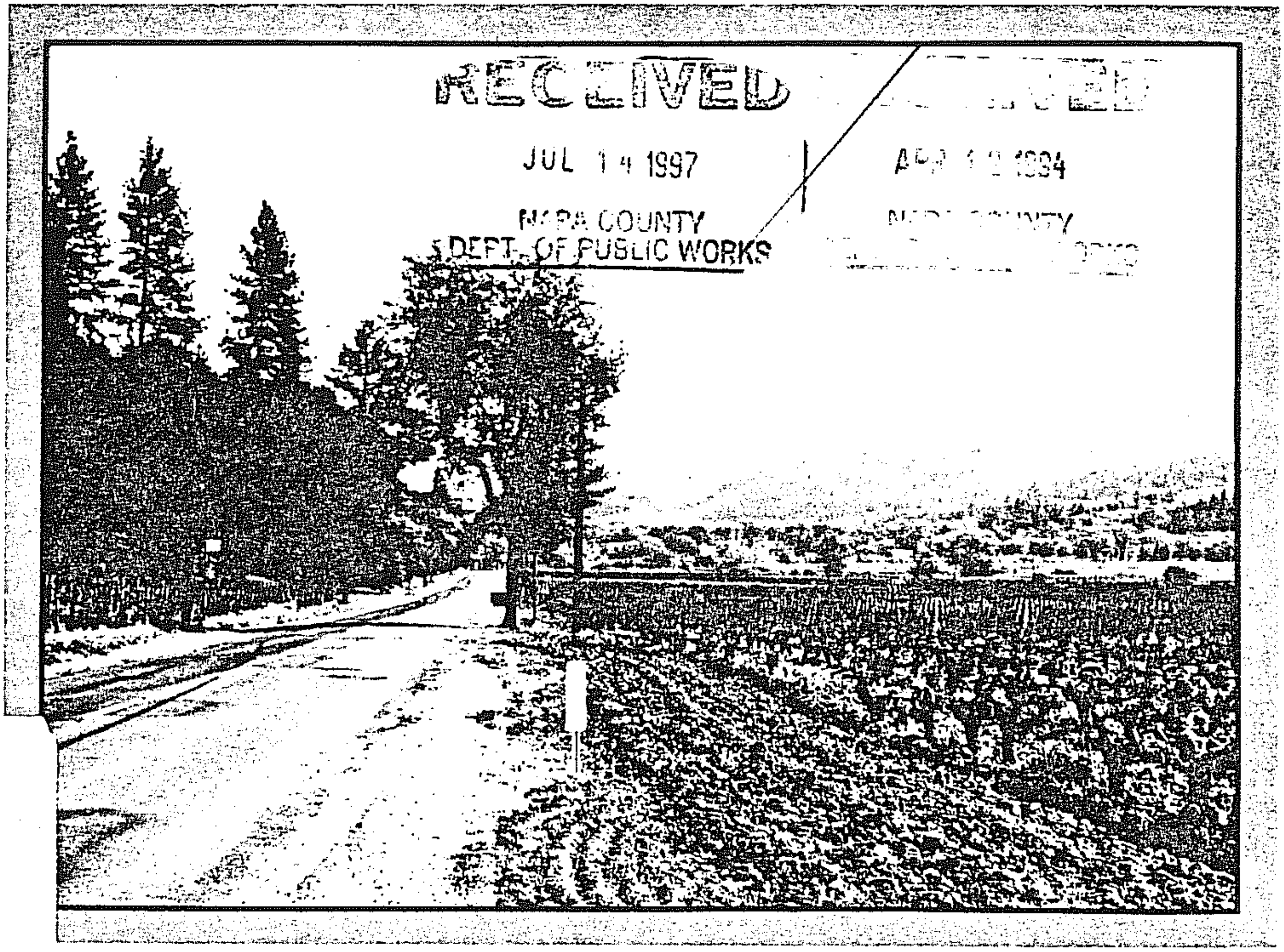
GROUND-WATER HYDROLOGY of NORTHERN NAPA VALLEY CALIFORNIA



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A model study of the alluvium in northern Napa Valley indicates that the alluvial aquifer is capable of supplying most of the future water needs of the area. Part of the hydrologic budget for the alluvium was derived from noting rainfall-runoff relations and rainfall and water-table recovery relations.

