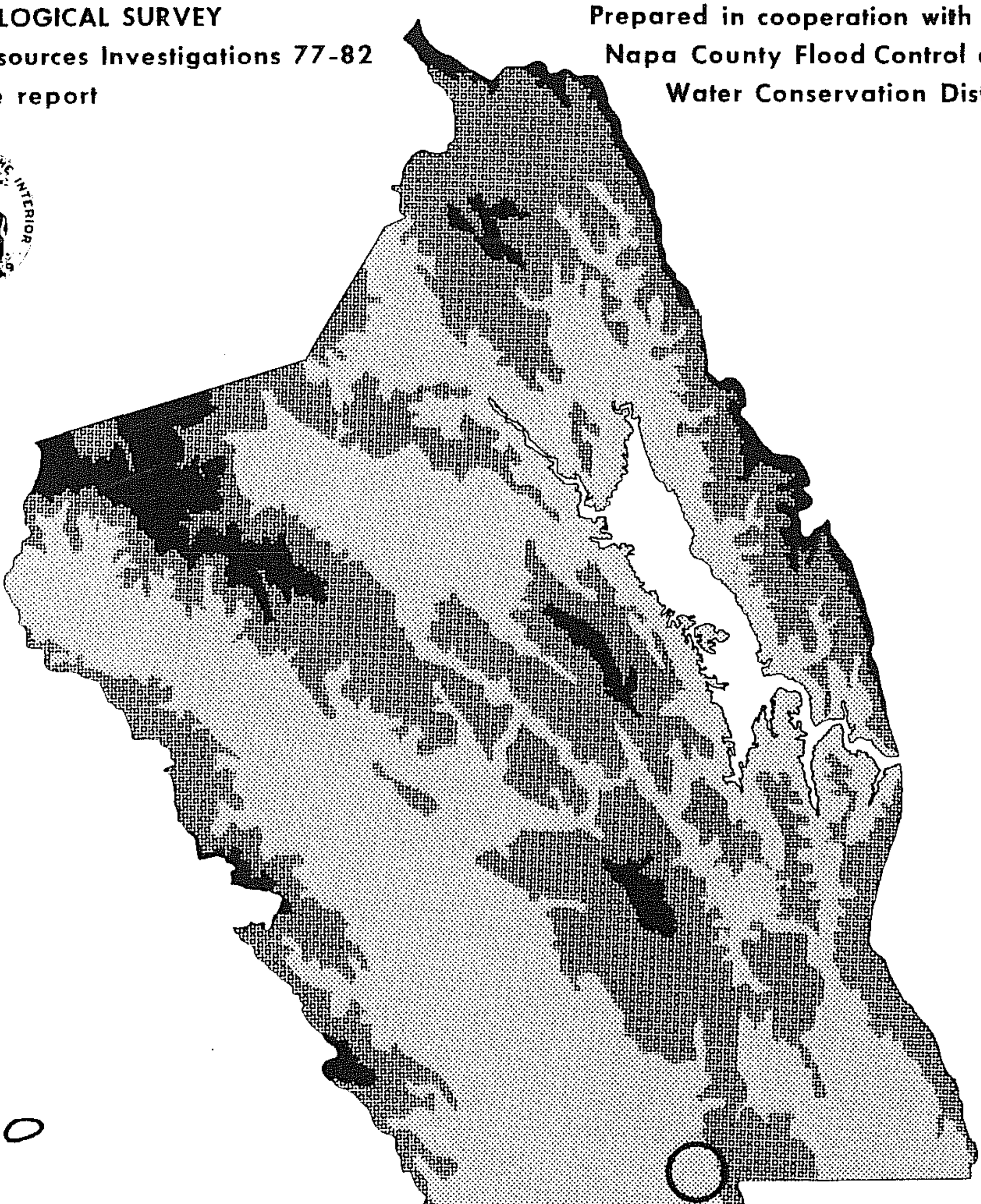
U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 77-82
Open-file report

Prepared in cooperation with the
Napa County Flood Control and
Water Conservation District



GROUND-WATER HYDROLOGY OF THE LOWER MILLIKEN-SARCO-TULUCAY CREEKS AREA, NAPA COUNTY, CALIFORNIA

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By Michael J. Johnson

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August 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

For additional information write to:

District Chief
Water Resources Division
U.S. Geological Survey
345 Middlefield Rd.
Menlo Park, Calif. 94025

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CONVERSION FACTORS

Factors for converting English units to metric units are shown to four significant figures. In the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric*
acres	4.047×10^{-1}	hm^2 (square hectometers)
acre-ft (acre-feet)	1.233×10^{-3}	hm^3 (cubic hectometers)
acre-ft/yr (acre-feet per year)	1.233×10^{-3}	hm^3/yr (cubic hectometers per year)
ft (feet)	3.048×10^{-1}	m (meters)
ft/yr (feet per year)	3.048×10^{-1}	m/yr (meters per year)
ft^2/d (feet squared per day)	9.290×10^{-2}	m^2/d (meters squared per day)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
gal/d (gallons per day)	3.785	L/d (liters per day)
gal/min (gallons per minute)	6.308×10^{-2}	L/s (liters per second)
(gal/min)/ft (gallons per minute per foot)	2.070×10^{-1}	(L/s)/m (liters per second per meter)
in (inches)	2.540×10	mm (millimeters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

GROUND-WATER HYDROLOGY OF THE LOWER MILLIKEN-SARCO-TULUCAY CREEKS AREA, NAPA COUNTY, CALIFORNIA

By Michael J. Johnson

ABSTRACT

The Sonoma Volcanics are the principal water-bearing materials in the lower Milliken-Sarco-Tulucay Creeks area, which occupies about 15 square miles (39 square kilometers) in and east of Napa, Calif. The distribution and composition of these volcanic units are highly variable and complex. Within the Sonoma Volcanics the tuffs constitute the best ground-water reservoir. They are principally pumicitic ash-flow tuffs, partly welded and moderately permeable. These tuffs extend to a depth exceeding 500 feet (150 meters), and are irregularly interbedded with clay, igneous flows, and other volcanically derived material of very low permeability which locally confine the tuffs. Recharge and movement of ground water within these tuffs are affected by the highly variable character of this rock sequence, by adjacent formations, and by tectonic features such as the Cup and Saucer ridge and the Soda Creek fault. The lithology of the area limits specific yields to about 4 percent (unconfined conditions). Specific capacities of wells average less than 3 gallons per minute per foot of drawdown (0.6 liter per second per meter) except in the most permeable areas.

Annual pumpage of 3,000 acre-feet (3.7 cubic hectometers), mostly from the Sonoma tuffs, represents a significant portion of the ground-water discharge. The seasonal change in ground-water storage was about 6,600 acre-feet (8.1 cubic hectometers) in 1975. Water-level data from the area reflect the seasonal change in ground-water storage, with fluctuations of 3 to 60 feet (1 to 18 meters). The storage capacity to a depth of 500 feet (150 meters) may be as much as 196,000 acre-feet (242 cubic hectometers) in the study area, but physical and economic factors may restrict the usable capacity to about 20,000 acre-feet (25 cubic hectometers).

Recharge within the area is generally inadequate to marginal under 1975 demand. There is insufficient recharge in the Milliken and Sarco Creeks area to support 1975 pumpage. Long-term changes in the seasonal peak water levels indicate an average decline of 1.5 feet per year (0.5 meter per year). By 1975 annual pumpage was not exceeding recharge in the Tulucay Creek area. Although a downward trend in water levels was noted in the western part of this basin in the late 1940's, the pumping distribution and its stress on the ground-water system have since changed, and no overall downward trend was evident in the Tulucay Creek area in 1975.

INTRODUCTION

Purpose and Scope

Ground water has become increasingly important in the lower Milliken-Sarco-Tulucay Creeks area of Napa County with increased urbanization and continued irrigation of agricultural land and recreational land, mostly golf courses. Water levels have declined, and there is concern that future use and development might accelerate this decline. Data on the hydrologic system and the factors that exert controls on this system should be available for long-term management of the ground-water resource.

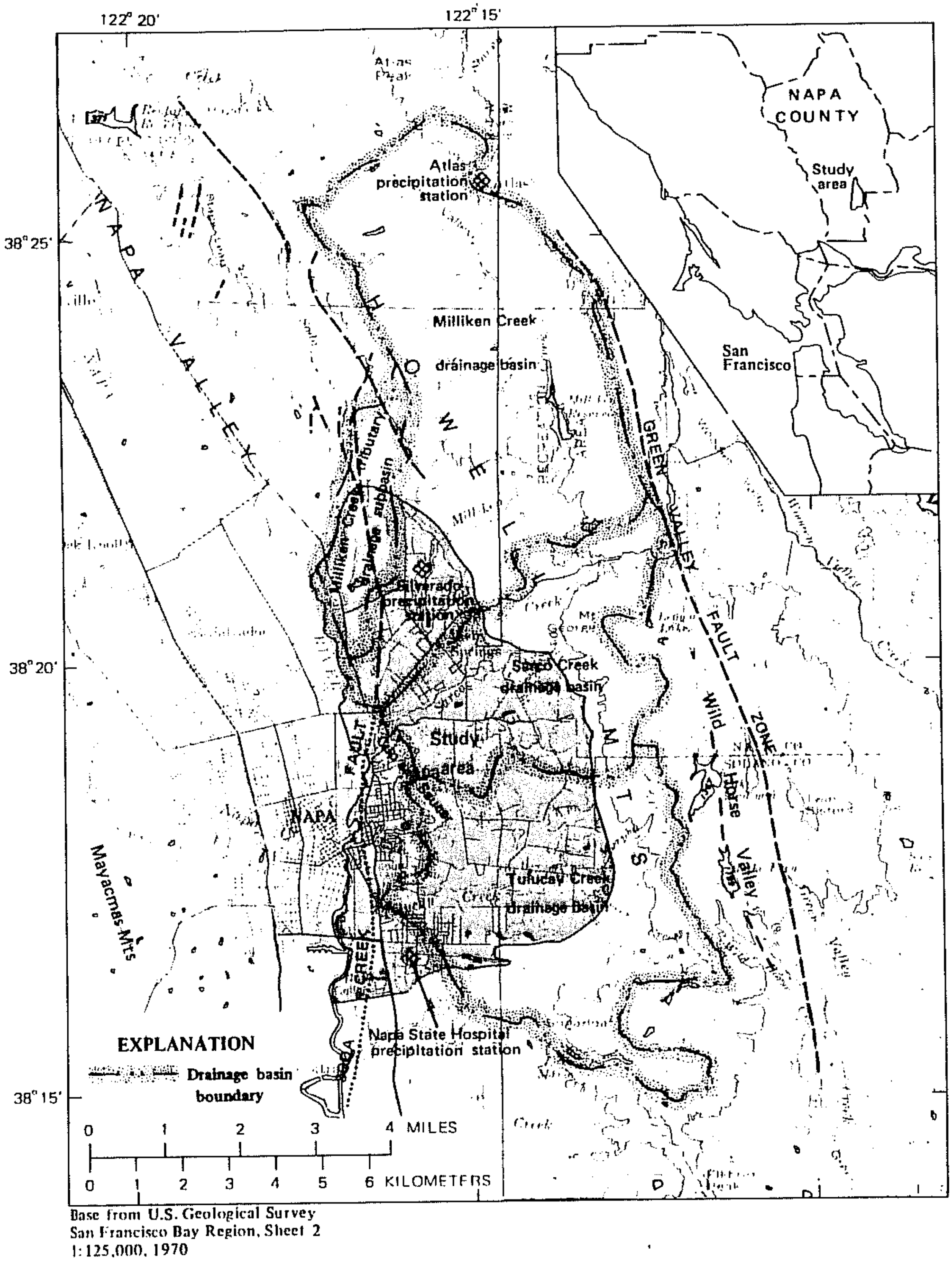
The purpose of this report, prepared by the U.S. Geological Survey in cooperation with the Napa County Flood Control and Water Conservation District, is to provide local planners with sufficient data to permit them to manage effectively the local ground-water resource for long-term use.

The scope of this report includes a description of the hydrologic system and the geologic features that affect the system. The report discusses the geology of the area, describes the occurrence and movement of ground water, identifies sources and areas of recharge and areas of discharge, includes estimates of pumpage and ground-water storage, and discusses changes in water levels and ground-water storage. Data used in the study were taken from previous investigations or acquired by fieldwork in 1974 and 1975.

Location and Extent of Study Area

The study area is adjacent to the city of Napa, approximately 40 mi (64 km) northeast of San Francisco (fig. 1). It is a 15-mi^2 (39-km^2) topographic depression underlain by volcanic debris, enclosed on three sides by the Howell Mountains and bounded on the west by the Napa River. An elevated hilly terrain exists in the central part, with the higher western edge termed the "Cup and Saucer". The topography and geology of the area have led geologists (K. F. Fox, oral commun., 1975) to speculate that part of the basin may be a collapsed caldera truncated by the Soda Creek fault.

The area includes the lower parts of the drainage basins of Milliken, Sarco, and Tulucay Creeks, and an area directly tributary to the Napa River (fig. 1). The three creeks drain the Howell Mountains on the east, cross the study area, and discharge into the Napa River. For this report the study area is referred to as the lower Milliken-Sarco-Tulucay Creeks area.



Base from U.S. Geological Survey
San Francisco Bay Region, Sheet 2
1:125,000, 1970

FIGURE 1.--Location and drainage basins of the study area.

Culture and Water Use

The study area is a rapidly urbanizing region, although vineyards and orchards are still common. Land use in 1970 is shown in figure 2. The western margin of the Tulucay Creek area is densely urbanized; improved open space predominates in the rest of that area, principally as pastureland but with an increasing number of new residences. Orchards are more prevalent in the Milliken and Sarco Creeks area, but residential use predominates. Two golf courses, the Silverado Country Club and the Napa Valley Country Club, are also here. A large block of homes within the city limits adjoins the Napa River just west of the Cup and Saucer. Vineyards are common north of the Cup and Saucer along the Napa River.

Data furnished by the Napa Department of Planning and Community Development indicate that about 13,000 people live within the study area; 8,800 of these people live outside the city limits in approximately 3,000 dwellings.

