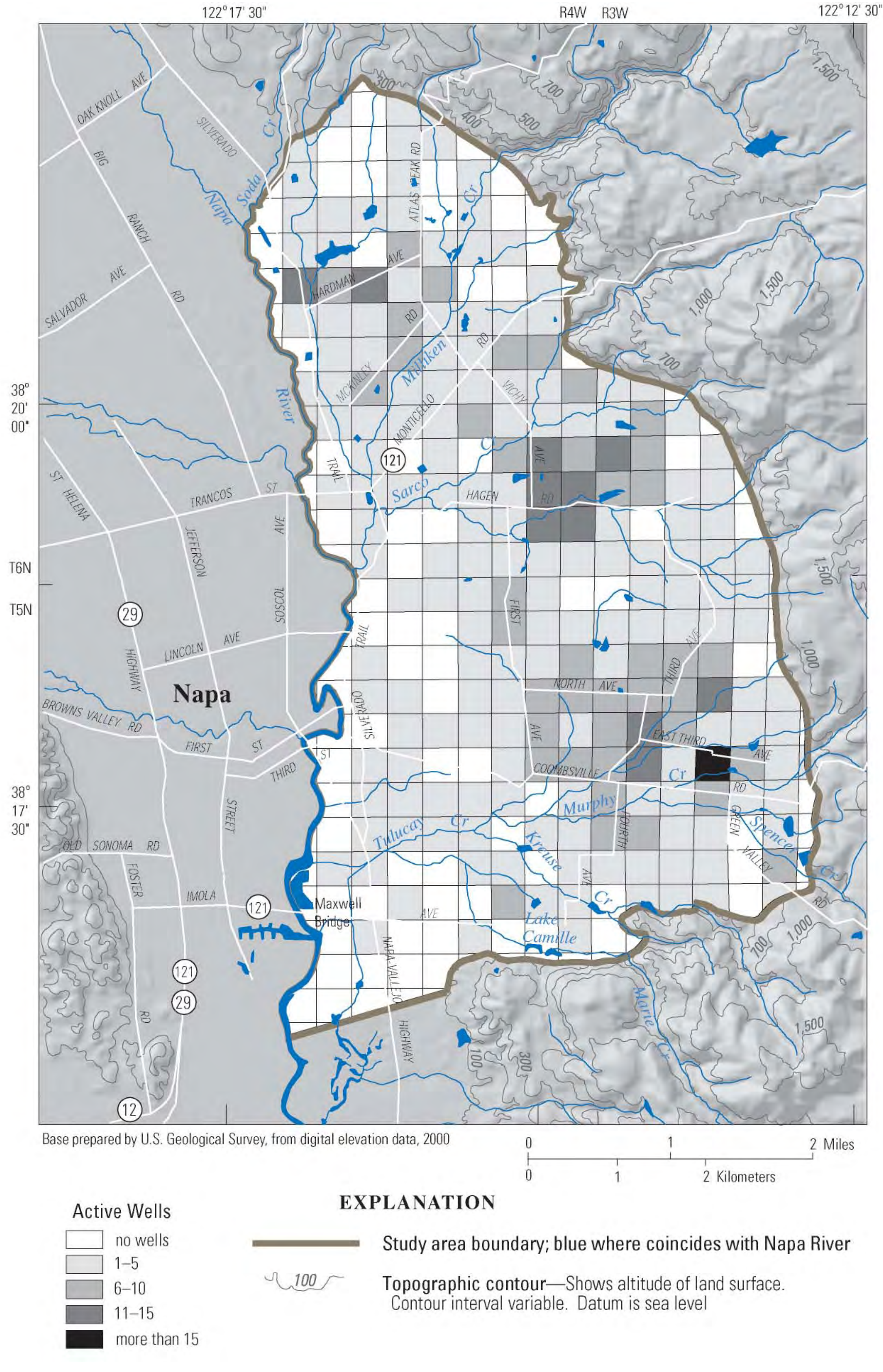


Figure 12. Geographic distribution of known active and potentially active wells per quarter-quarter section in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

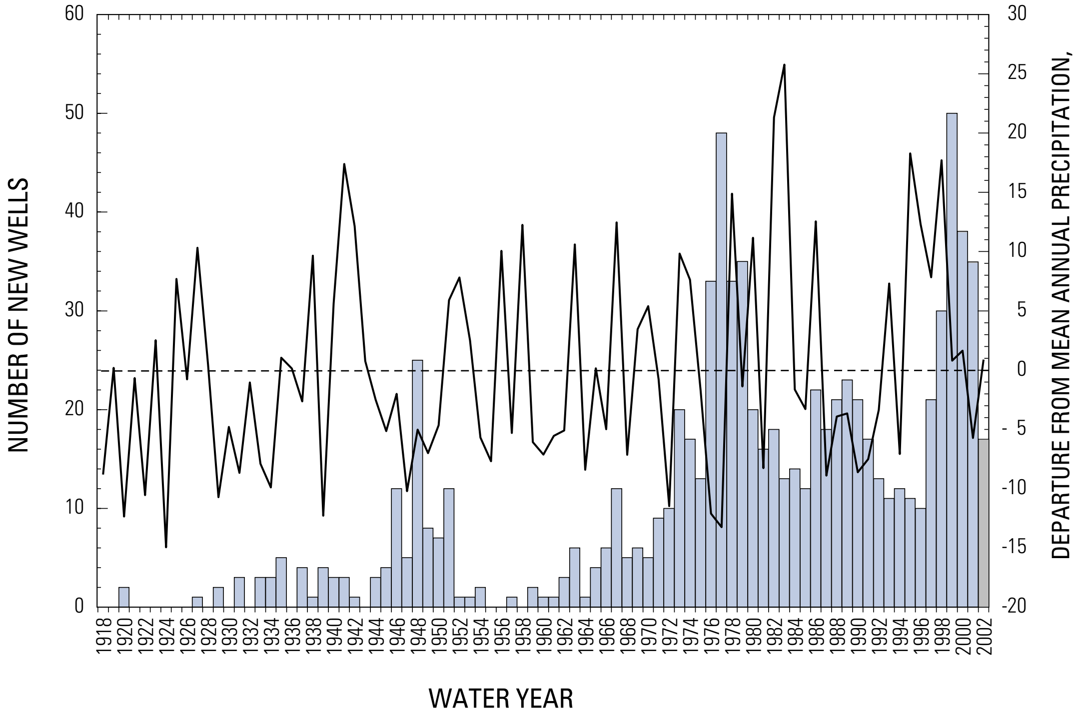


Figure 13. Historical well development (bars) and departure from mean annual precipitation (line) (at Napa State Hospital) in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, water years 1918-2002.

Well data incomplete for water year 2002.

Seepage measurements were attempted at the 22 reaches, referred to as streambed infiltration zones by Johnson (1977); but because of limited access and poor channel conditions, measurements were made in only three of the zones: Atlas Peak Road tributary to Milliken Creek (station 30 to station 29), main stem of Milliken Creek (station 31 to station 34), and main stem of Sarco Creek (station 2 to station 1). On the Altas Peak Road tributary to Milliken Creek reach, minor losses of 0.1 acre-ft/d were calculated for April 2000 and April 2001 (tables 2 and 4, respectively, at end of report), but a gain of about 0.3 acre-ft/d was calculated for March 2001 (table 3, at end of report). On the main stem of the Milliken Creek reach, streamflow losses of 4.4 and 0.1 acre-ft/d were calculated for the March and April 2001 seepage runs, respectively, but a streamflow gain of about 0.8 acre-ft/d was calculated for the April 2000 seepage run. On the main stem of the Sarco Creek reach, a streamflow loss of 0.1 acre-ft/d was calculated for the April 2001 seepage run. The results for the three seepage runs do not show significant streamflow losses along the streambed-infiltration zones that were delineated by Johnson (1977).

Measurements of streamflow as a function of stream distance for selected reaches of the main stem of Milliken Creek (fig. 11A), tributaries of Sarco Creek (fig. 11B), and tributaries of Tulucay Creek (fig. 11C) indicate a combination of gaining and losing reaches. Streamflow gains between some stations during the three seepage runs can be attributed to inflows from tributary streams, surface runoff, and water released from bank storage. Ground water also may be a source of streamflow gains in some of the lower reaches of

Milliken, Sarco, and Tulucay Creeks near the Napa River. For example, spring ground-water levels in well 69 were about 8 ft below land surface (table 5, at end of report), indicating that the regional water table may coincide with the channel bottom along the lower part of Sarco Creek near station 11, particularly during the winter and early spring when water levels usually reach their maximum.

Streamflow measurements from the three seepage runs indicate that significant infiltration occurs at various times in reaches other than the infiltration zones defined by Johnson (1977). On the main stem of Milliken Creek a loss of 16.5 acre-ft/d was calculated between stations 33 (Westgate Drive) and 38 (Atlas Peak Road) for the March 2001 seepage run (table 3, at end of report). This reach of Milliken Creek may be favorable for significant streambed infiltration because the underlying unconsolidated alluvial deposits are highly permeable (fig. 7, section A-A´). Smaller losses were measured on parts of Sarco and Tulucay Creeks and their tributaries. For example, on the Hagen Road tributary to Sarco Creek, between the confluence of the Hagen Road and Third Avenue tributaries (26A/26B) and station 9 (Grange Hall), streamflow losses ranged from negligible during the April 2000 seepage run to 1.1 acre-ft/d during the March 2001 seepage run. In the lower Tulucay Creek drainage basin, streamflow losses in the reach between station 16 (Mustang Road) and site 50 (Coombsville Road) averaged about 0.1 acre-ft/d for the three seepage runs.

In summary, the seepage run data collected for this study indicate that the total streamflow loss along the 22 streambed infiltration zones along the eastern margin of the study may be less than the 3,050 acre-ft/yr estimated by Johnson (1977). However, the data for this current study also indicate that infiltration takes place in reaches downstream from Johnson's infiltration zones. Although additional seepage runs could more accurately quantify gains and losses, such an effort would be difficult because of poor channel conditions, multiple sources of surface inflow, and surface-water diversions. Other approaches to quantify gains and losses can be tried, such as dye-dilution, which is not adversely affected by boulder covered channels or shallow water depths (Kilpatrick and Cobb, 1985).

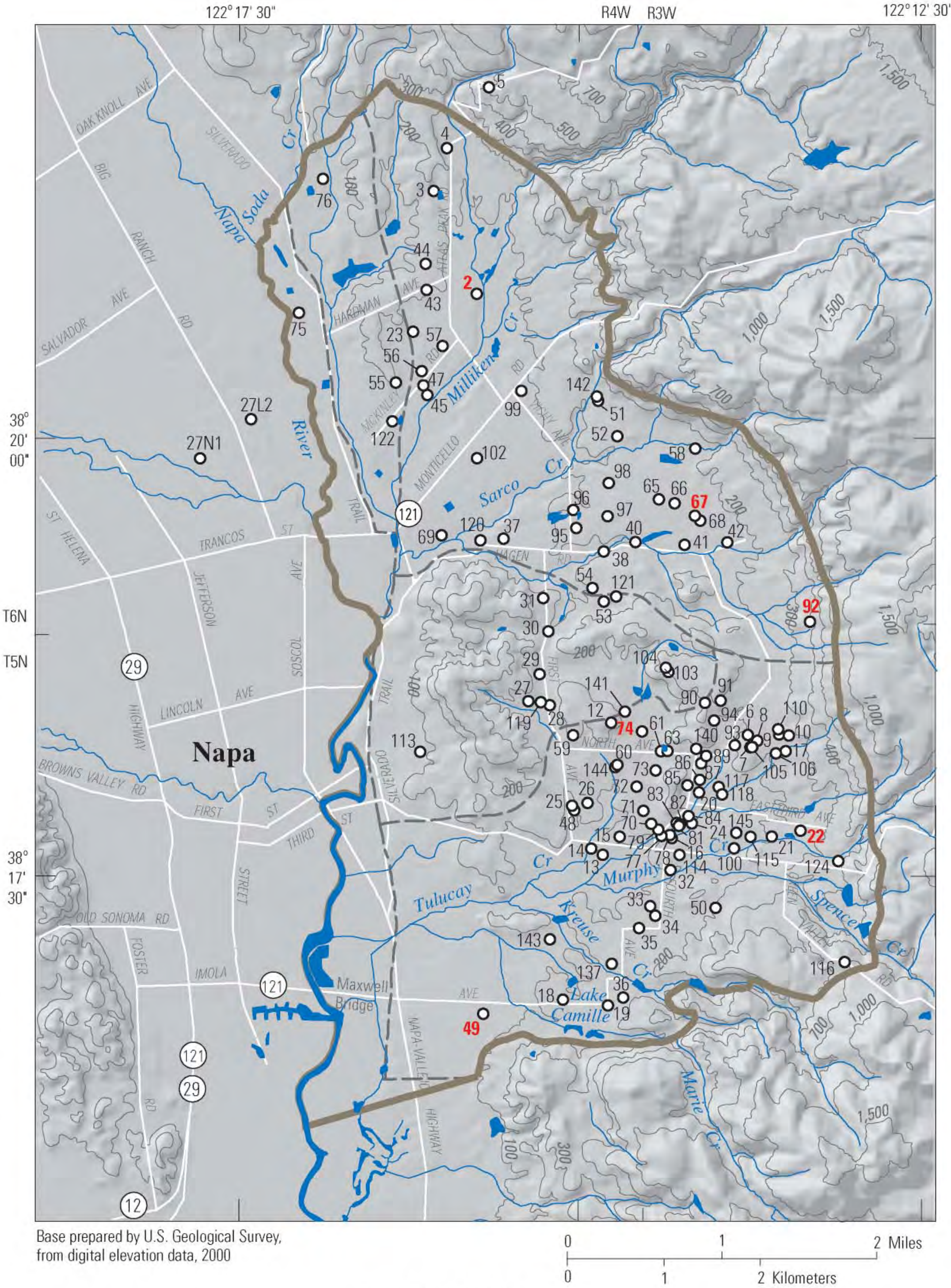
Discharge

Ground-water discharge from the study area is predominantly pumpage from wells and underflow across the western boundary. A small amount of ground water discharges to streams. Johnson (1977) estimated that the total ground-water discharge in 1975 was 5,650 acre-ft/yr: 3,000 acre-ft/yr of pumpage and 2,650 acre-ft/yr of underflow from the study area toward the Napa River. For this study, ground-water pumpage and underflow across the western boundary were estimated for hydrologic conditions during the period 2000–2002.

Discharge from Pumpage

A well inventory and (or) drill dates for January 1950 or later indicate that approximately 800 wells were known or were assumed to be active in the study area. The number of wells per quarter-quarter section (40 acres) is shown in figure 12. The greatest number of wells is near Hagen Road, in the east-central part of the study area, and centered around Third Avenue between Coombsville Road and North Avenue in the southeastern part of the study area.

The actual number of active wells in the study area is probably much larger than the approximately 800 wells for which specific information is available. Records from the County Tax Assessor and the City of Napa Municipal Water Department identify about 1,450 parcels as residential and about 132 parcels as either agricultural or agriculture mixed with residential use. Most of these parcels probably have individual water systems. Drillers' reports and parcel records indicate that there is an average of about 1.1 wells per residential parcel. The well inventory for this study confirmed that some residential properties have more than one well per parcel. Assuming an average of 1.1 wells per parcel, there are an estimated 1,595 domestic wells on the 1,450 residential parcels (table 6). A similar examination of drillers' reports for irrigation wells on agricultural and mixed agricultural and residential properties indicates an average of about 1.4 wells per agricultural or agricultural mixed with residential parcel. This translates to about 185 irrigation wells in the study area.



EXPLANATION

- Study area boundary; blue where coincides with Napa River
- Ground-water storage unit boundary (Johnson, 1977)
- 100 **Topographic contour**—Shows altitude of land surface. Contour interval variable. Datum is sea level
- 19 o Well and local well number

Figure 14. Locations of wells in the water-level monitoring network in the lower Milliken–Sarco–Tulucay Creek area, southeastern Napa County, California. Wells equipped with transducers for continuous monitoring identified by local well number (in red).

Approximately 570 of the estimated 1,595 wells existing in 2002 were constructed between 1975 and 2002, an increase of 56 percent from that estimated by Johnson (1977). Figure 13 shows the number of wells drilled annually between 1918 and 2002 compared to the departure from mean annual precipitation. The years with the greatest annual increases in the drilling of new wells generally coincide with periods when rainfall was at least 5 inches (20 percent) less than the annual mean. During the drought years of 1976–77 and 1987–91, well drilling increased markedly with respect to non-drought years. However, fairly large numbers of new wells were drilled between 1993 and 2002, a period when rainfall was normal or above normal. This recent surge in new well construction may have been due to, at least in part, a ground-water protection ordinance introduced by Napa County in 1996 to regulate the conditions under which a new well can be constructed (Christine Secheli, Napa County Department of Environmental Management, oral commun., 2002). The ordinance was adopted in 1999. Drillers' reports and other well records suggest that an average of only three wells per year were drilled in the study area prior to 1975, whereas an estimated average of 22 wells per year were drilled between 1975 and 2002. Although improved reporting over the years may account for part of the increased rate of well drilling, increases in both population and in irrigated agriculture probably account for most of the increase.

The amount of ground water pumped from the study area only can be estimated because domestic wells in the area are not metered and electrical power consumption records for irrigation wells are not readily available. Ground-water pumpage for residential domestic use and for irrigation for agricultural and improved open space (golf courses, cemeteries, and public institutions) were estimated using several different approaches (table 6).

Domestic pumpage was estimated using a well-based method and a population-based method. The well-based method involved multiplying the estimated number of residential wells (1,595) by an estimated average pumping rate (20 gal/min) and an assumed average daily use value of 1 hr/d. The population-based method involved multiplying the estimated self-supplied population in year 2000 (4,800) by an estimated per capita use value derived from water-use data for the Napa Municipal Water Department for 1990-2000 (148 gallons per person per day). The well-based method yielded a pumpage estimate of about 800 acre-ft and the population-based method yielded a pumpage estimate of about 2,100 acre-ft (table 6, at end of text).

Irrigation pumpage for agriculture was estimated using a well-based method and a land-use method. The well-based method involved multiplying the number of wells (185) by an estimated average pumping rate (75 gal/min) and an assumed average daily use (about 2.9 hr/d). The land-use method involved multiplying estimates of irrigated acreage (2,369 and 2,869 acres) by two different unit applied water coefficients for grapes (0.5 and 1.2 acre-ft/acre). The well-based method yielded a pumpage estimate of 2,690 acre-ft and the land-use method yielded pumpage estimates ranging from 1,180 to 3,440 acre-ft (table 6, at end of text).

Pumpage for irrigation of improved open space (golf courses, cemeteries, and public institutions) was estimated by multiplying acreage (391 acres) by a water coefficient for pasture (4.0 acre-ft/acre). The estimated annual pumpage for improved open space is about 1,560 acre-ft (table 6, at end of text).

In summary, estimates of the 2000-2002 annual ground-water pumpage in the study area range from 3,600 to 7,100 acre-ft, and average 5,350 acre-ft. Assuming that the average of the estimate (5,350 acre-ft) represents the annual ground-water pumpage, annual ground-water pumpage has increased by 2,350 acre-ft compared with the pumpage for 1975 of 3,000 acre-ft (Johnson, 1977). The estimated increase in the quantity of annual ground-water pumpage between 1975 and the 2000-2002 period is consistent with the marked increase in the number of new wells drilled in the study area and the large increase in irrigated agriculture during this period (fig. 13; table 1, at end of report).

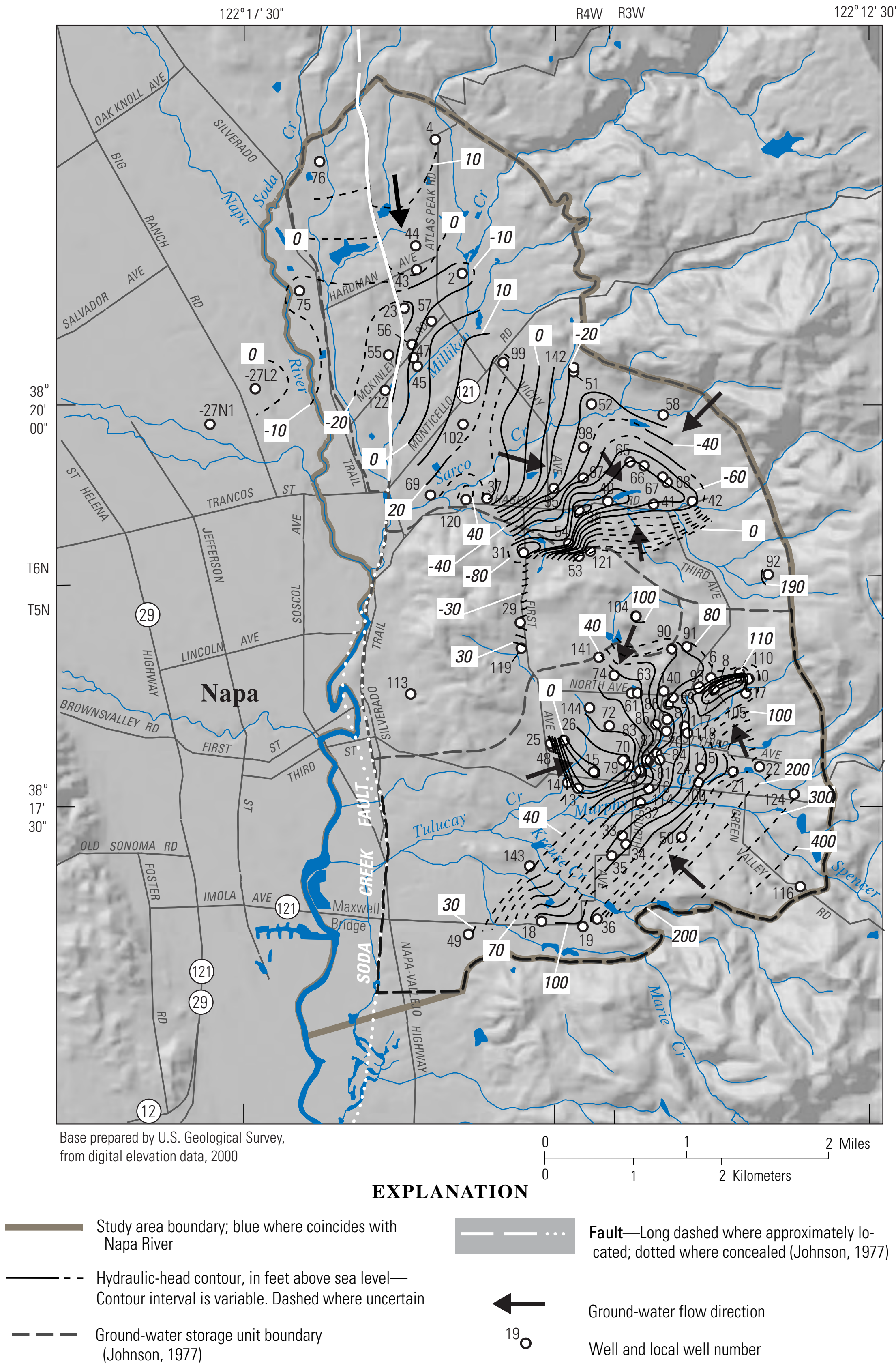


Figure 15. Generalized hydraulic head in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, October 2001.

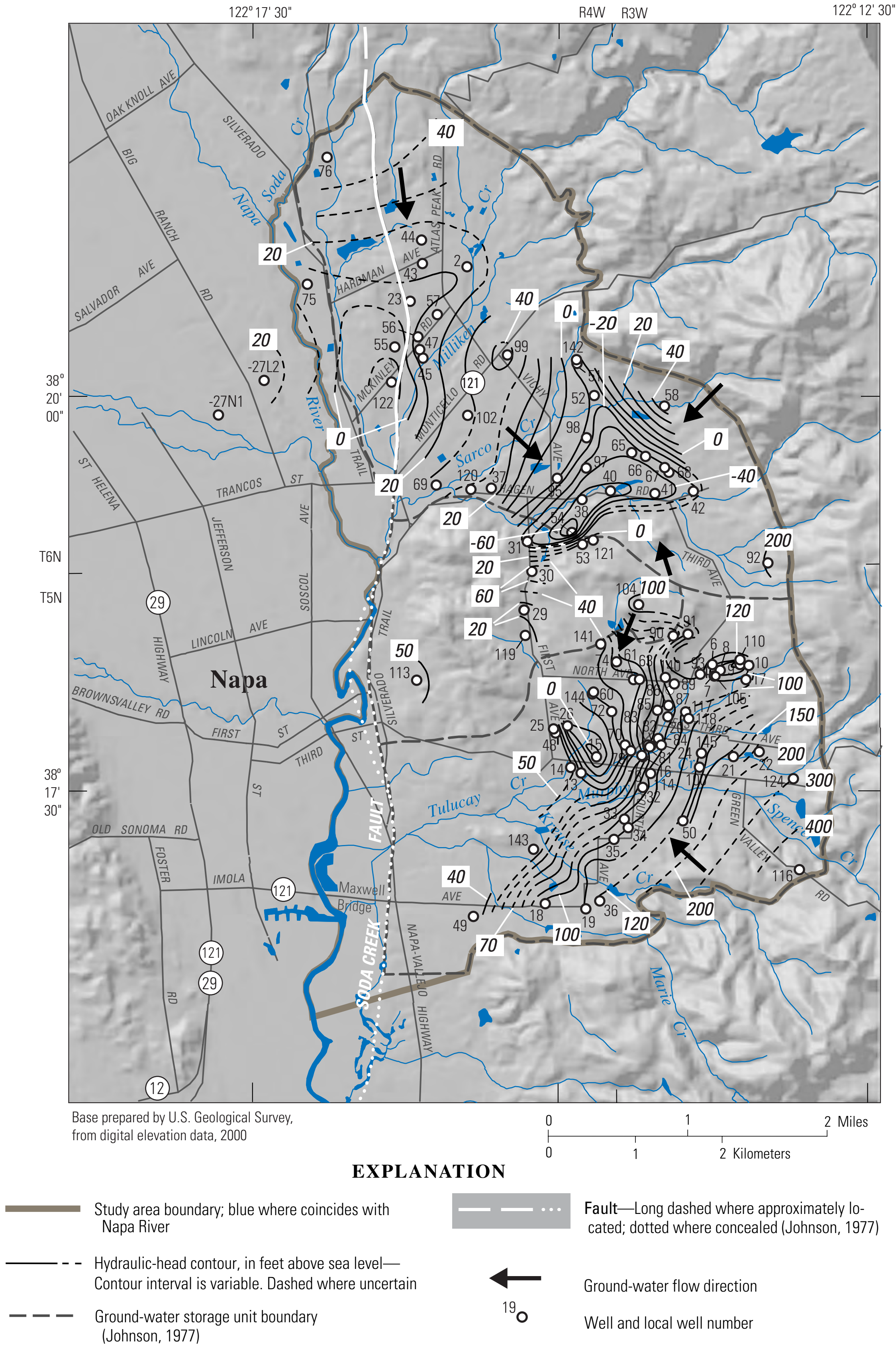


Figure 16. Generalized hydraulic head in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, April 2002.

Ground-Water Underflow

Ground-water underflow out of the study area occurs along the western boundary of storage unit 1, and ground-water underflow into the study area occurs across the western boundary of storage unit 4. Underflow out of storage unit 1 and into storage unit 4 was calculated on the basis of ground-water level data for 2000–2001. Insufficient ground-water level data were available for calculating underflow from storage unit 2, however, the quantity of underflow is probably small because of the low permeability of the deposits in this unit. The total quantity of underflow estimated for this study was compared with estimates made by Johnson (1977) for conditions during 1975.

For this study, underflow was estimated using the following form of Darcy's Law:

$$Q = KIA,$$

where Q is ground-water underflow (L^3/T), K is the average hydraulic conductivity of the saturated, unconsolidated deposits (L/T), I is the hydraulic gradient (L/L), and A is the cross-sectional area (L^2). The average hydraulic conductivity in storage unit 4, based on data from Johnson (1977), is 2 ft/d; the hydraulic gradient based on ground-water levels in 2000-2001 was 7×10^{-3} ft/ft toward the study area, and the cross-sectional area was 4.5×10^{6} ft^2. Ground-water inflow along the western boundary of storage unit 4 from outside the study area was calculated to be about 530 acre-ft/yr during 2000-2001. The average hydraulic conductivity in storage unit 1, based on Johnson (1977), was 2 ft/d; the hydraulic gradient based on ground-water levels in 2000-2001 was 1.5×10^{-2} ft/ft away from the study area, and the cross-sectional area was 4.5×10^{6} ft^2. Ground-water underflow for storage unit 1 was calculated to be about 1,130 acre-ft/yr. Therefore, the net ground-water underflow across the western boundaries of storage units 1 and 4 was about 600 acre-ft/yr leaving the study area. This value is about 2,050 acre-ft/yr less than the amount Johnson (1977) estimated for 1975. The 2,050 ace-ft/yr decrease closely matches the estimated increase in ground-water pumpage between 1975 and 2000 for the study area. Underflow across the western boundary has changed since 1975 because ground-water pumping has caused ground-water gradients in the study area to change.

Ground-Water Levels and Movement

Water-level monitoring can detect ground-water level declines related to excessive pumping and (or) deficient recharge. Water levels can be expressed in two ways: as depth-to-water below land surface or as hydraulic head. Hydraulic head is particularly useful because it expresses water level as an altitude relative to an arbitrary datum plane, such as sea level. Because ground water moves in the direction of decreasing hydraulic head, contour maps of hydraulic head can be used to determine the general direction of ground-water flow in an aquifer.

Monitoring Network

Water levels were measured semiannually by personnel from the Napa County Department of Public Works; as many as 120 wells were measured between the spring of 2000 and the spring of 2002 (fig. 14). The period of record for most wells is 1 year or more, but some were measured for less than 1 year. During the study, measurements at some wells were discontinued because of difficult access or well bore obstructions. As the study progressed, other wells were added to replace wells removed from the network or to improve areal coverage of the initial network. Measurements generally were made in April and October at the beginning and ending of the dry season, respectively.

Water levels in all the wells were measured using a 300-foot calibrated electric tape with graduations of 0.01 ft, but measurements were recorded and reported to the nearest 0.1 ft (table 5, at end of report). Care was taken to ensure that measurements were not made while wells were pumping or recovering from recent pumping. Despite these efforts, some water-level measurements may have been made during non-static conditions. Measurements suspected of having been affected by recent or nearby pumping were excluded from the analysis of water-level conditions in this report (table 5, at end of report).