Hydrothermal, sodium chloride ground water occurs in the northern part of Napa Valley and is only marginally suitable for irrigation. Model studies indicate that limited migration of sodium chloride water into intensively pumped parts of the alluvial aquifer probably will not be a serious problem.

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CALIFORNIA

By Robert E. Faye

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Water-Resources Investigations 13-73

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

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GROUND-WATER HYDROLOGY OF NORTHERN NAPA VALLEY, CALIFORNIA

By Robert E. Faye

ABSTRACT

The alluvium of northern Napa Valley is the principal aquifer of the area and is capable of yielding as much as 3,000 gallons per minute to wells. Generally the larger-yielding wells are along the Napa River where the alluvium is thickest and most permeable. Recharge to the alluvium is chiefly by percolation from streams and infiltration of precipitation. Discharge is chiefly flow to the Napa River, evapotranspiration, and pumpage from wells. Both recharge to, and discharge from, the alluvial aquifer are sensitively influenced by rainfall. About 190,000 acre-feet of water is presently (1972) stored in the alluvium of northern Napa Valley. Future annual water use in the project area will probably vary between 12,000 and 35,000 acre-feet and, for most purposes, can be supplied by the alluvial aquifer even during extended periods of limited rainfall. Generally low transmissivities in the alluvium, however, limit the opportunity for obtaining sustained, large yields from wells in much of the valley and require that large-scale development and operation of wells in much of the area be planned and synchronized.

Sustained drought conditions in the Napa Valley accompanied by expected increases in the use of ground water will probably cause significant reductions in the base flow of the Napa River and cause many shallow wells in the area to dry up.

Sodium chloride ground water occurs near Calistoga and in the vicinity of Oakville and in some places is not suitable for irrigation. Model studies indicate that limited migration of sodium chloride water into intensively pumped parts of the aquifer probably will not be a serious problem.

INTRODUCTION

Location and Extent of Project Area

The project area is within Napa Valley in the central Coast Ranges of California about 40 miles northeast of San Francisco (fig. 1). Comprising the northern part of Napa Valley, the project area extends from the vicinity of Oak Knoll Avenue, north of the city of Napa, to the northern end of the valley, north and west of the city of Calistoga. The area is a distinct topographic basin consisting of about 60 square miles of valley floor surrounded on three sides by foothills and mountain ranges.

Purpose and Scope

The purpose of this study was to assess the occurrence, availability and quality of ground water in the northern part of Napa Valley.

This report summarizes the geology and water-bearing characteristics of geologic formations; discusses the spatial and hydrologic parameters of water-bearing units with special emphasis on the alluvial aquifer; provides a qualitative and quantitative hydrologic assessment of the alluvial aquifer; discusses the quality of ground water with respect to occurrence, chemical composition, and use; and evaluates the quality of base flow and seasonal runoff in the Napa River.

The qualitative and quantitative hydrologic assessment of the alluvial aquifer includes a determination of: (1) The spatial distribution of thickness and hydraulic conductivity in the alluvial aquifer; (2) the quantity of water presently stored in the alluvial aquifer; (3) quantities of recharge to, and discharge from, the alluvial aquifer under given climatologic conditions; (4) recent quantities of pumpage from the alluvial aquifer; and (5) the response of water levels in the alluvial aquifer to specified pumping and recharge conditions.