The urbanized western part of the Tulucay Creek area and some homes in the Milliken and Sarco Creeks area receive water from the city of Napa. A majority of the homes outside the city of Napa and almost all the areas used for agriculture and recreation use water from privately owned wells. Excluding county homes on city water and allowing for some dwellings sharing a common well, there are at least 1,500 wells in use within the study area. Of these wells, approximately 400 have some form of well record. Figure 2 shows the distribution of 190 new wells recorded by the Napa County Health Department for the 4 years from 1970 through mid-1974. This distribution coincides with areas of increasing urbanization.

Previous Investigations

Early geologic studies north of San Francisco Bay were made by Osmont (1905) and Dickerson (1922). More detailed studies of the Napa Valley were made by Weaver (1949) and Kunkel and Upson (1960). Chesterman (1956) described pumice deposits in the study area. A map prepared by Koenig (1963) shows general geologic features of the Napa Valley. Detailed geologic mapping of the study area was done by Fox and others (1973) and Sims and others (1973).

The hydrology of the Milliken and Tulucay Creeks area was discussed briefly by Clark (1919), Bryan (1932), and Weaver (1949). A detailed hydrologic study of the Napa Valley was made by Kunkel and Upson (1960). Other hydrologic studies for the Napa Valley describe ground water (Faye, 1972, 1973), water development (Nolte, 1960; Metcalf & Eddy, 1973), ground-water resources (U.S. Bureau of Reclamation, 1972), and use of ground water for irrigation and frost protection (Napa County Flood Control and Water Conservation District, 1970, 1972).

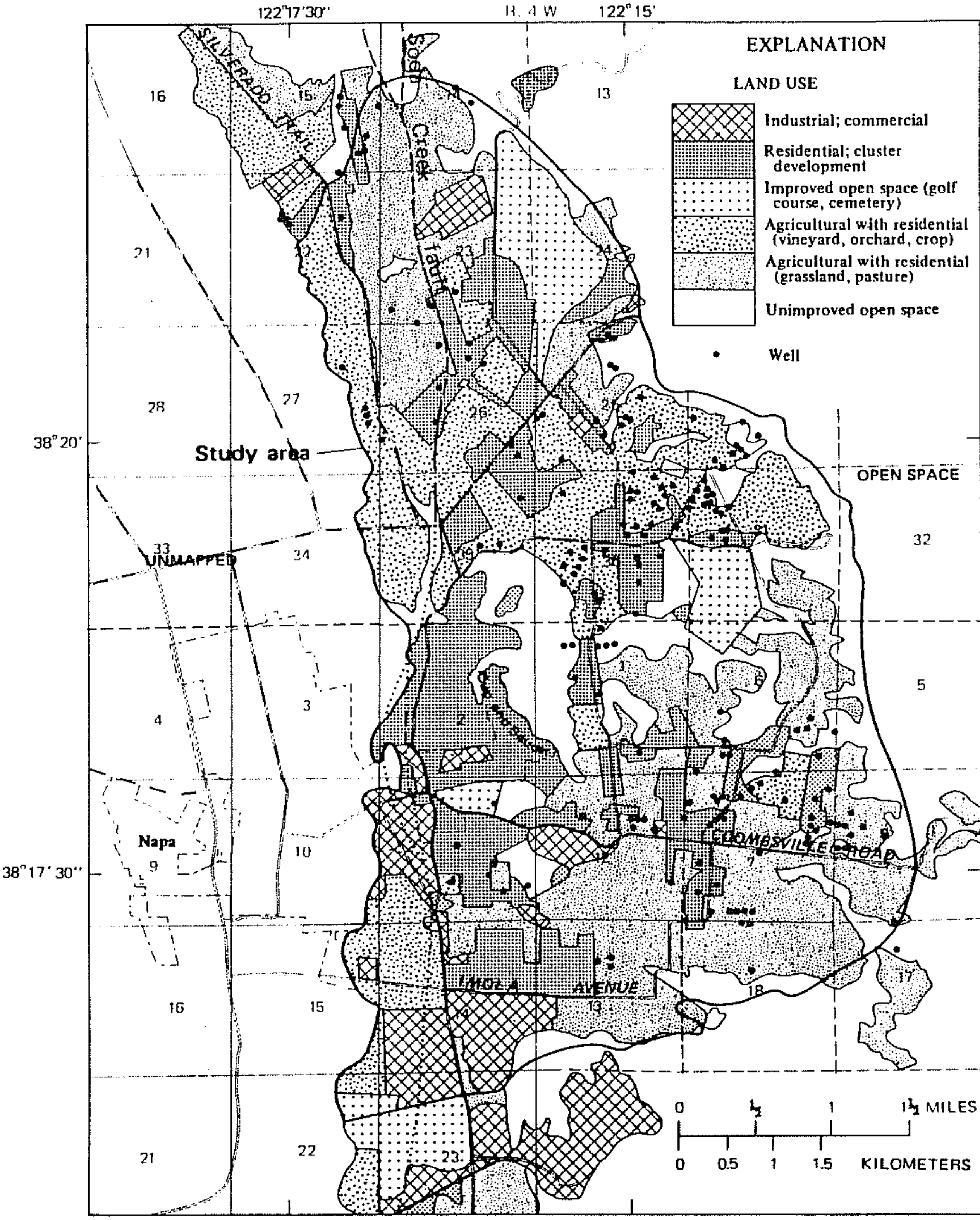


FIGURE 2.--Land use in 1970 (U.S. Geological Survey, 1973) and location of wells drilled from 1970 through mid-1974.

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public lands in California. For example, in the number 5N/4W-14J3, assigned to a well near Imola Avenue, that part of the number preceding the slash indicates the township (T. 5 N.,); the number between the slash and hyphen indicates the range (R. 4 W.); the digits following the hyphen indicate the section (sec. 14); the letter following the section number indicates the 40-acre (16-hm^2) subdivision of the section according to the following diagram. The final digit is a serial number for wells in each 40-acre (16-hm^2) subdivision. All wells mentioned in this report are referenced to the Mount Diablo base line and meridian.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

GROUND-WATER GEOLOGY

This study was concerned exclusively with the Sonoma Volcanics of Tertiary age and the surficial deposits of Quaternary age. These units are identified in figure 3 and are discussed briefly in the text. Detailed geologic descriptions of these units and their regional distribution are given in the reports listed in the section "Previous Investigations."

Sonoma Volcanics and Their Water-Bearing Properties

The Sonoma Volcanics of Tertiary age are divided into three informal volcanic members after Dickerson (1922, p. 551) and two subaqueous deposits. They are the lower andesitic member, the middle tuffaceous member, and the upper rhyolitic member, the diatomaceous deposits, and the sedimentary deposits. All tuffs that occur in these units are referred to as Sonoma tuffs and collectively constitute the area's major aquifer system.

Andesitic member.--The lower andesitic member consists mainly of andesitic to basaltic flows with some interbedded tuffs, the whole member lying unconformably on Miocene sandstone and grading into the overlying middle tuffaceous member. These flows vary considerably in thickness and texture and are highly fractured in the recharge area along the eastern hills. The dense fine-grained materials generally yield no water, whereas the vesicular and agglomeratic materials may be of low to moderate permeability.

The andesitic member underlies the entire study area. Its flows become more predominant with depth as the tuff beds decrease in number and thickness. Well logs show that a continuous sequence of flows will be reached at less than 800 ft (240 m). Generally below 500 ft (150 m) flows with interbedded sticky clay predominate, precluding good ground-water yield. In the hilly Cup and Saucer area these flows are within 100 ft (30 m) of the surface and yield little water to wells along First Avenue.

Tuffaceous member.--Most of the Sonoma tuffs are in the tuffaceous member. This member thus makes up the principal aquifer within the study area east of the Soda Creek fault.

The tuffaceous member contains volcanic ejecta including fragmental pumice, tuff, ash, and scoria, which are highly permeable and yield water freely. The member also contains mudflow agglomerates, welded tuff, flows, and silts which do not yield water freely but serve to locally confine the more permeable material within the member. The member is principally a pumicitic ash-flow tuff, partly welded and of moderate permeability. These tuffs are bedded in between confining clays, flows, and less permeable volcanic material.

The tuffaceous member overlies the andesitic member and is extensive north and south of the hilly central part of the study area (fig. 3, DD'). The hilly central area contains andesitic flows in its western part, draped by a thin, elevated layer of tuffs and erosional debris, and it contains diatomaceous deposits in its eastern part (fig. 3, BB'). These materials comprising the hilly central part of the study area are, for the most part, of very low permeability, and they separate the thick tuffaceous member on the north from that on the south. Thus, ground-water development in the tuffs of either the Milliken and Sarco Creeks ground-water basin or the Tulucay Creek ground-water basin is not expected to have hydraulic effects on the other. The thin, elevated tuffs of the hilly central part of the area grade irregularly down into the thicker tuffaceous member to the north and south. The principal outcrop area of the deeper tuffs of the Milliken and Sarco Creeks basin and the Tulucay Creek basin is along the eastern edge of the study area.

Water in the more deeply buried tuffs is confined (artesian), but water in the exposed, partly welded tuffs in the hilly central area and along the eastern hills is under unconfined to semiconfined conditions. Wells in the central area along First Avenue may have very low yields, with specific capacities as low as 0.01 (gal/min)/ft or 0.002 (L/s)/m of drawdown in a mixture of shallow Sonoma tuffs dissected by intrusions and the deeper andesitic flows.

Specific capacity, as determined from drillers' tests, ranges from less than 1 (gal/min)/ft or 0.2 (L/s)/m to 42 (gal/min)/ft or 8.7 (L/s)/m for two deep, high-capacity wells with 12-in (305-mm) casings penetrating porous Sonoma tuffs in the Milliken and Sarco Creeks basin. The typical well in the study area has a 6- to 8-in (150- to 200-mm) perforated casing, a depth from 130 to 350 ft (40 to 110 m), and more than an 85-percent chance of having a specific capacity of less than 3 (gal/min)/ft or 0.6 (L/s)/m. A specific capacity over 15 (gal/min)/ft or 3 (L/s)/m is unusual in the study area; 42 (gal/min)/ft or 8.7 (L/s)/m is exceptional.

Wells drilled to the deeper tuffs along the lower Tulucay Creek ground-water basin have moderate yields with an average specific capacity of 4 to 5 (gal/min)/ft or 0.8 to 1.0 (L/s)/m locally in secs. 13 and 14 (T5N/R4W). Within the Milliken and Sarco Creeks ground-water basin the average well yield from the deeper tuffs is similar to the Tulucay Creek basin. Paralleling the eastern foothills from Hagen Road north through Vichy Springs, however, is an area having higher yielding wells with a high degree of variability from well to well. Weaver (1949) described "an uncommonly large yield" from a 305-ft (93-m) well drilled in 1916 in the Vichy Springs area. In 1975, aquifer tests at two sites in this area indicated the storage coefficient of the buried tuffaceous member was 0.00016 (±20 percent). This value is indicative of an average confined aquifer; the storage coefficient of most confined aquifers ranges from 0.00001 to 0.001 (Lohman, 1972).

In both the Tulucay Creek and Milliken and Sarco Creeks ground-water basins the tuffaceous deposits constitute a leaky multilayered aquifer system where the permeable tuffs are separated by irregularly interbedded igneous flows and clay of very low permeability. Consequently the tuff beds that yield water to wells deeper in the sequence are more effectively confined than are the successively shallower tuff beds. Storage coefficients of the deeper tuffs are probably as low as 0.0001, whereas the tuff beds in the upper part of this multilayered sequence probably have storage coefficients of more than 0.001.

Rhyolitic member.--The upper rhyolitic member consists of banded rhyolitic lava with intercalated rhyolitic tuff. Where present it rests uncomformably on the other two members of the Sonoma Volcanics. It is not present in the study area at altitudes below 300 ft (90 m). This member comprises compact, brittle flows of very low permeability. Its tuffs contain perched water that emerges as springs along the eastern hills; open joints and fractures in the lava also yield some water.

Diatomaceous deposits.--The diatomaceous deposits consist of diatomaceous clay and silt deposited in a lake or swamp environment with water-laid ash and pumice. The diatomaceous deposits are of low yield; wells typically have specific capacities less than 1 (gal/min)/ft or 0.2 (L/s)/m. The water is of poor quality and is reported to have high iron and sulfur concentrations (Kunkel and Upson, 1960). Interbedded with these diatomaceous deposits are some permeable, lenticular tuff beds that vary in granularity, thickness, and extent. These beds have higher yields.

The diatomaceous deposits lie principally between the Cup and Saucer ridge area and the eastern hills (fig. 3). The unit is known to be as much as 300 ft (90 m) thick and centered in sec. 6 (T5N/R3W). It thins to the northwest and southeast, forming a surface crescent with less diatomite along the outer fringes. In the central area it rests on the andesitic member; elsewhere it overlies and confines the tuffaceous member.

Sedimentary deposits.--The sedimentary deposits are composed of interbedded, fine-grained yellow silt and clay, tuffaceous sand, and volcanic gravel. This unit was probably deposited as an alluvial fan by streams draining mostly uplifted areas underlain by Sonoma Volcanics. The streams flowed into a basin which may have been closed, at least at times. The lowermost beds of the fan deposits contain considerable tuffaceous material and are interbedded with thin lenses of predominantly pumiceous material; these facts indicate that, locally, deposition began before the last eruptions that produced the Sonoma Volcanics. Kunkel and Upson (1960) referred to these deposits as the Huichica Formation.

The sedimentary deposits are principally in the Milliken Creek area along Atlas Peak Road. They overlie and confine the Sonoma Volcanics. Logs of wells east of the Soda Creek fault indicate a maximum thickness for the deposits of 250 ft (76 m). The deposits thin to the southeast where they overlie the diatomaceous deposits.

In the past, many shallow domestic wells (less than 130 ft or 40 m) tapped water in low-yielding semiconfined lenses of gravel interbedded with the silt and clay. Today, many deeper wells penetrate both the confined lenses of volcanic gravels and the Sonoma tuffs in the lower sedimentary deposits and the underlying tuffaceous member; these wells have moderate yields. Heavy pumping in these deeper wells that tap the more permeable materials causes a gradual lowering of water levels in the overlying materials of tighter composition.