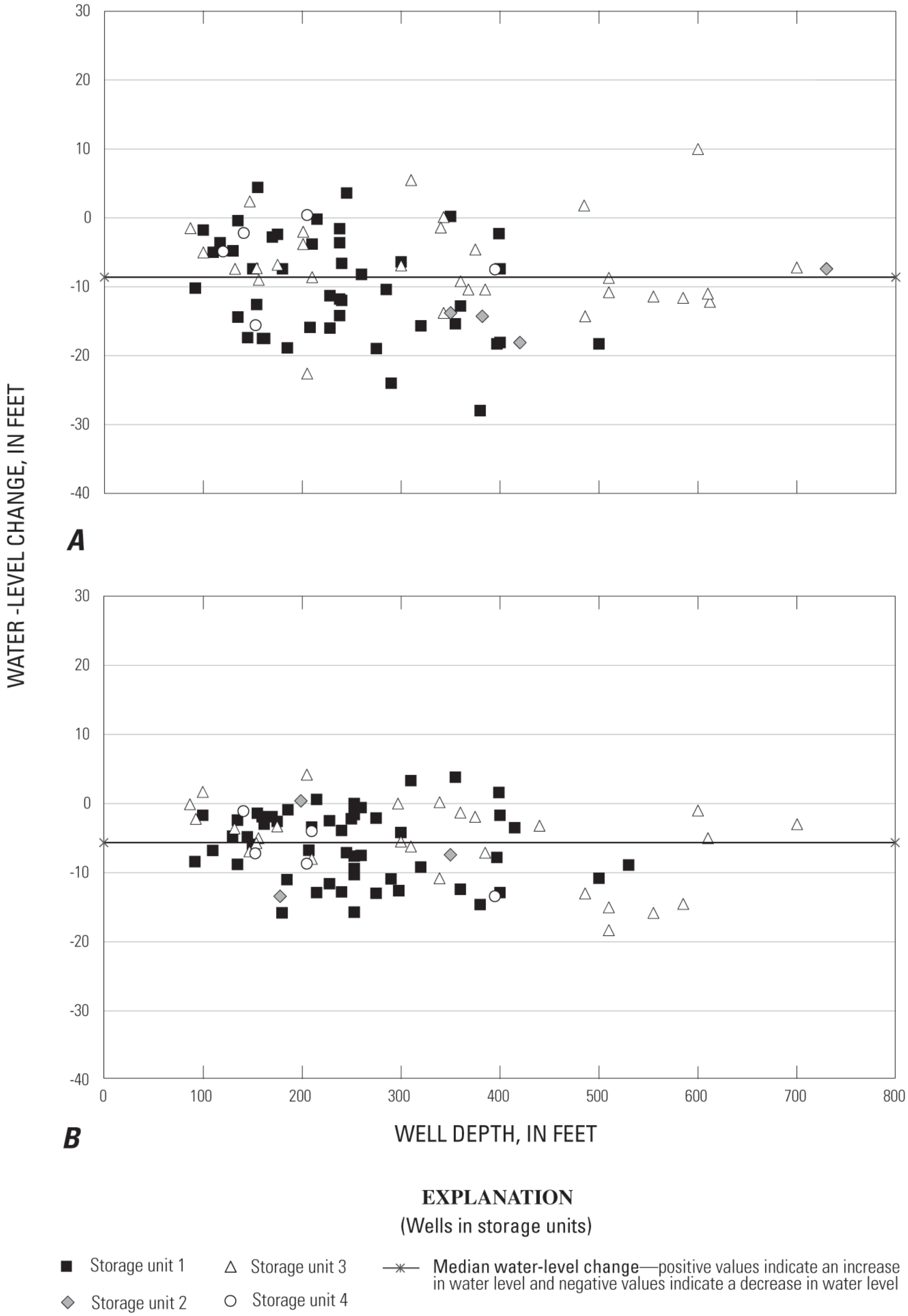


Figure 17. Change in water levels compared with well depth between (A) October 2000-October 2001 and (B) October 2001-October 2002 in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

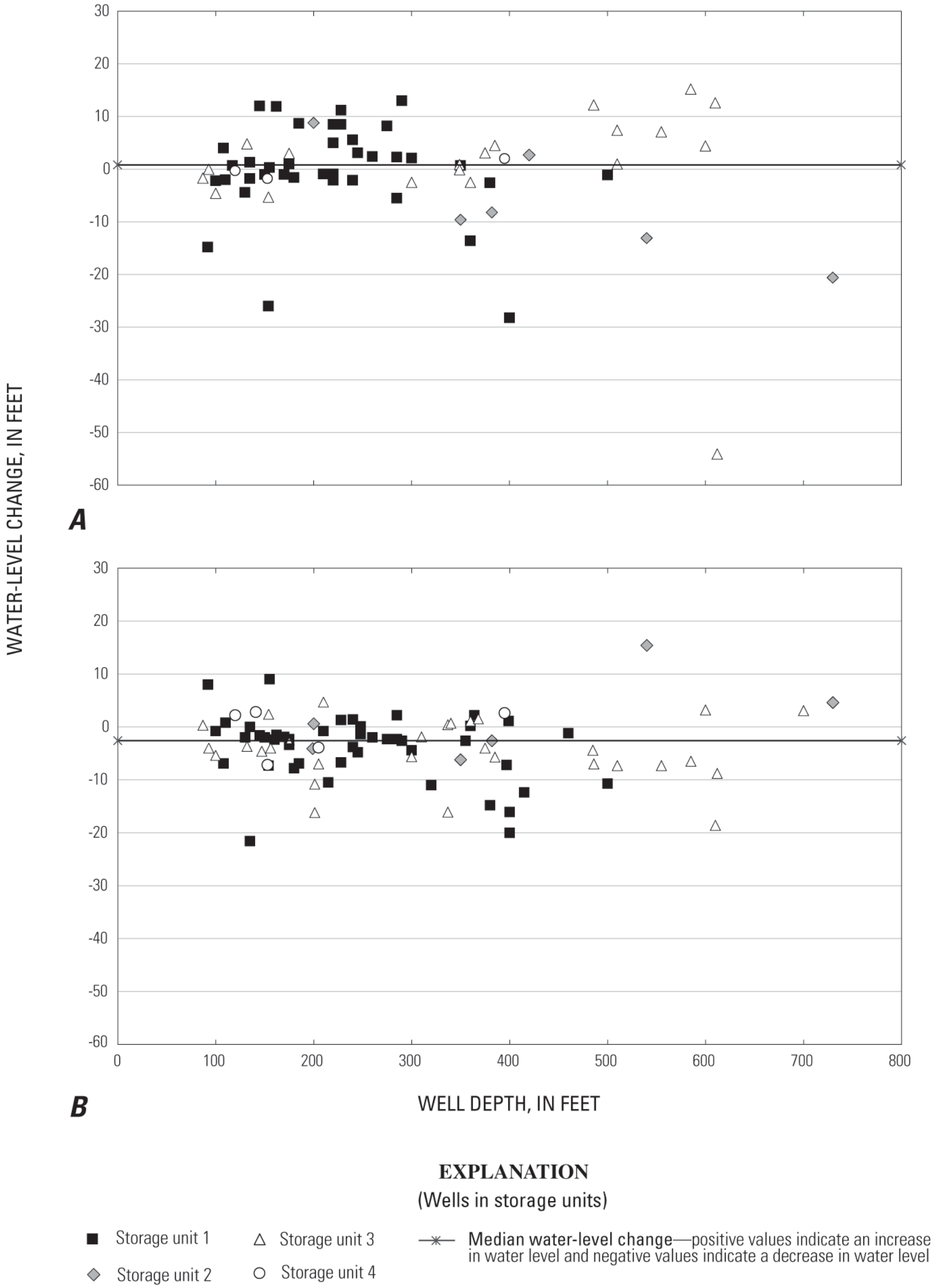


Figure 18. Change in water levels compared with well depth between (A) April 2000-April 2001 and (B) April 2001-April 2002 in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

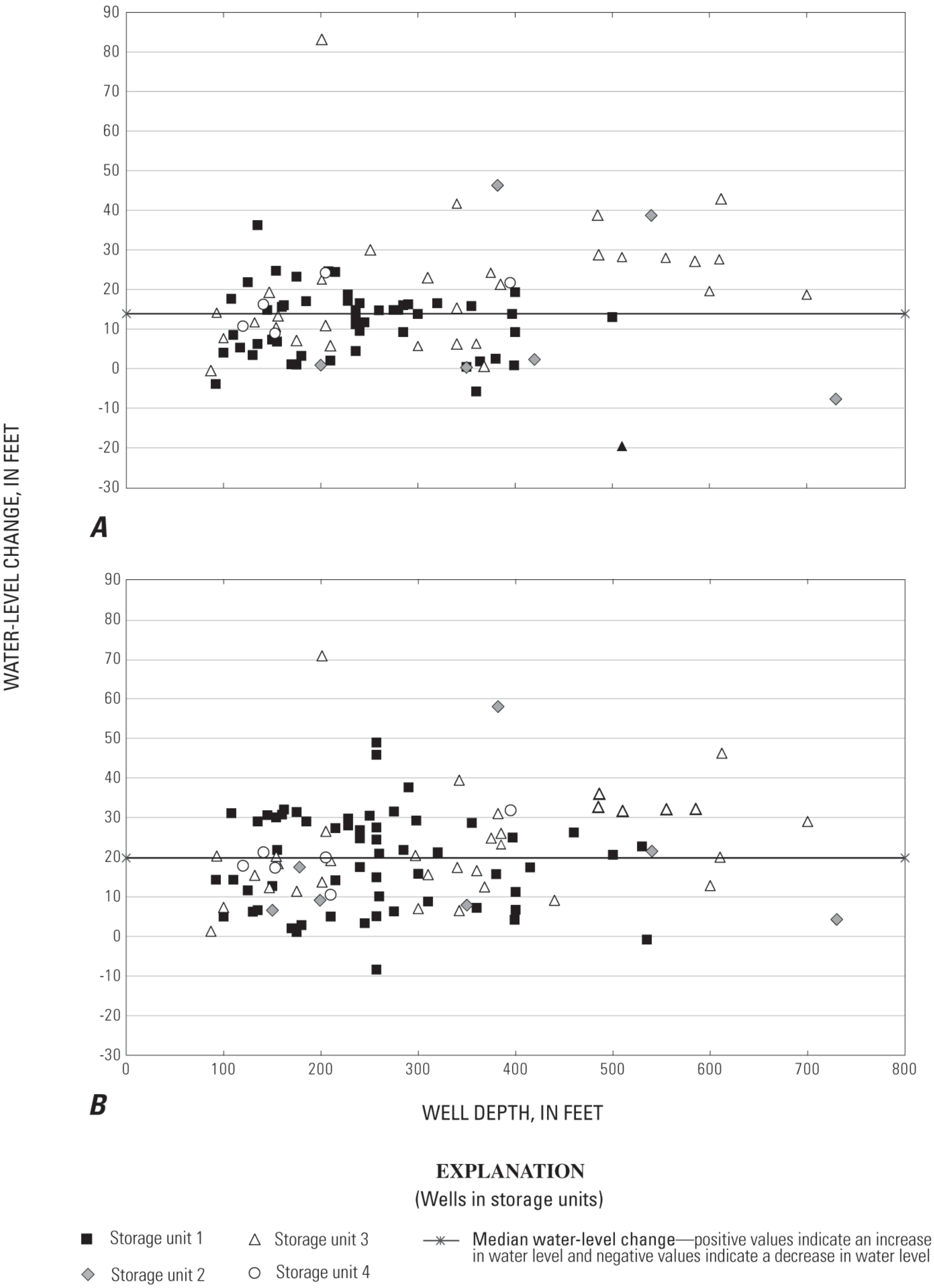


Figure 19. Change in water levels compared with well depth between (A) October 2000-April 2001, and (B) October 2001-April 2002 in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

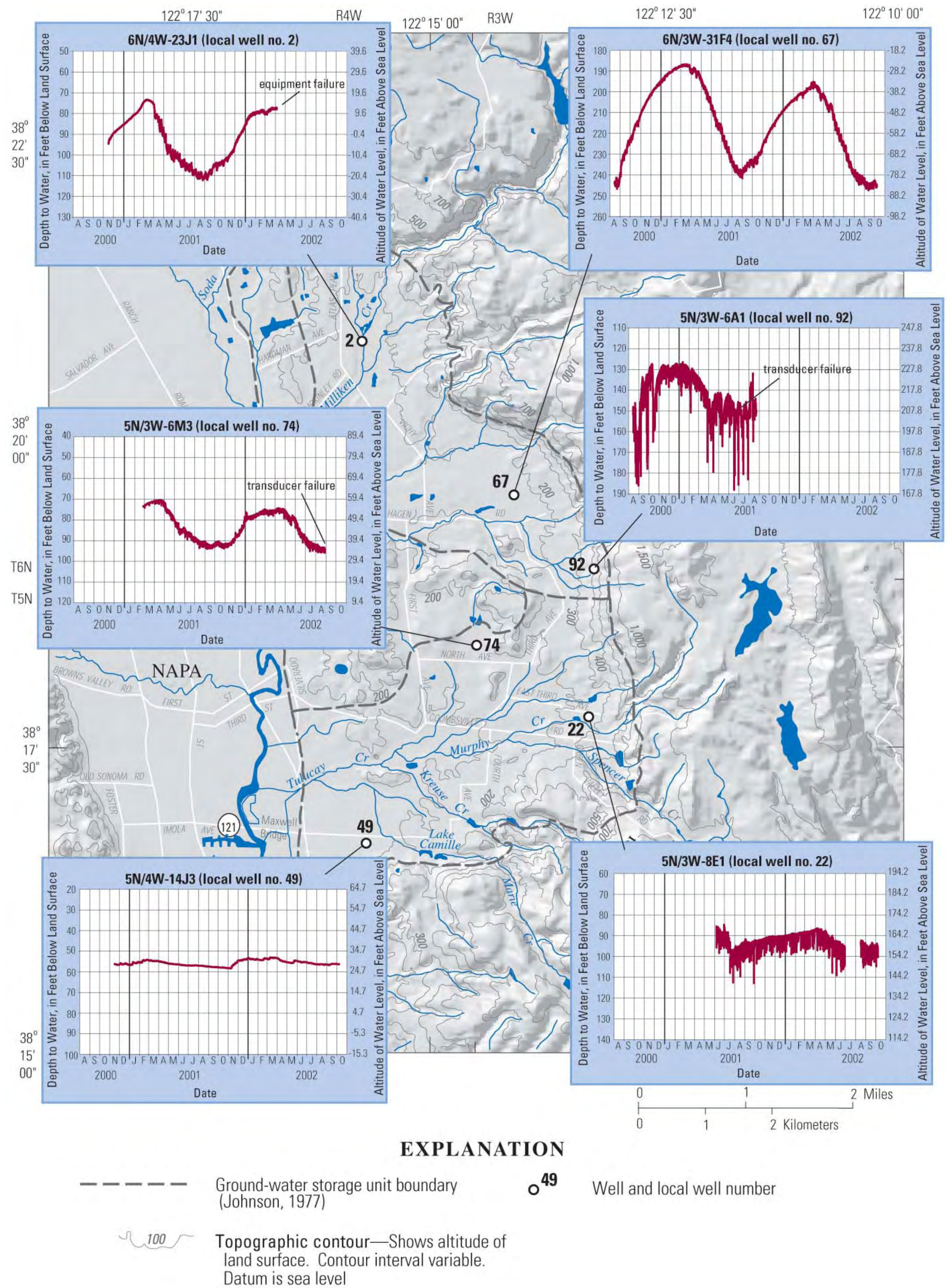


Figure 20. Continuous ground-water levels recorded in selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

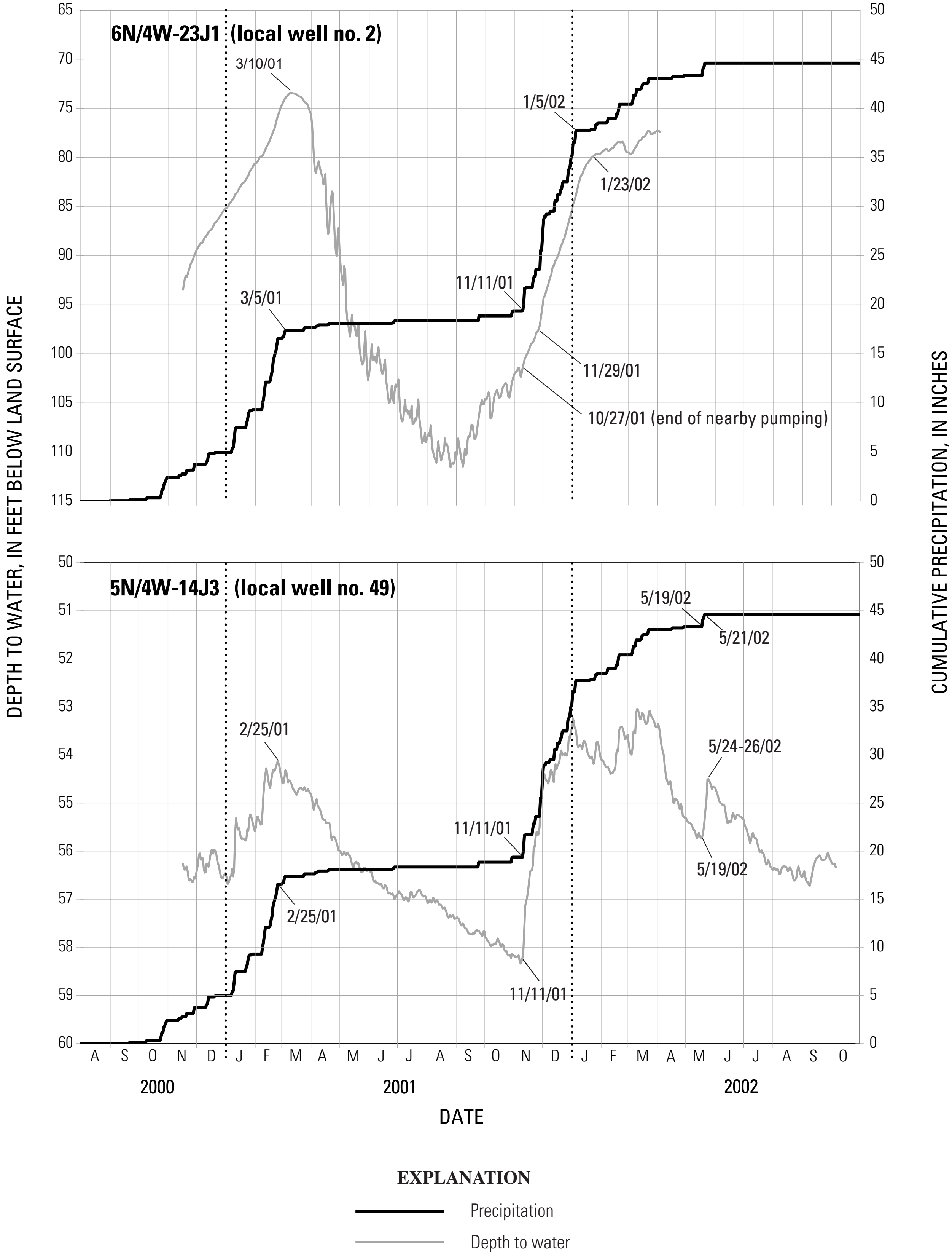


Figure 21. Ground-water levels in selected wells and cumulative precipitation in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

In addition to the periodic measurements made using the calibrated electric tape, continuous measurements were made in six wells on which submersible pressure transducers and data loggers were installed (fig. 14). Staff from the Napa County Department of Public Works downloaded the data to a laptop computer every 3 months, replaced the datalogger batteries, and measured the water levels to evaluate transducer performance (Lee Driggers, Napa County Department of Public Works, written commun., 2001). The continuous water-level data were converted from readings representing the submergence depth of the transducer below the water surface to values representing the depth to water below land surface. Transducer performance was evaluated by comparing water levels measured with a calibrated electric tape with water levels measured by the transducers; differences in water levels were attributed to transducer drift or to extraneous factors such as cable slippage. Corrections were applied to the data to compensate for these factors.

Land-surface altitudes at the wells were determined by Napa County Department of Public Works staff using a combination of differential Global Positioning System (GPS) surveying and third-order differential leveling surveying (Lee Driggers, Napa County Department of Public Works, written commun., 2002). The land-surface altitudes at the wells in the monitoring network at the beginning of the study in 2000 were derived from differential GPS surveying and have an accuracy of 0.5 ft. The land-surface altitudes at the wells added to the monitoring network in 2001 were derived from third-order differential leveling and have an accuracy of less than 0.1 ft. Land-surface altitudes at some wells that were not included in either survey were determined by interpolating between the 20-foot contour intervals on USGS 7-1/2-minute topographic maps for the Napa and Mt. George quadrangles. The contours have an accuracy of plus or minus 10 ft.

Ground-Water Levels

Graphs and a map showing long-term water-level changes were made using both recent measurements collected as part of this study and historical water-level measurements obtained from the Napa County Department of Public Works (internal files) and the California Department of Water Resources (1995). These measurements do not necessarily represent the water table because hydraulic head can vary with depth in an aquifer. Therefore, the water levels in wells open to large depth intervals represent composite heads for the respective depth intervals. The correct interpretation of ground-water level data is, in part, dependent upon complete well-construction information, including total depth, perforation intervals, seals, and gravel-pack depth. Complete construction information, however, was not available for several of the wells in the 2000–2002 network, which limited analysis and interpretation of the data.

Ground-Water Movement

Maps of hydraulic head were made using water-level data from October 2001 and April 2002 (figs. 15 and 16) to determine approximate ground-water flow directions; the direction of ground-water movement is from areas of higher hydraulic head toward areas of lower hydraulic head. Hydraulic-head values were calculated by subtracting the measured depth to water from the land-surface altitudes at the wells. Under present-day conditions, the general direction of ground-water movement is from recharge areas in the mountains around the perimeter of the study area toward pumping depressions in storage units 1, 3, and 4 (figs. 15 and 16). The locations of the pumping depressions in storage units 1 and 3 correspond with areas having the highest concentrations of active and potentially active wells (fig. 12). The water-level contours in figures 15 and 16 differ from the water-level contours in the maps by Johnson (1977) for April and September 1975. One obvious difference is the deep depression of hydraulic heads in the west-central part of storage unit 1 (figs. 15 and 16) that is not evident in the 1975 data. Other significant differences between 1975 and 2001–2002 are the deepening and broadening of the pumping depression in the south-central part of storage unit 3 and the reduction in the depth and lateral extent of the pumping depression in the northwest part of storage unit 3. Changes in hydraulic head and directions of ground-water movement are more complicated in storage unit 4. A comparison of hydraulic heads for April 2002 with hydraulic heads for 1975 indicate a pumping depression in the southern part of storage unit 4 that was not evident in 1975. In September 1975, a large part of storage unit 4 was underlain by a pumping depression, but in October 2002 the depression was not as deep as it was in 1975 and it had shifted farther to the east.

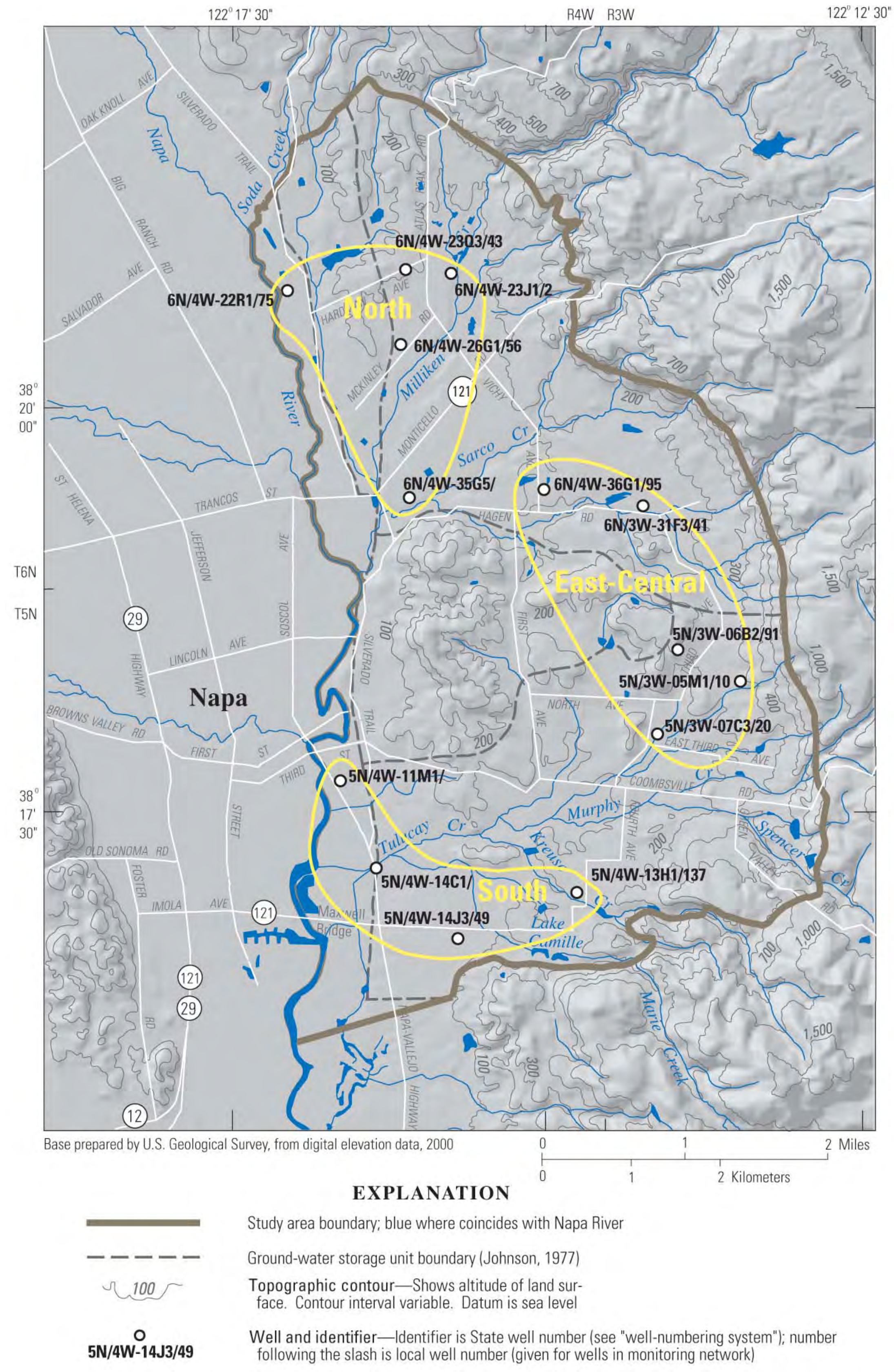


Figure 22. Locations of selected wells at which periodic water levels were made in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, early 1960s through 2002.

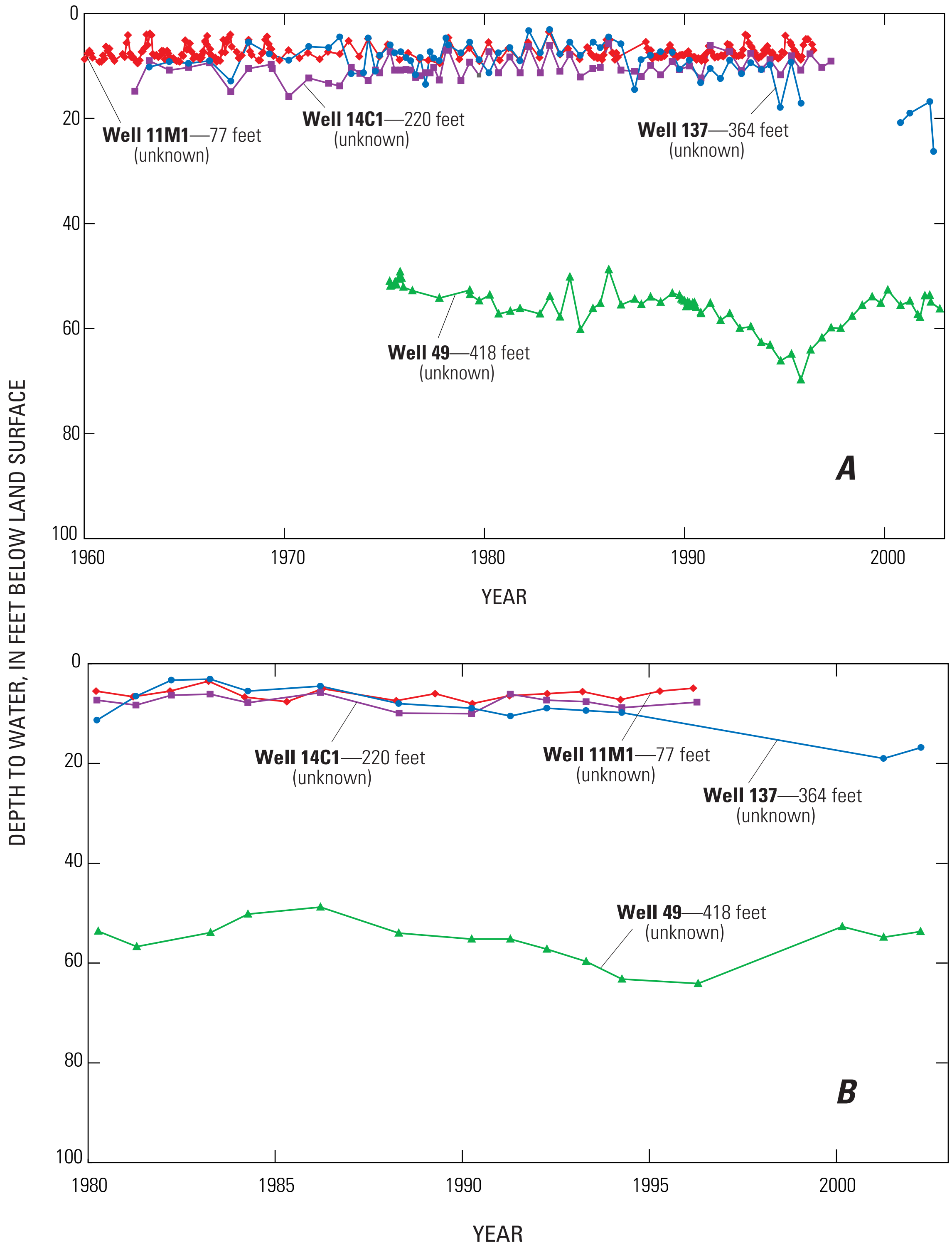


Figure 23. Periodic water levels in selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, early 1960s through 2002. A, south group, all data. B, south group, highest water levels measured in spring. C, north group, all data. D, north group, highest water levels measured in spring. E, east-central group, all data. F, east-central group,highest water levels measured in spring.