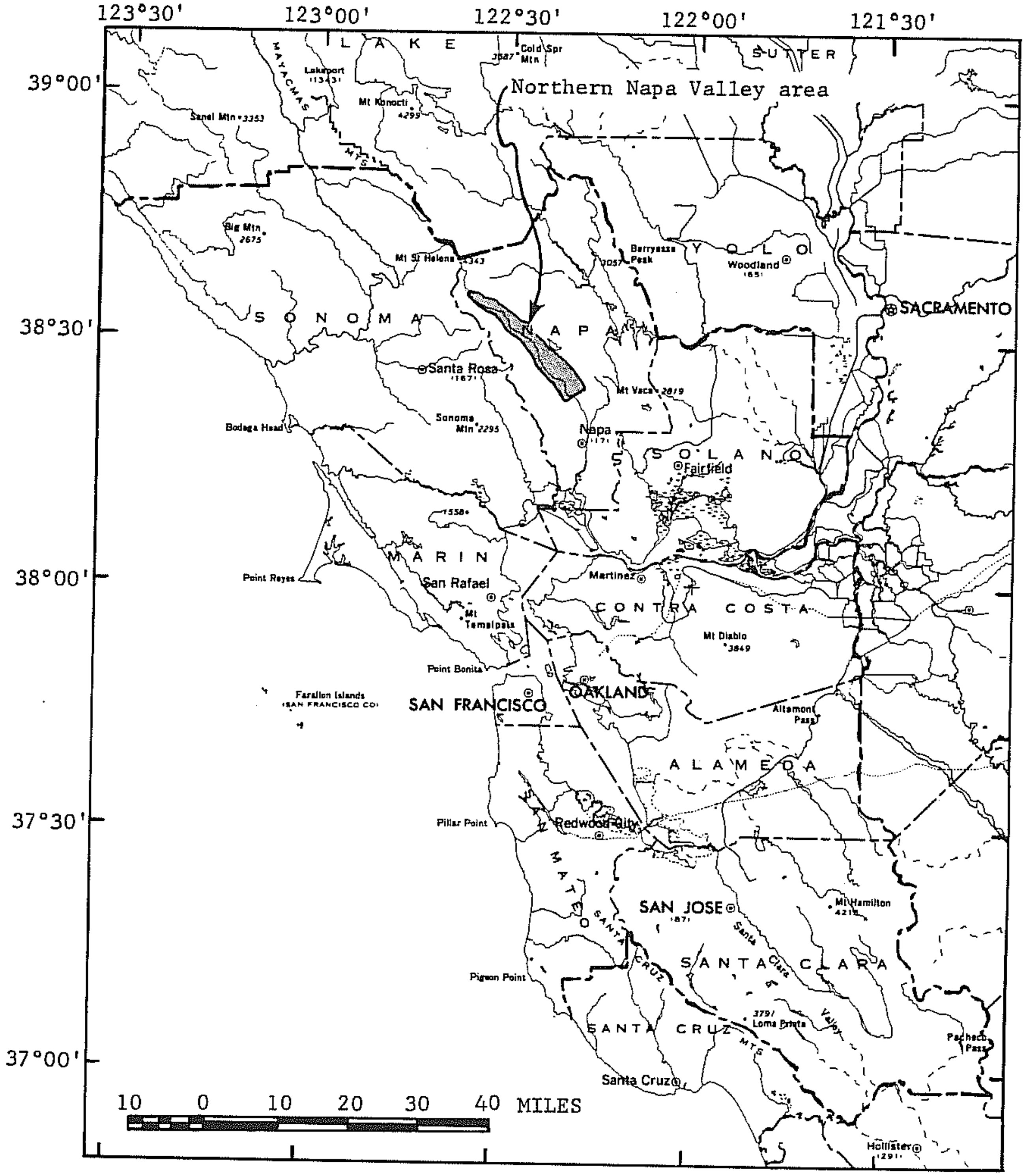

FIGURE 1.--LOCATION MAP OF PROJECT AREA.

The assessment of ground-water quality includes: (1) A chemical classification of ground water; (2) a determination of the occurrence of ground water containing high concentrations of boron and other undesirable constituents; (3) a determination of the redistribution of ground water of poor quality in the alluvial aquifer under specified recharge and pumping conditions; and (4) an evaluation of ground-water quality with respect to the use of ground water as an irrigation and domestic water supply.