Surficial Deposits and Their Water-Bearing Properties

Generally thin, Quaternary surficial deposits of older alluvium, younger alluvium, and fan deposits mask the Tertiary deposits in parts of the study area (fig. 3). West of the Soda Creek fault the alluvial deposits are considerably thicker and constitute the major aquifer in the Napa Valley to the west.

Older alluvium.--The older alluvium is in the western part of the study area where it overlies the deposits of Tertiary age. It is moderately permeable and yields water freely to wells. Many irrigation wells tap this unit between the Soda Creek fault and the Napa River where it is part of the main alluvial aquifer of the Napa Valley.

Younger alluvium and fan deposits.--The younger alluvium and fan deposits are moderately to highly permeable and where saturated yield water freely under unconfined conditions. These deposits within the study area are principally surficial and are generally above the saturated zone during dry seasons. No wells are known to tap these shallow units except where they are in hydraulic connection with stream channels or where they are recharged by springs along the eastern hills.

Structural Features

Regional faulting has displaced the rocks of the Napa Valley area. East of the study area the volcanic units are truncated by the Green Valley fault zone (fig. 1). From this fault zone the units dip westward toward the central part of the Napa Valley, interrupted by anticlinal and synclinal folding and further faulting.

A fault of hydrologic importance to the study area is the Soda Creek fault. It was described by Weaver (1949) as a normal fault with vertical displacement over 700 ft (210 m) at the north end of Soda Canyon. It extends southward with less vertical displacement as it passes along Soda Creek and becomes concealed beneath alluvial deposits at Milliken Creek (fig. 3). From there it skirts to the west of the Cup and Saucer ridge and extends under Tulucay Creek, parallel with the Napa River. North of Milliken Creek, in secs. 26, 23, and 14 (T6N/R4W), the fault has been mapped from traces of recent tectonic activity indicated by topographic features (Fox and others, 1973).

In the study area, clay derived from the decomposing volcanic minerals is prevalent throughout the three members of the Sonoma Volcanics and in higher concentrations in the two Tertiary sedimentary deposits of the Sonoma Volcanics. This clay limits the permeability of the units. It also contributes to the effectiveness of the Soda Creek fault as a hydrologic barrier. Where a fault has been active for a sufficient period, an impermeable clayey gouge may develop along the fault plane in clay-rich units, particularly in the unconsolidated materials. Also, clay may be produced by the rubbing and mashing of silicate minerals during displacement. The clay gouge seals the sheared edges of the permeable beds and limits permeability across the fault.

The younger surficial deposits of Quaternary age are more likely to be affected by abutment along the Soda Creek fault than by the development of a clay gouge. A fault may cause permeable beds to be displaced and abut less permeable beds or impermeable fault surfaces. As shown in section AA' (fig. 3), the Quaternary alluvium, of moderate to high permeability, abuts the Tertiary sedimentary deposits of low permeability. In section CC' the Quaternary alluvium on the west side of the fault does not necessarily abut a less permeable unit to the east. The older tuffaceous member of the Tertiary Sonoma Volcanics, however, is likely to have developed a clay gouge along its fault surface, against which the Quaternary alluvium abuts.

HYDROLOGY OF THE AREA

Precipitation

Most of the precipitation occurs as rain that falls from October through March. The distribution of this precipitation is affected mostly by topography. Heaviest precipitation occurs in the upper Milliken Creek drainage basin; there is less precipitation in the lower parts of the study area. The lightest recorded precipitation occurs at the Napa State Hospital weather station, where the average annual precipitation was 24.80 in (630 mm) during the base period 1941-70 (National Climatic Center). During an average year the drainage basins, comprising about 43 mi^2 (111 km^2), receive approximately 61,000 acre-ft (75.2 hm^3) of precipitation, based on calculations from regional isohyetal contours (Rantz, 1971) and from records at three precipitation stations (fig. 1).

Annual precipitation and the cumulative departure from average for the Napa State Hospital station are shown in figure 4 for the years 1878 through 1975. It shows that this study was made during an average water year preceded by two above-average years. Compared with the 30-year period 1941-70, a period of equivalent precipitation occurred prior to 1911, followed by a period of lower average precipitation lasting until 1940. These long-term precipitation trends indicate only the total amount of water available for ground-water recharge and for other hydrologic uses over a period of years.

A graph of average monthly precipitation is superimposed on the monthly precipitation for the 1974-75 water year in figure 5 to demonstrate that there are monthly departures even in a year of average annual precipitation. The monthly departures shown are small in relation to those of other years on record. Large monthly departures are common in this area.

In any given year the amount of preoipitation may have less direct effect on the recharge of ground water than the duration, intensity, and distribution of the precipitation. Light rains of short duration might add up to a large yearly total but contribute little to ground-water storage. Heavy downpours quickly saturate the surface materials, exceeding infiltration rates, and a high percentage of the precipitation runs off. Regional storms of moderate intensity over many days offer the greatest potential for ground-water recharge. These storms occur principally during the winter months but occasionally during the autumn and spring.

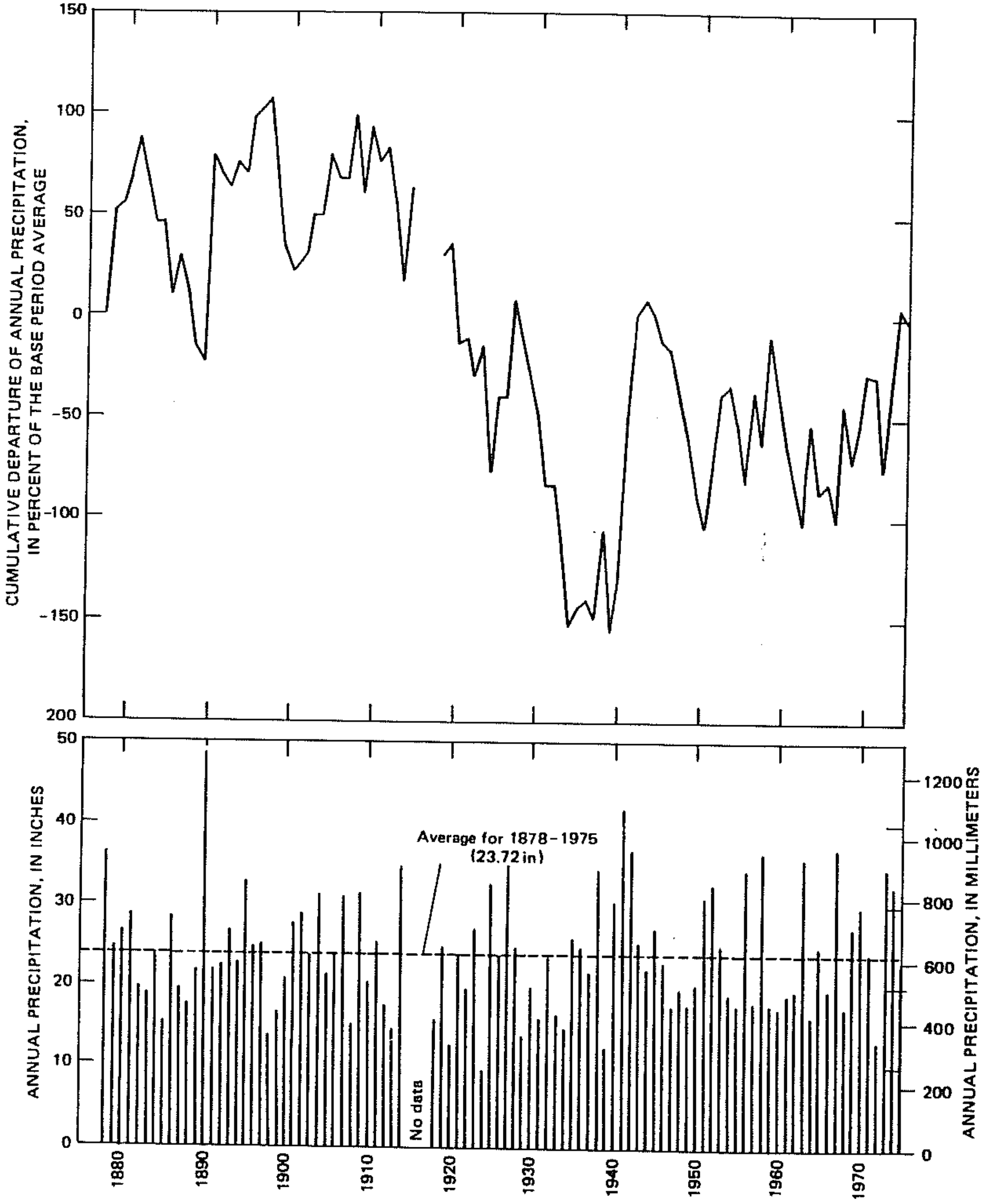


FIGURE 4.--Annual precipitation, 1878-1975, and cumulative departure from average precipitation at Napa State Hospital.

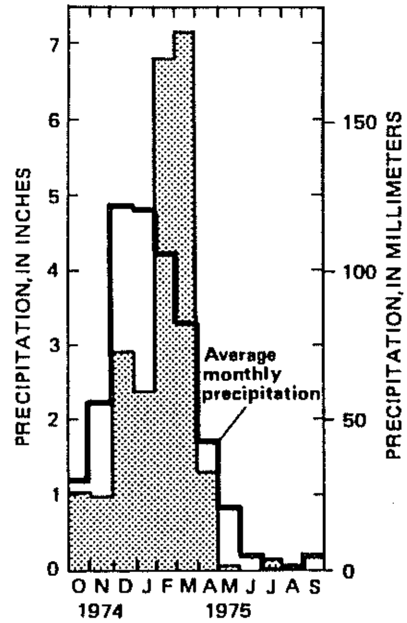


FIGURE 5.--Monthly precipitation at Napa State Hospital, 1975, compared to average monthly precipitation.

Surface Water

The study area is drained principally by Milliken, Sarco, and Tulucay Creeks[1] (fig. 1). The discharge of these creeks is highly variable, but most flow occurs during the winter months. Records obtained since 1970 from stream-gaging stations near the mouths of Milliken and Tulucay Creeks indicate the flashy characteristics of streams draining steep topography. Milliken Creek (at the gaging station) drains an area of 17.3 mi^2 (44.8 km^2) with an average annual discharge during the period 1971-74 of 22.5 ft^3/s (0.6 m^3/s) and a daily discharge rate of as much as 750 ft^3/s (21 m^3/s) with a maximum daily variation of 500 ft^3/s (14 m^3/s) (U.S. Geological Survey, 1970-74). The drainage areas for Tulucay and Sarco Creeks are 12.6 mi^2 (32.6 km^2) and 8.4 mi^2 (21.8 km^2). The flow variations in these smaller streams are similar to Milliken Creek. The estimated total discharge for the three creeks was 4,800 acre-ft (5.0 hm^3) in 1972 and 42,500 acre-ft (52.4 hm^3) in 1973, reflecting a variation in rainfall from 12 in (300 mm) in 1972 to 35 in (890 mm) in 1973 as recorded at the Napa State Hospital (National Climatic Center).

[1]The drainage basins for Milliken and Tulucay Creeks have gaging stations monitoring their discharge. One tributary of Milliken, Sarco Creek's drainage, and surface water flowing directly into the Napa River were not continuously monitored.

During an average year 24,100 acre-ft (29.7 hm^3) of surface water runs off through the study area. A total of 61,000 acre-ft (75.2 hm^3) of rain falls on these drainage basins during an average precipitation year (24.8 in or 630 mm). This means that about 9 in (230 mm) of the precipitation runs off as surface water. In addition, the city of Napa diverts water from Milliken Reservoir. This diverted water has averaged 1,200 acre-ft (1.5 hm^3) per year during the period 1966-75. The city of Napa recently completed the construction of a water-treatment facility at Milliken Reservoir which will permit an annual use of about 2,500 acre-ft (3.1 hm^3) of Milliken Creek water.

Evapotranspiration

The annual loss of water to the atmosphere by evapotranspiration (evaporation and plant transpiration) is difficult to measure in the field, because such variables as vapor pressure, temperature of soil and air, wind, soil type, vegetative cover, soil-moisture, and solar radiation must be monitored. It is common practice to determine evapotranspiration rate by relating the area to a State agroclimatic control station of similar vegetative and soil type where the evapotranspiration has been carefully monitored (California Department of Water Resources, 1975b). To transfer evapotranspiration data, evaporation from class "A" pans is measured at both sites. Pan evaporation reflects the amount of surface water evaporation at a given site, and it thereby indicates the maximum annual evapotranspiration that might occur when an adequate soil-moisture supply is available at all times throughout the year. Correlation factors are derived by comparing "A" pan evaporation rates in the area of interest with those at the control station. Consumptive-use formulas have also been derived (Veihmeyer, 1964), with coefficients to correct for differences in types of vegetation.

Within the study area, application of the Blaney-Criddle equation (Blaney and Hanson, 1965), with a maximum annual consumptive-use coefficient of unity, indicates a maximum annual potential evapotranspiration of 59 in (1,500 mm), a value that agrees with the State's pan evaporation measurements (California Department of Water Resources, 1975b). Actual evapotranspiration would be considerably less. Most evapotranspiration losses occur during periods of minimum precipitation from March through October when temperature, vapor pressure, solar radiation, and plant growth are major factors contributing to water loss. Part of the time from June through September (depending on precipitation patterns), the soil moisture is low, and this considerably reduces evapotranspiration.

The amount of soil-moisture depletion at the end of the dry season can give a realistic figure of actual evapotranspiration in this climatic area. The first rains after the dry season must resupply the depleted soil moisture before appreciable runoff or ground-water recharge can begin. The amount of this initial precipitation is approximately equivalent to the annual evapotranspiration. Therefore, an estimate of actual evapotranspiration may be obtained if the amount of the initial precipitation is determined.

The amount of precipitation needed to saturate the soil at the beginning of the rainy season can be inferred by comparing accumulated precipitation with runoff. The few years of runoff data available, compared with the precipitation data at Napa State Hospital (fig. 6), indicate that about 12 in (300 mm) of initial precipitation is needed before the soil is saturated and the rate of runoff increases appreciably within the study area. Water levels also begin to rise in wells in the unconfined aquifers throughout the study area at the time 10 to 14 in (250 to 350 mm) of precipitation has accumulated at the Napa State Hospital station. Using the precipitation record at the Napa State Hospital to index the commencement of recharge and appreciable runoff, the total evapotranspiration from the drainage basins containing the study area is estimated to be 30,500 acre-ft (37.6 hm^3) per year. This figure does not include any adjustment for initial runoff while soil moisture is being replaced during early rains or for some evapotranspiration between winter storms; these two factors are minimal and possibly cancel each other.