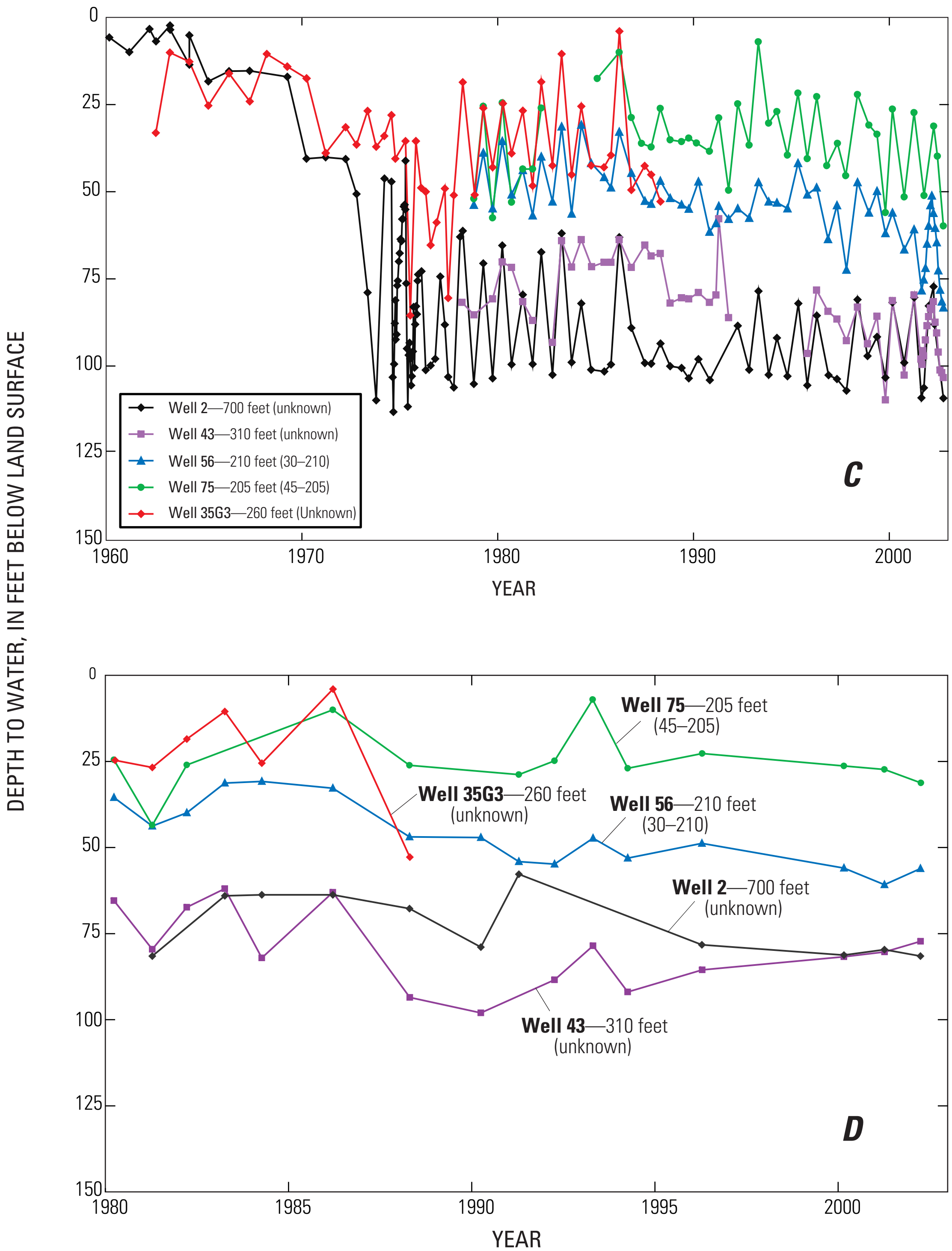


Figure 23.—Continued.

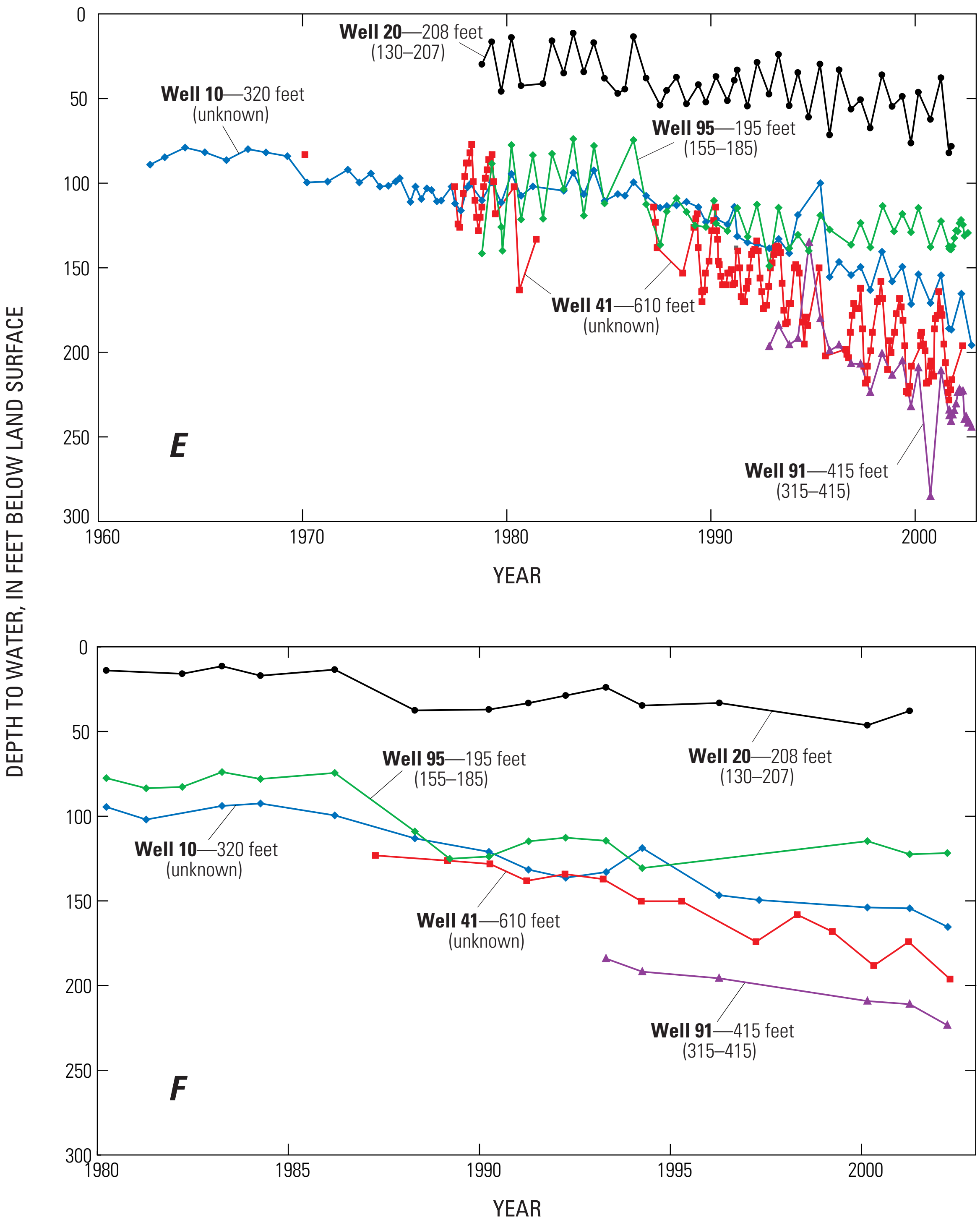


Figure 23.—Continued.

Insufficient data were collected during this current study to determine precisely the direction of ground-water flow in storage unit 2. However, given that large pumping depressions were mapped for October 2001 and April 2002 near the northeast and southeast periphery of storage unit 2, it is likely that ground water moves from storage unit 2 toward these depressions. West of the surface-water divide, running north-south through the central part of storage unit 2, ground water probably generally moves westward toward the Napa River.

The Soda Creek Fault, on the west side of the study area, is a partial barrier to ground-water movement between storage units 3 and 4. This fault is described as a normal fault having more than 700 ft of vertical displacement (Weaver, 1949) that juxtaposes different geologic units on either side of the fault. In October 2001 water-level altitudes were about 10 ft higher on the east side of the fault than on the west side of the fault (figs. 15 and 16).

Annual and Seasonal Water-Level Fluctuations

Measured water levels and calculated hydraulic heads, as altitudes above sea level, in wells in the monitoring network are given in table 5 (at end of report) for October and April 2000 to 2002. Changes in water levels for October and April 2000 through 2002 as related to well depth are shown in figures 17, 18, and 19 and table 7, at end of report. Water levels generally declined between October 2000 and October 2001 (median water-level change was –8.6 ft) and between October 2001 and October 2002 (median water-level change was –5.5 ft) (fig. 17A, B). Water levels generally were unchanged between April 2000 and April 2001 (median water-level change was +0.7 ft), but declined slightly between April 2001 and April 2002 (median water-level change was -2.6 ft) (fig. 18A, B). Comparisons of annual water-level changes as related to well depth for autumn (fig. 17A, B) and for spring (fig. 18A, B) showed no clear correlation between water-level change and total depth of well. Water levels rose in almost every well between October 2000 and April 2001 (fig. 19A) and between October 2001 and April 2002 (fig. 19B); the median water-level change was +14.1 ft and +19.9 ft, respectively. Ground-water levels generally rise between October and April owing to a reduction of ground-water pumping during the winter rainy season, ground-water inflow from outside the study area, and possibly minor direct recharge. The slightly higher water-level rise during the winter of 2002 can be attributed to greater rainfall in 2002 than in 2001 (fig. 3).

Water levels were measured continuously in six wells in the study area from 2000 to 2002 (fig. 20). Two of the wells (2 and 49) were not pumped; the other four wells (22, 67, 74, and 92) were pumped frequently. Water levels fluctuated 20 to 50 ft seasonally in wells 2, 67, 74, and 92 but fluctuated only 5 to 15 ft seasonally in wells 22 and 49. The larger water-level fluctuations were in wells located near pumping depressions in storage units 1 and 3 (figs. 15 and 16). The continuous hydrographs show seasonal ground-water level changes more precisely than semiannual measurements. The hydrographs for the six continuously measured wells show that maximum annual ground-water levels can occur in individual wells any time between January and April and that the minimum annual ground-water level can occur any time between August and October. These data suggest continuous water-level monitoring is the most reliable means of determining the seasonal maximum and minimum ground-water levels. If other considerations necessitate a semiannual measurement schedule, then measuring during the periods March to April and September would be best for recording the maximum and minimum water levels.

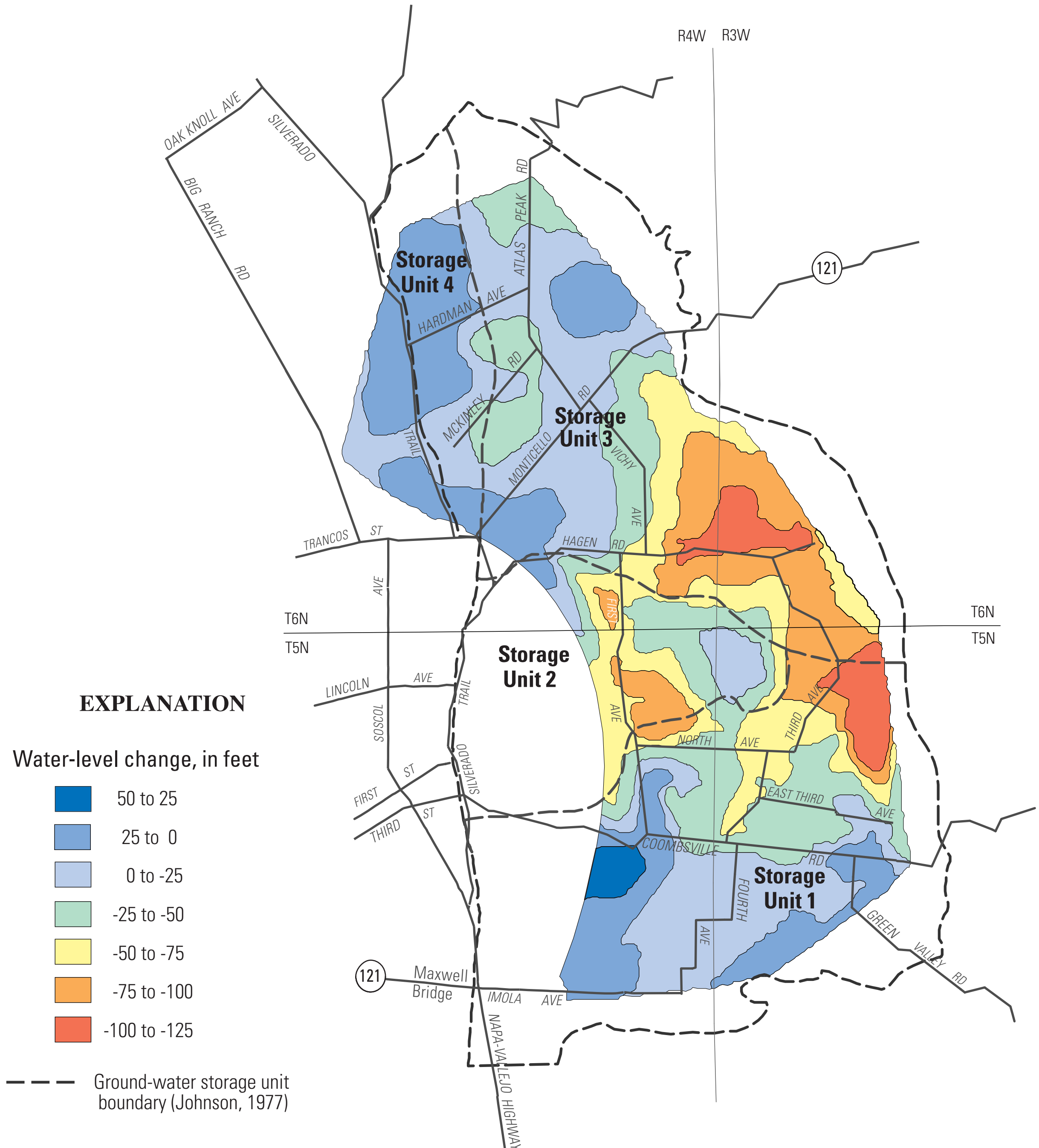


Figure 24. Change in water levels in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, autumn 1975 to autumn 2001.

Water levels in well 2 (unused) fluctuated about 35 ft between the highest and the lowest levels. This is a response to recharge from nearby Milliken Creek and recovery after cessation of pumping in nearby wells used for golf course and landscape irrigation. Examination of the expanded hydrograph for well 2 clearly illustrates the overall decline and daily fluctuations in water levels between March and November owing to nearby pumping (fig. 21). The transition from a cessation of nearby pumping to rapid water-level recovery in late October 2001 is marked by the beginning of a smooth and more steeply rising hydrograph. In late November 2001, the rate of water-level recovery increased in response to the onset of heavy winter rains several weeks earlier. A 2- to 3-week lag time between precipitation and water-level response in January 2002 also is clearly evident in figure 21. The heavy precipitation tapered off in early January, and by the third week of January, the rate of water-level recovery also was leveling off.

The hydrograph for unused well 49 shows little water-level response to seasonal stresses due to the lack of pumping at nearby wells and its location away from major natural sources of recharge. Without complete well-construction information, an unambiguous interpretation of water-level fluctuations was not possible; however, water level seems to respond rapidly to precipitation (fig. 21). If any part of the well is screened in a confined aquifer, part of the water-level rise may be attributable to diminished pumping in distant wells.

Long-Term Changes in Ground-Water Levels

In the early 1900s, water flowed to land surface from many of the wells drilled in the area; by the 1950s, most of the wells had ceased flowing (Kunkel and Upson, 1960). Although water-level records for this period were insufficient for creating hydrographs, long-term hydrographs for the early 1960s through 2002 were created for 14 wells in the study area using periodic water-level measurements of 10 or more years. The locations of these wells are shown in figure 22, and the hydrographs for them are shown in figure 23.

The hydrographs are divided into three groups on the basis of geographic location and similarities in water-level fluctuations. The three groups are delineated in figure 22 and are identified as south, north, and east-central. The depth range of perforated intervals is known for only five of the wells. The lack of information on the perforated intervals of nine of the wells limits understanding similarities and differences in ground-water level fluctuations and trends between wells and geographic locations. The ground-water level network can be improved by using only wells that have complete construction information. However, the long-term trends of ground-water levels in these 14 wells still are instructive because they show areas where ground-water level declines have been greatest and areas where ground-water levels have not changed significantly over periods of several years.

Water-level data for each group of wells are shown in two hydrographs—one shows all available data for each well from 1960 to 2002; the second shows the highest water level measured each spring from 1980 to 2002. The data used for the spring water levels includes only values measured for March or April. The annual high water level generally occurs in the spring and is a measure of ground-water level recovery in the aquifer near the well. The amount of recovery depends upon recharge derived from precipitation during the previous season and the amount of reduction in ground-water pumping during October to February.

Long-term water-level data were available from four wells in the southern part of the study area. . Water-level measurements were discontinued in the mid-1990s for wells 11M1 and 14C1, however, prior to that time, there was no significant long-term trend in increasing or decreasing water levels. The other two wells (49 and 137) in the south group show small water-level declines between the 1980s and 2002 of about 1 and 12 ft, respectively (fig. 23B). Annual water-level fluctuations in the wells in this area were generally much less than 10 ft.

Water-level declines have been greater in the northern part of the study area than in the southern part but have been less than those in the east-central part. Long-term water-level data were available for five wells in the northern part of the area (fig. 23C). Water levels in well 2 declined by about 70 ft between 1960 and 1975 and by less than 10 ft between 1975 and 2002. Water levels in well 6N/4W-35G3 declined about 40 ft between 1962 and 1975, recovered to near 1962 levels by the mid 1980s, and then declined by about 30 ft by 1988, when measurements were discontinued. Wells 43, 56, and 75 have water-level data from about 1980 to 2002, and the water levels in these wells declined by about 10 to 25 ft during this period (fig. 23D). Annual water-level fluctuation in wells from this group were more than 25 ft during many years (fig. 23C).

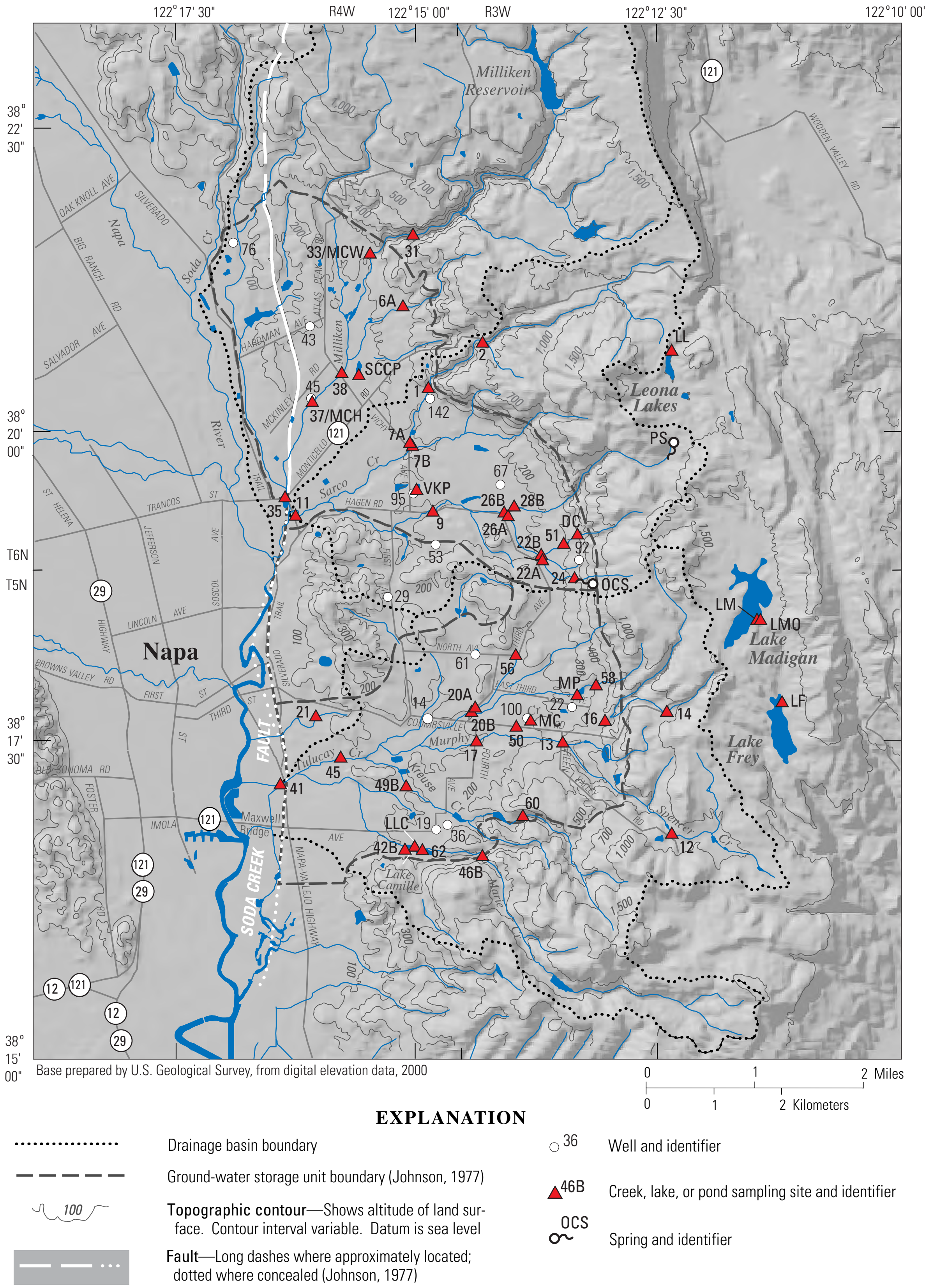


Figure 25. Locations of ground-water, surface-water, and miscellaneous water-chemistry sampling sites in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

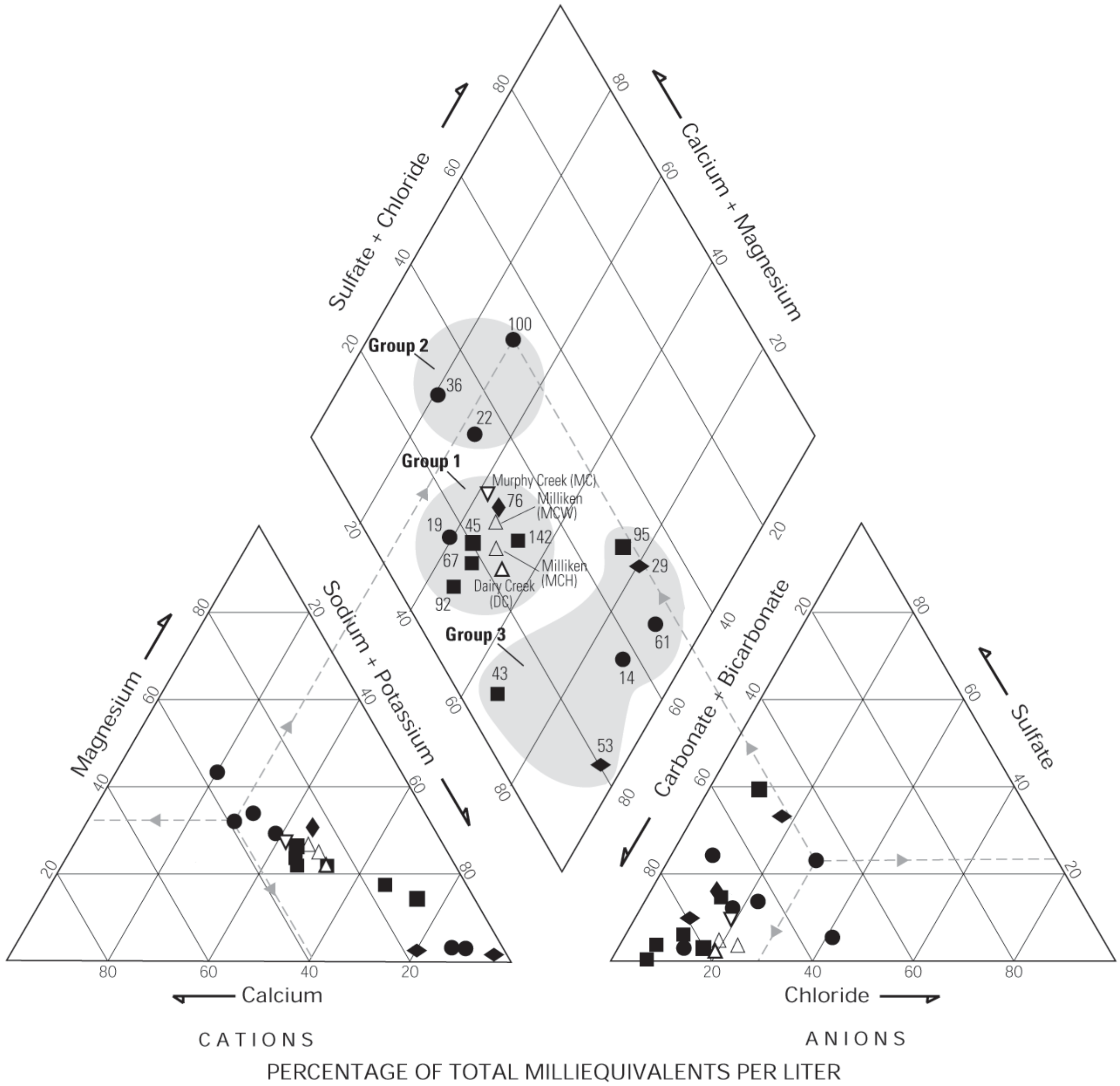
Long-term water-level data were available from five wells in the east-central part of the study area, and show that water-level declines were largest in this part of the study area (fig. 23E). Water levels in well 10, which has the longest period of record for the east-central group, declined by more than 100 ft between 1962 and 2002. Annual high water levels measured in wells 20 and 41 (fig. 23F) declined between about 25 and 70 ft between the 1980s and the 2000-2002 period. Annual water-level fluctuations in wells in this group range from about 10 to more than 50 ft (fig. 23E).

In summary, ground-water levels have declined since the 1960s over large parts of the study area especially in the central part. These water-level declines have occurred despite near average to above average precipitation for the past four decades. A decade by decade comparison of precipitation recorded at the Napa State Hospital for the 1960s, 70s, 80s, and 90s shows that precipitation was 95, 99, 117, and 115 percent of the average. Water levels declined in 9 of 10 key monitoring wells (figs. 23B, 23D, and 23F) during the period 1980–2002. The water levels in five of these wells declined by greater than 20 ft since the 1980s. The general decline in ground-water levels in the study area may be attributed to an increase in ground-water pumping as more wells were constructed in the area especially since the mid 1970s.

Ground-Water Level Changes, 1975-2001

A water-level change map for the study area (fig. 24) was developed by computing the differences between the hydraulic-head map for autumn 2001 (fig. 15) presented in this report and the hydraulic-head map for autumn 1975 presented in Johnson (1977). Because most of the wells used to measure water levels during 2000-2002 were not the same wells measured by Johnson during 1974-75, the changes in figure 24 cannot be related to specific wells. In addition, it is important to recognize that water-level data used for the autumn 2001 and autumn 1975 hydraulic-head maps represent composite hydraulic heads because the water levels were measured in wells that mostly were constructed with long gravel packs, long screens, or multiple-depth zones open to geologic formations.

The water-level changes shown in figure 24 are consistent with the water-level changes evident in the long-term hydrographs (fig. 23A–F). In general, water levels declined in the northeastern part of ground-water storage unit 1, in the central part of storage unit 2, and in the southeastern part of storage unit 3. Water levels during 1975–2001 declined 100 to 125 ft in an area east of Third Avenue, straddling storage units 1 and 3, and along and north of Hagen Road in an area that is underlain by a pumping depression (figs. 15 and 16). In the central part of storage unit 2 along First Avenue, ground-water levels during 1975–2001 declined as much as 75 to 100 ft. Water-level declines were moderate (25 to 75 ft) in large areas of storage units 1, 2, and 3, including the western and the northern parts of storage unit 3 along Atlas Peak Road (fig. 24). Water-levels declines were small (0 to 25 ft) in storage unit 1 along Fourth Avenue between Imola Avenue and Coombsville Road and throughout a large part of the western half of storage unit 3. Water levels rose 0 to 50 ft throughout much of the western part of storage unit 1 between Imola Avenue, near Napa State Hospital, and at First Avenue south of North Avenue. Areas of 0- to 25-foot water-level rises extended through the central and southern parts of storage unit 4, the southwest part of storage unit 3, and a small area in the northeast part of storage unit 3, in the vicinity of the Silverado Country Club. Although water-level monitoring in and west of storage unit 4 was less extensive during 2000–2002 than during 1974–75 (Johnson, 1977), the limited data collected for this study indicate that water levels in most of this area rose less than 25 ft during 1975–2001.



EXPLANATION

Ground-water sample data groups:

Group 1: Samples similar to composition of surface water

Group 2: Calcium-magnesium-bicarbonate type water

Group 3: Sodium-bicarbonate type water

Well samples

100 Storage unit 1 and site identifier
29 Storage unit 2 and site identifier
92 Storage unit 3 and site identifier
76 Storage unit 4 and site identifier

Surface-water samples

MCH Milliken Creek drainage basin and site identifier
DC Sarco Creek drainage basin and site identifier
MC Tulucay Creek drainage basin and site identifier

Example of how to read a trilinear diagram

Figure 26. Chemical composition of water from selected ground-water and surface-water sampling sites in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, September-November 2001.

SURFACE-WATER AND GROUND-WATER QUALITY

Surface water and ground water were sampled for analyses of major ions, selected trace elements, silica, nutrients, the stable isotopes of oxygen and hydrogen, selected dissolved atmospheric gases [nitrogen (N_2), argon (Ar), oxygen (O_2), carbon dioxide (CO_2), methane (CH_4), helium (He), hydrogen (H_2), and neon (Ne)], chloroflurocarbons (CFCs), and tritium. These data, summarized in tables 8 and 9 (at back of report) and tables10 and 11 (at back of report), were used to help characterize the areal variations in ground-water and surface-water chemistry and to help identify the ages and sources of ground waters. Surface-water samples were collected from sites along Milliken, Sarco, and Tulucay Creeks and their tributaries and at several lakes and ponds. Ground-water samples were collected from 15 wells in ground-water storage units 1 through 4 and from 2 springs in the Howell Mountains (fig. 25). Selection of wells was based on accessibility, type of well construction, and proximity to other wells selected for sampling in order to maximize the geographic coverage.

In general, water chemistry and (or) isotopic composition can vary with depth in ground-water systems. Most wells in the study area have shallow (less than 50 ft) seals and are perforated over long intervals, from shallow depths (less than 100 ft) to near the bottom of the well. This type of well construction is used to maximize well yield, but it greatly restricts the number of wells that tap only the deeper parts of the ground-water system and limits the utility of chemical data for characterizing the ground-water flow system. Of the 15 wells sampled for this study, only 2 are known to have perforated intervals that begin at depths greater than 100 ft (wells 92 and 142). For this reason, no statistically meaningful comparison of water chemistry or isotopes between deep and shallow ground water can be made for the 15 samples collected.

Methods of Water Sampling and Analysis

Surface-water samples were collected using a DH-81 sampler according to methods given in Wilde and others (1999); for streams too shallow for this method, water was collected in a polyethylene beaker from near the centroid of flow. Ground-water samples from wells were collected from faucets either at or near the well head to minimize potential chemical alteration of the water between the well and the sampling point. Prior to the collection of the ground-water samples, the wells were purged a minimum of three casing volumes of water. Sequential measurements of specific conductance, pH, and temperature were made at 5-minute intervals until readings had stabilized. All samples collected for the analysis of major ions, trace elements, silica, and nutrients were collected, treated, and preserved following procedures outlined by U.S. Geological Survey (1997 to present). These samples were analyzed at the USGS National Water Quality Laboratory in Denver, Colorado, using standard analytical methods described by Fishman and Friedman (1989), Fishman (1993), and Struzeski and others (1996).

Water samples for determinations of stable isotopes of hydrogen and oxygen were collected in unrinsed 60-mL glass bottles. Surface-water samples were collected directly from creeks, lakes, ponds, and springs by immersing the bottle until filled. Ground-water samples were bottom filled using a tygon tubing connected to the sampling point and allowed to overflow several sample volumes of water prior to being capped. Bottles were capped with conical-seal caps. Ratios of stable isotopes of oxygen and hydrogen were determined by the USGS Isotope Fractionation Project in Reston, Virginia, using a hydrogen water-equilibration technique (Coplen and others, 1991).