The scope of this study included: (1) An evaluation of geologic and hydrologic data for the Napa Valley area; (2) the development of a transient-state mathematical model that adequately simulated the ground-water hydrology of the alluvial aquifer; and (3) a model analysis to evaluate the response of water levels in the alluvial aquifer to critical climatologic and pumping stresses.

Previous Work

The earliest known hydrologic work in the Napa Valley was an unpublished U.S. Geological Survey inventory of "deep" wells in 1895. Waring (1915) cataloged the various hot springs and "health resorts" located in the project area in the early 1900's. More comprehensive water-resources studies were completed by Bryan (1932) and Kunkel and Upson (1960). Interest in increased utilization of ground water for irrigation and frost protection resulted in ground-water investigations by the U.S. Bureau of Reclamation (1966) and the Napa County Flood Control and Water Conservation District (1972).

Early geologic work was done by Osmont (1905) and Dickerson (1922). Mapping of the volcanic rocks, older consolidated sedimentary rocks, and younger unconsolidated deposits was completed by Weaver (1949), Kunkel and Upson (1960), and Koenig (1961, 1963). Crutchfield (1953) and Johnston (1948) prepared detailed geologic maps of areas in the Calistoga quadrangle.

A soil survey and review of the contemporary agricultural industry in Napa County was issued by Carpenter and Cosby (1938). As of 1972, the U.S. Soil Conservation Service was preparing a comprehensive report on the soils of Napa County.

Well-Numbering System

The well-numbering system used by the Geological Survey in Napa Valley shows the location of wells and springs according to the rectangular system for the subdivision of public land. For example, in the number 9N/7W-26R2, which was assigned to a well located near Calistoga (fig. 3), the part of the number preceding the slash indicates the township (T. 9 N.,); the number between the slash and the hyphen indicates the range (R. 7 W.); the digits between the hyphen and the letter indicate the section (sec. 26); and the letter following the section number indicates the 40-acre subdivision of the section, as shown in figure 2. Within each 40-acre tract the wells are numbered serially, as indicated by the final digit of the number. Thus, well 9N/7W-26R2 is the second well to be listed in the SE¼SE¼ sec. 26. The letter X after the section number indicates the site was located only to the section.

Definitions of Hydrologic Terms

Aquifer: An aquifer is a formation, group of formations, or a part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Artesian: Synonymous with confined.

Base flow: Sustained or fair weather runoff composed largely of ground-water effluent.

Cone of depression: A three-dimensional conical depression that develops around a pumping well, the outer boundary of which, defines the area of influence of the well.

Confined water: Ground water that is under sufficient pressure to rise above the level at which it is encountered by a well, but which does not necessarily rise to or above land surface.

Evapotranspiration: The total water removed from an area by transpiration and by evaporation from soil, snow, and water surfaces.

Gaining stream: A gaining stream is a stream, or reach of a stream, whose flow is being increased by inflow of ground water.

Hydraulic conductivity: A measure of an aquifer's capacity to transmit water, expressed in feet per day (fpd) or feet per second (fps).

Losing stream: A losing stream is a stream, or reach of a stream, that is losing water to the ground-water reservoir.

pH: The negative logarithm of the hydrogen ion concentration. A neutral water has a pH of 7; an alkaline water a pH greater than 7; and an acid water a pH less than 7.

Permeability: Synonymous with hydraulic conductivity.

Potentiometric: A surface that represents the static head of water in an aquifer.

Specific capacity: The discharge of a well expressed as rate of yield per unit of drawdown, generally gallons per minute per foot of drawdown (gpm/ft).

Specific yield: The specific yield of a rock or soil, with respect to water, is the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume.

Transmissivity: Transmissivity is the rate of flow in feet squared per second (ft^2/s) at prevailing water temperature, through a 1-foot wide vertical strip of aquifer extending the full saturated height of the aquifer under a unit hydraulic gradient.