The Blaney-Criddle equation indicates that the annual consumptive-use coefficient would be 0.21 in the study area. This means that the actual evapotranspiration is approximately 21 percent of the maximum A-pan evaporation of 59 in (1,500 mm) for the area.

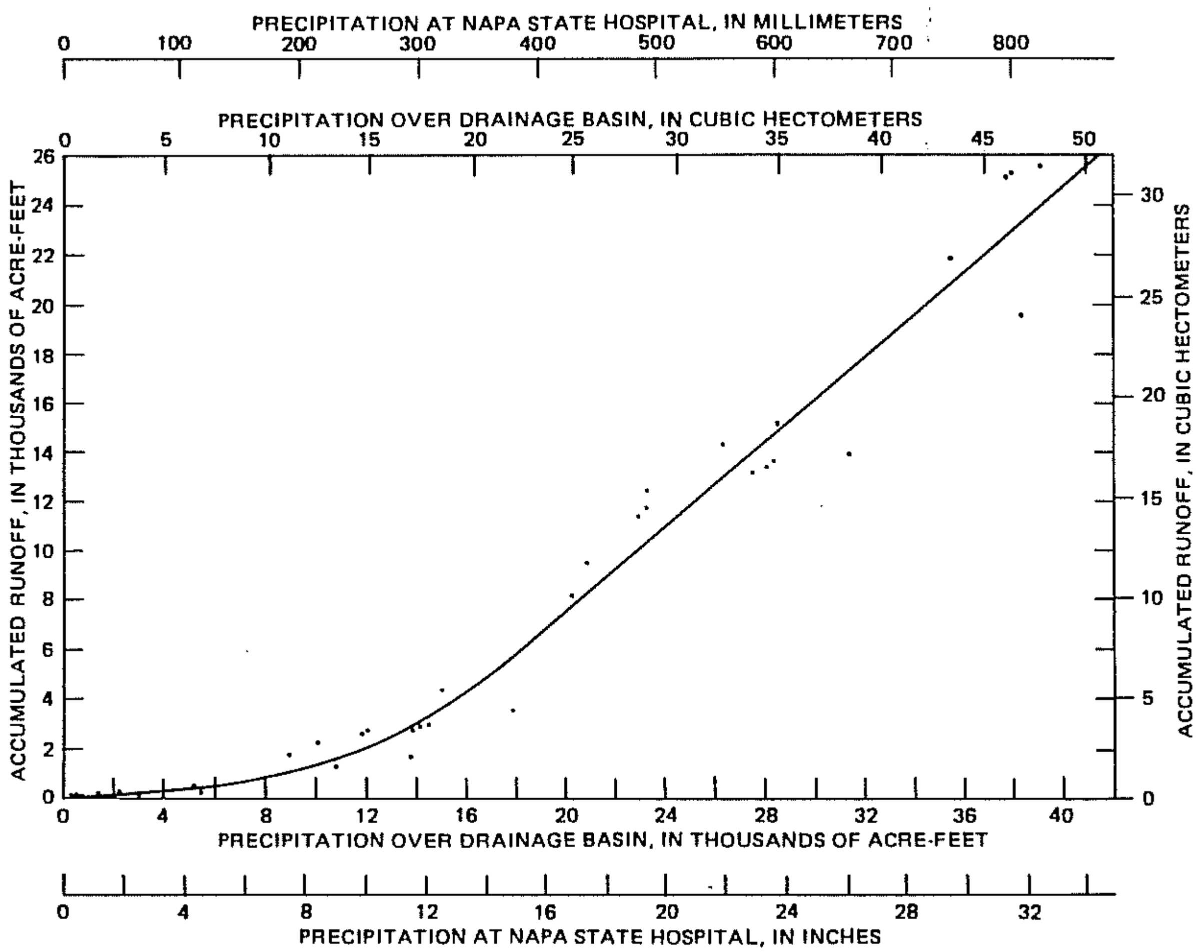


FIGURE 6.--Relation between accumulated runoff and precipitation for Milliken Creek drainage basin based on the average 1971-74 accumulations.

Ground Water

Occurrence

The principal occurrence of ground water in the study area is in the Sonoma tuffs east of the Soda Creek fault, mostly under confined conditions. West of the Soda Creek fault it occurs mainly in the older alluvial material of the Napa Valley, mostly under unconfined conditions.

The depth to water as shown in figures 7 and 8 is the difference between the water-level altitude and the topographic altitude. In general, where topographic altitude is greatest the depth to water is greatest.

The depth to water in the alluvial aquifer between the Napa River and the Soda Creek fault was typically 10 to 30 ft (3 to 9 m) below land surface during the spring of 1975 (fig. 7). In the Sonoma tuffs the depth to water in the Milliken and Sarco Creeks drainage basins during the spring of 1975 was typically 30 to 60 ft (9 to 18 m) below land surface; in the Tulucay Creek drainage basin it was typically 20 to 50 ft (6 to 15 m). In parts of these drainage basins the head is above the land surface. For example, in secs. 14 and 23 (T5N/R4W) unused wells 5N/4W-14P1, 5N/4W-23C1, and 5N/4W-23C2 flow the year around through leaks in their casing seals, and in sec. 13 (T5N/R4W) and sec. 26 (T6N/R4W) some wells, such as 5N/4W-13G and 6N/4W-26L, flow intermittently during the year (fig. 3).

Where the artesian pressure in the Sonoma tuffs is great enough, water penetrates the confining materials as "blowthroughs" or "sand boils" (defined by Ferris and others, 1962). In sec. 13 (T5N/R4W) (fig. 3) the diatomaceous member is penetrated by artesian water and supplies a small pond in the center of the section, while a new excavation just south of this pond has made the confining material incompetent, and observable sand boils have created a new pond.

Movement

The movement of ground water in the study area, as described by Kunkel and Upson (1960) and as indicated by water-level surveys for this report, is generally from areas of replenishment in the east toward areas of discharge in the west. Available evidence indicates that no ground water moves into the study area from farther east than the Green Valley fault zone (fig. 1).

The 1975 spring and autumn ground-water level contours shown in figures 9 and 10 demonstrate the general east to west direction of ground-water movement through the study area east of the Soda Creek fault. Locally the general flow pattern is altered by ground-water pumping centers, and in the hilly central part of the study area some natural ground-water flow is to the north and south into the Milliken and Sarco Creeks and Tulucay Creek basins, respectively. In the main alluvial aquifer of the Napa Valley the ground water moves generally southward, paralleling the Soda Creek fault. The water-level contours for April 1975 (fig. 9) show the composite potentiometric head after the winter rains when water levels are at the maximum for the area and presumably when pumping is minimal. Conversely, the water-level contours for September 1975 (fig. 10) show the composite potentiometric head during low water-level conditions when pumping stress is high. The water-level configurations depicted on the maps are derived from heads measured in wells, some of which are in the shallow unconfined parts of the aquifer system and others are in the deeper confined parts of the system.

The damming effect of the Soda Creek fault cannot be conclusively determined from the spring water-level contours (fig. 9). The autumn water-level contours (fig. 10) show, however, that the geologically active part of the fault serves as a subterranean dam during periods of low water levels, impounding water in the older Tertiary volcanics on the east side of the fault. Pumping along Silverado Trail in secs. 22, 23, 26, 27 (T6N/R4W) is being compensated by subsurface inflow of ground water moving from the north parallel with the fault and from the northwest down the Napa Valley. The difference in water levels across the fault is 20 to 30 ft (6 to 9 m).

In the area of the Milliken and Sarco Creeks basin south of Milliken Creek, water levels indicate ground-water movement across the upper part of the fault in sec. 35 (T6N/R4W). This is confirmed by the hydraulic interaction among wells on both sides of the fault. In response to a large-capacity well west of the fault that was pumping continuously for many days, water levels in deep wells directly east of the fault (sec. 35) dropped about 10 ft (3 m), and some shallow wells east of the fault reportedly went dry. This upper section of the fault in the area from Milliken Creek to the Cup and Saucer coincides with the presence of thick surficial deposits of older alluvium that extend across the fault (fig. 3).

In the Tulucay Creek basin, ground water moves westward across the Soda Creek fault, at least in the upper older alluvium shown in figure 3 (sec. CC'). The fault probably acts as an effective barrier in the lower tuffaceous member, but this has not been confirmed. No deep wells immediately west of the fault are available to monitor artesian head in this member. Immediately east of the fault, deep wells flow the year around. Maintenance of these high heads results, possibly, from the fault serving as a hydraulic barrier. The movement of ground water through the upper older alluvium from the Napa Valley into the Tulucay Creek part of the study area was observed by Kunkel and Upson (1960) when heavy pumping in sec. 14 (T5N/R4W) reversed the direction of flow.

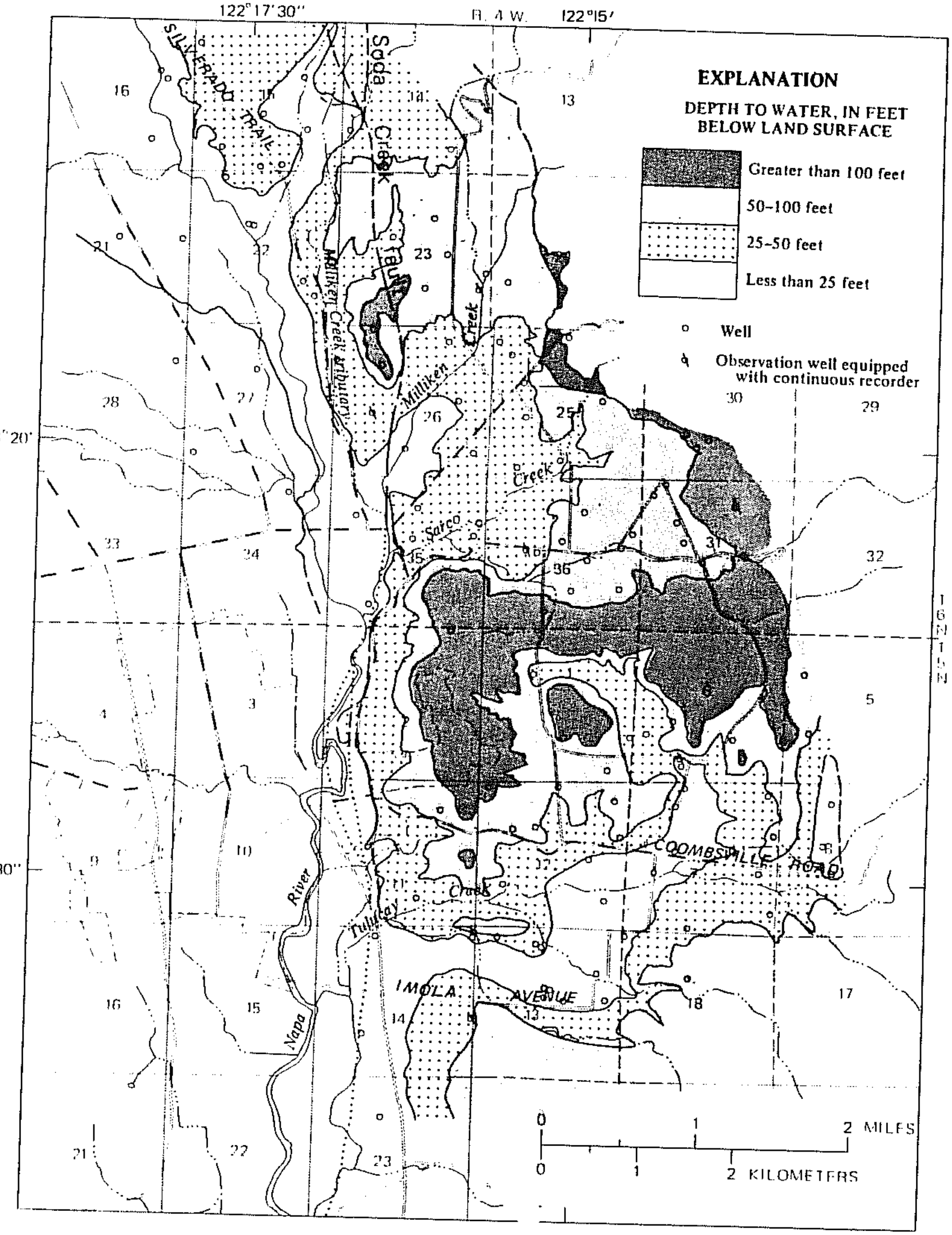


FIGURE 7.--Depth to water, April 1975.