Samples for dissolved N_2, Ar, O_2, CO_2, and CH_4 analysis were collected by submerging 150-mL glass bottles in a plastic bucket that was continuously filled to overflowing with well water. A copper tube attached to the sample point and used to fill the plastic bucket was placed in the bottom of the glass sample bottle and allowed to displace several bottle volumes of water from the sample bottle prior to sealing the bottle. While the bottle was submerged in water, a rubber stopper pierced through by a syringe needle was firmly inserted in the bottle. The syringe needle allowed water, displaced by insertion of the stopper, and bubbles to escape. The syringe needle was removed with the bottle still submerged in water. A replicate sample was collected for each ground-water sampling site for quality assurance and control. Samples were stored and shipped on ice to the USGS Dissolved Gas Laboratory in Reston, Virginia, for analysis using gas-chromatographic methods as described by the U.S. Geological Survey (2001).

Water sampled for CFCs was pumped through copper tubing that was attached to the sampling point with hose fittings. The copper tubing was used to avoid contamination by chlorofluorocarbons that might diffuse through the tygon tubing used for chemical samples. Samples for CFCs were collected in five 62-mL ampoules that had been pre-flushed with ultrapure nitrogen gas for 1 minute to exclude atmospheric gases. The ampoules were then flushed with well water for several minutes before being filled and sealed with an oxygen-MAPP gas torch. Samples for CFCs (CFC-11, CFC-12, and CFC-113) were analyzed by the USGS CFC Laboratory in Reston, Virginia, using purge-and-trap gas chromatography methods described by Busenberg and Plummer (1992).

Samples for dissolved helium (He), hydrogen (H_2), and neon (Ne) were collected using the same bottles and procedures as described for the collection of dissolved gases. These samples were also collected in duplicate for quality assurance and control. Samples were analyzed for He by thermal conductivity detection at the USGS Dissolved Gas Laboratory in Reston, Virginia, using methods similar to those described by Sugisaki and others (1982).

Samples for tritium analyses were collected in unrinsed 1-L polyethylene bottles. The bottles were bottom filled using a tygon tubing connected to the sampling point and allowed to overflow with several sample volumes of water prior to being capped. Bottles were sealed with conical-seal caps to minimize exchange with the atmosphere. These samples were analyzed at the USGS Tritium Laboratory in Menlo Park, California, by electrolytic enrichment and gas counting as described by Ostlund and Dorsey (1975).

Surface-Water and Ground-Water Chemistry

Selected samples were measured on site for dissolved oxygen, pH, specific conductance, water temperature, and alkalinity following procedures outlined by U.S. Geological Survey (1997 to present). Dissolved-oxygen concentrations ranged from less than 0.1 to 8.9 milligrams per liter (mg/L); the highest concentrations were in the creek samples. The dissolved-oxygen concentrations exceeded 1 mg/L in water from six wells; the maximum concentration (6.6 mg/L) was in a sample from well 53.

The pH of all the samples ranged between 6.3 and 8.6 (table 8, at end of report). The lowest and highest values, 6.3 and 8.6, respectively, do not meet the secondary drinking-water standard range of 6.5 to 8.5 established for the protection of taste, odor, or appearance of drinking water (California Department of Health Services, 2003).

Specific conductance, a measurement of the ability of water to conduct an electrical current and an indicator of ionic concentration, varied widely depending on the type of the sample, the location, and the time of year. The specific conductance measured in stream samples ranged from 58 to 610 microsiemens per centimeter (µS/cm) (tables 8 and 9, at end of report). The lowest specific conductance values were measured in samples collected from creeks, lakes, and ponds on the Howell Mountain block. The highest specific conductance values were measured in samples collected from small culverts or tributaries to Milliken, Sarco, and Tulucay Creeks that drain areas of concentrated residential development (sites 20A, 21, and 9) or vineyards (sites 56, and 22B). Specific conductance of creek water was highest when streamflow was lowest. This suggests that recently discharged ground water makes up a greater part of streamflow during low-flow conditions than during times of high runoff. Specific conductance values in samples from lakes and ponds in the lower Milliken and Tulucay drainage basins in September 2001 ranged from 166 to 317 µS/cm. Samples from wells in the lower Milliken, Sarco, and Tulucay drainage basins in September and November 2001 ranged from 124 to 1,220 µS/cm. Water from one well (61) exceeded the State secondary drinking-water standard of 900 µS/cm (California Department of Health Services, 2003).

Major-ion concentrations in surface- and ground-water samples are plotted in a trilinear diagram (fig. 26). A trilinear diagram shows the proportions of common cations and anions for comparison and classification of water samples independent of total analyte concentrations (Hem, 1985). Trilinear diagrams can be used to identify groups of samples that have similar relative ionic concentrations (Freeze and Cherry, 1979). Water samples from the lower Milliken–Sarco–Tulucay Creeks area were separated into three groups, each group having a different relative chemical composition (fig. 26).

Group 1 includes samples from six wells (19, 45, 67, 76, 92, and 142), four of which exceed 350 ft in total depth, and all four surface-water samples [Murphy Creek (MC), a tributary of Tulucay Creek; Dairy Creek (DC), a tributary of Sarco Creek; and at two sites (site 33/MCW and site 37/MCH) along Milliken Creek]. Wells 45, 76, 92, and 142 are located close to creeks. Group 1 samples can be characterized as a mixed cation-bicarbonate type water. Sodium was the predominant cation in all group 1 water samples. Samples in this group had relatively low ionic concentrations compared with samples in groups 2 and 3. Dissolved-solids concentrations (solids, sum of constituents) for the creek samples ranged from 128 to 164 mg/L and for ground-water samples ranged from 144 to 282 mg/L (compared with the median of 282 mg/L for all 15 well samples).

Group 2 includes samples from three wells (22, 36, and 100, all having total depths of less than 250 ft) in the southeastern part of the study area (fig. 25). The chemical composition of this group is characterized as a calcium-magnesium bicarbonate (two samples) or a calcium-magnesium mixed anion type water (one sample). The dissolved-solids concentrations for this group, which were higher than those for group 1, ranged from 217 to 435 mg/L.

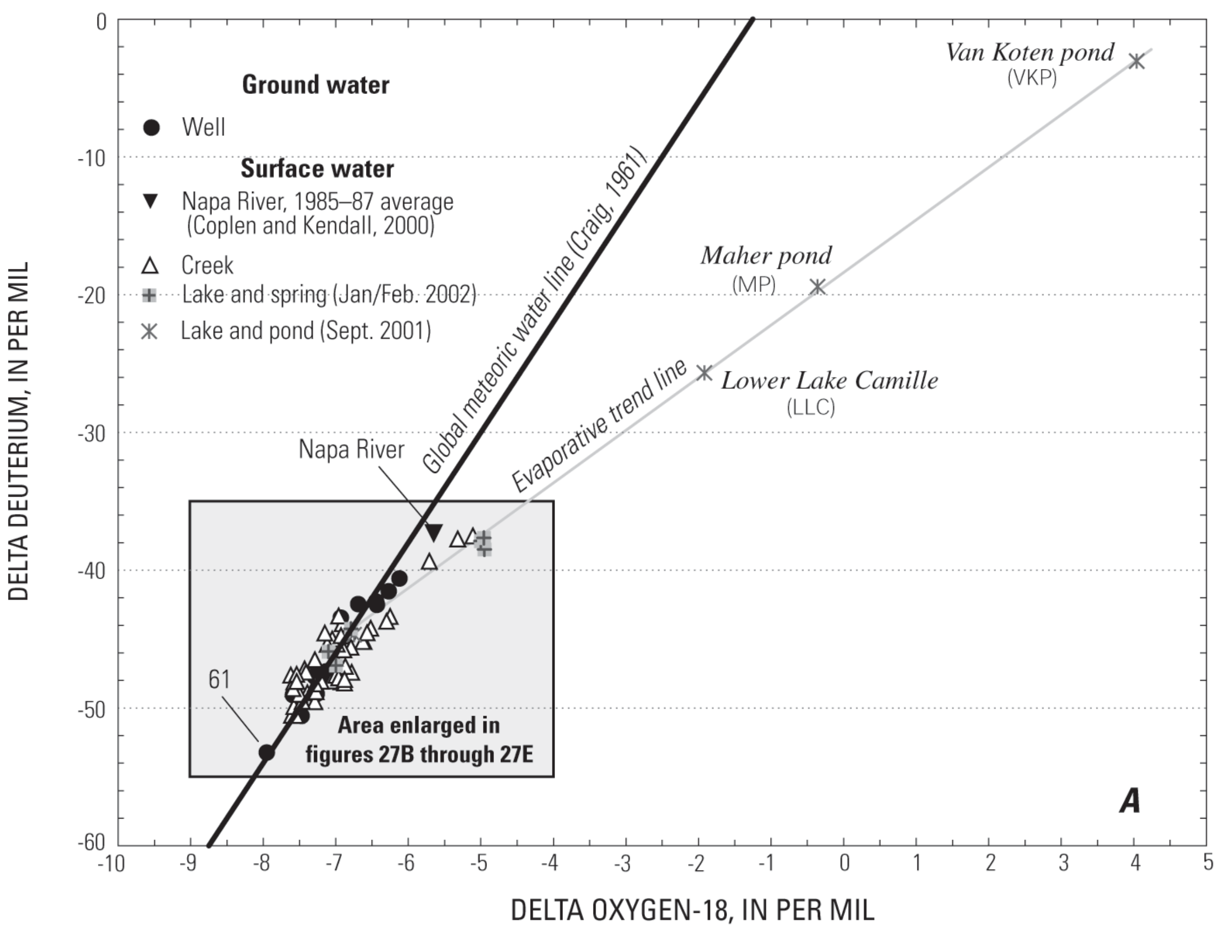


Figure 27. Relation between delta deuterium and delta oxygen-18 in water samples for the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California. A, all water samples. B, enlargement of part of figure 27A. C, creek samples grouped by month. D, creek samples for March and April 2001 grouped by range. E, ground-water samples and selected surface-water samples.

Group 3 includes samples from six wells (14, 29, 43, 53, 61, and 95). Five of the wells are located in or within 1 mi of the hilly region in ground-water storage unit 2 referred to as the Cup and Saucer (Johnson, 1977). Group 3 samples are sodium-bicarbonate type water (fig. 26). Most samples in this group had higher ionic concentrations than the samples in groups 1 and 2. Dissolved-solids concentrations ranged from 285 to 732 mg/L. Concentrations of sodium ranged from 51 to 247 mg/L and were higher compared with those in the samples from groups 1 and 2. Samples from wells in group 3 had the highest concentrations of chloride (175 mg/L in the sample from well 61), fluoride (1.5 mg/L in the sample from well 61), and sulfate (80 mg/L in the sample from well 95).

Boron concentrations in samples from wells 14 and 61 were 1.4 mg/L (1,440 micrograms per liter [μg/L]) and 11 mg/L (11,000 μg/L), respectively. These concentrations exceeded the California Department of Health Services action level (AL) of 1 mg/L (California Department of Health Services, 2002). The high boron concentration in well 61, as well as a strong hydrogen sulfide odor noted at the time of sampling and the overall chemical composition of the sample, indicates that the chemical composition of water in this well is similar to the composition of the samples collected in 1950 from two wells in the same area (Kunkel and Upson, 1960). Water from wells identified as State well numbers 5N/3W-6N2 and -6P1 had boron concentrations in 1950 of 18 and 8 mg/L, respectively (Kunkel and Upson, 1960). Wells 5N/3W-6N2 and -6P1 were of comparable depth to well 61 (completed depth 260 ft) at 205 and 285 ft, respectively, suggesting that aquifers underlying the diatomaceous deposits of the Sonoma Volcanics in this particular area yield poor quality water.

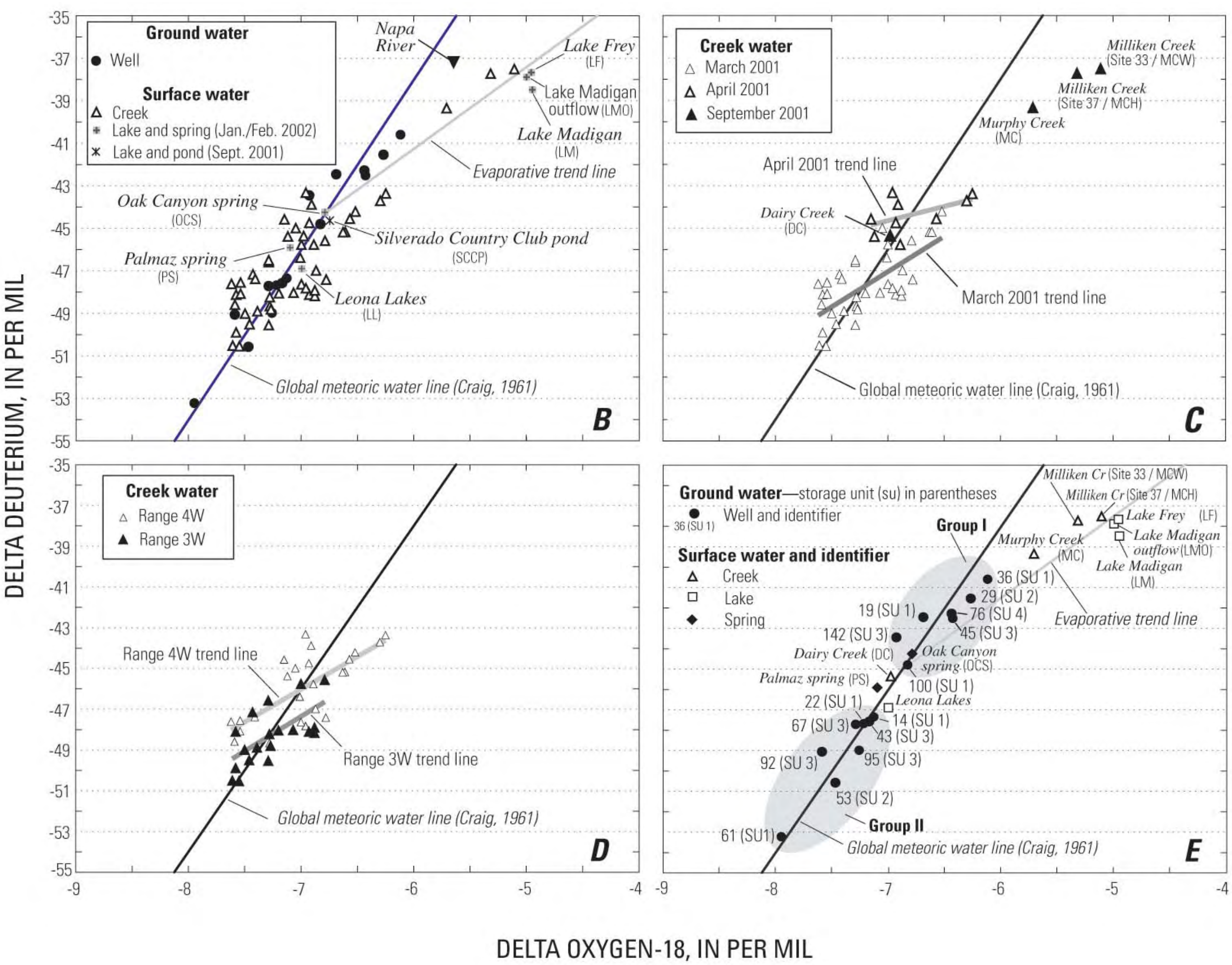


Figure 27.—Continued.

The concentration of arsenic in samples from wells 29, 36, 43, 45 and 76 ranged from 11 to 67 µg/L. These concentrations exceeded the primary maximum contaminant level (MCL) of 10 µg/L (U.S. Environmental Protection Agency, 2002). Wells 43, 45, and 76 are located in the northwestern part of the study area near the Soda Creek Fault, where deep up-flow of ground water along the fault may account for the relatively high concentration of arsenic in these well samples compared with that in other well samples from the study area.

Samples from several wells contained dissolved iron and manganese in concentrations exceeding the secondary Federal and State MCL of 300 µg/L for iron and 50 µg/L for manganese (U.S. Environmental Protection Agency, 2002; California Department of Health Services, 2003).

Variations in ground-water composition within the study area can be summarized as follows:

1. Ground water from the perimeter of the study area, nearest recharge areas in the Howell Mountains, generally was less mineralized than ground water closer to the central part of the study area. Surface-water and ground-water samples from the perimeter of the area can be characterized as calcium-magnesium bicarbonate composition, low dissolved solids, and relatively high silica concentrations compared with samples from other parts of the study area.
2. Ground water in the southeastern part of the lower Tulucay drainage basin contains higher percentages of calcium and magnesium (greater hardness), slightly lower percentages of bicarbonate, and intermediate dissolved solids, compared with ground water in other parts of the study area.
3. Ground water in the central part of the study area, centered near the Cup and Saucer area, is characterized by higher dissolved-solids concentrations, a higher percentage of sodium, a higher percentage of chloride or sulfate, and higher concentrations of boron than ground water from areas closer to the Howell Mountains. Ground water from three wells (14, 61, 100), ranging in total depth from 228 to 260 ft, have the highest dissolved solids (all greater than 400 mg/L) and highest chloride concentrations (54 to 175 mg/L). These three wells are all located within about 0.5 mi of Coombsville Road and Fourth Avenue.
4. Ground water having high arsenic concentrations may be related to deep upward circulation of ground water along the Soda Creek Fault. Water samples with the highest arsenic concentrations (16 to 67 µg/L) came from three wells located within 0.5 mi of the Soda Creek Fault in the northwest part of the area.
5. Water in contact with volcanic rocks often has high concentrations of dissolved boron, iron, and manganese (Hem, 1985). The volcanic rocks that underlie the study area are probably the source of the observed high concentration of the constituents.

Oxygen-18 and Deuterium

Water samples were collected from selected sites in the study area for analysis of oxygen-18 (^{18}O) and deuterium (^{2}H). Oxygen-18 and deuterium data can provide information on the source and movement of ground water.

Background

Oxygen-18 and deuterium are naturally occurring stable isotopes of oxygen and hydrogen. The abundance of oxygen-18 and deuterium relative to lighter oxygen-16 (^{16}O) and hydrogen (^{1}H) atoms can be used to help infer the source and the evaporative history of water. Oxygen-18 and deuterium abundances are expressed in delta notation (δ as per mil (parts per thousand [‰]) differences in the ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ in samples relative to a standard known as Vienna Standard Mean Ocean Water (VSMOW) (Gat and Gonfiantini, 1981):

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{VSMOW}} - 1\right] \times 1,000$$

and

$$\delta D = \left[\frac{(^{2}H/^{1}H)_{sample}}{(^{2}H/^{1}H)_{VSMOW}} - 1\right] \times 1,000$$

Because the source of much of the world's precipitation is derived from the evaporation of seawater, the $\delta^{18}O$ and δD composition of precipitation throughout the world cluster along a line known as the global meteoric water line (Craig, 1961)

$$\delta D = \delta^{18}O + 10.$$

Differences in the isotopic composition of precipitation occur along this line if water vapor originated from evaporation of cooler or warmer seawater (Gat and Gonfiantini, 1981). Storms that originate over the cold waters in the Gulf of Alaska have a lighter isotopic composition than storms that originate over warm tropical waters in the vicinity of Hawaii. Differences also occur as the result of moist air masses moving over land; as storms move inland from coastal areas, the concentration of heavier isotopes relative to lighter isotopes decreases as water molecules repeatedly undergo evaporation and condensation. In addition, precipitation that condenses at high altitudes and at cool temperatures tends to be isotopically lighter than precipitation that forms at low altitudes and warm temperatures (Muir and Coplen, 1981). Water that has not undergone evaporation will plot near the global meteoric water line.

Stable Isotope Results

The $\delta^{18}O$ and δD values for the entire suite of water samples ranged from +4.04 to −7.95 per mil and −3.04 to −53.23 per mil, respectively (table 9, at end of report). These values plot on either side of and along the global meteoric water line (fig. 27A). Waters affected by evaporation plot to the right of the meteoric water line; the sample from a small artificial impoundment, designated as Van Koten pond for the purposes of this report, has the isotopically heaviest (least negative) water ($\delta^{18}O$ and δD values, +4.04 and −3.04 per mil, respectively) and exemplifies the effect of evaporation. The sample from well 61, located in ground-water storage unit 1, was the isotopically lightest (most negative) water sampled ($\delta^{18}O$ and δD values of −7.95 and −53.23 per mil, respectively). Figure 27B is an enlargement of part of the plot shown in figure 27A and shows in more detail the distribution of data for all samples except the three lake or pond samples that are most strongly affected by evaporation.

The $\delta^{18}O$ and δD composition of surface-water samples from creeks in the lower Milliken, Sarco, and Tulucay drainage basins ranged from −5.11 to −7.62 per mil for $\delta^{18}O$ and from −37.51 to −50.54 per mil for δD (fig. 27C, table 9, at end of report). In contrast, the average $\delta^{18}O$ and δD composition for the Napa River near Napa (Station number 1145800; fig. 1) for 1985-87 was −5.64 and −37.32, respectively (Coplen and Kendall, 2000). The average isotopic composition of the Napa River is representative of the average for streams in the part of Napa Valley (about 218 mi^2) upstream of station 1145800 and is heavier than the composition of nearly all the creek samples collected in the study area (fig. 27B). The creek water samples, excluding those from Milliken Creek, are composed of recently discharged ground water and seepage of shallow soil water (they were collected long after any significant rainfall). Milliken Creek is fed by controlled releases from Milliken Reservoir, therefore the water samples from this stream can contain large fractions of water derived from precipitation and surface-water runoff.

Seasonal variations in the isotopic composition of creek water between March 2001 and September 2001 are illustrated in figure 27C. The isotopic composition of creek samples from March, April, and September 2001 became progressively heavier due to higher air and water temperatures that result in greater losses of lighter isotopes through evaporation. The isotopic composition of creek water was progressively lighter (more negative) from west (range 4W) to east (range 3W) (fig. 27D), probably because the higher altitude in the eastern part of the study area results in fractionation of the isotopes in rainfall. Evaporation from creeks, however, can cause isotopic concentrations to become heavier as water flows from the headwaters to locations in the western part of the study area.

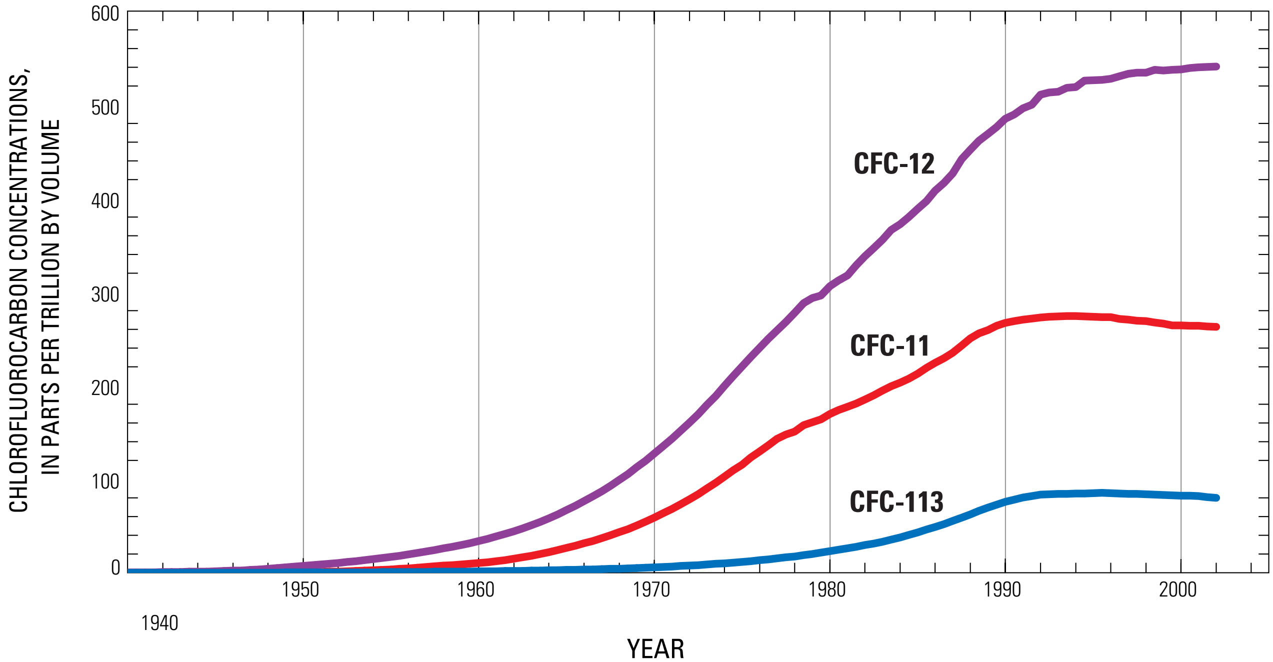


Figure 28. Concentrations of chlorofluorocarbons CFC-11, CFC-12, and CFC-113 in North American air. (Modified from Plummer and Busenberg, U.S. Geological Survey, written commun., 2002)

The $\delta^{18}O$ and δD composition of the samples from the lakes, ponds, and springs showed a wider variation of isotopic composition than the samples from the creeks, ranging from +4.04 to –7.10 per mil for $\delta^{18}O$ and –3.04 to –46.90 per mil for δD (table 9, at end of report). Three of four lake and pond samples collected in September 2001 had the heaviest isotopic composition of any sample collected and analyzed. Samples from lower Lake Camille (LLC), located in the lower Tulucay Creek drainage basin, and from two private artificial ponds, Maher pond (MP), located in the lower Tulucay Creek drainage basin, and Van Koten pond (VKP), located in the Sarco Creek drainage basin, define an evaporative trend line (fig. 27A). The isotopic composition of the fourth sample collected in September 2001 from a pond at the Silverado Country Club (SCCP) plots slightly to the right of the global meteoric water line but within the same area of fig. 27B where most of the creek and ground-water samples plot. This sample most likely represents ground water pumped to fill and maintain the Silverado Country Club pond.

Four samples collected in January 2002 from three lakes, located east of the surface-water divide in the Howell Mountains, plot to right of the global meteoric water line (fig. 27E). The three samples from Lake Madigan and Lake Frey plot along the evaporative trend line and have an isotopic composition similar to the samples collected from Milliken Creek in September 2001. The fourth sample collected from Lake Leona, had an isotopic composition similar to most of the creek and ground-water samples, indicating that the water in this lake was relatively unaffected by evaporation compared with water from other sites, perhaps owing to recent runoff or ground-water inflow. Samples collected from Oak Canyon spring and Palmaz spring had a similar composition and plot close to the global meteoric water line (fig. 27B). The samples from Leona Lakes, Oak Canyon spring, and Palmaz spring probably are the most representative of the isotopic composition of ground-water recharge to the study area that originates in the Howell Mountains.

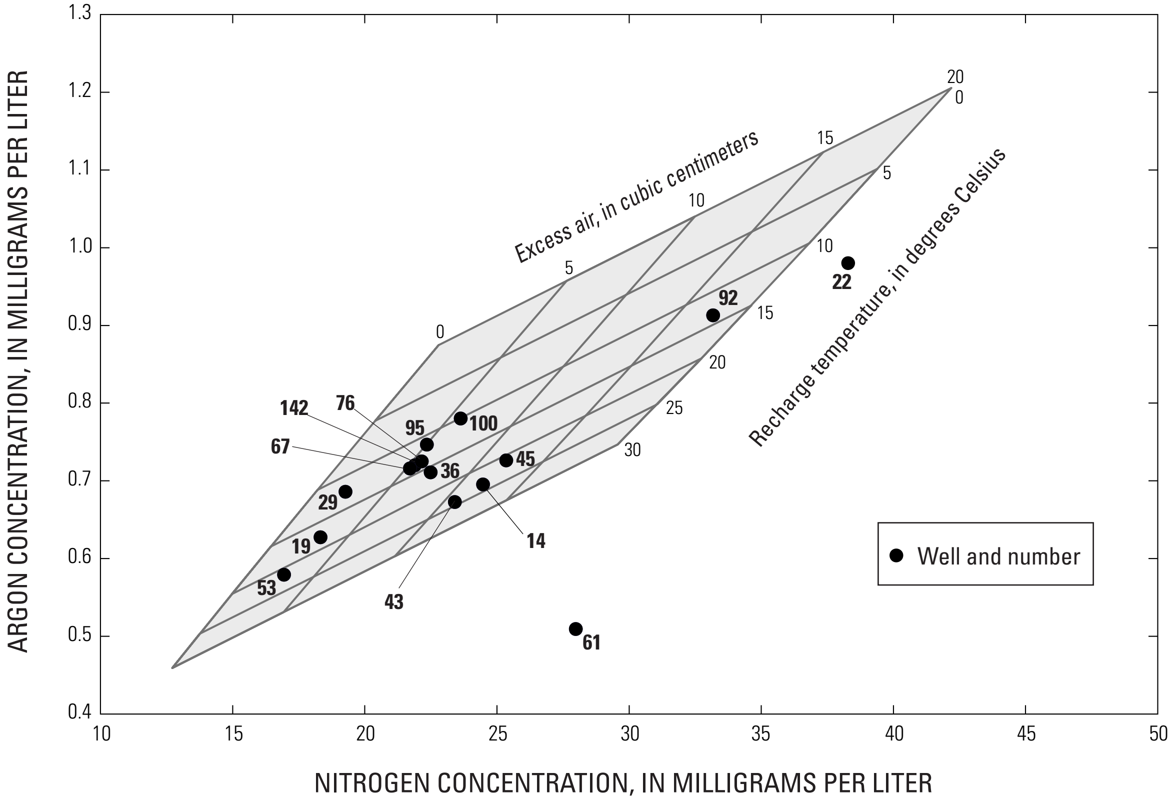


Figure 29. Comparison of argon and nitrogen concentrations in ground-water samples from wells and calculated water temperatures at the time of recharge, lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California.

The $\delta^{18}O$ and δD compositions of ground-water samples collected from wells in the study area generally were similar to the isotopic composition of the samples collected from creeks in spring 2001, ranging from –6.12 to –7.95 per mil for $\delta^{18}O$ and –40.6 to –53.23 per mil for δD (fig. 27B; table 9, at end of report). The isotope samples from wells can be divided into two groups based on where they plot in figure 27E. Group I includes water samples from seven wells having $\delta^{18}O$ and δD greater than –7 and –45 per mil, respectively. The seven wells are distributed throughout the study area: three in ground-water storage unit 1 (19, 36, and 100), one in ground-water storage unit 2 (29), two in ground-water storage unit 3 (45 and 142), and one in ground-water storage unit 4 (76). The water from well 36 had the heaviest isotopic composition of all ground-water samples possibly because of its proximity to Lake Camille, which may be a recharge source. The group I samples generally plot between the samples that are most representative of precipitation that recharges ground water in the Howell Mountains (samples from Leona Lakes, Palmaz spring, Dairy Creek, and Oak Canyon spring) and samples that were affected by evaporation (samples from Murphy and Milliken Creeks and from Lakes Madigan and Lake Frey) (fig. 27E): the samples probably represent mixing of infiltrated precipitation and partly evaporated water in lakes in the Howell Mountains.