Water table: The water table is that surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells penetrating to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

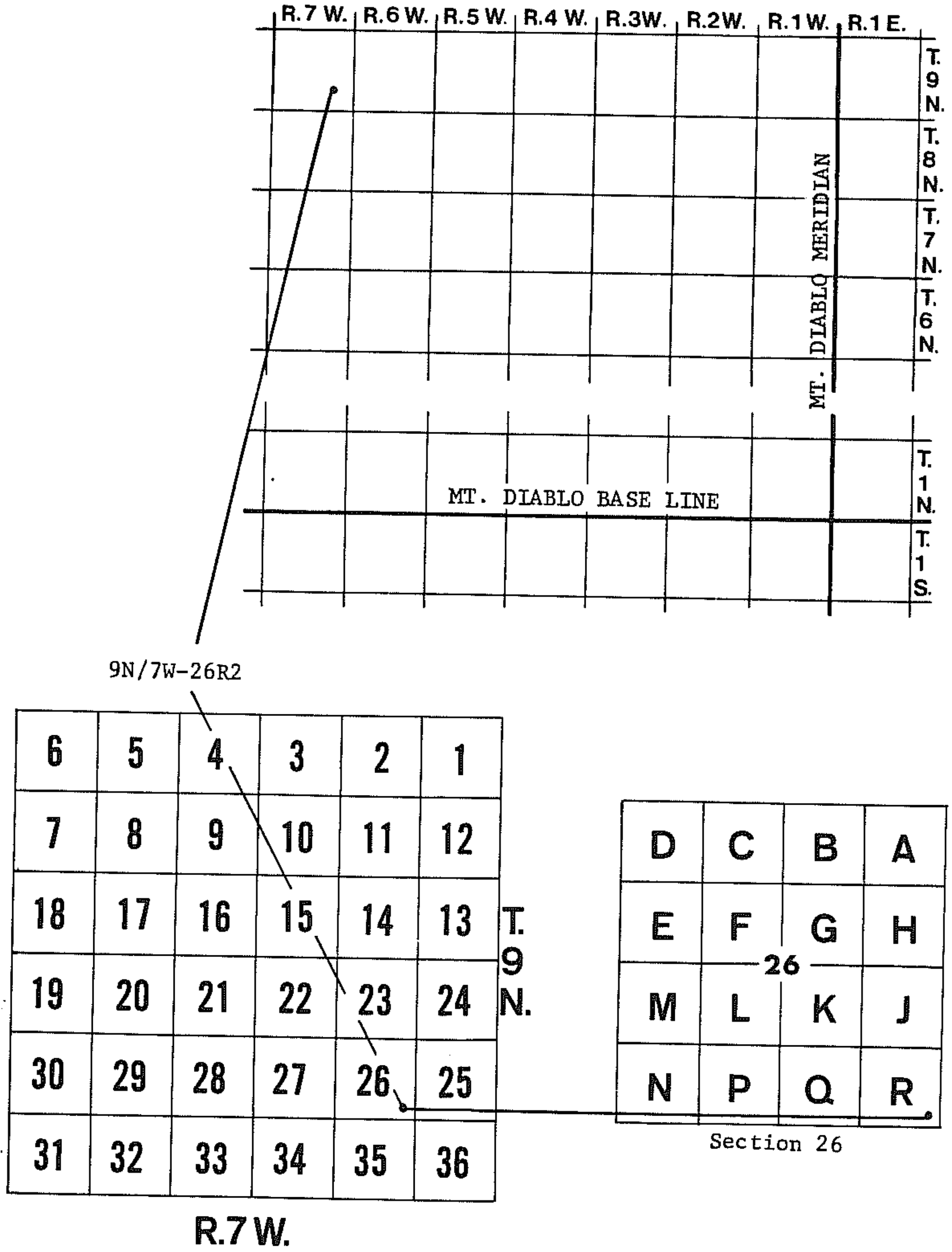

FIGURE 2.--WELL-NUMBERING SYSTEM.