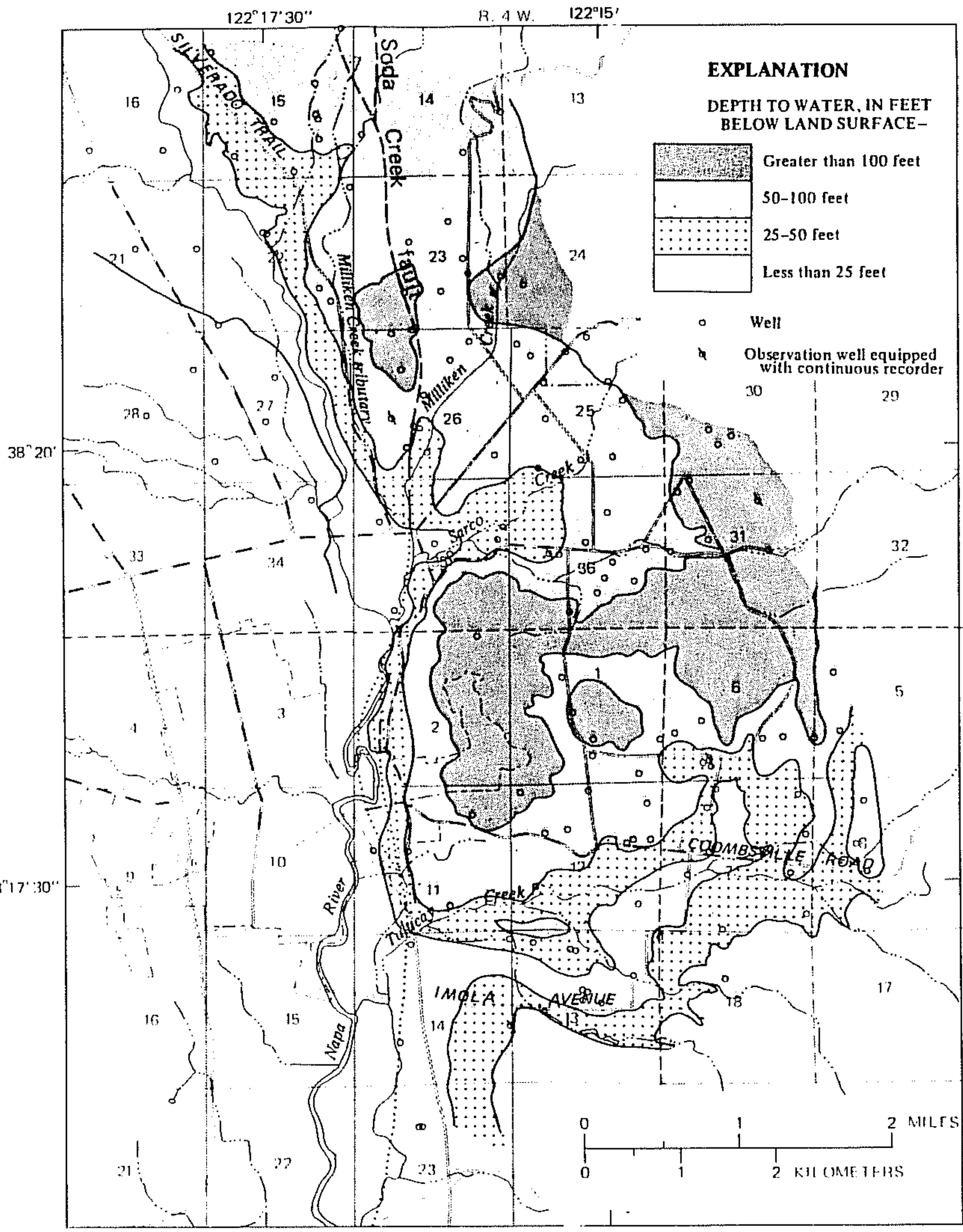


FIGURE 8.--Depth to water, September 1975.

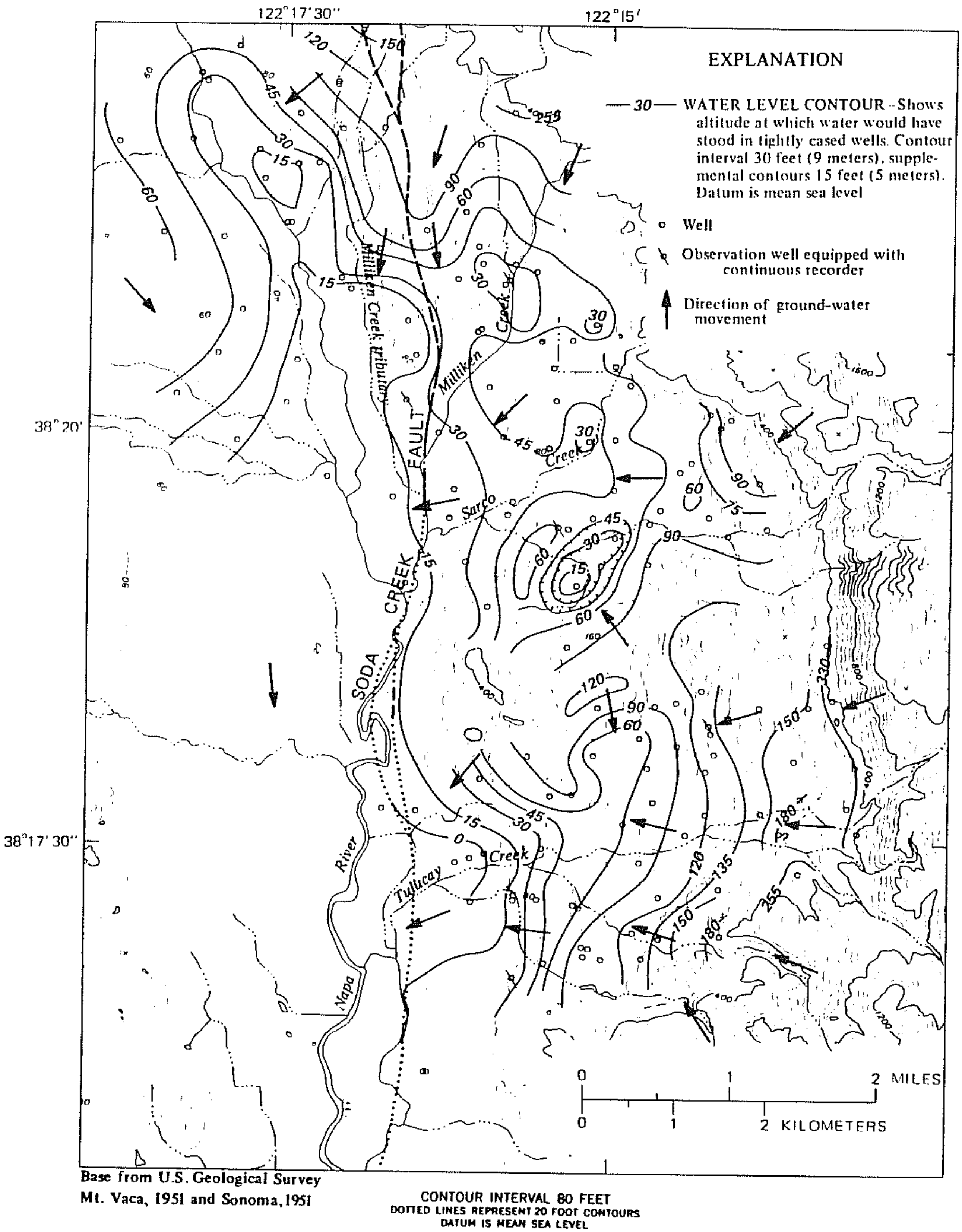


FIGURE 9.--Water-level contours, April 1975.

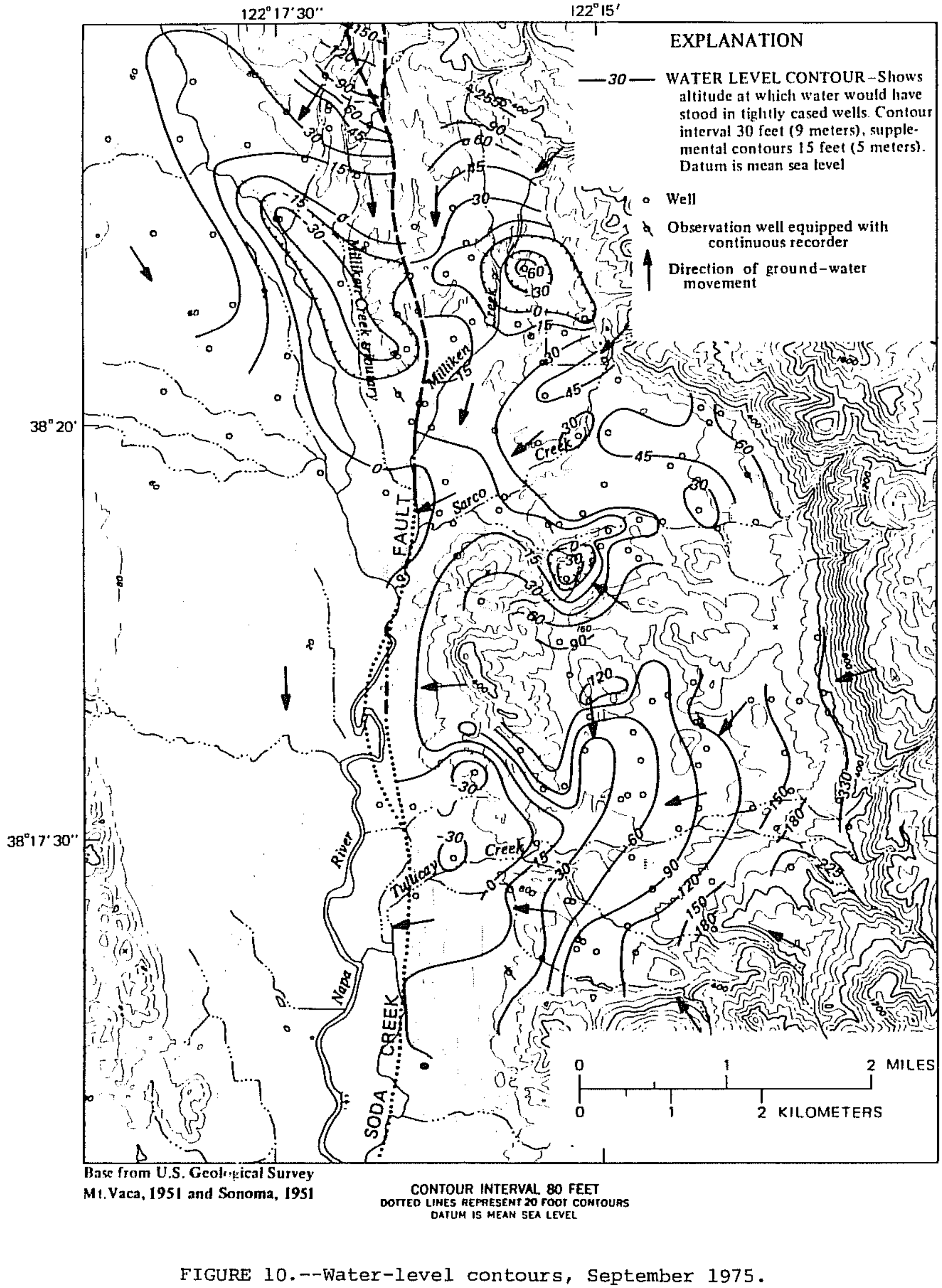


FIGURE 10.--Water-level contours, September 1975.

Recharge

The alluvial aquifer west of the Soda Creek fault is part of the major alluvial aquifer that extends up the Napa Valley where it is recharged by percolation from streams and infiltration of rain. It was described by Faye (1973) and will not be discussed further in this report.

The major source of ground water in the Sonoma tuffs is precipitation over the study area's drainage basins and some underflow from the Wild Horse Valley area (fig. 1). Recharge is supplied to the study area's confined ground-water system by infiltration from streams and by near-surface ground water moving downgradient through tuffs in the eastern hills. Most of this recharge occurs east of the infiltration boundary shown in figure 11. It is derived from precipitation over a 33-mi^2 (55-km) area. At lower altitudes, west of the infiltration boundary, recharge to the shallow unconfined aquifer is from local precipitation. Much of this precipitation is eventually lost to surface drainage and evapotranspiration, although some leaks downward to recharge the upper confined part of the tuffaceous member where pumping has locally reduced the artesian head. In the elevated hilly central area, precipitation infiltrates surface tuffs through which flow is mostly to the alluvial deposits around the base of the hills. However, some of the precipitation in the hilly central area does percolate down through tuffs in the underlying volcanics to ultimately recharge the deeper confined tuffs north and south of the hilly central area. The water level in well 6N/4W-36L2 reacts quickly to this recharge from precipitation in the central area; the majority of wells in the study area react more slowly and uniformly to recharge from the major source area to the east.

The infiltration boundary shown in figure 11 was defined from seepage runs made on the major creeks and tributaries in the study area during the winter, spring, and summer 1975. Significant losses were recorded where Milliken and Sarco Creeks cross tuff outcrops, where tributaries of Sarco and Tulucay Creeks cross the long fan deposit in the eastern part of the study area, and where other tributaries cross the geologic contact between the rhyolitic or andesitic member and the Tertiary deposits (fig. 3). It is estimated that 25,000 linear ft (7,600 m) of streambeds may be infiltration zones along the eastern edge of the study area (fig. 11).

From these infiltration studies and observation of springs and infiltration areas in the eastern hills, it was concluded that where tuffs are exposed or underlie shallow Quaternary deposits the infiltration rate from precipitation and runoff is greatest. In large areas where tuffs are not exposed, joints and fractures in otherwise impermeable rhyolitic and andesitic rock allow water to percolate to underground strata.