Group II consists of water samples from eight wells having $\delta^{18}O$ and δD less than –7 and –47 per mil, respectively; samples are lighter than the group I samples. The eight wells in group II are distributed among three of the four ground-water storage units—three in storage unit 1 (14, 22, and 61), one in storage unit 2 (53), and four in storage unit 3 (43, 67, 92, and 95). Samples from five of the six wells (14, 43, 53, 61, and 95) having the group-II isotopic composition had a group-3 water-chemistry characterized by sodium-chloride type water and high dissolved solids. Water from well 61 had the lightest (most negative) isotopic concentration and the greatest dissolved-solids concentration of any sample. The relatively light isotopic composition of the Group II samples, compared with that of the Group I samples, may be due to a mixture of water in creeks during the winter and water recharged in the Howell Mountains or from a mixture of recent and older recharge due to precipitation during a cooler and wetter climatic period. Over time, the older recharge water could have become mineralized due to water-rock interaction or this older mineralized water may have originated from deeper ground water, possibly including geothermal sources.

Ground-Water Age Dating

Water samples were collected from 15 wells and analyzed for dissolved gases and chlorofluorocarbons (CFCs). Six of those wells also were sampled for tritium (^3H), the radioactive isotope of hydrogen. Concentrations of CFCs and tritium can provide information on the ages of the water samples, which can be used to infer rates of ground-water flow. Ground-water age, when based on measurements of the concentrations of a chemical or isotope, refers to the time elapsed since the water containing the chemical or isotope was recharged and isolated from the atmosphere. Age dating ground water requires matching the concentrations of a chemical or isotope in the water to the historical atmospheric concentrations of the substances. Historical atmospheric concentrations of both CFCs and tritium are well documented (Plummer and Busenberg, 2000). Concentrations of dissolved gases were used to interpret the results of CFC analyses by providing data to estimate recharge temperatures, quantities of excess air, and redox conditions.

Chlorofluorocarbons

Chlorofluorocarbons CFC-11 ($CFCl_3$), CFC-12 (CF_2Cl_2), and CFC-113 ($C_2F_3Cl_3$) are stable synthetic organic compounds that were first produced in the 1930s for use as refrigerants, aerosol propellants, cleaning agents, solvents, and blowing agents for foam rubber and plastics (Busenberg and Plummer, 1992). CFCs provide excellent tracers and dating tools for modern water (0- to 50-year time scale). The analytical detection limit of CFC-12, CFC-11, and CFC-113 in water is about 0.3 picogram per kilogram (pg/kg) of water, corresponding to water recharged in approximately 1941, 1947, and 1955, respectively. Atmospheric CFC concentrations have increased steadily over time with CFC-11 and CFC-113 peaking in North America during the early 1990s (Niwot Ridge, Colorado) at values of about 275 and 85 parts per trillion by volume (pptv), respectively (fig. 28) (Plummer and Busenberg, 2000). CFC-12 may have reached its peak concentration in North America within the last several years (prior to 2002) at about 545 pptv. Once in the atmosphere, CFCs undergo equilibrium partitioning with water vapor and become incorporated into the hydrologic cycle through precipitation.

The accuracy of CFC-determined ground-water ages can be limited by chemical and physical processes including CFC exchange between recharge water and the atmosphere, degradation and sorption during transit along ground-water flow paths, and ground-water mixing (Plummer and Busenberg, 2000). Local point-source CFC contamination, for example from septic tanks or leaking sewer lines, also may affect the accuracy of CFC-determined ages. Environmental contamination usually is indicated by large differences between CFC-11, CFC-12, and CFC-113 concentrations or CFC concentrations that are greater than that possible for atmospheric concentrations. If CFC contamination occurs, CFC-determined ages will be interpreted as younger than the actual ages. Young-age bias of CFC-determined ages also can result if the recharge temperature and (or) recharge elevation are overestimated and if excess air (air entrapped in recharge water and transported into the saturated zone) is not accounted for in the age interpretation (Plummer and Busenberg, 2000). In contrast, CFC-determined ages will be interpreted as older in water from geologic formations that have thick unsaturated zones (greater than about 100 ft) because air in deep unsaturated zones tends to be older and therefore has lower CFC concentrations than the present-day atmosphere. Old-age bias of CFC-determined ages also can result from underestimation of the recharge temperature and (or) the recharge elevation, as well as from microbial degradation, particularly in anaerobic (oxygen-poor), sulfate-reducing, or methane rich environments (Plummer and Busenberg, 2000). Because of the difficulty in accounting for all of the physical and chemical processes that affect the concentrations of CFCs in ground water, age is usually referred to as "model" or "apparent" age.

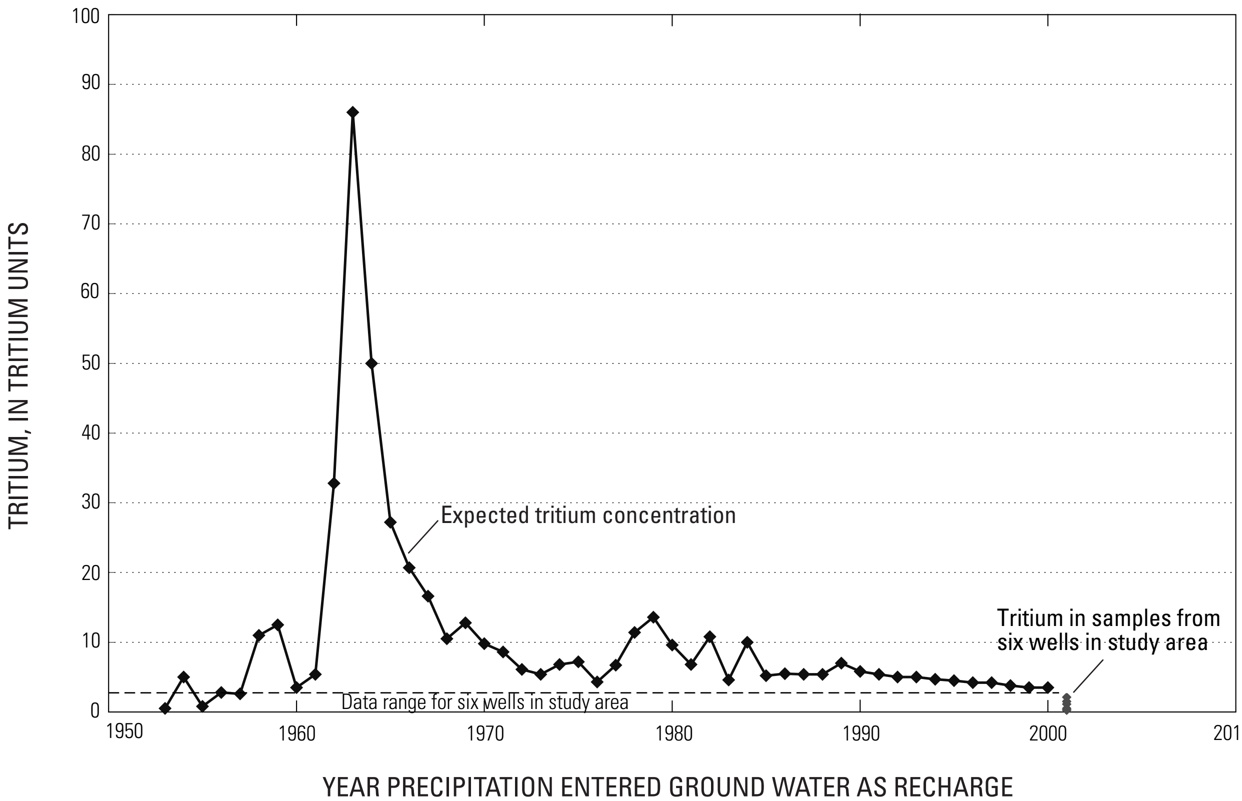


Figure 30. Tritium concentrations in samples from six wells and tritium concentrations expected in ground water in southeastern Napa County, California, that originated as precipitation between 1953 and 2000, southeastern Napa County, California.

Calculation of CFC-model ages requires estimating water temperature at the time of recharge and determining the amount of excess air in samples. The water temperature at the time of recharge is needed because the solubility of gases varies as a function of temperature and atmospheric partial pressures (Busenberg and Plummer, 1992). Excess air is important because high concentrations, common in fractured rock aquifers, may result in calculated CFC ages younger than actual ages if not taken into account (Busenberg and Plummer, 1992). Water temperature at the time of recharge can be estimated from ratios of nitrogen (N_2) and argon (Ar) corrected for excess air. Calculated recharge temperatures, based on nitrogen and argon-gas analyses of samples from 15 wells in the study area, range from 10.2 to 90.7 degrees Celsius (°C) (fig. 29; table 10, at end of report). The high recharge temperature (90.7°C), combined with a high excess air value of almost 25 cubic centimeters per liter (cm^3/L) of solution in the sample from well 61 is attributable to degassing, specifically the loss of nitrogen and argon, from ground water in the presence of high methane (14.7 mg/L) and low oxygen (less than 0.1 mg/L) concentrations. Excluding the sample from well 61, the mean recharge temperature for the remaining 14 well samples is 15.7°C. This value agrees well with the 30-year (1961–90) average air temperature for the Napa area of 14.7°C (National Oceanic and Atmospheric Administration, 2002).

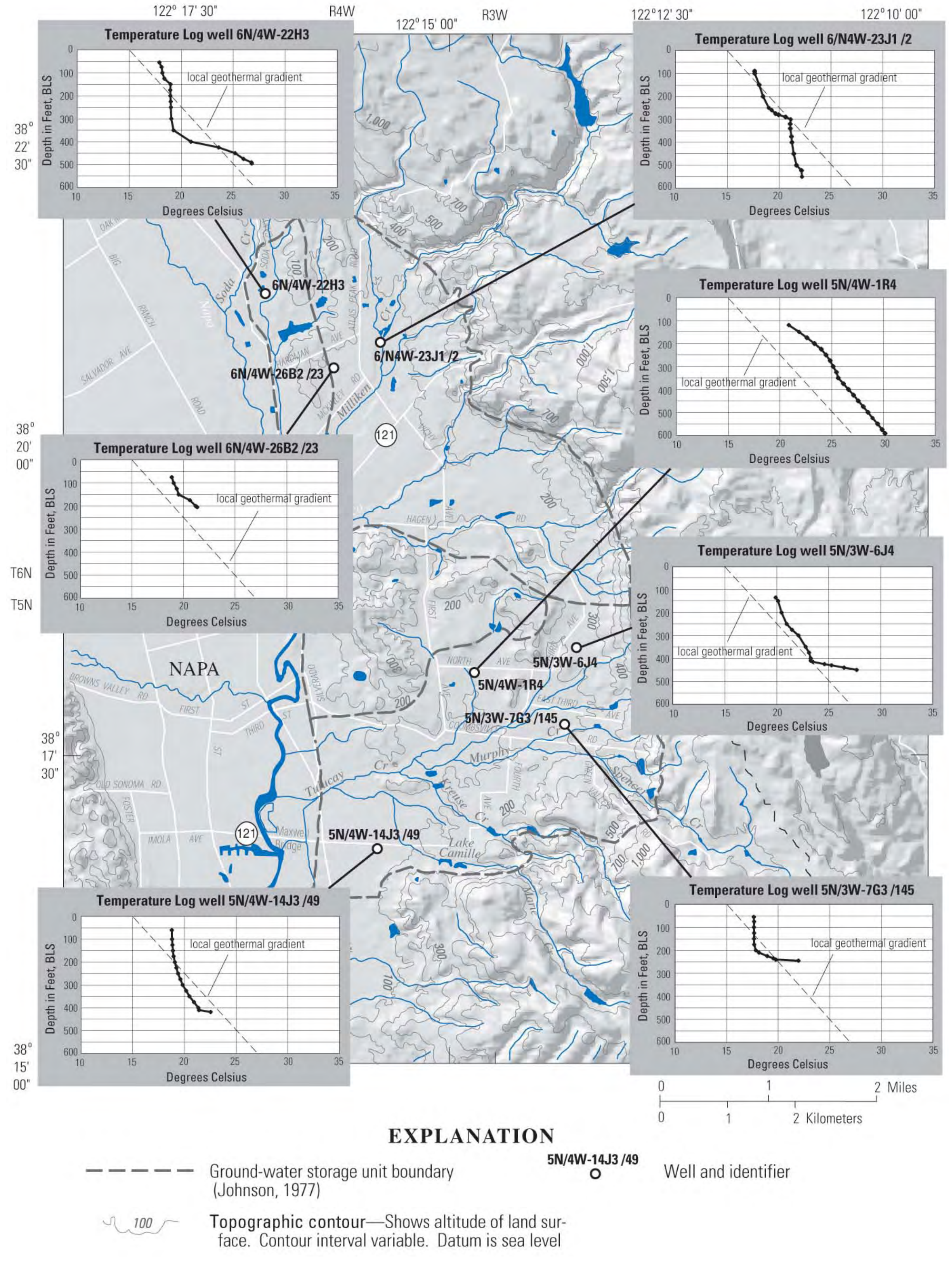


Figure 31. Temperature logs for selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California. (bls, below land surface)

Table 10 (at end of report) contains ranges of recharge dates and CFC-model ages. The ages are the median ground-water ages that represent the differences between the midpoints of the recharge ranges and 2001, the year of sample collection. The ages correspond to recharge in the 1950s through the 1980s for all well samples. The samples representing the youngest waters, based on CFC-model ages, are from wells 29 and 53 located in ground-water storage unit 2; water from these wells have median ages of 21 and 15 years, respectively. Three of four water samples representing median ages between 25 and 35 years old are from wells located near creeks in ground-water storage units 3 and 4 (wells 45, 76, and 92). The younger age of these samples may be due to infiltration of modern surface water. Most of the samples (nine) have median ages between 40 and 50 years, including the samples from five of six wells in ground-water storage unit 1 (14, 19, 36, 61, and 100). The CFC-model ages for the samples from the shallow and the deep wells are similar, supporting the conclusion that most recharge originates in the hills on the east side of the study area and flows laterally into shallow and deeper permeable layers (fig. 9). Strong vertical mixing of ground water or small contributions of water from wells from depths below 350 ft may explain the lack of clear age differences between the deep and the shallow wells. The young age dates for the samples from wells 29 and 53, both of which are in storage unit 2, suggest that the hills underlain by tuff in the Cup and Saucer area may be a catchment area for some local recharge.

Age dates based on CFC concentrations should be used with caution due to the possibility of local contamination of ground water by CFCs or of modification of CFC concentrations in the aquifer by geochemical, biological, or hydrologic processes (Busenberg and Plummer, 1992). Samples from only seven wells (14, 36, 43, 61, 67, 95, and 100) had fairly consistent age dates (varying by 10 years or less) for all three CFC compounds and for the three samples from each well. The median age dates of the samples from these seven wells are between 1951 and 1961, but comments from the USGS CFC Laboratory caution that the samples from wells 14, 36, 61, and 100, as wells as the samples from wells 45, 76, and 142, may have degraded, degassed, or been contaminated by local sources of CFCs. For example, the age date of the sample from well 61 may be older than its actual age because of CFC losses caused by degassing and (or) chemical degradation under reducing conditions. Another example is the age date of the samples from well 76, which contained CFC-12 in concentrations greatly exceeding the historical atmospheric concentrations of this compound; this suggests possible contamination from a local source.

Tritium

Tritium (^3H) is the radioactive isotope of hydrogen; it has a half-life of 12.43 years. Tritium, because of its short half-life, is useful for determining the age of water that generally is less than 50 years old. Tritium activity is measured in disintegrations per unit of time and is commonly reported in tritium units (TU); each tritium unit equals one ^3H atom in 10^{18} atoms of hydrogen. Approximately 800 kg of ^3H were released as a result of atmospheric testing of nuclear weapons during 1952–62 (Michel, 1976). As a result, ^3H concentrations in precipitation and in ground water recharged during that time increased. Because ^3H is part of the water molecule and its concentration is not affected significantly by reactions other than radioactive decay, ^3H is an excellent tracer of the movement of water on time scales ranging from 0 to 50 years before present (2002).

Tritium can be used alone to determine the age of water, but in some cases this yields a non-unique value. A specific age can be determined if the amounts of ^3H and its radiogenic daughter, helium (^3He), are quantified (Clark and Fritz, 1997). Samples were collected from six wells with the intention of using the tritium-helium method to determine recent ground-water ages. However, results from analysis of dissolved helium (table 11, at end of report) indicated that this method may not yield reliable tritium-based ages because of the presence of helium [derived from the Earth's crust and mantle (terrigenic helium)] that greatly exceeded concentrations derived from thermonuclear tritium. Elevated He concentrations and $^3He/^4He$ ratios are common in some areas underlain by volcanic rocks or near fault zones; therefore, six samples were analyzed for tritium alone to provide qualitative estimates of recent ground-water ages.

Tritium concentrations expected in ground water in the Napa area, the source of which was precipitation between 1953 and 2000, are shown in figure 30. These expected concentrations were calculated by determining the radioactive decay of tritium between the time that the precipitation fell and the time that the ground water was sampled. Historical tritium concentrations were based on measured concentrations at several stations in North America and correlations with tritium concentrations in precipitation at Ottawa, Canada, and Vienna, Austria (Robert Michel, U.S. Geological Survey, written commun., 2002). Given a half-life of 12.43 years, ground-water samples collected in 2001 should have tritium levels of 0.6 TU if they were recharged entirely in 1952. A more recent recharge date (after 1952) would yield higher tritium levels; whereas, an older recharge date would yield lower levels (less than 0.6 TU). For this study, ground water that had ^3H concentrations less than the detection limit of 0.3 TU was interpreted as water recharged prior to 1952; ground water that had detectable levels ^3H was interpreted as water recharged after 1952.

Concentrations of tritium ranged from 0.25 to 2.12 TU in six of the ground-water samples (table 10). The concentrations in these samples are consistent with that for water recharged prior to 1956 (fig. 30), assuming the sampled waters are not mixtures of waters of two or more ages. Tritium concentrations ranged from 0.25 to 0.50 TU in samples collected from three shallow wells (22, 36, and 95), all less than 200 ft deep. Tritium concentrations ranged from 1.12 to 2.12 TU for three deeper wells (29, 76, and 142), all greater than or equal to 350 ft in depth. The three shallow wells are perforated in fractured volcanic rocks and volcanic tuff. The low concentrations of tritium in water from these three wells may indicate that the water is relatively old and unmixed compared with water from the three deep wells, possibly owing to longer travel paths or slow movement through geologic units having low hydraulic conductivity. The higher concentrations of tritium in the three deep wells may be the result of the mixing of younger ground water with older ground water. The deep wells have long perforated sections in volcanic sediments or alluvium. Wells 76 and 142 are located less than 0.25 mi from creeks, and well 29 is located in an area that may receive local runoff from surrounding hills, which may be the sources of the recent recharge to these wells. Tritium ages for water from wells 36, 95, and 142 are in fair to good agreement with the CFC-model ages of the early 1960s or earlier.

Water Temperature

Ground-water temperatures were measured at the land surface in water samples pumped from 15 wells; water-temperature logs were made from the water surface to the bottom of 11 other wells. The sample temperature measurements were made after several minutes of pumping, when temperatures were stable and measurements were within 0.5°C. The temperature logs were made using a precision thermistor suspended on a calibrated 4-conductor cable. The number and spacing of measurements were chosen on the basis of the total depth of the water-filled section of the well and the rate of temperature change with depth. Resistance at discrete depths was recorded after the thermistor output stabilized. The recorded resistance was converted to temperature using a polynomial calibration curve. This system provides temperature measurements accurate to 0.1°C.

The temperatures ranged from 17.5 to 27.0°C in the samples pumped from wells that ranged from 93 to 500 ft in depth. The maximum temperatures in the 11 wells that were logged ranged from 18.5 to 30.5°C. The temperature logs are for depths ranging from 68 to 592 ft; in all cases, the maximum temperature was recorded at the bottom depths. Temperature logs for seven wells are shown in figure 31. Temperature logs are not shown for the remaining four logged wells because they had short water-filled sections that had less than 3°C of temperature variation.

The occurrence of warm ground water in some areas of Napa County has been known since the 1800s. Kunkel and Upson (1960) cite ground-water temperatures of as much as 60°C in wells completed in the Sonoma Volcanics northwest of the study area. The mean annual air temperature is about 14.7°C. Shallow ground water typically has a temperature close to the mean annual air temperature. Ground-water temperatures rise with depth owing to the prevailing geothermal gradient. Todd (1980) cites an average geothermal gradient of 1°C per 100 ft. On the basis of a linear best-fit correlation of temperature as related to depth, the geothermal gradient in the study area is about 2°C per 100 ft from a base temperature of about 16°C. The local geothermal gradient is approximately twice the average for continental temperate zones worldwide.

All the wells having depths greater than 400 ft had water temperatures higher than 22°C. For the 22 sites for which well depths and water temperatures were available, the estimated temperatures for depths of 500 ft below land surface, based on the bottom-hole temperature and a gradient of 0.02°C per foot, ranged from 22 to 29°C. Nineteen of the 22 sites have estimated temperatures greater than or equal to 25°C. The temperatures for the three sites that had lower temperatures ranged from 22 to 24°C. The temperatures at two of these three sites, which are located in the northern part of study area, probably are cooled by recharge from nearby perennial streams. Although the estimated temperatures at depths of 500 ft below land surface are fairly uniform throughout the study area, the highest temperatures (27–29°C) were from wells in the southern half of the study area, primarily in the northern and eastern parts of storage unit 1. The area that had the highest temperatures has diatomaceous sediments at the surface. The diatomaceous sediments have low permeability and restrict vertical flow. The lack of recharge may be a contributing factor to the high ground-water temperatures.

In many areas, ground water having elevated temperatures correlates with poor water quality. This is because the solubility of most common minerals increases with temperature. Thermal waters often contain trace elements such as arsenic, fluoride, and boron in concentrations that exceed drinking-water standards (Hem, 1985). No strong correlation between water chemistry and temperature was evident for the 15 wells sampled in the study area.

The deepest well sampled for water quality is 500 ft deep and is screened in shallow formations. Water in deep wells that were not sampled may be 30°C or higher and the chemical quality may be diminished. The uniformly high water temperatures at depth in the study area could place a depth limitation on high quality ground water and limit the total amount of useable ground water in storage.

Temperature logs for wells 5N/3W-7G3, 5N/4W-14J3, 6N/4W-22H3, and 6N/4W-23J1 show isothermal or near isothermal sections over lengths of 100 to 200 ft. These isothermal sections are likely caused by lateral ground-water flow that masks the conductive temperature gradient. The isothermal sections in wells 6N/4W-22H3 and 23J1, which are in the northern part of the study area, are from 150 to 350 ft and 300 to 500 ft, respectively. The isothermal sections in wells 5N/3W-7G3 and 5N/4W-14J3, which are in the southern part of the study area, are shallower (between depths of 50 to 200 ft). The differences in the depths of the isothermal sections may be due to differences in the depths of the geologic units that have the highest hydraulic conductivity; thicker and deeper in the northern part and thinner and shallower in the southern part. All four logs are consistent with a conceptual model of ground-water flow depicting recharge in the Howell Mountains, downward percolation of recharge water to permeable zones, and lateral flow away from the mountain front toward the Napa River (fig. 9).

SUMMARY AND CONCLUSIONS

The entire study area is underlain by the Sonoma Volcanics, a geologic formation consisting of a complex sequence of volcanic rocks and volcanic sedimentary units. The volcanic rocks are covered in places by thin clastic sedimentary formations. In general, the geologic units have low hydraulic conductivity, which inhibits recharge and limits well yields. Lithologic variations in the study area affect well productivity and water quality. Areas underlain by hard rock formations at shallow depths are more likely to have low well yields and to be more adversely affected by declining water levels (common in storage units 1, 2, and 3) than areas underlain by thick unconsolidated materials (typical in storage unit 4).

The predominant source of local recharge to the ground-water system is precipitation falling within the Milliken, Sarco, and Tulucay Creeks drainage basins; however, a small amount of the recharge may be from infiltration of water piped into the area from sources external to the drainage basins and from local sources including septic tank leakage. The principal source of ground-water replenishment to the study area is lateral flow of ground water that is recharged in the Howell Mountains to the east of the study area. Additional ground water enters the study area by inflow through the permeable alluvium along parts of the northwestern boundary of the study area. The amount of inflow varies depending on the local distribution of hydraulic heads. In 2000, ground-water outflow across the western boundary exceeded inflow by an estimated 600 acre-ft/yr. Precipitation over the entire Milliken, Sarco, and Tulucay Creeks drainage basins totals an estimated 69,000 acre-ft/yr. Nearly half of this amount (29,000 acre-ft/yr) flows out of the study area as surface-water discharge to the Napa River. Evapotranspiration from the drainage basins is estimated to be about 34,000 acre-ft/yr. This leaves 6,000 acre-ft/yr residual, but because of the uncertainity in estimates of precipitation, runoff, and evapotranspiration, this value is not a precise estimate of potential ground-water recharge and should not be construed as the safe yield for the study area.

Population and agricultural irrigation have increased substantially in the study area since 1975. An estimated 16,500 people lived in the area at the time of the 2000 census, an increase of 21 percent since 1975. About 4,800 people living in the area rely solely on ground water from individual private wells. Vineyards are the predominant use of agricultural land; in 2000, about 2,400 acres were cultivated. Increases in population and in irrigation for grape production in the past few decades have increased water demand. Ground-water pumpage was estimated to be about 3,000 acre-ft/yr in 1975; by 2000, it was about 5,350 acre-ft/yr, an increase of about 80 percent but could be as much as 7,100 acre-ft/yr. Ground-water pumpage for domestic use, improved open-space irrigation, and agriculture was estimated to be about 27, 29, and 43 percent of the total pumpage, respectively.

Ground-water pumping has produced dramatic changes in hydraulic heads within the study area. Under pre-pumping conditions, hydraulic heads probably were highest around the perimeter of the area, and ground water generally flowed westward toward the Napa River from recharge areas in the mountains on the north, east, and south sides. Under present-day conditions, ground-water pumping has reduced hydraulic heads sufficiently to form three large ground-water level depressions within the study area. Under current (2001–2002) conditions, ground water flows from the perimeter predominantly toward the hydraulic depressions. A comparison of maps of hydraulic heads in 1975 and in 2001 showed that water levels increased in much of the western part of the area but declined by 50 to 125 ft in pumping depressions in the central and eastern parts of the study area These two pumping depressions coincide with the areas having the highest density of active or potentially active wells in study area. Water levels declined by 25 to 50 ft in a third pumping depression, which is located in the northwestern part of the study area. Long-term hydrographs for wells in the study area indicate that the greatest rate of decline occurred after the early 1970s and coincides with an increase in the number of wells drilled in the study area. Declining ground-water levels evident over a large part of the Milliken, Sarco, and Tulucay Creeks area is an indication that current (2000–2002) ground-water use exceeds average ground-water replenishment.

The chemical quality of ground water in the study, which was based on the water samples collected from 15 wells, generally is acceptable. The water from some wells, however, contains one or more constituents in excess of the recommended standards for drinking water. Total dissolved solids ranged from 144 to 732 mg/L; water in one sample exceeded the recommended standard of less than 500 mg/L. Arsenic concentrations ranged from less than 2 to 67 µg/L; concentrations in samples from five of the wells exceeded the standard of less than 10 µg/L. Samples from three wells located in the northwestern part of the study area, close to the Soda Creek Fault, had arsenic concentrations greater than 15 µg/L. The source of the arsenic may be ground water that circulates deeply along the fault zone. Samples from two wells located in the southern part of the study area had boron in excess of 1 mg/L. Water in samples from five wells had concentrations of iron that exceed the secondary drinking-water standard of 300 µg/L. Water samples from 12 of the 15 wells contained concentrations of manganese that exceed the secondary drinking-water standard of 50 µg/L. The arsenic, boron, iron, and manganese probably are derived from minerals in the volcanic rocks or from the deeper and older rocks of the Franciscan Complex or Great Valley Sequence.

The observed variations in the chemical composition of ground water are consistent with that shown by the conceptual model of the study area which shows recharge in the Howell Mountains and lateral inflow around the northern, eastern, and southern parts of the study area. As ground water moves into and through the study area it reacts with and dissolves minerals in the rocks and sediments along the flow path, increasing the concentrations of some elements. The samples with the highest concentrations of dissolved solids were from wells in the central part of the study area in and around the Cup and Saucer area. Major ion compositions in samples from storage units 1 and 3 are variable, but the ranges in variation overlap to a considerable degree. This suggests that recharge water to both areas is chemically similar and that similar reactions take place along ground-water flow paths in both areas. The lack of chemical distinctions between water from storage units 1 and 3 is consistent with the hydraulic connections between the two storage units, which behave as one contiguous ground-water reservoir.

The maximum ground-water temperatures measured in 15 samples pumped from wells and from 11 temperature logs ranged from 17.5 to 30.5°C in wells that ranged from 68 to 592 ft deep. The temperature gradient for the study area was calculated to be about 0.02°C per foot, approximately double the average for continental United States. The deepest temperature logs suggest that temperatures at depths greater than 600 ft may exceed 30°C in parts of the area. No correlation between temperature and chemical composition is apparent for the 15 ground-water samples; but as a general principal, the solubilities of inorganic compounds increase with increasing temperatures, except for bicarbonate. On the basis of this general principal, ground water at depths greater than 600 ft in parts of the study area may contain objectionable concentrations of some constituents. Abnormally high water temperatures may limit the use of ground water in some parts of the study area.

Ratios of the stable isotopes of hydrogen and oxygen showed a greater range in the surface-water samples than in the ground-water samples; this is because the surface-water samples were affected by evaporation, which concentrates the heavier isotopes. Samples from lakes, ponds, and Milliken Creek (downstream from Milliken Reservoir) collected during the warmest and driest part of the year had the heaviest isotopic ratios because of evaporation. Most of the other surface-water samples, including those from unregulated creeks and springs, plot along or close to the global meteoric water line. The isotopic ratios of the ground-water samples plot in two distinct groups (I and II) along the global meteoric water line. Samples in group I plot between the slightly lighter samples from springs and the slightly heavier samples from Milliken Creek. The waters in group I samples probably are mixtures of precipitation that infiltrated in the Howell Mountains and infiltrated surface water affected by evaporation. The group II samples are lighter than the group I samples and probably were mixtures of precipitation that infiltrated in the Howell Mountains and winter streamflow or water that was recharged during an earlier time when climatic conditions were cooler than at present. Most of the group II samples came from wells that also produced water with higher dissolved-solids concentrations than the wells in group I. The higher dissolved-solids concentrations are an indication that these waters have been in the ground-water system longer than waters with lower dissolved-solids concentrations.

Ground-water ages based on chloroflurocarbon and tritium analyses ranged from 15 to about 50 years before present (2002). These ages, especially the CFC-determined ages, should be used with caution because the actual ages may have been overestimated or underestimated because of difficulties in accounting for all the geochemical, biological, and hydrologic processes. Samples for age dating probably were mixtures of waters of different ages because most of the wells available for sampling for this study were constructed with gravel packs and long screens open to the geologic formation. The presence of tritium and CFCs in water from the study area is evidence that modern recharge (post 1950) does take place.