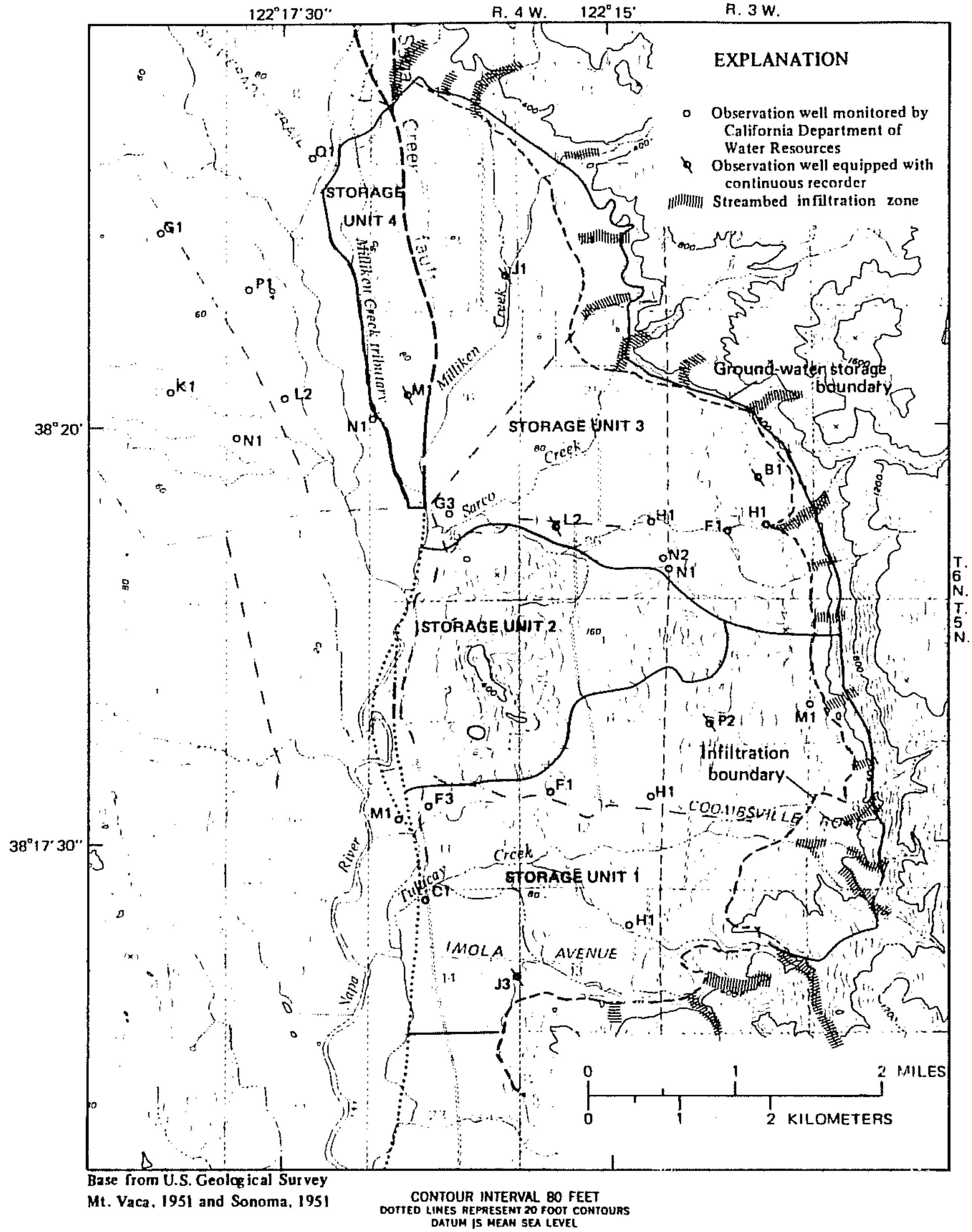


FIGURE 11.--Infiltration boundary, location of observation wells, and ground-water storage units.

The total amount of recharge during an average water year is estimated at 5,400 acre-ft (6.7 hm^3) from stream infiltration, subsurface inflow along the eastern hills, and infiltration at the higher altitudes within the study area. Stream infiltration of 3,050 acre-ft (3.8 hm^3) is based on measured and extrapolated seepage values over stream courses. Subsurface inflow of 2,100 acre-ft (2.6 hm^3) is estimated along the 9.5-mi (15.3-km) eastern boundary of the study area by applying Darcy's law where values of hydraulic gradient are known (averaging 0.1) and transmissivity values are calculated from specific capacities that average between 0.1 and 0.5 (gal/min)/ft or 0.02 and 0.1 (L/s)/m. Infiltration of 250 acre-ft (0.3 hm^3) is from precipitation estimated to percolate into the elevated tuffs in the central area. Of the estimated 5,400 acre-ft (6.7 hm^3) of recharge, about 3,000 acre-ft (3.8 hm^3) supplies the Milliken and Sarco Creeks drainage area and the remaining 2,400 acre-ft (2.9 hm^3) supplies the Tulucay Creek drainage area.

This ground-water recharge figure is in close agreement with estimates based on precipitation minus surface runoff, water diverted out of the study area, and evapotranspiration. It is about one-half of L. H. Haeki's original estimate in 1918 (Clark, 1919) of inflow to the basin from the 33-mi^2 (85-km^2) source area east of the infiltration boundary. Haeki's estimate was made on limited hydrologic data when the basin was in an early stage of development.

Discharge

Natural discharge across the Soda Creek fault into the alluvial aquifer of the Napa Valley is known to occur principally where the upper surficial deposits cross the Soda Creek fault and when water levels (or potentiometric heads) are higher than the base of these deposits. Based on the geology, Darcy's law, and water-level gradients, the average annual natural discharge into the Napa Valley is estimated to be 2,650 acre-ft (3.3 hm^3), under 1975 pumping conditions.

Before wells were drilled, the ground-water basin was in equilibrium. The average annual inflow (recharge) to the basin was balanced by the average annual outflow (discharge). Except for seasonal fluctuations which caused changes in artesian pressure, the total volume of water in storage was virtually stable over many years.

Under present conditions, discharge is the sum of natural discharge and the amount of water pumped by wells. An estimated 3,000 acre-ft (3.7 hm^3) of water is pumped each year from the ground-water basin in the study area and used for irrigation and domestic purposes. This pumpage results in a decrease in natural discharge, a reduction in the quantity of water in storage as indicated by long-term water-level declines, and a potential increase in recharge owing to reduction in evapotranspiration and rejected recharge. Recharge could increase because storage now remains deficient throughout more of the wet season. This is particularly true in the Milliken and Sarco Creeks area where storage remains below its 1918 value throughout the year.

Irrigation pumpage was calculated from power records for the years 1966-75 (table 1). It was computed from the total electrical energy used for pumping water and the electrical energy required to pump a unit volume of water. Data on the electrical energy used for pumping were obtained from metered accounts of the Pacific Gas and Electric Co. The electrical energy required to pump a unit volume of water was computed from pump efficiency tests made by the same company.

During the period 1968-75, irrigation pumpage in the study area remained fairly constant--about 2,000 acre-ft/yr (2.5 hm^3/yr). Most of the water is pumped from May through October. Pumpage in the part of the study area between the Soda Creek fault and the Napa River (fig. 3), along Silverado Trail, has increased as vineyard cultivation increased. Pumpage for this purpose represents only a small part of the ground water that is being removed from the Napa Valley alluvial aquifer as a whole. About two-thirds of the irrigation pumpage in the study area is from the lower drainage basins of Milliken and Sarco Creeks. Prior to 1968, irrigation pumpage within the study area was considerably less than 2,000 acre-ft/yr (2.5 hm^2/yr).

TABLE 1.--*Irrigation pumpage in the study area, 1966-75*

Year	Pumpage (acre-ft per year)
1966	976
1967	1,606
1968	1,907
1969	1,907
1970	2,079
1971	2,348
1972	1,902
1973	2,190
1974	2,199
1975	1,808

During the period 1968-75, domestic pumpage undoubtedly increased. Although no figures on domestic pumpage are available for 1975 it was estimated to be 1,100 acre-ft (1.4 hm^3) based on the number of dwellings using ground water, the city of Napa's 1973 population estimate of 2.94 persons per dwelling, and a per capita usage of 150 gal/d (570 L/d). County building permits indicate housing starts peaked in the study area during 1973. Water-well permits recorded with the County Health Department also peaked in that year. Domestic demand for ground water is stabilizing largely owing to zoning laws which have increased minimum lot size and permitted fewer homes to be built on available land.

Water-Level Fluctuations

Water-level fluctuations in the study area indicate the continuous adjustment of ground water in storage to changes in recharge and discharge. The amount of ground water in storage changes seasonally, from spring high to autumn low, and it can also change from year to year. Seasonal changes within the area are monitored by water-level measurements obtained during the spring high and the autumn low periods. Timing of the seasonal water-level measurements is determined by daily monitoring. Long-term trends are monitored by measurements of water levels over many years. The long-term trends reflect the recharge-discharge balance.

Seasonal changes.--Seasonal fluctuations in water levels in the study area can be calculated from the water-level contour maps for 1975 (figs. 8 and 9). The maps are based on measurements of 145 wells. The timing of these measurements was determined from the continuous water-level recorders on six observation wells (fig. 11) of various depths and tapping different geologic formations. Hydrographs for three of these wells (fig. 12) show the yearly cycle with a peak at the end of the wet season and a low late in the dry season. The maximum seasonal fluctuation was 60 ft (18 m) at well 6N/4W-23J1 (at the Silverado Country Club) and the minimum seasonal fluctuation was 3 ft (1 m) at well 5N/4W-14J3 (at the Napa State Hospital). These seasonal fluctuations are determined from daily high water levels.

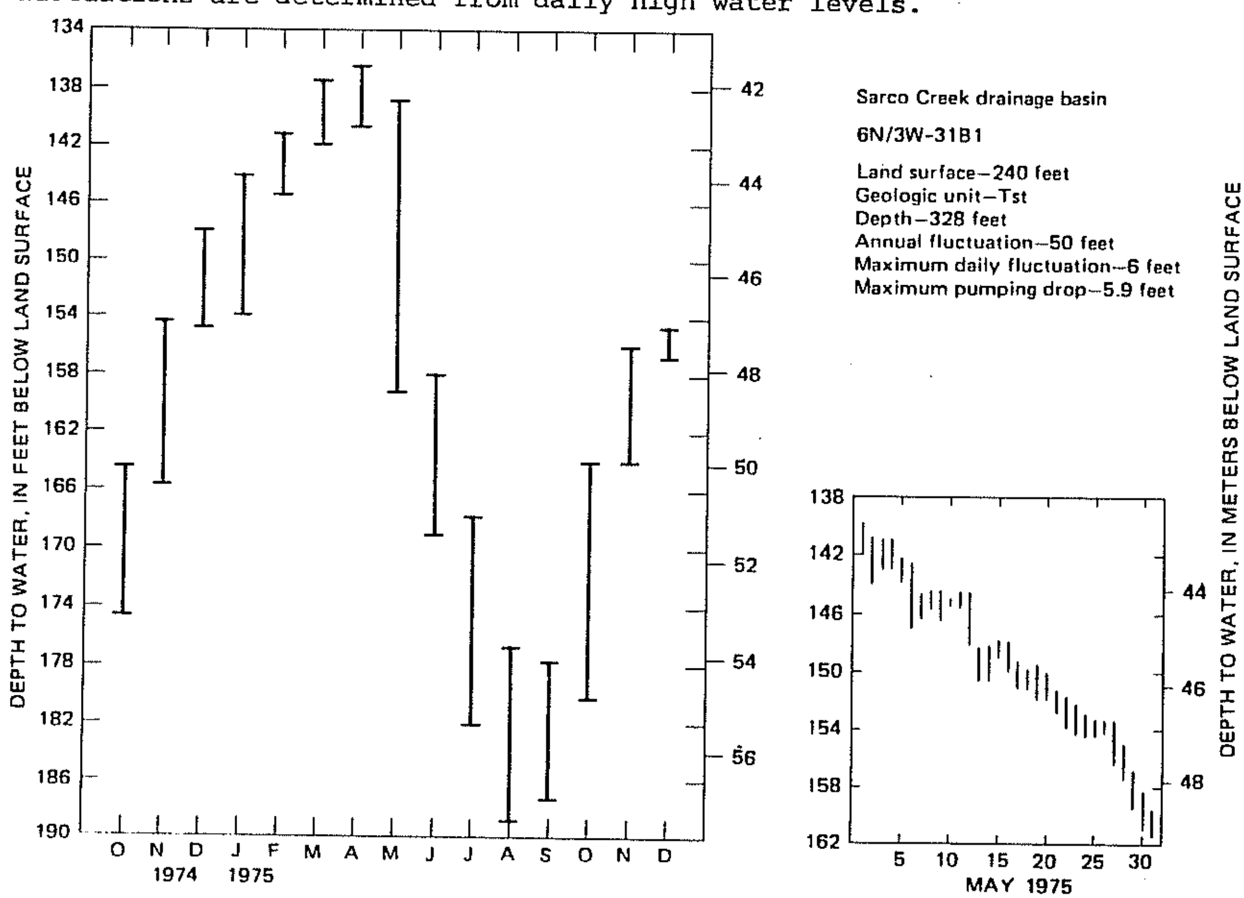


FIGURE 12.--Water-level fluctuations in three wells.

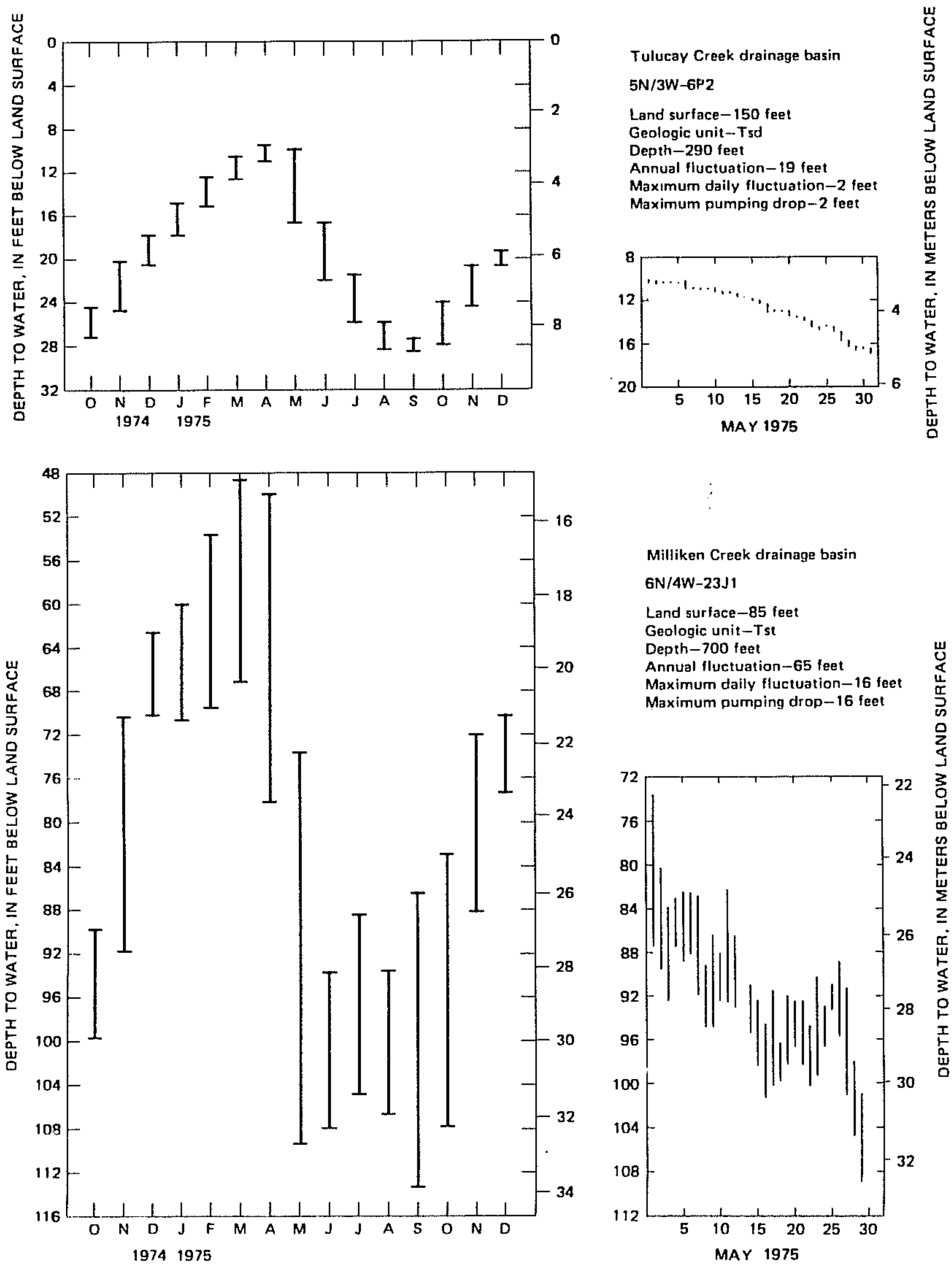
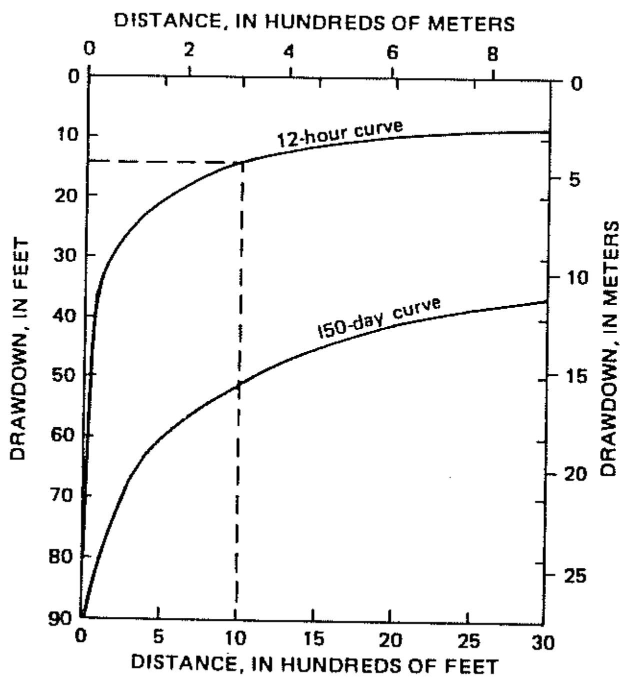


FIGURE 12.--Water-level fluctuations in three wells--Continued.

In the Milliken and Sarco Creeks area east of the Soda Creek fault, the average fluctuation was 24 ft (7.3 m), ranging from 5 to 60 ft (1.5 to 18 m). In the Napa River drainage area west of the fault, the average fluctuation was 27 ft (8.8 m), ranging from 5 to 50 ft (1.5 to 15 m). In the Tulucay Creek area, the average fluctuation was 14 ft (4.3 m); fluctuation in the northwestern and northeastern parts reached 30 ft (9.1 m), while in the southwestern part it was as little as 3 ft (1 m).

Besides seasonal fluctuations within the study area, water levels fluctuate daily, reacting to changes in barometric pressure and to pumping in the area. Observation wells in the tighter Tertiary sediments of the Sonoma Volcanics showed the least daily fluctuations in water levels (2 ft or 0.6 m) resulting from pumping in the area. Water levels in observation wells in the more permeable Sonoma tuff had greater daily variations (6 ft or 1.8 m). The water level in an observation well is influenced by the properties of the water-bearing materials, the rate and duration of pumping in nearby wells, and their distance from the observation well. One observation well (6N/4W-23J1) near a high-capacity well (both in the Sonoma tuffs) had a maximum 1-day fluctuation of 16 ft (4.9 m). Figure 13 shows how this fluctuation in the observation well could be caused by a nearby pumping well.



Drawdown curve based on Theis nonequilibrium formula (Johnson, 1972) and the following assumptions:

1. No water immediately available for recharge, and pumpage is from storage
2. Single well is pumped continuously for 12 hours at a rate of 750 gal/min (47L/s)
3. Transmissivity is 2,600 ft^2/d (240 m^2/d)
4. Storage coefficient of aquifer is 0.00016
5. Aquifer boundary is 3,000 ft (900 m) from pumping well

Continuous pumping for 150 days, for example from May 1 to October 1, would cause a maximum decline of 52 ft (16 m) at a distance of 1,000 ft (300 m), or less than four times that of the 12-hour pumping curve

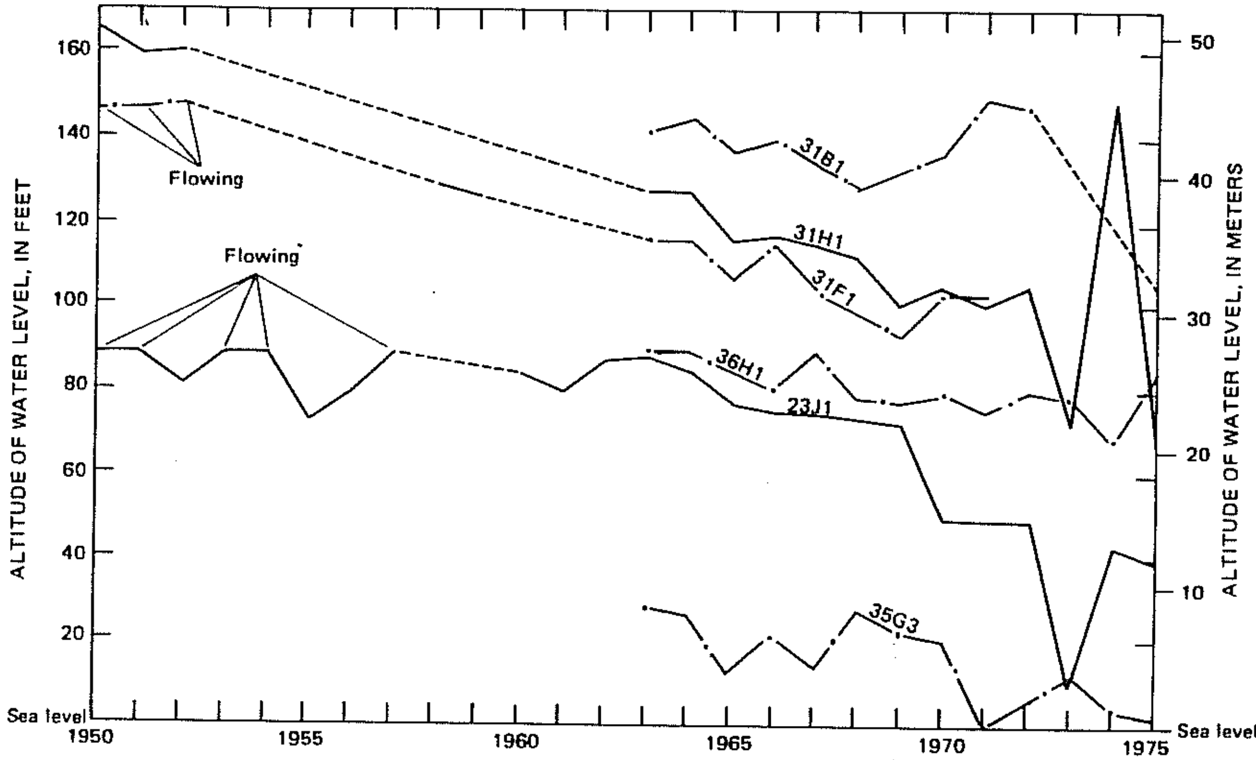
FIGURE 13.--Drawdown curve for high-capacity well in the Sonoma tuffs.

Long-term changes.--Information on long-term trends is available from observation wells (located in fig. 11) monitored by the State, principally during the spring of each year. The California Department of Water Resources (1975a) has monitored springtime water levels in the study area since the early 1960's; a few records go back to the early 1950's. These water levels may not show the spring peak; daily monitoring is needed as a control to determine accurately and consistently the spring peak water levels. For two of these wells (6N/3W-31B1 and 6N/4W-23J1), continuous hydrographs during 1975 (fig. 12) show how a steep drop in water levels after rains stop, coupled with daily pumping variations, affect annual spring measurements.

Figure 14 shows the spring water levels from 1950 through 1975 in six wells monitored by the Department of Water Resources in the Milliken and Sarco Creeks area. These water levels indicate a downward trend, between 1960 and 1975, of 2 to 4 ft/yr (0.6 to 1.2 m/yr) in general. As most of these wells are located near heavy drawdown zones (compare figs. 10 and 11), these water-level declines are not representative of the entire Milliken and Sarco Creeks area. Figure 10 indicates that water-level declines near Sarco Creek (between Hagen and Monticello Roads) and over most of the Milliken and Sarco Creeks area outside the deeper pumping cones are similar to those shown for wells 6N/4W-36H1 and 6N/4W-35G3. These wells showed declines, from 1963 through 1975, of about 1.5 ft/yr (0.6 m/yr).

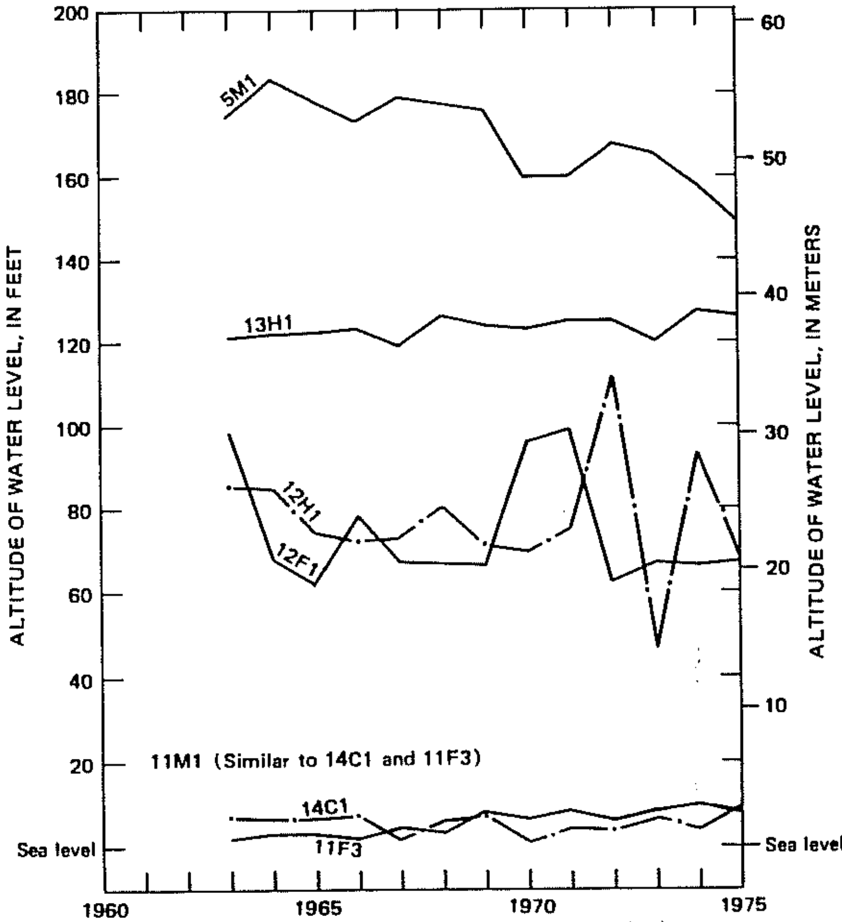
In the Tulucay Creek area, water levels monitored by the Department of Water Resources from 1963 through 1975 (fig. 15) generally show only slight recovery or loss. Only one well (5N/3W-5M1) monitored by the State, in the northeastern part of the area, showed a downward trend. Water levels in the southwestern part of the area have continued to rise since heavy pumping was curtailed in 1949 (U.S. Bureau of Reclamation, 1972). The water level in a well at Napa State Hospital (5N/4W-23C1) was more than 100 ft (30 m) below land surface in May 1932 (Bryan, 1932). In 1960 the water level was within 30 ft (9 m) of land surface (U.S. Bureau of Reclamation, 1972). In 1975 water was flowing through its partly sealed casing throughout the year. Another unused well (5N/4W-14P1) was also flowing. Well 5N/4W-14J3 recorded a depth to water of 116 ft (35.4 m) in December 1949 (Kunkel and Upson, 1960). In May 1975 the depth to water was 52 ft (16 m), comparable to the 56-ft (17-m) depth measured in May 1918.

In summary, long-term changes indicate a decline in water levels throughout the Milliken and Sarco Creeks area and a gradual depletion in ground-water storage. The declines from 1960 through 1975 averaged 15-30 ft or about 1.5 ft/yr (0.5 m/yr); overall declines in the area since 1918 may be 45-60 ft (14-18 m). In the Tulucay Creek area, water levels in the large central section fluctuate, but there has been no definite trend since 1963. Water levels in the southwestern section have risen, possibly to the 1918 levels. In the northeastern section, water levels downgradient from well 5N/3W-5M1 have declined in response to a new distribution of wells in the area, but water levels may be stabilizing.



Well number	Altitude of land surface (feet)	Depth of well (feet)
6N/3W-31B1	240.0	328
6N/4W-23J1	87.5	700
6N/4W-35G3	38.0	260
6N/3W-31H1	180.0	330
6N/3W-31F1	145.0	465
6N/4W-36H1	105.0	525

FIGURE 14.--Spring ground-water levels in six wells in the Milliken and Sarco Creeks area, 1950-75.



Well number	Altitude of land surface (feet)	Depth of well (feet)
5N/3W-5M1	255.0	117
5N/4W-13H1	132.0	364
5N/4W-12H1	121.0	478
5N/4W-12F1	130.0	203
5N/4W-14C1	17.0	220
5N/4W-11F3	16.0	165
5N/4W-11M1	13.0	58

FIGURE 15.--Spring ground-water levels in seven wells in the Tulucay Creek area, 1960-75.