The results of this study indicate that ground water is being depleted under current pumping and recharge conditions. To achieve a hydrologic balance that stops ground-water level declines, it would be necessary to supply additional water to the area or to decrease the amount of ground-water withdrawn. If ground-water levels continue to decline, especially near the western boundary of the area, additional ground water may flow into the area from the main part of Napa Valley. However, increasing ground-water inflow from the west probably would reduce future water-level declines in the study area but would not increase heads in the main pumping depressions along Hagen Road and in the Coombsville area.

The area of this current (2002) study was subdivided by Johnson (1977) into four ground-water storage units on the basis of topography and geology. Results of this current study found evidence that storage units 1 and 3 are not hydraulically separate. The low hydraulic conductivity of most of the geologic units in the study area greatly restrict the feasibility of artificial recharge through wells or from surface retention facilities. Encouraging reductions in ground-water pumping by supplying imported water or reclaimed water to users in and near the pumping depressions might hold the greatest promise of reducing or reversing ground-water level declines. Small improvements to the hydrologic balance may be made by increasing recharge along streams by building a number of retention dams, directing water from agricultural subdrains to infiltration ponds rather than to storm drains or streams, or increasing the use of best-management practices for irrigation of agricultural lands.

Hydrologic monitoring cannot improve the water balance of an area, but data from monitoring programs can be used to better understand how a particular hydrologic system functions and to determine changes that take place in the system in response to water-resource use. The long-term records of ground-water levels in the study area were critical for analysis of present-day conditions and changes that have happened over the past few decades. Likewise, land-use, surface-water discharge, and climatological data are critical for understanding the water balance.

Most wells in the study area were constructed with gravel packs and long screens open to the geologic formation to maximize well yield. This type of well construction is not optimal for ground-water monitoring because depth-dependent differences in hydraulic head, water chemistry, and ground-water age cannot be distinguished. Future monitoring of the ground-water system can be improved by using wells perforated at short depth intervals, including the shallow wells (100 to 200 ft); intermediate depth wells (greater than 200 to 400 ft); and deep wells (greater than 400 ft). Because locating existing supply wells with these characteristics may not be possible, it would be necessary to drill new wells specifically for monitoring. The new monitoring wells can be drilled and constructed to tap and isolate different depth zones to provide information on vertical variations in hydraulic head and water quality.

A continuation of the semi-annual water-level measurements in the current (2002) network of about 10 wells may provide enough data to track changes in the ground-water system over periods of a few years. The timing of the annual maximum and minimum water levels in any given year varies depending on the timing and quantity of precipitation and pumping during the antecedent period. Data from the use of continuous water-level monitoring at some wells may help to accurately identify seasonal fluctuations in water levels. To prepare maps of hydraulic heads would require a larger number of monitoring wells. Ground-water level measurements made on a 5-year cycle in a network similar to that used for this and earlier studies (consisting of more than 100 wells) would provide sufficient data for constructing hydraulic-head maps and water-level change maps. These maps could be used to determine the effectiveness of water-conservation programs or of the use of imported water for reducing local ground-water use in parts of the study area.

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TABLES

Table 1. Summary of land-use change in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, 1958–2000

[See figure 2 for distribution of land use in 2000. <, actual value is less than value shown]

Land-use category	Total acreage inventoried				Percent change
	1958	Percent of total	2000	Percent of total	
Urban (residential, commercial, and industrial)	2,252	20	3,567	31	+58
Improved open space (golf course, cemetery)	120	1	391	4	+226
Irrigated agriculture with residential (vineyard)	586	5	2,369	21	+304
Non-irrigated agriculture with residential (grassland, pasture)	1,340	12	388	3	–71
Unimproved open space with residential	7,023	62	4,562	40	–35
Surface water (ponds, lakes)	30	<1	74	<1	+147
Total	11,351	100	11,351	100	

Table 2. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 17–26, 2000

[See figure 10 for station locations. Measurement rating: excellent (less than 2 percent error), good (2 percent to less than 5 percent error), fair (5 to 8 percent error), poor (greater than 8 percent error). ft^3/s, cubic foot per second; acre-ft/d, acre-foot per day; mi, mile; (acre-ft/d)/mi, acre-foot per day per mile. <, actual value is less than value shown; na, not applicable]

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
Milliken Creek Drainage Basin—Silverado Trail tributary								
36	2200 block of Silverado Trail, 0.7 mi north of West Trancas Road (near old gage site 11458120)	< 0.5	< 0.1	estimated	poor	na	na	na
Milliken Creek Drainage Basin—Atlas Peak Road tributary								
30	Atlas Peak Road, 0.6 mi north of Westgate Drive	0.11	0.2	float	poor	na	na	na
29	Atlas Peak Road	0.04	0.1	volumetric	poor	–0.1	0.6	–0.2
Milliken Creek Drainage Basin—Silverado Country Club tributary								
5	East of Hillcrest Drive near Westgate Drive	0.02	< 0.1	float	poor	na	na	na
6A	West of Hillcrest Drive near Westgate Drive	[1] 0.11	[1] 0.2	flume/float	good	na	< 0.1	na
Milliken Creek Drainage Basin—Hillcrest Drive tributary								
3	2100 block Monticello Road	0.00	0.00	observed	na	na	na	na
4	Silverado Country Club, east of Hillcrest Drive, near St. Andrews Drive	0.04	0.1	flume	good	+0.1	0.4	+0.2
Milliken Creek Drainage Basin—Milliken Creek main stem								
31	0.5 mi northeast of Westgate Drive	6.67	13.2	pygmy	fair	na	na	na
32	0.4 mi northeast of Westgate Drive	6.99	13.8	pygmy	fair	+0.6	0.1	+6.0
34	0.2 mi northeast of Westgate Drive	7.07	14.0	pygmy	good	+0.2	0.2	+1.0
33	Westgate Drive bridge	6.76	13.4	pygmy	good	–0.6	0.2	–3.0
38	Altas Peak Road	8.53	16.9	pygmy	fair	+3.5	1.2	+2.9
37	Hedgeside Avenue (old gage site 11458100)	8.19	16.2	pygmy	good	–0.7	0.4	–1.8
35	West Trancas Road bridge	9.15	18.1	pygmy	good	+1.9	1.0	+1.9
Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch, south fork								
24	0.2 mi east of 2200 block Third Avenue	0.05	0.1	estimated	poor	na	na	na
52	2200 Third Avenue	< 0.01	< 0.1	estimated	poor	[2] <–0.1	0.2	[2] <–0.5
25	Unnamed tributary, west of Third Avenue above confluence with Third Avenue branch, south fork	0.05	0.1	estimated	poor	na	na	na
	Below confluence [3]	[4] < 0.06	[4] 0.1	na	na	[2] + 0.1	0.2	[2] +0.5
22A	2400 block Third Avenue	0.01	< 0.1	estimated	poor	[2] <–0.1	0.1	[2] < –1.0

See footnotes at end of table.

Table 2. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 17–26, 2000—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch, middle fork							
23	NW 1/4, Section 5, T5N, R3W	0.00	0.0	observed	na	na	na	na
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch main stem							
51	SE 1/4, Section 31, T6N, R3W	0.02	< 0.1	flume	fair	na	na	na
22B	2400 block Third Avenue	< 0.05	< 0.1	estimated	poor	[2]< +0.1	0.3	[2]< +0.3
22A/22B	Below confluence [5]	[6] < 0.06	[6] 0.1	na	na	[2] +0.1	na	na
26A	Third Avenue and Hagen Road	[7] 0.12	[7] 0.2	flume	good	[2] +0.1	0.5	[2] +0.2
	Sarco Creek Drainage Basin—Hagen Road tributary, Napa Valley Country Club tributary							
55	NW1/4, Section 6, T5N, R3W	0.00	0.0	observed	na	na	na	na
27	Above confluence with Hagen Road tributary main stem	0.05	0.1	flume	fair	+0.1	0.8	+0.1
	Sarco Creek Drainage Basin—Hagen Road tributary main stem							
28A	NE 1/4 Section 31, T6N, R3W	0.06	0.1	flume	fair	na	na	na
26B	East branch Hagen Road tributary	[8] 0.20	[8] 0.4	pygmy/flume [8]	poor/fair	+0.3	0.6	+0.5
26A/26B	Below confluence [9]	[10] 0.32	[10] 0.6	na	na	[2] +0.2	na	na
9	Grange Hall	0.31	0.6	pgymy	poor	[2] 0.0	0.8	[2] 0.0
	Sarco Creek Drainage Basin—La Grande Avenue/Mt. George Avenue tributary, north branch							
8A	SW 1/4 Section 30, T6N, R3W	0.01	< 0.1	estimated	poor	na	na	na
	Sarco Creek Drainage Basin—La Grande Avenue/Mt. George Avenue tributary main stem							
7B	Vichy Avenue bridge	0.18	0.4	flume	poor	na	na	na
	Sarco Creek Drainage Basin - Sarco Creek main stem							
2	SW 1/4 Section 19, T6N, R3W	2.14	4.2	pgymy	good	na	na	na
1	Langley Park	8.00	15.8	estimated	poor	[2] +11.6	0.8	[2] +14.5
7A	Vichy Avenue bridge, east side	2.03	4.0	pgymy	good	[2] –11.8	0.6	[2] –19.7
10	Vichy Avenue bridge, west side	0.90	1.8	pgymy	good	–2.2	na	na
11	Silverado Trail bridge	1.14	2.2	pygmy	poor	+0.4	1.4	+0.3
	Tulucay Creek Drainage Basin–Murphy Creek tributary, Wild Horse Valley Road branch							
14	Wild Horse Valley Road	0.04	0.1	flume	good	na	na	na
15	Mustang Road	0.06	0.1	flume	good	< +0.1	0.6	< +0.1

See footnotes at end of table.

Table 2. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 17–26, 2000—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Tulucay Creek Drainage Basin—Murphy Creek tributary main stem							
16	Mustang Road	0.38	0.8	pygmy	poor	na	na	na
50	Coombsville Road	0.30	0.6	pygmy	fair	–0.2	0.9	–0.2
	Tulucay Creek Drainage Basin—Spencer Creek tributary main stem							
12	SW 1/4, Section 16, T5N, R3W	0.10	0.2	estimated	poor	na	na	na
13	Green Valley Road	0.29	0.6	pygmy	fair	[2] +0.4	1.4	[2] +0.3
	Tulucay Creek Drainage Basin—Third Avenue tributary, west culvert							
20A	Above confluence with Third Avenue tributary main stem	0.04	0.1	flume	good	na	na	na
	Tulucay Creek Drainage Basin—Third Avenue tributary main stem							
18	Kirkland Road	0.05	0.1	estimated	poor	na	na	na
19	East Third Avenue	0.04	0.1	flume	good	[2] 0.0	0.1	[2] 0.0
20B	Above confluence with Third Avenue tributary west culvert	0.04	0.1	flume	good	0.0	0.7	0.0
20A/20B	Below confluence [11]	[12] 0.08	[12] 0.2	na	na	[2] +0.1	na	na
	Tulucay Creek Drainage Basin—Kreuse Creek tributary main stem							
49A	Fourth Avenue	0.01	< 0.1	estimated	poor	na	na	na
48	Los Robles Drive	0.00	0.0	observed	na	[2] <–0.1	0.9	[2] <–0.1
	Tulucay Creek Drainage Basin—Marie Creek tributary, Penny Lane branch							
40	Penny Lane	0.02	< 0.1	flume	fair	na	na	na
44A	Shurtleff Park above confluence with Marie Creek tributary	0.10	0.2	pygmy	poor	+0.1	0.5	+0.2
	Tulucay Creek Drainage Basin—Marie Creek tributary main stem							
46A	SW 1/4, Section 18, T5N, R3W	0.30	0.6	pygmy	poor	na	na	na
42A	Lower Lake Camille, west spillway	0.15	0.3	pygmy	poor	[13] na	na	[13] na
43A	Shurtleff Park above confluence with Penny Lane branch	0.01	< 0.1	estimated	poor	[2] –0.2	0.8	[2] –0.2
44A/43A	Below confluence [14]	[15] 0.11	[15] 0.2	na	na	[2] +0.1	na	na
39	Terrace Drive	0.00	0.0	observed	na	[2] –0.2	0.4	[2] < –0.5

See footnotes at end of table.

Table 2. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 17–26, 2000—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Tulucay Creek Drainage Basin—Tulucay Creek main stem							
17	Fourth Avenue	0.66	1.3	pgymy	good	na	na	na
45	Shurtleff Avenue.	1.04	2.1	pygmy	fair	+0.8	1.4	+0.6
41	Tulucay Creek at Napa (discontinued stream gage 11458350)	2.08	4.1	pygmy	good	+2.0	0.7	+2.9

[1] Summation of two small culverts; (A) main east–west channel from site 5, and (B) secondary north–south culvert parallel to Hillcrest Drive.
[2] Estimated.
[3] Below confluence of unnamed tributary west of Third Avenue and south fork of Third Avenue branch of Hagen Road tributary to Sarco Creek.
[4] Summation of sites 52 and 25 streamflow estimates.
[5] Below confluence of upper and middle forks of Third Avenue branch of Hagen Road tributary to Sarco Creek.
[6] Summation of sites 22A and 22B streamflow measurements/estimates.
7 Average of two streamflow measurements on two separate days (4/21/00 and 4/26/00).
[8] Average of two streamflow measurements on two separate days (4/21/00 and 4/26/00) and two different methods, pygmy and flume, respectively.
[9] Below confluence of main stem of Third Avenue branch of Hagen Road tributary and Hagen Road tributary main stem.
[10] Summation of sites 26A and 26B streamflow measurements/estimates.
[11] Below confluence of Third Avenue tributary main stem and Third Avenue tributary west culvert.
[12] Summation of sites 20A and 20B streamflow measurements.
[13] Not comparable with previous site.
[14] Below confluence of Marie Creek tributary, Penny Lane branch, and Marie Creek tributary main stem.
[15] Summation of sites 44A and 43A streamflow measurements.

Table 3. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, March 13–16, 2001

[See figure 10 for station locations. Measurement rating: excellent (less than 2 percent error), good (2 percent to less than 5 percent error), fair (5 to 8 percent error), poor (greater than 8 percent error). ft^3/s, cubic foot per second; acre-ft/d, acre-foot per day; mi, mile; (acre-ft/d)/mi, acre-foot per day per mile. <, actual value is less than value shown; na, not applicable]

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Milliken Creek Drainage Basin—Silverado Trail tributary							
36	2200 block of Silverado Trail, 0.7 mi north of West Trancas Road (near old gage site 11458120)	0.72	1.4	pygmy	fair	na	na	na
	Milliken Creek Drainage Basin—Atlas Peak Road tributary							
30	Atlas Peak Road, 0.6 mi north of Westgate Drive	0.13	0.3	pygmy	poor	na	na	na
29	Atlas Peak Road	0.30	0.6	pygmy	fair	+0.3	0.6	+0.5
	Milliken Creek Drainage Basin—Silverado Country Club tributary							
5	East of Hillcrest Drive near Westgate Drive	0.02	< 0.1	flume	good	na	na	na
6A	West of Hillcrest Drive near Westgate Drive, main east–west channel	0.03	0.1	flume	good	na	< 0.1	na
6B	West of Hillcrest Drive near Westgate Drive, secondary north–south culvert	0.01	< 0.1	flume	good	na	na	na
6A/6B	Below confluence [1]	[2] 0.04	[2] 0.1	na	na	na	na	na
	Milliken Creek Drainage Basin—Hillcrest Drive tributary							
3	2100 block Monticello Road	0.04	0.1	flume	good	na	na	na
4	Silverado Country Club, east of Hillcrest Drive, near St. Andrews Drive	0.02	< 0.1	flume	good	<–0.1	0.4	< –0.2
	Milliken Creek Drainage Basin—Milliken Creek main stem							
31	0.5 mi northeast of Westgate Drive	46.2	91.5	AA meter	good	na	na	na
32	0.4 mi northeast of Westgate Drive	53.8	106.5	AA meter	good	+15.0	0.1	+150.0
34	0.2 mi northeast of Westgate Drive	44.0	87.1	AA meter	good	–19.4	0.2	–97.0
33	Westgate Drive bridge	51.7	102.4	AA meter	good	+15.3	0.2	+76.5
38	Altas Peak Road	43.4	85.9	AA meter	good	–16.5	1.2	–13.8
64	1100 block Monticello Road	44.6	88.3	AA meter	good	+2.4	0.7	+3.4
35	West Trancas Road bridge	42.5	84.2	AA meter	good	–4.1	0.6	–6.8
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch, south fork							
24	0.2 mi east of 2200 block Third Avenue	0.02	< 0.1	flume	good	na	na	na
52	2200 Third Avenue	0.03	0.1	flume	good	< +0.1	0.2	< +0.5
22A	2400 block Third Avenue	[3] 0.08	[3] 0.2	flume	good	+0.1	0.3	+0.3

See footnotes at end of table.

Table 3. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, March 13–16, 2001—Continued

Station identifier	Station location	Streamflow (ft^3/s)	Streamflow (acre-ft/d)	Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch, middle fork							
23	NW 1/4, Section 5, T5N, R3W	0.03	0.1	flume	good	na	na	na
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch main stem (Dairy Creek)							
51	SE 1/4, Section 31, T6N, R3W	0.07	0.1	flume	good	na	na	na
22B	2400 block Third Avenue	0.15	0.3	flume	good	+0.2	0.3	+0.7
22A/22B	Below confluence [4]	[5] 0.22	[5] 0.4	na	na	[6] +0.1	na	na
26A	Third Avenue and Hagen Road	0.48	1.0	pygmy	poor	+0.6	0.5	+1.2
	Sarco Creek Drainage Basin—Hagen Road tributary, Napa Valley Country Club tributary							
55	NW1/4, Section 6, T5N, R3W	< 0.01	< 0.1	estimated	poor	na	na	na
27	Above confluence with Hagen Road tributary main stem	0.11	0.2	pygmy	poor	+0.1	0.8	+0.1
	Sarco Creek Drainage Basin—Hagen Road tributary main stem							
28B	NW 1/4 Section 31, T6N, R3W	0.46	0.9	pygmy	fair	na	na	na
26B	East branch Hagen Road tributary	0.50	1.0	pygmy	fair	+0.1	0.1	+1.0
26A/26B	Below confluence [7]	[8] 0.98	[8] 1.9	na	na	[6] +0.9	na	na
9	Grange Hall	0.43	0.8	pygmy	poor	[6] –1.1	0.8	[6] –1.4
	Sarco Creek Drainage Basin—La Grande Avenue/Mt. George Avenue tributary, north branch							
8A	SW 1/4 Section 30, T6N, R3W	0.02	< 0.1	flume	good	na	na	na
	Sarco Creek Drainage Basin—La Grande Avenue/Mt. George Avenue tributary main stem							
65	Mt. George Avenue	0.00	0.0	observed	na	na	na	na
	Above confluence [9]	[10] 0.10	[10] 0.2	na	na	[6] +0.2	0.5	[6] +0.4
8B	SE 1/4 Section 25, T6N, R4W	0.12	0.2	flume	good	na	na	na
7B	Vichy Avenue bridge	0.62	1.2	pygmy	fair	+1.0	0.5	+2.0
	Sarco Creek Drainage Basin—Sarco Creek main stem							
2	SW 1/4 Section 19, T6N, R3W	0.83	1.6	pygmy	fair	na	na	na
7A	Vichy Avenue bridge, east side	1.05	2.1	pygmy	fair	+0.5	1.4	+0.4
10	Vichy Avenue bridge, west side	1.49	3.0	pygmy	fair	+0.9	na	na
11	Silverado Trail bridge	2.34	4.6	pygmy	fair	+1.6	1.4	+1.1
	Tulucay Creek Drainage Basin—Murphy Creek tributary, Wild Horse Valley Road branch							
59	NW 1/4 Section 9, T5N, R3W	0.01	< 0.1	flume	fair	na	na	na
14	Wild Horse Valley Road	0.06	0.1	flume	good	+0.1	0.4	+0.2
15	Mustang Road	0.12	0.2	flume	fair	+0.1	0.6	+0.2

See footnotes at end of table.

Table 3. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, March 13–16, 2001—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Tulucay Creek Drainage Basin—Murphy Creek tributary main stem							
16	Mustang Road	0.71	1.4	pygmy	fair	na	na	na
50	Coombsville Road	0.72	1.4	pygmy	fair	0.0	0.9	0.0
	Tulucay Creek Drainage Basin—Spencer Creek tributary main stem							
12	SW 1/4, Section 16, T5N, R3W	0.64	1.3	pygmy	fair	na	na	na
13	Green Valley Road	0.87	1.7	pygmy	fair	+0.4	1.4	+0.3
	Tulucay Creek Drainage Basin—Third Avenue tributary, west culvert							
56	North Avenue	0.12	0.2	flume	good	na	na	na
20A	Above confluence with Third Avenue tributary main stem	0.27	0.5	pygmy	fair	+0.3	0.7	+0.4
	Tulucay Creek Drainage Basin—Third Avenue tributary, middle branch							
57	Country Lane	< 0.01	< 0.1	estimated	poor	na	na	na
	Tulucay Creek Drainage Basin—Third Avenue tributary main stem							
58	4300 block East Third Avenue	0.09	0.2	pygmy	poor	na	na	na
18	Kirkland Road	0.49	1.0	float	fair	+0.8	0.5	+1.6
19	East Third Avenue	0.30	0.6	pygmy	fair	–0.4	0.1	–4.0
20B	Above confluence with Third Avenue tributary west culvert	0.32	0.6	pygmy	good	0.0	0.7	0.0
20A/20B	Below confluence [11]	[12] 0.59	[12] 1.2	na	na	[6] +0.6	na	na
	Tulucay Creek Drainage Basin—Kreuse Creek tributary, south branch							
61	End of Madrone Drive	0.01	< 0.1	flume	good	na	na	na
	Tulucay Creek Drainage Basin—Kreuse Creek tributary main stem							
60	Kreuzer Lane	0.30	0.6	pygmy	poor	na	na	na
49B	Near end of Penny Lane	0.35	0.7	pygmy	poor	+0.1	1.3	+0.1
48	Los Robles Drive	0.33	0.6	pygmy	poor	–0.1	0.4	–0.2
	Tulucay Creek Drainage Basin—Marie Creek tributary, Penny Lane branch							
40	Penny Lane	0.04	0.1	flume	good	na	na	na
44A	Above confluence [13]	[14] 0.88	[14] 1.7	estimated	na	[6] +1.6	0.5	[6] +3.2
	Tulucay Creek Drainage Basin—Marie Creek tributary main stem							
46B	West of 46A in SW 1/4, Section 18, T5N, R3W	1.10	2.2	pygmy	fair	na	na	na
63	SE 1/4 Section 13, T5N, R4W	1.20	2.4	pygmy	fair	+0.2	0.2	+1.0

See footnotes at end of table.

Table 3. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, March 13–16, 2001—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Tulucay Creek Drainage Basin—Marie Creek tributary main stem—Continued							
62	Minor culvert, northwest side of Upper Lake Camille	0.19	0.4	pygmy	poor	[15] na	na	[15] na
42B	Lower Lake Camille, north spillway	0.65	1.3	pygmy	fair	[15] na	na	[15] na
43B	Shurtleff Park at Shetler Avenue	0.00	0.0	observed	na	[15] na	na	[15] na
44B	Shurtleff Park below confluence with Marie Creek tributary, Penny Lane branch	0.88	1.7	pygmy	fair	+1.7	0.5	[15] na
39	Terrace Drive	0.56	1.1	pygmy	poor	–0.6	0.4	–1.5
	Tulucay Creek Drainage Basin—Tulucay Creek main stem							
17	Fourth Avenue	1.93	3.8	pygmy	good	na	na	na
45	Shurtleff Avenue.	4.38	8.7	pygmy	fair	+4.9	1.4	+3.5
41	Tulucay Creek at Napa (discontinued stream gage 11458350)	5.62	11.1	pygmy	fair	+2.4	0.7	+3.4

[1] Below confluence of Silverado Country Club tributary main east–west channel and secondary north–south culvert.
[2] Summation of sites 6A/6B streamflow measurements.
[3] Average of two streamflow measurements at slightly different locations on same day (3/14/01).
[4] Below confluence of upper and middle forks of Third Avenue branch of Hagen Road tributary to Sarco Creek.
[5] Summation of sites 22A and 22B streamflow measurements.
[6] Estimated.
[7] Below confluence of main stem of Third Avenue branch of Hagen Road tributary and Hagen Road tributary main stem.
[8] Summation of sites 26A and 26B streamflow measurements.
[9] Above confluence of La Grande Avenue/Mt. George Avenue tributary, north branch and La Grande Avenue/Mt. George Avenue tributary main stem.
[10] Difference of sites 8B and 8A streamflow measurements.
[11] Below confluence of Third Avenue tributary main stem and Third Avenue tributary west culvert.
[12] Summation of sites 20A and 20B streamflow measurements.
[13] Above confluence of Marie Creek tributary, Penny Lane branch, and Marie Creek tributary main stem.
[14] Difference of sites 44B and 43B streamflow measurements.
[15] Not comparable with previous site.

Table 4. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 10–12, 2001

[See figure 10 for station location. Measurement rating: excellent (less than 2 percent error), good (2 percent to less than 5 percent error), fair (5 to 8 percent error), poor (greater than 8 percent error). ft^3/s, cubic foot per second; acre-ft/d, acre-foot per day; mi, mile; (acre-ft/d)/mi, acre-foot per day per mile. <,

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Milliken Creek Drainage Basin—Silverado Trail tributary							
36	2200 block of Silverado Trail, 0.7 mi north of West Trancas Road (near old gage site 11458120)	0.03	0.1	flume	good	na	na	na
	Milliken Creek Drainage Basin—Atlas Peak Road tributary							
30	Atlas Peak Road, 0.6 mi north of Westgate Drive	0.06	0.1	pygmy	poor	na	na	na
29	Atlas Peak Road	0.00	0.0	observed	na	–0.1	0.6	–0.2
	Milliken Creek Drainage Basin—Silverado Country Club tributary							
5	East of Hillcrest Drive near Westgate Drive	0.00	0.0	observed	na	na	na	na
6A	West of Hillcrest Drive near Westgate Drive, main east–west channel	< 0.01	< 0.1	volumetric	good	na	< 0.1	na
6B	West of Hillcrest Drive near Westgate Drive, secondary north–south culvert	< 0.01	< 0.1	flume	good	na	na	na
6A/6B	Below confluence [1]	[2] < 0.01	[2] < 0.1	na	na	na	na	na
	Milliken Creek Drainage Basin—Hillcrest Drive tributary							
3	2100 block Monticello Road	< 0.01	< 0.1	estimated	poor	na	na	na
4	Silverado Country Club, east of Hillcrest Drive, near St. Andrews Drive	0.00	0.0	observed	na	na	0.4	na
	Milliken Creek Drainage Basin—Milliken Creek main stem							
31	0.5 mi northeast of Westgate Drive	3.40	6.7	pygmy	good	na	na	na
32	0.4 mi northeast of Westgate Drive	2.23	4.4	pygmy	good	–2.3	0.1	–23.0
34	0.2 mi northeast of Westgate Drive	3.36	6.6	pygmy	good	+2.2	0.2	+11.0
33	Westgate Drive bridge	2.40	4.8	pygmy	good	–1.8	0.2	–9.0
38	Altas Peak Road	2.53	5.0	pygmy	fair	+0.2	1.2	+0.2
37	Hedgeside Avenue (old gage site 11458100)	3.13	6.2	pygmy	good	+1.2	0.4	+3.0
64	1100 block Monticello Road	3.12	6.2	pygmy	fair	0.0	0.4	0.0
35	West Trancas Road bridge	3.25	6.4	pygmy	good	+0.2	0.6	+0.3

See footnotes at end of table.

Table 4. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 10–12, 2001—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch, south fork							
24	0.2 mi east of 2200 block Third Avenue	0.00	0.0	observed	na	na	na	na
52	2200 Third Avenue	< 0.01	< 0.1	estimated	poor	[3] < +0.1	0.2	[3] < +0.5
25	Unnamed tributary, west of Third Avenue above confluence with Third Avenue branch, south fork	< 0.01	< 0.1	estimated	poor	na	na	na
	Below confluence [4]	[5] < 0.01	[5] < 0.1	na	na	[3] 0.0	0.2	[3] 0.0
22A	2400 block Third Avenue	[6] < 0.01	< 0.1	flume	good	0.0	0.1	0.0
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch, middle fork							
23	NW 1/4, Section 5, T5N, R3W	0.02	< 0.1	flume	good	na	na	na
	Sarco Creek Drainage Basin—Hagen Road tributary, Third Avenue branch main stem (Dairy Creek)							
51	SE 1/4., Section 31, T6N, R3W	0.02	< 0.1	flume	good	na	na	na
22B	2400 block Third Avenue	[6] 0.02	[6] < 0.1	flume	fair	0.0	0.3	0.0
22A/22B	Below confluence [7]	[8] < 0.03	[8] < 0.1	na	na	[3] < +0.1	na	na
26A	Third Avenue and Hagen Road	0.08	0.2	flume	good	+0.1	0.5	+0.2
	Sarco Creek Drainage Basin—Hagen Road tributary, Napa Valley Country Club tributary							
55	NW1/4, Section 6, T5N, R3W	0.00	0.0	observed	na	na	na	na
27	Above confluence with Hagen Road tributary main stem	0.01	< 0.1	flume	fair	+0.1	0.8	+0.1
	Sarco Creek Drainage Basin—Hagen Road tributary main stem							
28B	NW 1/4 Section 31, T6N, R3W	0.16	0.3	pygmy	fair	na	na	na
26B	East branch Hagen Road tributary	0.15	0.3	flume	good	0.0	0.1	0.0
26A/26B	Below confluence [9]	[10] 0.23	[10] 0.5	na	na	[3] +0.2	na	na
9	Grange Hall	0.09	0.2	pgymy	poor	[3] –0.3	0.8	[3] –0.3
	Sarco Creek Drainage Basin—La Grande Avenue/Mt. George Avenue tributary, north branch							
8A	SW 1/4 Section 30, T6N, R3W	< 0.01	< 0.1	flume	fair	na	na	na
	Sarco Creek Drainage Basin—La Grande Avenue/Mt. George Avenue tributary main stem							
65	Mt. George Avenue	0.00	0.0	observed	na	na	na	na
	Above confluence [11]	[12] 0.00	[12] 0.0	na	na	[3] 0.0	0.5	[3] 0.0
8B	SE 1/4 Section 25, T6N, R4W	< 0.01	< 0.1	flume	poor	na	na	na
7B	Vichy Avenue bridge	[13] 0.08	[13] 0.2	estimated	poor	[3] +0.1	0.5	[3] +0.2

See footnotes at end of table.