Ground-Water Storage Capacity

The ground-water storage capacity is the total quantity of water in underground storage available for extraction. The amount of this storage that can be removed economically is termed the usable ground-water storage capacity (Poland and others, 1951, p. 621).

In an unconfined aquifer the storage capacity depends on the total volume of material that is or can be saturated and the material's specific yield--the ratio of the volume of water which can be drained by gravity to a unit volume of the saturated material. In a confined aquifer, storage capacity also depends on pressure, or head. The water stored in a confined aquifer increases slightly with an increase in head, but this accounts for only a small part of the aquifer's storage capacity. When pumping water from a confined aquifer, the head must be lowered below the base of the confining layer before dewatering of the aquifer can begin. Dewatering is necessary in order to withdraw the major part of the water available from storage in the confined aquifer. This part of the storage capacity of a confined aquifer depends on the same factors as does the storage capacity of an unconfined aquifer.

In calculating the ground-water storage capacity, it was not feasible to make field determinations of specific yield for the water-bearing materials; therefore, an estimated value for specific yield was assigned to lithologic units reported on drillers' logs. This relation of specific-yield values to drillers' terms is based on a San Joaquin Valley investigation (Davis and others, 1959) and on a previous Napa Valley investigation (Kunkel and Upson, 1960).

The study area was divided into four storage units (fig. 11). Unit 1 is the major part of the lower Tulucay Creek drainage basin, bounded on the west by the Soda Creek fault; unit 2 is the central hilly area with elevated tuffs that lies between the adjacent lowlands; unit 3 is the lower drainage basins of Milliken and Sarco Creeks east of the Soda Creek fault; and unit 4 is a small part of the Napa Valley that lies within the study area.

In estimating the specific yield for each depth interval, the storage units were subdivided into smaller zones of approximately 160 acres (65 hm^2). Well logs were then grouped and an average specific-yield value assigned by depth to each zone, thereby minimizing the effect on the unit of improper weighting of clustered wells.

Table 2 shows the number of well logs used in the calculation of the average specific yield, the amount of material classified, and the average specific yield for each depth interval. Sufficient data were available only to project specific-yield estimates to 500 ft (150 m), even though some wells penetrate to depths of 600-700 ft (180-210 m). Most new wells are being drilled to 150-500 ft (45-150 m); this constitutes the major zone of usable water.

TABLE 2.--*Average specific yield for selected depth intervals*

[Well footage, in feet; specific yield, in percent]

Ground-water storage unit	Depth intervals						Number of logs in unit
	10-50	50-100	100-200	200-300	300-400	400-500	
Unit 1							
Well footage	4,036	4,870	5,093	2,596	1,172	493	105
Average specific yield	4.3	4.7	4.4	5.2	5.2	3.7	
Unit 2							
Well footage	1,014	1,135	1,854	1,063	310	110	24
Average specific yield	2.2	1.9	2.8	3.7	3.6	3.3	
Unit 3							
Well footage	2,875	3,335	5,394	3,219	1,658	903	71
Average specific yield	5.4	4.0	4.3	4.6	4.6	4.0	
Unit 4							
Well footage	772	983	961	296	198	100	17
Average specific yield	5.0	4.9	4.8	5.3	4.8	5.2	

The storage capacity of each unit was estimated by multiplying the acreage, as determined by a planimeter, by the saturated thickness of the depth zone, times the specific yield. Table 3 shows the estimated storage capacities computed for the four units.

The storage shown in table 3 represents the volume of water stored in the 9,910-acre (4,010 hm^2) study area to a depth of 500 ft (150 m) when the material is saturated to within 10 ft (3 m) of the surface. By dividing the total volume of material (4,561,000 acre-ft or 5,624 hm^3) into the storage capacity (195,800 acre-ft or 241 hm^3 of water) an overall specific yield of 4.3 percent is obtained for the study area. This value is low when compared with the alluvial aquifer in the Napa Valley which has an average specific yield of 6 percent with values ranging from 25 percent for gravel to 3 percent for clay.

The accuracy of this method depends on an interpretation of the various drillers' descriptions of the lithology and on the quantity of data available. For example, the 100-200 ft (30-60 m) depth interval for storage unit 3 had the greatest well footage interpreted (5,394 ft or 1,644 m), but this is equivalent to only 54 wells completely penetrating the 100-200 ft (30-60 m) depth interval over an area of 3,584 acres (1,430 hm^2)--or one well every 66 acres (27 hm^2).

TABLE 3.--*Estimated ground-water storage capacity for*

[Volume, in acre-feet; storage capacity, in acre-feet

Ground-water storage unit (surface area, in acres)		Ground-water storage capacity					
		10-50		50-100		100-200	
		Volume	Storage	Volume	Storage	Volume	Storage
Unit 1	(3,873)	155,000	6,600	188,000	8,800	372,000	16,300
Unit 2	(1,638)	65,000	1,400	82,000	1,500	164,000	4,500
Unit 3	(3,584)	143,000	7,700	174,000	6,900	344,000	14,700
Unit 4	(815)	33,000	1,600	41,000	2,000	82,000	3,900
Totals	(9,910)	396,000	17,300	485,000	19,200	962,000	39,400

Total volume 4,561,000 acre-feet.
Average specific yield 4.3 percent.

Usable Ground-Water Storage Capacity

The ground-water storage capacity (based on unconfined conditions) shown in table 3 together with the relatively small amount of storage capacity resulting from confining pressure represents the total storage capacity of the study area. The usable ground-water storage capacity is considerably less. Of the water in the pore spaces which can be pumped, not all will be removed, owing to physical and economic limitations. Well spacing and depth are not uniform over the area, nor is it practical to try to dewater the saturated material to a depth of 500 ft (150 m).

Based on previous estimates of storage capacity in the younger, shallower alluvium of the Napa Valley (Kunkel and Upson, 1960; U.S. Bureau of Reclamation, 1972) and estimates of its usable storage (Faye, 1972; U.S. Bureau of Reclamation, 1972), the usable storage in the older, deeper Sonoma Volcanics is probably less than 20,000 acre-ft (25 hm^3), or 10 percent of the ground-water storage capacity to a depth of 500 ft (150 m). Extracting this much water during the dry season would lower water levels considerably below sea level in many areas.

saturated material, based on unconfined conditions adjusted for specific yield from table 2]

for indicated depth zones						
200-300		300-400		400-500		Storage
Volume	Storage	Volume	Storage	Volume	Storage	
356,000	18,500	341,000	17,700	325,000	12,000	79,900
164,000	6,000	163,000	5,800	163,000	5,300	24,500
333,000	15,300	319,000	14,600	308,000	12,300	71,500
82,000	4,300	82,000	3,900	82,000	4,200	19,900
935,000	44,100	905,000	42,000	878,000	33,800	195,800

Changes in Ground-Water Storage

Seasonal changes in the quantities of ground water in storage occur owing to removal of water from both the upper unconfined and underlying confined parts of the system. In the confined part water removal reflected by reduced pressure was about 350 acre-ft (0.4 hm^3) for 1975, based on artesian head losses, estimated storage coefficients, and areal extent of the aquifer. Estimated changes in storage in the upper unconfined parts of the system are shown in table 4 for each of the storage units. The estimated total quantity of ground water removed in 1975 by dewatering the unconfined aquifers, partly by leakage into the underlying confined aquifers, is about 6,600 acre-ft (8.1 hm^3). This estimate is based on the difference in storage between the spring high and autumn low water levels and the specific-yield values in table 2. The seasonal change in the quantity of ground water in storage in 1975 was about one-third the estimated usable ground-water storage capacity.

A comparison with pumpage estimates for 1975 indicates that less than one-half the change in storage, or 3,000 acre-ft (3.7 hm^3), was pumpage. Less than 30 percent of the water removed from storage in unit 1 was pumpage, but pumpage accounts for about 70 percent of that removed from unit 3. For the study area as a whole, annual pumpage of about 3,000 acre-ft (3.7 hm^3) is an appreciable part of the annual change in storage.

TABLE 4.--*Seasonal change in ground-water storage, 1975*

[Storage, in acre-feet]

Ground-water storage unit	Ground-water storage above sea level		Annual change in storage
	Spring	Autumn	
Unit 1	18,200	16,200	2,000
[1]Unit 2	3,000	2,500	500
Unit 3	9,770	6,970	2,800
Unit 4	1,550	260	1,290
Totals	32,520	25,930	6,590

[1]Estimates based on few data.

As pumpage increases, its effect on long-term changes in ground-water storage is moderated by a consequent reduction in natural ground-water discharge to the west through the upper unconfined deposits. This reduction will continue, but ultimately natural ground-water discharge can be reduced no further. Continued increase in pumping will then tend to deplete the storage units, with consequent further declines in water levels. In storage unit 1 (Tulucay Creek area), water levels for the period 1966-75 indicate no significant change; some areas have declined and others have recovered. In storage unit 3 (Milliken and Sarco Creeks area) the lowering of water levels from year to year indicates gradual depletion of the aquifer in that area.

To deplete the 20,000 acre-ft (25 hm^3) of usable ground water in storage, assuming normal recharge-discharge conditions and a uniform distribution of wells throughout the study area, it would be necessary to pump at double the 1975 rate for the 8-year period 1976-83. With natural discharge but no recharge to the ground-water system, the 1975 pumpage rate could theoretically be maintained for about 6 years. However, with the unequal distribution of pumpage over the study area, the period for sustained pumpage without recharge would be much less in heavily pumped localities.

In the lower drainage basins of Milliken and Sarco Creeks (storage unit 3) the average water-level decline of 1.5 ft/yr (0.46 m/yr) may represent a reduction of 250 acre-ft (0.31 hm^3) of water per year in storage. At the 1975 pumping rate in storage unit 3, and with normal recharge, it might take 30 years to deplete the 7,000 acre-ft (8.6 hm^3) of water in usable storage. Without recharge, pumpage in storage unit 3 could be continued at the 1975 rate for 2 or possibly 3 years, depending on well distribution and depth.

CONCLUSIONS

The quantity of ground water available in the study area depends on three main factors--the specific yield of the reservoir material, the size of the reservoir, and recharge to the reservoir. Any one of these factors could limit the available supply of ground water. If the materials composing the reservoir are fine grained, poorly sorted, or cemented they may not transmit water at a sufficiently rapid rate to supply it in quantity. If the reservoir is small it may be depleted rapidly by pumping unless there is continuous recharge at a rate equal to the rate of withdrawal. If recharge is less than withdrawal, the supply will not be replenished in full, and water levels will decline even though the yield may be large when the reservoir is first tapped.

The specific yield of materials in the lower Milliken-Sarco-Tulucay Creeks area is highly variable even within the same geologic unit. The predominance of fine sediments and impermeable rubble cemented by clay severely limits the yield of many wells, while a few permeable zones permit high yields for limited periods of time. The average well has a specific capacity of less than 3 (gal/min)/ft or 0.6 (L/s)/m of drawdown. The porosity distribution within the different geologic units indicates an overall average specific yield of about 4 percent over the study area under unconfined conditions--2 percent less than the average specific yield of the alluvial deposits in the main Napa Valley. Geologic formations in the study area are less homogeneous and permeabilities are lower than in the Napa Valley; these are major factors limiting individual well yields.

The size of the reservoir is more than adequate for the 3,000 acre-ft (3.7 hm^3) of water pumped annually. Well logs indicate the occurrence of water-bearing formations generally to a depth of 500 ft (150 m) over the study area with a storage capacity of 196,000 acre-ft (242 hm^3) and a usable storage capacity of 20,000 acre-ft (25 hm^3). The change in ground-water storage in 1975 was 6,600 acre-ft (8.1 hm^3), causing an average fluctuation in water levels of 20 ft (6 m) over the study area. With natural discharge but no recharge to the ground-water system, pumpage could theoretically be maintained at the 1975 rate for about 6 years in the area as a whole. With the unequal distribution of pumpage over the study area, the period for sustained pumping without recharge would be much less in heavily pumped areas, such as those in the lower drainage basins of Milliken and Sarco Creeks (storage unit 3). Pumping at the 1975 rate of about 2,100 acre-ft/yr (2.6 hm^3) in storage unit 3 could continue for 2 or possibly 3 years without recharge. With some recharge the period over which the water could be withdrawn is substantially increased.

Ground-water recharge seems to be inadequate to marginal throughout the study area under the 1975 demand. About 10 percent of precipitation from the Howell Mountains in the east, an area of about 33 mi^2 (85 km^2), eventually migrates to the study area's ground-water system. Low transmissivities impede the infiltration and movement of this water from the source areas.

For the ground-water supply in the lower Milliken-Sarco-Tulucay Creeks area to be permanent, discharge cannot continually exceed recharge. This does not mean that at times the discharge may not exceed recharge. In California this may happen for several years, but the overdraft should not be so great that a series of wet years will not bring the water levels back to normal. A water level stabilized below its original level does not preclude a permanent supply if the depth to water is within economic pumping lifts; but it does mean the water removed in permanently lowering the water level has depleted the supply in the previously saturated materials.

Water-level declines of about 1.5 ft/yr (0.5 m/yr) in the Milliken and Sarco Creeks area (storage unit 3) indicate recharge is not supplying the additional water needed to equal pumpage under the climatic conditions existing during the period 1965-75. Present pumpage in this storage unit is estimated at 2,000 acre-ft/yr (2.5 hm^3/yr), part of which is obtained from depleting existing storage. Pumping probably has also reduced the ground-water outflow.

Distributed over the Tulucay Creek area (storage unit 1), pumpage of about 600 acre-ft/yr (0.7 hm^3/yr) is not exceeding recharge and, over the long term, water levels seem stable. Pumping in the area caused considerable water-level declines during the late 1940's. At that time wells were concentrated in the southwestern part of the area at Napa State Hospital, and pumpage exceeded 400 acre-ft/yr (0.5 hm^3/yr) and reached 800 acre-ft/yr (1 hm^3/yr) (U.S. Bureau of Reclamation, 1972). Pumping cones extended into secs. 12 and 13, T5N/R4W (Kunkel and Upson, 1960). Pumpage in the mid-1970's is more uniformly distributed in the Tulucay Creek area. There is little pumpage in the southwestern part. There are indications of locally heavy pumpage in the northwestern part and a heavy concentration of domestic pumpage, with some local interference between pumping cones, in the northeastern part.

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