Table 4. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 10–12, 2001—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
	Sarco Creek Drainage Basin—Sarco Creek main stem							
2	SW 1/4 Section 19, T6N, R3W	0.25	0.5	pgymy	fair	na	na	na
1	Langley Park	0.18	0.4	pgymy	poor	–0.1	0.8	–0.1
7A	Vichy Avenue bridge, east side	0.08	0.2	pgymy	poor	–0.2	0.6	–0.3
10	Vichy Avenue bridge, west side	0.16	0.3	pgymy	poor	+0.1	na	na
11	Silverado Trail bridge	0.13	0.2	pygmy	poor	–0.1	1.4	–0.1
	Tulucay Creek Drainage Basin—Murphy Creek tributary, Wild Horse Valley Road branch							
59	NW 1/4 Section 9, T5N, R3W	< 0.01	< 0.1	estimated	poor	na	na	na
14	Wild Horse Valley Road	0.01	< 0.1	flume	fair	[3] < +0.1	0.4	[3] < +0.2
15	Mustang Road	0.02	< 0.1	flume	fair	< +0.1	0.6	< +0.2
	Tulucay Creek Drainage Basin—Murphy Creek tributary main stem							
16	Mustang Road	0.19	0.4	flume	poor	na	na	na
50	Coombsville Road	0.13	0.3	flume	good	–0.1	0.9	–0.1
	Tulucay Creek Drainage Basin—Spencer Creek tributary main stem							
12	SW 1/4, Section 16, T5N, R3W	0.00	0.0	observed	na	na	na	na
13	Green Valley Road	0.17	0.3	pygmy	fair	+0.3	1.4	+0.2
	Tulucay Creek Drainage Basin—Third Avenue tributary, west culvert							
56	North Avenue	< 0.01	< 0.1	flume	good	na	na	na
20A	Above confluence with Third Avenue tributary main stem	0.02	< 0.1	flume	good	< +0.1	0.7	< +0.1
	Tulucay Creek Drainage Basin—Third Avenue tributary, middle branch							
57	Country Lane	0.00	0.0	observed	na	na	na	na
	Tulucay Creek Drainage Basin—Third Avenue tributary main stem							
58	4300 block East Third Avenue	0.01	< 0.1	flume	fair	na	na	na
18	Kirkland Road	0.01	< 0.1	volumetric	fair	0.0	0.5	0.0
19	East Third Avenue	0.00	0.0	observed	na	<–0.1	0.1	<–1.0
20B	Above confluence with Third Avenue tributary west culvert	0.06	0.1	flume	good	+0.1	0.7	+0.1
20A/20B	Below confluence [14]	[15] 0.08	[15] 0.2	na	na	+0.1	na	na
	Tulucay Creek Drainage Basin—Kreuse Creek tributary, south branch							
61	End of Madrone Drive	0.00	0.0	observed	na	na	na	na

See footnotes at end of table.

Table 4. Streamflow measurements, gain or loss of streamflow between stations, flow distance between stations, and rate of gain or loss of streamflow between stations at sites along Milliken, Sarco, and Tulucay Creeks and their tributaries, southeastern Napa County, California, April 10–12, 2001—Continued

Station		Streamflow		Measurement method	Measurement rating	Gain (+) or loss (–) of streamflow between stations (acre-ft/d)	Flow distance between stations (mi)	Rate of gain (+) or loss (–) of streamflow between stations [(acre-ft/d)/mi]
Station identifier	Location	(ft^3/s)	(acre-ft/d)					
Tulucay Creek Drainage Basin—Kreuse Creek tributary main stem								
60	Kreuzer Lane	0.03	0.1	flume	good	na	na	na
49B	Near end of Penny Lane	0.00	0.0	observed	na	–0.1	1.3	–0.1
48	Los Robles Drive	0.00	0.0	observed	na	0.0	0.4	0.0
Tulucay Creek Drainage Basin—Marie Creek tributary, Penny Lane branch								
40	Penny Lane	< 0.01	< 0.1	flume	good	na	na	na
44A	Above confluence [16]	[17] 0.05	[17] 0.1	na	na	[3] +0.1	0.5	[3] +0.2
Tulucay Creek Drainage Basin - Marie Creek tributary main stem								
46B	West of 46A in SW 1/4, Section 18, T5N, R3W	0.23	0.5	pygmy	poor	na	na	na
63	SE 1/4 Section 13, T5N, R4W	0.21	0.4	pygmy	poor	–0.1	0.2	–0.5
62	Minor culvert, northwest side of Upper Lake Camille	0.01	< 0.1	estimated	poor	[18] na	na	[18] na
42B	Lower Lake Camille, north spillway	0.02	< 0.1	estimated	poor	[18] na	na	[18] na
43B	Shurtleff Park at Shetler Avenue	< 0.01	< 0.1	estimated	poor	[18] na	na	[18] na
44B	Shurtleff Park below confluence with Marie Creek tributary, Penny Lane branch	0.05	0.1	flume	good	[3]<+0.1	0.5	[18] na
39	Terrace Drive	0.00	0.0	observed	na	–0.1	0.4	–0.2
Tulucay Creek Drainage Basin—Tulucay Creek main stem								
17	Fourth Avenue	0.33	0.6	pgymy	fair	na	na	na
45	Shurtleff Avenue	0.78	1.5	pygmy	fair	+0.9	1.4	+0.6
41	Tulucay Creek at Napa (discontinued stream gage 11458350)	2.81	5.6	pygmy	fair	+4.1	0.7	+5.8

[1] Below confluence of Silverado Country Club tributary main east–west channel and secondary north–south culvert.
[2] Summation of sites 6A/6B streamflow measurements.
[3] Estimated.
[4] Below confluence of unnamed tributary west of Third Avenue and south fork of Third Avenue branch of Hagen Road tributary to Sarco Creek.
[5] Summation of sites 52 and 25 streamflow estimates.
[6] Measured on 4/18/01.
[7] Below confluence of upper and middle forks of Third Avenue branch of Hagen Road tributary to Sarco Creek.
[8] Summation of sites 22A and 22B streamflow measurements.
[9] Below confluence of main stem of Third Avenue branch of Hagen Road tributary and Hagen Road tributary main stem.
[10] Summation of sites 26A and 26B streamflow measurements.
[11] Above confluence of La Grande Avenue/Mt. George Avenue tributary, north branch and La Grande Avenue/Mt. George Avenue tributary main stem.
[12] Difference of sites 8B and 8A streamflow measurements.
[13] Difference of sites 10 and 7A streamflow measurements.
[14] Below confluence of Third Avenue tributary main stem and Third Avenue tributary west culvert.
[15] Summation of sites 20A and 20B streamflow measurements.
[16] Above confluence of Marie Creek tributary, Penny Lane branch and Marie Creek tributary main stem.
[17] Difference of sites 44B and 43B streamflow measurements.
[18] Not comparable with previous site.

Table 5. Construction data and water-level data for April and October of 2000 through 2002 for selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California

[State well No.: See well-numbering diagram in text. See figures 14, 25, and 31 for well locations. USGS (U.S. Geological Survey) identification number consists of latitude, longitude, and sequence number. Depths in feet below land surface; well depth, completed well depth unless otherwise noted. Elevation of land surface in feet above sea level. Altitude, altitude of potentiometric surface in feet above sea level. —, no data]

State well No.	USGS site identification number	Local well number	Well depth	Depth of perforated interval	Elevation of land surface	April 2000 water level		October 2000 water level		April 2001 water level		October 2001 water level		April 2002 water level		October 2002 water level	
						Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude
5N/3W-5M1	381818122133201	10	320	—	259.6	—	—	170.9	88.7	154.4	105.2	186.6	73.0	165.4	94.2	195.8	63.8
5N/3W-6A1[1]	381858122132601	92	368	148–368	357.8	—	—	148.5	209.3	147.9	209.9	158.9	198.9	146.4	211.4	—	—
5N/3W-6B2	381831122140501	91	415	315–415	314.1	—	—	—	—	211.0	103.1	240.8	73.3	223.4	90.7	244.3	69.8
5N/3W-6E1	381841122142801	103	—	—	318.8	—	—	210.7	108.1	206.0	112.8	—	—	—	—	—	—
5N/3W-6E2	381842122142901	104	730	170–730	315.7	190.5	125.2	203.4	112.3	211.1	104.6	210.8	104.9	206.5	109.2	—	—
5N/3W-6J2	381821122134001	110	530	170–530	241.8	—	—	—	—	—	—	170.2	71.6	147.5	94.3	179.1	62.7
5N/3W-6J3	381819122134001	9	215	—	242.3	—	—	126.5	115.8	102.1	140.2	126.7	115.6	112.6	129.7	126.1	116.2
5N/3W-6J4[2]	381820122135101	—	[3]455	260–455	[4]227	—	—	—	—	—	—	—	—	126.5	[5]100	—	—
5N/3W-6K2	381819122135301	6	500	140–500	222.2	117.2	105.0	131.3	90.9	118.3	103.9	149.6	72.6	129.0	93.2	160.4	61.8
5N/3W-6L1	381830122141201	90	380	260–380	299.2	209.9	89.2	215.0	84.2	212.5	86.6	243.0	56.2	227.3	71.8	257.5	41.6
5N/3W-6L2	381824122140801	94	285	165–285	228.6	107.5	121.1	121.2	107.4	105.2	123.4	—	—	107.5	121.1	126.9	101.7
5N/3W-6M3	381820122144001	74	300	100–300	129.4	73.1	56.3	84.8	44.6	71.0	58.4	91.2	38.2	75.4	54.0	95.4	34.0
5N/3W-6N4	381814122142901	63	400	—	130.8	43.4	87.4	90.9	39.9	71.6	59.2	98.3	32.5	91.6	39.2	100.0	30.8
5N/3W-6N5	381807122143401	73	460	200–460	123.5	—	—	—	—	164.5	–41.0	191.9	[5]–68.4	165.7	[5]–42.2	—	—
5N/3W-6N6[1]	381814122143101	61	260	80–260	124.4	69.4	55.0	81.7	42.7	67.0	57.4	89.9	34.5	69.0	55.4	90.5	33.9
5N/3W-6P3	381809122141401	87	185	—	147.6	47.4	100.2	55.7	91.9	38.7	108.9	74.6	73.0	45.6	102.0	85.6	62.0
5N/3W-6P5	381814122141601	140	298	100–298	174.6	—	—	—	—	—	—	107.6	67.0	78.4	96.2	120.2	54.4
5N/3W-6Q1	381812122141201	89	[6]228	24–88	156.8	62.5	94.3	70.0	86.8	51.3	105.5	86.0	70.8	58.0	98.8	97.6	59.2
5N/3W-6Q3	381815122135201	7	350	70–350	279.6	169.3	110.3	169.0	110.6	168.6	111.0	168.8	110.8	—	—	—	—
5N/3W-6Q4	381815122135101	105	175	—	277.8	157.7	120.1	157.7	120.1	156.7	121.1	160.1	117.7	159.0	118.8	162.7	115.1
5N/3W-6Q5	381815122135901	93	397	177–397	195.0	[7]93.5	[7]101.4	100.1	94.8	86.3	108.6	118.5	76.4	93.6	101.4	126.4	68.6
5N/3W-6R1	381817122134901	8	180	—	250.7	128.9	121.8	133.7	117.0	130.5	120.2	141.1	109.6	138.3	112.4	156.9	93.8
5N/3W-6R2	381813122133701	17	400	220–400	255.0	—	—	155.7	99.3	146.5	108.5	173.8	81.2	162.6	92.4	186.7	68.3
5N/3W-6R3	381813122134101	106	207	—	255.3	—	—	111.6	143.6	—	—	129.8	[5]125.5	—	—	136.4	118.9
5N/3W-7B1	381801122140601	117	[6]215	—	143.0	—	—	—	—	[7]48.4	[7]94.6	69.3	73.7	42.0	101.0	82.2	60.8

See footnotes at end of table.

Table 5. Construction data and water-level data for April and October of 2000 through 2002 for selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California—Continued

State well No.	USGS site identification number	Local well number	Well depth	Depth of perforated interval	Elevation of land surface	April 2000 water level		October 2000 water level		April 2001 water level		October 2001 water level		April 2002 water level		October 2002 water level	
						Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude
5N/3W-7B2	381759122140501	118	240	120–240	149.2	—	—	—	—	[7]50.1	[7]99.0	71.2	78.0	44.4	104.8	83.9	65.2
5N/3W-7C3	381744122141901	20	208	130–207	131.6	—	—	62.4	69.2	37.8	93.8	78.3	53.3	—	—	—	—
5N/3W-7C4	381802122142001	85	240	—	137.3	60.1	77.2	71.0	66.3	54.5	82.8	83.0	54.3	58.3	79.0	86.9	50.4
5N/3W-7C5	381804122141501	86	275	—	138.2	61.8	76.4	68.4	69.8	53.6	84.6	87.4	50.8	55.9	82.3	89.5	48.7
5N/3W-7D3	381801122144201	72	245	120–245	133.2	102.3	30.9	110.9	22.3	99.2	34.0	107.3	25.9	104.0	29.2	114.4	18.8
5N/3W-7D4	381753122143901	71	186	—	122.4	—	—	104.4	18.0	—	—	—	—	86.7	35.7	123.3	–0.9
5N/3W-7E4	381744122142801	78	160	—	109.4	—	—	66.8	42.6	51.2	58.2	84.3	25.1	53.6	55.8	86.2	23.2
5N/3W-7E5	381748122143601	70	175	75–175	119.8	[8]83.8	[8]36.0	100.6	19.2	77.4	42.4	[8]112.2	[8]7.6	80.9	39.0	101.7	18.2
5N/3W-7E6	381744122143201	77	110	—	105.3	50.0	55.3	63.6	41.7	46.0	59.3	—	—	52.9	52.4	63.2	42.1
5N/3W-7E7	381746122143301	79	154	30–100	115.4	43.8	71.6	94.5	20.9	69.8	45.6	107.1	8.3	77.1	38.3	—	—
5N/3W-7E8	381744122142701	16	135	—	114.8	34.2	80.6	69.1	45.7	32.9	81.9	83.5	31.3	54.5	60.3	92.3	22.5
5N/3W-7F1	381749122141801	24	—	—	122.6	38.0	84.6	47.7	74.8	33.0	89.6	61.9	60.6	34.4	88.2	69.6	53.0
5N/3W-7F2	381751122142001	84	—	—	129.1	50.9	78.2	55.8	73.3	42.4	86.7	67.6	61.5	43.2	85.9	77.9	51.2
5N/3W-7F3	381748122142401	81	290	50–290	114.9	41.2	73.7	44.4	70.5	28.2	86.7	68.4	46.5	30.8	84.1	79.3	35.6
5N/3W-7F4	381748122142402	82	145	—	115.6	39.9	75.6	42.7	72.8	27.9	87.6	60.1	55.4	29.5	86.0	65.0	50.6
5N/3W-7F5	381749122142501	83	162	—	115.0	41.6	73.4	45.7	69.3	29.7	85.3	63.2	51.8	31.2	83.8	66.2	48.8
5N/3W-7G2[1]	381740122140001	100	228	—	154.6	42.6	112.0	51.2	103.4	34.1	120.5	62.5	92.1	32.8	121.8	65.0	89.6
5N/3W-7G3[2]	381745122135901	145	250	50–250	168.3	—	—	—	—	—	—	77.9	90.4	47.5	120.8	80.1	88.2
5N/3W-7H4	381744122134301	21	355	175–355	203.2	—	—	75.2	128.0	59.4	143.8	90.6	112.6	62.0	141.2	86.8	116.4
5N/3W-7H5	381744122135301	115	—	—	179.9	—	—	—	—	[7]40.5	[7]139.4	—	—	41.2	138.7	64.1	115.8
5N/3W-7L3	381738122142401	114	—	—	120.4	—	—	—	—	—	—	67.0	53.4	21.2	99.2	67.1	53.3
5N/3W-7M4	381732122142801	32	—	—	98.3	12.9	85.4	25.0	73.3	13.8	84.5	28.6	69.7	13.7	84.6	38.0	60.3
5N/3W-7N2	381717122143501	34	150	—	147.5	45.4	102.1	53.7	93.8	46.4	101.1	61.1	86.4	48.4	99.1	67.0	80.5
5N/3W-7N3	381720122143601	33	110	50–110	127.3	29.5	97.8	40.0	87.3	31.5	95.8	45.0	82.3	30.7	96.6	51.8	75.5
5N/3W-7PL6	381719122140801	50	170	70–100	189.2	64.1	125.1	66.2	123.0	65.1	124.1	69.0	120.2	67.0	122.2	70.9	118.3

See footnotes at end of table.

Table 5. Construction data and water-level data for April and October of 2000 through 2002 for selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California—Continued

State well No.	USGS site identification number	Local well number	Well depth	Depth of perforated interval	Elevation of land surface	April 2000 water level		October 2000 water level		April 2001 water level		October 2001 water level		April 2002 water level		October 2002 water level	
						Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude
5N/3W-8E1[1]	381746122133101	22	135	—	254.2	85.6	168.6	93.6	160.6	87.4	166.8	94.0	160.2	87.4	166.8	96.4	157.8
5N/3W-8L2	381735122131401	124	310	—	360.4	—	—	—	—	[7]65.0	[7]295.4	69.1	291.3	60.3	300.1	65.8	294.6
5N/3W-17C2	381700122131201	116	—	—	684.7	—	—	—	—	[7]205.2	[7]479.5	195.7	489.0	[8]204.1	[8]480.6	211.4	473.3
5N/3W-18D1	381712122144101	35	92	—	135.9	29.5	106.4	40.4	95.5	44.3	91.6	50.6	85.3	36.3	99.6	59.0	76.9
5N/4W-1C2	381856122152101	30	200	—	105.0	38.5	66.5	30.6	74.4	29.7	75.3	—	—	29.1	75.9	43.2	61.8
5N/4W-1F2	381831122153001	27	420	260–420	165.4	121.6	43.8	121.2	44.2	118.9	46.5	[8]139.3	[5, 8]26.1	—	—	—	—
5N/4W-1F3[1]	381841122152401	29	350	50–350	131.4	103.5	27.9	113.4	18.0	113.1	18.3	127.2	4.2	119.3	12.1	134.6	–3.2
5N/4W-1J2	381824122145301	12	460	300–460	272.1	—	—	—	—	180.5	91.6	—	—	—	—	—	—
5N/4W-1J3	381827122144701	141	535	115–535	156.8	—	—	—	—	—	—	120.9	35.9	[8]121.7	[8]35.1	[8]141.9	[8]14.8
5N/4W-1K2	381820122151001	59	280	—	218.5	—	—	210.0	8.5	195.2	23.3	—	—	—	—	—	—
5N/4W-1L1	381830122152001	28	400	140–400	149.7	121.9	27.8	134.0	15.8	—	—	—	—	128.5	21.2	—	—
5N/4W-1L2	381831122152401	119	150	50–150	135.8	—	—	—	—	[7]96.2	[7]39.6	102.8	33.0	96.2	39.6	108.4	27.4
5N/4W-1R2	381809122145101	60	117	—	141.7	108.9	32.8	113.5	28.2	108.2	33.5	dry	dry	dry	dry	dry	dry
5N/4W-1R3	381808122145201	144	260	140–260	138.0	—	—	—	—	—	—	117.3	20.7	107.2	30.8	124.7	13.2
5N/4W-1R4[2]	381812122145201	—	[9]595	275–595	[4]150	—	—	—	—	—	—	—	—	113.0	[5]37	—	—
5N/4W-2Q1	381814122161701	113	—	—	83.4	—	—	—	—	26.6	56.8	39.9	43.6	30.8	52.6	39.4	44.0
5N/4W-12B4	381753122151001	48	[6]100	—	101.0	29.7	71.3	35.9	65.1	31.9	69.1	37.7	63.3	32.7	68.3	39.4	61.6
5N/4W-12B5	381755122151001	25	—	—	99.5	27.5	72.0	34.0	65.6	29.6	69.9	35.6	63.9	30.5	69.0	37.2	62.3
5N/4W-12B6	381756122150401	26	155	—	113.3	113.2	0.1	119.7	–6.4	112.9	0.4	115.3	–2.0	103.9	9.4	116.7	–3.4
5N/4W-12G1[1]	381740122150201	14	240	60–240	82.6	23.8	58.8	35.4	47.2	25.9	56.7	42.0	40.6	24.5	58.1	[8]55.1	[8]27.5

See footnotes at end of table.

Table 5. Construction data and water-level data for April and October of 2000 through 2002 for selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California—Continued

State well No.	USGS site identification number	Local well number	Well depth	Depth of perforated interval	Elevation of land surface	April 2000 water level		October 2000 water level		April 2001 water level		October 2001 water level		April 2002 water level		October 2002 water level	
						Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude
5N/4W-12H2	381744122145001	15	[10] —	—	104.3	[8]102.2	[8] 2.1	114.0	–9.7	92.2	12.1	[8]120.9	[8]–16.6	[8]109.3	[8]–5.0	[8]132.6	[8]–28.3
5N/4W-12J2	381738122145701	13	285	—	82.9	43.0	39.9	57.7	25.2	48.5	34.4	68.1	14.8	46.3	36.6	[8]87.3	[8]–4.4
5N/4W-13C1	381709122152101	143	[11] —	—	85.6	—	—	—	—	—	—	48.8	36.8	42.5	43.1	61.8	23.8
5N/4W-13G4	381648122151501	18	210	105–126	120.6	16.1	104.5	19.0	101.6	17.0	103.6	22.8	97.8	17.8	102.8	26.2	94.4
5N/4W-13H1	381700122145001	137	364	—	[4]132	—	—	20.8	111.2	19.0	113.0	—	—	16.8	115.2	—	—
5N/4W-13H3[1]	381649122144901	36	130	70–130	156.6	28.9	127.7	36.7	119.9	33.3	123.3	41.5	115.1	35.3	121.3	46.2	110.4
5N/4W-13J1[1]	381646122145601	19	360	45–360	144.9	21.2	123.7	29.0	115.9	34.8	110.1	41.8	103.1	34.6	110.3	54.2	90.7
5N/4W-14J3[2]	381644122154601	49	[6,12]399	—	84.7	—	—	55.6	29.1	54.8	29.9	57.9	26.8	53.7	31.0	56.3	28.4
6N/3W-30P1	381958122141601	58	—	—	168.0	—	—	186.2	–18.2	103.0	65.0	190.0	–22.0	119.2	48.8	—	—
6N/3W-31D1	381941122143201	65	585	65–565	145.9	193.5	–47.6	205.4	–59.5	178.3	–32.4	217.0	–71.1	184.8	–38.9	231.5	–85.6
6N/3W-31D2	381939122142501	66	555	—	156.3	193.3	–37.0	214.2	–57.9	186.2	–29.9	225.6	–69.3	193.5	–37.2	241.4	–85.1
6N/3W-31F2	381933122141301	68	510	—	161.7	198.3	–36.6	219.1	–57.4	190.9	–29.2	229.9	–68.2	198.2	–36.5	244.9	–83.2
6N/3W-31F3	381925122142101	41	610	—	147.7	190.2	–42.5	205.2	–57.5	177.6	–29.9	216.2	–68.5	196.2	–48.5	221.2	–73.5
6N/3W-31F4[1]	381935122141601	67	486	—	161.8	201.5	–39.6	—	—	189.2	–27.4	232.3	–70.4	196.3	–34.4	245.2	–83.4
6N/3W-31G2	381926122140201	42	382	160–382	165.4	202.3	–36.9	—	—	—	—	234.5	–69.1	203.5	–38.1	—	—
6N/4W-13E1	382204122154501	5	510	80–510	515.0	285.8	229.2	265.2	249.8	284.8	230.2	273.9	[5]241.1	—	—	292.2	222.8
6N/4W-14Q1	382143122160301	4	385	55–315	138.4	99.4	39.0	116.2	22.2	94.9	43.5	126.6	11.8	100.6	37.8	133.7	4.7
6N/4W-15R5[1]	382135122165901	76	395	60–395	94.0	47.2	46.8	66.9	27.1	45.2	48.8	74.4	19.6	42.6	51.4	87.8	6.2
6N/4W-22H3[2]	382114122165801	—	[13]500	120–500	[4]65	—	—	—	—	—	—	—	—	50.6	[5]14	—	—
6N/4W-22R1	382047122170501	75	205	45–205	37.5	—	—	51.5	–14.0	27.3	10.2	51.1	–13.6	31.2	6.3	59.8	–22.3

See footnotes at end of table.

Table 5. Construction data and water-level data for April and October of 2000 through 2002 for selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California—Continued

State well No.	USGS site identification number	Local well number	Well depth	Depth of perforated interval	Elevation of land surface	April 2000 water level		October 2000 water level		April 2001 water level		October 2001 water level		April 2002 water level		October 2002 water level	
						Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude
6N/4W-23B1	382128122161001	3	612	352–612	144.8	46.6	98.2	143.5	1.3	100.7	44.1	155.7	[5]–10.9	109.5	35.3	—	—
6N/4W-23J1[2]	382053122154701	2	700	—	89.6	—	—	99.0	–9.4	80.3	9.3	106.2	–16.6	77.2	12.4	109.2	–19.6
6N/4W-23K3	382103122161301	44	300	60–300	126.4	104.7	21.7	112.9	13.5	107.2	19.2	119.8	6.6	112.8	13.6	125.3	1.1
6N/4W-23Q3[1]	382050122160901	43	310	150–310	100.1	—	—	102.6	–2.5	79.6	20.5	97.1	3.0	81.5	18.6	103.3	–3.2
6N/4W-25E3	382019122153201	99	154	134–154	94.3	47.7	46.6	63.5	30.8	53.0	41.3	70.8	23.5	50.6	43.7	76.5	17.8
6N/4W-25G1	382016122145801	51	175	—	119.7	131.7	–12.0	135.8	–16.1	128.7	–9.0	142.6	–22.9	131.2	–11.5	145.9	–26.2
6N/4W-25G2[1]	382017122145801	142	440	160–440	119.9	—	—	—	—	—	—	142.7	–22.8	133.6	–13.7	145.9	–26.0
6N/4W-25J1	382003122145001	52	360	238–360	129.0	143.9	–14.9	152.7	–23.7	146.4	–17.4	161.9	–32.9	145.3	–16.3	163.2	–34.2
6N/4W-26B2	382035122160601	57	132	—	71.5	58.7	12.8	65.6	5.9	53.9	17.6	73.0	–1.5	57.6	13.9	76.6	–5.1
6N/4W-26B3[2]	382039122161901	23	205	—	71.7	[7]67.0	[7]4.7	73.4	–1.7	62.5	9.2	96.0	–24.3	69.5	2.2	91.8	–20.1
6N/4W-26F2	382022122162601	55	153	—	66.8	63.7	3.1	74.4	–7.6	65.5	1.3	90.0	–23.2	72.7	–5.9	97.2	–30.4
6N/4W-26G1	382035122161101	56	210	30–210	60.1	—	—	66.6	–6.5	[8]60.8	[8]–.7	75.2	–15.1	56.1	4.0	83.2	–23.1
6N/4W-26G2	382021122161401	47	156	—	53.1	—	—	48.0	5.1	34.7	18.4	57.0	–3.9	38.7	14.4	62.0	–8.9
6N/4W-26G3[1]	382018122161301	45	93	—	48.4	29.1	19.3	43.2	5.2	29.1	19.3	53.4	–5.0	33.1	15.3	55.6	–7.2
6N/4W-26L5	382008122162801	122	210	60–150	55.8	—	—	—	—	[7]67.8	[7]–12.0	82.9	–27.2	72.4	–16.6	87.0	–31.2
6N/4W-26R3	381956122155101	102	147	—	77.5	—	—	64.7	12.8	45.4	32.1	62.3	15.2	50.0	27.5	69.2	8.3
6N/4W-27L2[14]	—	—	120	60–120	50	[15]26.0	[15]24.0	[15]37.0	[15]13.0	[15]26.3	[15]23.7	[15]41.9	[15]8.1	[15]24.1	[15]25.9	—	—
6N/4W-27N1	381953122175401	—	141	39–141	50	—	—	39.5	10.5	23.3	26.7	41.7	8.3	20.5	29.5	42.8	7.2
6N/4W-35G5	381929122160701	69	—	—	39.0	8.1	30.9	14.4	24.6	8.2	30.8	14.3	24.7	7.8	31.2	14.1	24.9
6N/4W-35H1	381927122155001	120	297	157–297	68.4	—	—	—	—	47.8	20.6	62.6	5.8	42.2	26.2	62.6	5.8

Table 5. Construction data and water-level data for April and October of 2000 through 2002 for selected wells in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California—Continued

State well No.	USGS site identification number	Local well number	Well depth	Depth of perforated interval	Elevation of land surface	April 2000 water level		October 2000 water level		April 2001 water level		October 2001 water level		April 2002 water level		October 2002 water level	
						Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude	Depth	Altitude
6N/4W-36A1	381947122145401	98	375	240–375	122.2	132.5	–10.3	153.6	–31.4	129.4	–7.2	158.2	–36.0	133.4	–11.2	160.1	–37.9
6N/4W-36B4	381937122150901	96	87	—	105.9	49.5	56.4	50.7	55.2	51.2	54.7	52.2	[5]53.7	50.9	[5]55.0	52.3	53.6
6N/4W-36E1	381927122154001	37	100	—	78.1	38.2	39.9	50.5	27.6	42.8	35.3	55.5	22.6	48.2	29.9	53.8	24.3
6N/4W-36G[1]	381939122150401	95	195	155–185	112.6	—	—	137.8	–25.2	122.5	–9.9	139.2	–26.6	121.8	–9.2	—	—
6N/4W-36H4	381926122144201	40	[6, 16] 485	—	105.0	—	—	191.4	–86.4	152.6	–47.6	189.6	–84.6	156.9	–52.0	—	—
6N/4W-36H6	381935122145501	97	600	100–600	138.2	180.5	–42.2	195.7	–57.4	176.0	–37.8	185.7	–47.4	172.9	–34.6	186.7	–48.4
6N/4W-36J3	381923122145601	38	—	—	87.3	126.8	–39.5	167.6	–80.3	125.9	–38.6	181.4	–94.1	142.0	–54.7	192.2	–104.9
6N/4W-36K2	381910122150101	54	—	—	103.4	—	—	183.1	–79.7	160.6	–57.2	185.1	–81.7	171.4	–68.0	—	—
6N/4W-36P1	381907122152301	31	382	—	128.4	155.5	–27.1	210.0	–81.6	163.7	–35.3	224.3	–95.9	166.3	–37.9	[8]241.8	[8]–113.4
6N/4W-36R1[1]	381905122145601	53	530	30–530	126.2	106.1	20.1	—	—	119.2	7.0	125.3	0.9	103.8	22.4	—	—
6N/4W-36R2	381907122145001	121	[17]≥178	—	154.0	—	—	—	—	[7] 139.1	[7] 14.9	155.8	–1.8	138.3	15.7	169.2	–15.2

[1] Well used for water-chemistry sampling.
[2] Well used for temperature logging.
[3] Well depth remeasured by USGS in April 2002 is approximately 450 feet.
[4] Determined from topographic map with an accuracy of plus or minus 10 feet.
[5] Water-level measurement not included in the contouring (figs. 15 and 16).
[6] Reported drill or hole depth.
[7] Water-level measurement made in mid-May.
[8] Water-level measurement may have been affected by recent or nearby pumping, but if measured in October 2001 or April 2002 was included in the contouring on figures 15 and 16, respectively.
[9] Well depth remeasured by USGS in April 2002 is approximately 590 feet.
[10] Well depth 120 to 130 feet according to owner.
[11] Well depth 250 to 300 feet according to owner.
[12] Well depth remeasured by USGS in April 2002 is approximately 418 feet.
[13] Well depth remeasured by USGS in April 2002 is approximately 520 feet.
[14] Well monitored by the California Department of Water Resources (California Department of Water Resources, accessed August 1, 2002).
[15] Water-level data from California Department of Water Resources (California Department of Water Resources, accessed August 1, 2002).
[16] Well depth approximately 475 feet according to owner.
[17] Well depth at least 178 feet according to owner.

Table 6. Summary of estimated ground-water pumping for domestic and irrigation uses in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, 2000–2002

[Well to parcel ratio based on distribution of identifiable wells amongst identifiable properties. Estimated average yield is approximately 0.45 of reported average yield of all wells with driller's logs; ratio of 0.45 based on the proportion of measured to reported yields for 11 wells included in this study. Assumed average daily use values from Metzger and Fio (1997). Unit applied water is an estimated value of average countywide irrigation water applied during 1980. DWR, California Department of Water Resources. FMMP, California Department of Conservation Farmland Mapping and Monitoring Program. gal/min, gallon per minute; acre-ft/acre, acre-foot per acre. na, not applicable]

Basis of estimate	Well to parcel ratio	Number of parcels	Estimated number of wells	Estimated average pumping rate (gal/min)	Assumed average daily use (hours)	Area (acres)	Unit applied water (acre-ft/acre)	Approximate population (2000 census)	Per capita use (gallon/per person/ day)	Estimated annual pumpage (acre-feet)
Domestic Use (residential use excluding residential mixed with agricultural properties)										
Well and parcel data	[1] 1.1	1,450	1,595	[2] 20	[3] 0.98	na	na	na	na	2,101
Population and water use data	na	na	na	na	na	na	na	[4] 4,800	[5] 148	796
Average										1,448
Irrigation Use—Agriculture (includes agriculture mixed with residential use)										
Well and parcel data	[6] 1.4	132	185	[7] 75	[8] 2.88	na	na	na	na	2,686
FMMP land use and DWR water use coefficient	na	na	na	na	na	[9] 2,369	[10] 1.2	na	na	2,843
FMMP land use and local water use coefficient	na	na	na	na	na	[9] 2,369	[11] 0.5	na	na	1,185
Napa County land use and DWR water use coefficient	na	na	na	na	na	[12] 2,869	[10] 1.2	na	na	3,443
Napa County land use and local water use coefficient	na	na	na	na	na	[12] 2,869	[11] 0.5	na	na	1,435
Minimum										1,185
Maximum										3,443
Average										2,318
Irrigation Use—Improved open space (includes golf courses, cemeteries, and public institutions)										
FMMP land use and DWR water use coefficient	na	na	na	na	na	[9] 391	[13] 4.0	na	na	1,564

[1] Estimated from 643 wells identified on 577 residential properties.

[2] Approximately 0.45 of average reported well yield (48 gal/min) for 589 wells identified on driller's logs as domestic use.

[3] Average daily pumping time for residential wells, from Metzger and Fio (1997).

[4] Estimated population of county portion of study area not served by public supply water.

[5] Average daily per capita water use for the City of Napa Municipal Water Department, 1990–2001 (Alan Aguilar, Department of Water Resources, written commun., 2002; Don Ridenhour,City of Napa, written commun., 2002). In comparison, per capita rate for part of study area outside of city limits estimated to be 156 gallons per person per day based on 2002 water use data from the City of Napa Municipal Water Department (Gil Harrington, City of Napa, written commun., 2002).

[6] Estimated from the identification of 104 wells distributed among 73 agricultural and agriculture mixed with residential properties.

[7] Approximately 0.45 of average reported well yield (168 gal/min) for 93 wells identified on driller's logs as irrigation use.

[8] Average daily pumping time for institutional wells used primarily for landscape irrigation, from Metzger and Fio (1997).

[9] Average determined from FMMP year 2000 land use. See figure 2.

[10] Average amount of water applied per acre for grapes in Napa County in 1980 (California Department of Water Resources, 1986).

[11] Average amount of water applied per acre for grapes in Napa County in 2001 according to local residents (John Stewart, Napa County Department of Public Works, oral commun., 2001).

[12] Acreage determined from Napa County Assessor parcel database (2002).

[13] Average amount of water applied per acre for pasture in Napa County in 1980 (California Department of Water Resources, 1986).

Table 7. Summary of median water-level change in the lower Milliken–Sarco–Tulucay Creeks area, southeastern Napa County, California, 2000–2002

[Median water-level change in feet]

Time period	Storage unit 1		Storage unit 2		Storage unit 3		Storage unit 4		All storage units	
	Number of wells measured	Median	Number of wells measured	Median	Number of wells measured	Median	Number of well measured s	Median	Number of wells measured	Median
October 2000–October 2001	45	–10.4	4	–14.0	31	–7.4	5	–4.9	85	–8.6
October 2001–October 2002	51	–5.9	4	–6.5	27	–5.0	5	–7.2	87	–5.5
Average annual change:	48	–8.2	4	–10.3	29	–6.2	5	–6.1	86	–7.1
April 2000– April 2001	38	0.5	6	–8.9	20	2.0	3	–0.3	67	0.7
April 2001-April 2002	47	–2.3	6	–1.0	30	–4.2	5	2.2	88	–2.6
Average annual change:	43	–0.9	6	–5.0	25	–1.1	4	1.0	78	–1.0
October 2000–April 2001	50	13.6	6	1.6	32	19.0	5	16.2	93	14.1
October 2001–April 2002	60	20.8	7	9.1	34	20.1	6	18.8	107	19.9
Average annual change:	55	17.2	7	5.4	33	19.6	6	17.5	100	17.0

Table 8. Field data and laboratory analyses of samples from streamflow-measurement stations and wells in southeastern Napa County, California, 2001

[State well No.: See well-numbering diagram on page ix. See figure 25 for location of streamflow-measurement stations, lakes and ponds, springs, and wells. USGS (U.S. Geological Survey) identification No. consists of latitude, longitude, and sequence number. Parameter code, in brackets, is a five-digit number in the USGS computerized data system, National Water Information System (NWIS, used to uniquely identify a specific constituent or property. $CaCO_3$, calcium carbonate; mg/L, milligram per liter; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; µg/L, microgram per liter. e, value estimated by the USGS National Water Quality Laboratory, Denver, Colorado; <, actual value is less than value shown; —, no data]

Stream site identifier or State well No. (abbreviated or local identifier)	USGS identification No.	Sample date	Solids, residue on evaporation at 180°C, dissolved (mg/L) [70300]	Solids, sum of constituents, dissolved (mg/L) [70301]	Oxygen, dissolved (mg/L) [00300]	pH, field (standard units) [00400]	Specific conductance, field (µS/am) [00095]	Temperature, water (°C) [00010]
Streamflow-measurement stations								
Murphy Creek (MC)	381739122140001	9-19-01	174	164	8.9	7.3	130	15.0
Dairy Creek (DC)	381909122132701	9-18-01	150	146	8.9	7.4	97	14.5
Site 33 (MCW)	382130122153501	9-20-01	130	128	—	7.1	172	15.5
Site 37 (MCH)	382017122161101	9-20-01	136	133	—	7.2	184	18.0
Wells								
5N/3W-6A1 (92)	381858122132601	9-18-01	194	196	3.5	7.2	124	26.0
5N/3W-6N6 (61)	381814122143101	11-06-01	640	732	<.1	7.8	[1] 1,220	23.0
5N/3W-7G2 (100)	381740122140001	9-19-01	451	435	<.1	6.7	638	19.5
5N/3W-8E1 (22)	381746122133101	9-19-01	282	282	1.3	6.9	356	21.5
5N/4W-1F3 (29)	381841122152401	11-07-01	278	286	3.2	7.4	386	20.5
5N/4W-12G1 (14)	381740122150201	11-06-01	([2])	417	<.1	8.0	564	20.0
5N/4W-13H3 (36)	381649122144901	11-07-01	230	217	2.4	[1] 6.3	255	19.0
5N/4W-13J1 (19)	381646122145601	11-08-01	216	217	.6	7.1	248	23.5
6N/3W-31F4 (67)	381935122141601	9-21-01	218	144	<.1	7.4	265	27.0
6N/4W-15R3 (76)	382135122165901	11-08-01	220	227	1.6	6.7	269	20.0
6N/4W-23Q3 (43)	382050122160901	9-20-01	288	296	.1	7.3	402	21.5
6N/4W-25G2 (142)	382017122145801	9-17-01	256	255	<.1	7.3	260	24.0
6N/4W-26G3 (45)	382018122161301	9-20-01	279	282	.1	7.0	404	17.5
6N/4W-36G1 (95)	381939122150401	9-18-01	324	334	<.1	6.6	310	20.0
6N/4W-36R1 (53)	381905122145601	11-05-01	280	285	6.6	[1] 8.6	428	26.0

See footnotes at end of table.

Table 8. Field data and laboratory analyses of samples from streamflow-measurement stations and wells in southeastern Napa County, California, 2001—Continued

Stream site identifier or State well No. (abbreviated or local identifier)	Sample date	Hardness, total (mg/L as $CaCO_3$) [00900]	Calcium, dissolved (mg/L) [00915]	Magnesium, dissolved (mg/L) [00925]	Potassium, dissolved (mg/L) [00935]	Sodium, dissolved (mg/L) [00930]	Alkalinity, field (mg/L as $CaCO_3$) [39086]	Bicarbonate, field (mg/L) [00453]
Streamflow-measurement stations								
Murphy Creek (MC)	9-19-01	52	11.2	5.75	2.68	15.2	59	72
Dairy Creek (DC)	9-18-01	27	6.02	3.02	3.90	11.7	45	54
Site 33 (MCW)	9-20-01	46	9.47	5.43	2.75	16.7	59	71
Site 37 (MCH)	9-20-01	46	9.53	5.38	3.59	18.5	66	79
Wells								
5N/3W-6A1 (92)	9-18-01	71	16.1	7.36	4.17	24.3	114	138
5N/3W-6N6 (61)	11-06-01	65	19.2	4.1	1.51	247	328	395
5N/3W-7G2 (100)	9-19-01	220	49.5	24.4	4.74	39.3	157	189
5N/3W-8E1 (22)	9-19-01	120	24.8	14.7	3.19	24.2	124	148
5N/4W-1F3 (29)	11-07-01	40	14.1	1.11	.69	72.1	98	118
5N/4W-12G1 (14)	11-06-01	37	11.6	2.06	5.09	109	223	268
5N/4W-13H3 (36)	11-07-01	100	18.4	13.1	1.52	10.6	90	108
5N/4W-13J1 (19)	11-08-01	79	16.7	9.14	1.82	21.9	108	132
6N/3W-31F4 (67)	9-21-01	74	17.7	7.32	4.29	26.9	113	139
6N/4W-15R3 (76)	11-08-01	73	12.9	9.83	6.67	23.3	98	118
6N/4W-23Q3 (43)	9-20-01	70	14.0	8.51	20.4	50.9	192	232
6N/4W-25G2 (142)	9-17-01	76	16.4	8.47	5.63	35.2	115	138
6N/4W-26G3 (45)	9-20-01	110	23.9	12.6	11.8	34.0	163	197
6N/4W-36G1 (95)	9-18-01	52	9.48	6.84	9.25	62.7	110	133
6N/4W-36R1 (53)	11-05-01	10	2.52	.793	1.15	97.7	176	183

Table 8. Field data and laboratory analyses of samples from streamflow-measurement stations and wells in southeastern Napa County, California, 2001—Continued

Stream site identifier or State well No. (abbreviated or local identifier)	Sample date	Chloride, dissolved (mg/L) [00940]	Fluoride, dissolved (mg/L) [00950]	Silica, dissolved (mg/L) [00955]	Sulfate, dissolved (mg/L) [00945]	Nitrogen, ammonia, dissolved (mg/L) [00608]	Nitrite plus nitrate as N, dissolved (mg/L) [00631]	Nitrogen, nitrite, dissolved (mg/L) [00613]
Streamflow-measurement stations								
Murphy Creek (MC)	9-19-01	10.9	<0.2	74.4	7.7	<0.04	e 0.03	<0.006
Dairy Creek (DC)	9-18-01	7.45	.2	85.4	1.0	<.04	.08	<.006
Site 33 (MCW)	9-20-01	12.9	<.2	42.7	2.1	0.04	.09	<.006
Site 37 (MCH)	9-20-01	11.5	e .1	41.7	3.3	<.04	e .03	<.006
Wells								
5N/3W-6A1 (92)	9-18-01	6.18	0.3	65.2	4.3	<0.04	<0.05	e 0.003
5N/3W-6N6 (61)	11-06-01	175	1.5	46.0	30.2	1.47	<.05	<.008
5N/3W-7G2 (100)	9-19-01	67.1	.3	81.7	71.7	.15	<.05	<.006
5N/3W-8E1 (22)	9-19-01	10.2	.3	88.8	41.9	e .04	<.05	e .004
5N/4W-1F3 (29)	11-07-01	16.2	.6	48.6	61.6	<.04	2.90	<.008
5N/4W-12G1 (14)	11-06-01	54.0	.6	56.5	43.9	.53	<.05	<.008
5N/4W-13H3 (36)	11-07-01	10.7	.2	84.5	14.8	<.04	2.09	<.008
5N/4W-13J1 (19)	11-08-01	11.6	.2	86.5	3.4	.05	e .04	<.008
6N/3W-31F4 (67)	9-21-01	11.1	.3	—	7.7	.06	e .02	<.006
6N/4W-15R3 (76)	11-08-01	12.9	.2	81.9	19.7	e .03	<.05	<.008
6N/4W-23Q3 (43)	9-20-01	9.98	e .1	75.4	.6	.24	<.05	<.006
6N/4W-25G2 (142)	9-17-01	16.2	.4	81.4	22.0	.04	<.05	<.006
6N/4W-26G3 (45)	9-20-01	24.1	<.2	71.3	5.5	.24	<.05	<.006
6N/4W-36G1 (95)	9-18-01	15.4	e .1	76.1	80.3	2.57	<.05	<.006
6N/4W-36R1 (53)	9-19-01	15.5	.9	40.8	20.3	.06	<.05	<.008

Table 8. Field data and laboratory analyses of samples from streamflow-measurement stations and wells in southeastern Napa County, California, 2001—Continued

Stream site identifier or State well No. (abbreviated or local identifier)	Sample date	Phosphorus, orthophosphate, dissolved (mg/L) [00671]	Arsenic, dissolved (μg/L) [01000]	Boron, dissolved (μg/L) [01020]	Iron, dissolved (μg/L) [01046]	Lithium, dissolved (μg/L) [01130]	Manganese, dissolved (μg/L) [01056]
Streamflow-measurement stations							
Murphy Creek (MC)	9-19-01	0.15	e 1	20	62	7.4	e 2.9
Dairy Creek (DC)	9-18-01	.17	e 2	20	32	10.5	e 1.9
Site 33 (MCW)	9-20-01	<.02	<2	200	55	13.8	e 2.3
Site 37 (MCH)	9-20-01	e .01	<2	160	59	12.6	8.1
Wells							
5N/3W-6A1 (92)	9-18-01	0.04	2	60	28	43.0	[1] 136
5N/3W-6N6 (61)	11-06-01	.02	<2	[3] 11,000	<10	90.7	[1] 93.0
5N/3W-7G2 (100)	9-19-01	<.02	<2	830	1,710	58.3	[1] 314
5N/3W-8E1 (22)	9-19-01	.04	4	110	[1] 991	43.4	[1] 261
5N/4W-1F3 (29)	11-07-01	.06	[1] 11	230	<10	19.1	<2.0
5N/4W-12G1 (14)	11-06-01	.03	6	[3] 1,440	11	34.6	[1] 54.5
5N/4W-13H3 (36)	11-07-01	.12	[1] 11	e 10	e 7	7.7	5.6
5N/4W-13J1 (19)	11-08-01	.07	3	140	102	97.5	[1] 81.4
6N/3W-31F4 (67)	9-21-01	e .02	e 1	200	18	50.3	[1] 117
6N/4W-15R3 (76)	11-08-01	.17	[1] 17	70	31	51.4	[1] 309
6N/4W-23Q3 (43)	9-20-01	.33	[1] 67	160	12	82.6	[1] 491
6N/4W-25G2 (142)	9-17-01	.04	6	380	[1] 310	51.4	[1] 131
6N/4W-26G3 (45)	9-20-01	.14	[1] 16	200	[1] 462	62.7	[1] 831
6N/4W-36G1 (95)	9-18-01	.62	3	490	[1] 2,290	187	[1] 656
6N/4W-36R1 (53)	9-19-01	.02	4	900	18	36.8	19.9

[1]Value exceeds the maximum contaminant level (MCL) or is outside of the acceptable range for primary or secondary Federal and State drinking-water standards (California Department of Water Resources, 1997; U.S. Environmental Protection Agency, 2002).

[2]Insufficient sample for analysis.

[3]Value exceeds State active level (California Department of Health Services, 2002).

Table 9. Field measurements and oxygen-18 and deuterium ratios in samples from streamflow-measurement stations, lakes and ponds, springs, and wells, southeastern Napa County, California, 2001–02

[See figure 25 for location of streamflow-measurement stations, lakes and ponds, springs, and wells. USGS (U.S. Geological Survey) identification No. consists of latitude, longitude, and sequence number. State well No.: see well-numbering diagram on page ix. Subarea "outside" refers to sites located outside of the Milliken, Sarco, and Tulucay drainage basins. ft^3/s, cubic foot per second; per mil, parts per thousand; µS/cm, microsiemen per centimeter at 25°C; °C, degree Celsius; µg/L, microgram per liter. —, no data]

Station identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Subarea	Sample date	Instaneous streamflow (ft^3/s)	Delta oxygen-18 (per mil)	Delta deuterium (per mil)	Field measurements	
							Specific conductance (µS/cm)	Water temperature (°C)
Streamflow-measurement stations								
Site 12	381644122123001	Tulucay	3-14-01	0.64	–7.61	–50.52	58	16.0
Site 13	381728122133801	Tulucay	3-13-01	.87	–7.39	–48.9	114	13.0
Site 14	381744122123601	Tulucay	3-13-01	.06	–7.58	–49.9	81	12.0
Site 16	381739122131101	Tulucay	3-13-01	.71	–7.29	–46.59	110	12.5
Site 17	381730122143101	Tulucay	3-14-01	1.93	–7.29	–49.55	155	11.0
Site 20A	381745122143401	Tulucay	3-14-01	.27	–6.93	–48.12	470	16.0
Site 20B	381745122143402	Tulucay	3-14-01	.32	–7.07	–48.03	242	13.0
Site 41	381709122163301	Tulucay	3-13-01	5.62	–6.87	–46.98	264	11.5
			4-10-01	2.81	–6.25	–43.36	306	11.5
Site 42B	381639122151001	Tulucay	3-13-01	.65	–6.61	–45.17	120	15.0
Site 45	381723122155501	Tulucay	3-13-01	4.38	–7.00	–47.63	270	12.0
			4-10-01	.78	–6.30	–43.7	337	11.0
Site 46B	381634122142901	Tulucay	3-13-01	1.10	–7.00	–45.77	99	11.5
Site 49B	381707122151801	Tulucay	3-14-01	.35	–7.28	–48.66	122	11.0
Site 50	381738122140601	Tulucay	3-13-01	.72	–7.20	–48.06	—	12.5
Site 56	381813122140601	Tulucay	3-15-01	.12	–6.88	–48.18	610	10.0
Site 58	381758122131601	Tulucay	3-15-01	.09	–7.55	–50.54	72	10.0
Site 60	381653122140201	Tulucay	3-14-01	.30	–7.46	–49.51	96	11.5
Site 62	381638122150501	Tulucay	3-13-01	.19	–6.96	–47.82	109	12.5
Murphy Creek (MC)	381739122140001	Tulucay	9-19-01	.10	–5.71	–39.34	130	15.0
Site 21	381743122161001	([1])	3-14-01	.01	–6.78	–47.41	498	13.0
Site 1	382024122145901	Sarco	4-12-01	.18	–6.89	–45.77	110	9.5
Site 2	382046122142501	Sarco	3-16-01	.83	–7.43	–47.16	90	9.5
Site 7A	381956122151101	Sarco	3-15-01	1.05	–7.41	–47.38	113	11.0
Site 7B	381956122151102	Sarco	3-15-01	.62	–6.63	–45.18	246	14.0
Site 9	381923122145701	Sarco	3-14-01	.43	–6.52	–44.21	462	13.5
Site 11	381922122162201	Sarco	3-15-01	2.34	–7.01	–46.38	210	11.5
			4-11-01	.13	–6.57	–44.55	270	12.5
Site 22A	381901122135201	Sarco	3-14-01	.08	–6.88	–47.92	488	13.0
Site 22B	381900122135101	Sarco	3-14-01	.15	–7.27	–48.81	213	12.0
Site 24	381849122132901	Sarco	3-14-01	.02	–7.29	–46.5	109	12.0
Site 26A	381922122141201	Sarco	3-14-01	.48	–6.79	–45.58	328	14.5
Site 26B	381922122141202	Sarco	3-14-01	.50	–7.50	–49.01	143	13.0
Site 28B	381925122140801	Sarco	3-14-01	.46	–7.58	–48.12	138	12.0
Site 51	381906122133501	Sarco	3-14-01	.07	–7.28	–48.24	128	12.0
Dairy Creek (DC)	381909122132701	Sarco	9-18-01	.04	–6.98	–45.36	97	14.5
Site 6A	382104122151401	Milliken	3-15-01	.03	–7.05	–44.99	119	11.5
Site 31	382139122150801	Milliken	3-15-01	46.2	–7.59	–48.59	61	10.0
			4-11-01	3.40	–7.12	–45.38	104	12.0
Site 33 (MCW)	382130122153501	Milliken	3-15-01	51.7	–7.62	–47.61	61	10.0
			4-11-01	2.40	–7.15	–44.57	107	12.0
			9-20-01	.43	–5.32	–37.72	172	15.5

See footnote at end of table.

Table 9. Field measurements and oxygen-18 and deuterium ratios in samples from streamflow- measurement stations, lakes and ponds, springs, and wells, southeastern Napa County, California, 2001–02—Continued

Station identifier or State well No. (abbreviated or local identifier)	USGS Identification No.	Subarea	Sample date	Instaneous streamflow (ft^3/s)	Delta oxygen-18 (per mil)	Delta deuterium (per mil)	Field measurements	
							Specific conductance (µS/cm)	Water temperature (°C)
Streamflow-measurement stations—Continued								
Site 35	381931122162901	Milliken	3-15-01	42.5	–7.54	–47.55	78	11.0
			4-12-01	3.25	–6.91	–43.88	153	11.0
Site 37 (MCH)	382017122161101	Milliken	4-11-01	3.13	–6.96	–43.32	156	13.0
			9-20-01	.46	–5.11	–37.51	184	18.0
Site 38	382031122155301	Milliken	3-15-01	43.4	–7.54	–48.08	71	10.0
			4-11-01	2.53	–6.93	–44.74	149	13.0
Lakes and ponds								
lower Lake Camille (LLC)	381638122151601	Tulucay	9-21-01		–1.92	–25.68	166	20.0
Maher pond (MP)	381752122132801	Tulucay	9-19-01		–.36	–19.42	220	—
Van Koten pond (VKP)	381934122150701	Sarco	9-18-01		4.04	–3.04	—	—
Silverado Country Club pond (SCCP)	382030122154201	Milliken	9-21-01		–6.75	–44.67	317	22.0
Lake Frey (LF)	381749122112101	([2])	1-15-02		–4.96	–37.66	64	9.5
Lake Leona (LL)	382041122122801	([2])	1-15-02		–7.00	–46.90	88	9.0
Lake Madigan (LM)	381829122113501	([2])	1-15-02		–4.95	–38.48	70	10.0
Lake Madigan outflow (LMO)	381829122113401	([2])	1-15-02		–5.00	–37.88	69	9.5
Springs								
Oak Canyon spring (OCS)	381848122131801	Sarco	1-16-02		–6.79	–44.25	98	11.5
Palmaz spring (PS)	381956122122701	Sarco	2-06-02		–7.10	–45.91	73	14.0
Wells								
5N/3W-6A1 (92)	381858122132601	Storage Unit 3	9-18-01		–7.59	–49.06	124	26.0
5N/3W-6N6 (61)	381814122143101	Storage Unit 1	11-06-01		–7.95	–53.23	1,220	23.0
5N/3W-7G2 (100)	381740122140001	Storage Unit 1	9-19-01		–6.83	–44.8	638	19.5
5N/3W-8E1 (22)	381746122133101	Storage Unit 1	9-19-01		–7.22	–47.68	356	21.5
5N/4W-1F3 (29)	381841122152401	Storage Unit 2	11-07-01		–6.27	–41.54	386	20.5
5N/4W-12G1 (14)	381740122150201	Storage Unit 1	11-06-01		–7.13	–47.35	564	20.0
5N/4W-13H3 (36)	381649122144901	Storage Unit 1	11-07-01		–6.12	–40.6	255	19.0
5N/4W-13J1 (19)	381646122145601	Storage Unit 1	11-08-01		–6.69	–42.46	248	23.5
6N/3W-31F4 (67)	381935122141601	Storage Unit 3	9-21-01		–7.29	–47.72	265	27.0
6N/4W-15R3 (76)	382135122165901	Storage Unit 4	11-08-01		–6.44	–42.28	269	20.0
6N/4W-23Q3 (43)	382050122160901	Storage Unit 3	9-20-01		–7.17	–47.58	402	21.5
6N/4W-25G2 (142)	382017122145801	Storage Unit 3	9-17-01		–6.93	–43.45	260	24.0
6N/4W-26G3 (45)	382018122161301	Storage Unit 3	9-20-01		–6.43	–42.52	404	17.5
6N/4W-36G1 (95)	381939122150401	Storage Unit 3	9-18-01		–7.26	–48.99	310	20.0
6N/4W-36R1 (53)	381905122145601	Storage Unit 2	11-05-01		–7.47	–50.58	428	26.0

[1]Outside of the Tulucay Creek subarea.
[2]Outside subarea in the Howell Mountains.

Table 10. Dissolved gas, chlorofluorocarbon (CFC), and tritium concentrations in samples from wells, and calculations of CFC concentrations in air and corresponding CFC-model age, southeastern Napa County, California, 2001

[State well No.: See well-numbering diagram on page ix. See figure 25 for locations of wells. Mean of CFC-laboratory measurements from three of five ampoules, unless otherwise noted, collected at each site; the remaining two ampoules used for quality control. N_2, nitrogen; Ar, argon; O_2, oxygen; CO_2, carbon dioxide; CH_4, methane; CFC, chlorofluorocarbon; H_2S, hydrogen sulfide. mg/L, milligram per liter; °C, degree Celsius; cm^3/L, centimeter cubed per liter; pg/kg, picogram per kilogram; TU, tritium units; pptv, parts per trillion by volume. —, no data]

State well No. (local well number in parenthesis)	Laboratory measurements											Calculated CFC concentrations in air			CFC-model age	
	Dissolved gas							CFC								
	N_2 [1] (mg/L)	Ar [1] (mg/L)	O_2 [1] (mg/L)	CO_2 [1] (mg/L)	CH_4 [1] (mg/L)	N_2/Ar temp. [1] (°C)	Excess air [1] (cm^3/L)	CFC-11 (pg/kg; mean)	CFC-12 (pg/kg; mean)	CFC-113 (pg/kg; mean)	Tritium concentration (TU)	CFC-11 (pptv)	CFC-12 (pptv)	CFC-113 (pptv)	Time of recharge and laboratory comments	Median ground-water age (years)
5N/3W-6A1 (92)	32.0	0.9	2.9	9.0	0.0	13.5	16.0	62.7	71.0	23.2	—	27.4	133.0	24.5	Late 1960s to early 1970s	31
5N/3W-6N6 (61)	27.0	.5	.0	4.8	14.7	[2] 90.7	24.9	1.6	42.0	.0	—	[2] .8	[2] 83.1	[2] .0	1950s or younger; CFCs probably degraded and degassed; high CH_4, H_2S	46
5N/3W-7G2 (100)	22.8	.8	.1	32.6	.0	10.2	5.5	1.1	19.6	.0	—	.4	31.6	.0	Mid to late 1950s; CFCs could be degraded	45
5N/3W-8E1 (22)	36.9	.9	.1	16.5	.0	15.3	21.7	21.1	35.1	6.1	.32	10.2	71.5	7.2	Mid 1960s to early 1970s	33
5N/4W-1F3 (29)	18.6	.7	3.2	4.1	.0	12.3	1.9	119.0	169.3	15.9	1.50	48.8	299.9	15.7	Late 1970s to early 1980s	21
5N/4W-12G1 (14)	23.6	.7	.0	1.7	1.0	23.3	10.2	1.7	9.8	.0	—	1.2	27.9	.0	Mid to late 1950s; CFCs could be degraded	45
5N/4W-13H3 (36)	21.7	.7	.7	41.0	.0	16.1	6.3	12.0	6.8	.0	.50	6.0	14.3	.0	Mid 1950s or younger; CFCs could be degraded	46
5N/4W-13J1 (19)	17.7	.6	.1	9.6	.0	17.8	2.7	[3] 19.0	[3] 13.2	[3] 1.9	—	[3] 10.2	[3] 29.8	[3] 2.5	Late 1950s to early 1960s	41
6N/3W-31F4 (67)	20.9	.7	.1	4.4	.1	13.6	4.7	3.1	5.4	.0	—	1.4	10.1	.0	Early 1950s	50
6N/4W-15R3 (76)	21.4	.7	.1	15.7	.0	13.4	5.1	26.7	1,450.8	6.5	2.12	11.7	2,720.1	6.8	Early 1970s; excess CFC-12	30
6N/4W-23Q3 (43)	22.6	.6	.1	10.7	.0	24.2	9.4	4.9	9.0	.0	—	3.6	26.4	.0	Mid to late 1950s	45
6N/4W-25G2 (142)	21.1	.7	.1	6.9	.3	13.5	4.9	4.9	15.7	1.7	1.12	2.2	29.8	1.8	Mid 1950s; CFCs could be degraded	46
6N/4W-26G3 (45)	24.4	.7	.1	20.9	.9	20.8	10.5	3.8	76.7	2.3	—	2.4	197.6	3.5	Mid 1970s; CFCs probably degraded	26
6N/4W-36G1 (95)	21.5	.7	.1	30.5	.0	11.4	4.6	4.0	24.1	.0	.25	1.5	40.9	.0	Early 1960s	40
6N/4W-36R1 (53)	16.5	.6	3.6	.7	.0	21.8	2.6	[3] 122.4	[3] 171.2	[3] 35.3	—	[3] 79.8	[3] 459.2	[3] 58.0	Mid to late 1980s	15

[1] Mean of measurements for two samples collected at each site.

[2] The 30-year (1961–90) average air temperature at Napa, California (National Oceanic Atmospheric Administration, 2002); 14.7°C was used for this calculation.

[3] Mean of measurements from two ampoules; the third ampoule was "contaminated" (concentration greater than 2001 air) (Plummer and Busenberg, U.S. Geological Survey, written commun., 2002).

Table 11. Helium, hydrogen, and neon gas concentrations in water samples from wells, southeastern Napa County, California, 2001

[See figure 25 for location of wells. cc/g, cubic centimeter per gram; STP, standard temperature and pressure; He, helium; H_2, hydrogen; Ne, neon. —, no data]

State well No. (local well number in parenthesis)	Dissolved gas concentrations[1] (10^{-8} cc/g at STP)		
	He	H_2	Ne
5N/3W-6N6 (61)	534.3	3.8	—
5N/3W-7G2 (100)	29.8	74.5	22.6
5N/3W-8E1 (22)	27.7	74.6	28.0
5N/4W-12G1 (14)	96.7	6.6	—
6N/4W-26G3 (45)	255.3	26.4	—
6N/4W-36G1 (95)	20.6	1.9	31.0

[1]Mean for two samples collected at each site.