Acknowledgments

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GEOGRAPHY

Topography

Napa Valley is a distinct topographic basin consisting of a central valley floor with bordering foothills and mountains. Situated within the north-central Coast Ranges, the basin is oriented generally to the northwest, parallel to the California coastline (fig. 1). The northern part of the Napa Valley--about 24 miles of alluvial plain along the Napa River--is of major interest in this investigation. Mountain ranges surround the valley on three sides and include the Mayacmas Mountains to the north and unnamed sections of the Coast Ranges to the east and west. The bordering mountains are, for the most part, steep and brush covered. Peaks in the surrounding mountain ranges have elevations ranging from less than 1,000 feet to more than 4,000 feet. The southern border of the project area was arbitrarily placed across the Napa Valley in the vicinity of Oak Knoll Avenue (fig. 3).

The approximately 60 square miles of alluvial plain in the project area slope gently from the periphery of the valley toward the Napa River. The plain is less than a mile wide at the northern end of the valley, but gradually broadens to a width of about 3½ miles in the vicinity of Oak Knoll Avenue. The elevation of the valley floor drops from 343 feet at Calistoga to about 50 feet near the Napa River at Oak Knoll Avenue.

The basin is drained by the Napa River and its principal tributaries; Conn, Dry, Sulphur, Rector, and Mill Creeks. The Napa River is incised within steep banks of alluvium, as are the lower parts of the principal tributaries. The tributary streams are, with few exceptions, intermittent under most climatological and water-use conditions. The Napa River is perennial except during years of less than normal rainfall. At present (1972) a significant part of the low flow of the Napa River is water discharged from municipal sewage-treatment plants at Calistoga and St. Helena. Controlled releases of water are made to downstream users from Lake Hennessey on Conn Creek.

Climate

The climate in Napa Valley is characterized by warm, dry summers and cool, moist winters. Most of the annual precipitation occurs as rain that falls during the winter and early spring months. The distribution of this precipitation is dependent upon the topography and the prevailing winds. Precipitation generally increases with increases in topographic elevation. Most of the rain comes with southwesterly winds and falls in a zone of high rainfall extending south to north along the slopes of the bordering western mountains. A less pronounced zone of high rainfall extends similarly along the slopes of the eastern mountains, but the precipitation is not as great there due to the generally lower elevations. The area of highest rainfall occurs at the northern end of the valley where the eastern and western rainfall zones join and are influenced by rain-bearing winds coming through wind gaps in the vicinity of Calistoga.

Rainfall data are available from U.S. Weather Bureau Climatological Data for California and from Kunkel and Upson (1960). For purposes of this report the rainfall record at St. Helena is considered most representative of annual precipitation throughout the project area, and references to rainfall or precipitation amounts refer to this record. The mean annual precipitation at St. Helena over the period of record 1906-70 is 33.5 inches. The standard deviation is 11.3 inches and the skew coefficient is 0.49. The median annual precipitation at St. Helena was 30.6 inches, or very near to the mean value. The small difference between mean and median values and the correspondingly small skew coefficient indicate that a frequency distribution of the annual rainfall at St. Helena will be generally symmetrical about the mean. Thus, for purposes of this report, rainfall is assumed to be normally distributed.

Table 1 shows the probability of exceeding, in any water year, the given amount of rainfall at St. Helena along with the probability that this rainfall will be exceeded for 2 years, consecutively. These probabilities are based on the assumption that values of annual rainfall at St. Helena are normally distributed, mutually exclusive, and independent.

TABLE 1.--*Probability that given amounts of annual rainfall at St. Helena will be exceeded in 1 and 2 water years, consecutively*

Annual rainfall at St. Helena (inches)	Probability that annual rainfall at St. Helena will be exceeded in any water year (percent)	Probability that annual rainfall at St. Helena will be exceeded in 2 consecutive water years (percent)
10	98	96
15	95	90
20	88	77
25	77	59
30	62	38
35	45	20
40	28	8
45	15	2
50	7	.5
55	2	.0
60	1	.0

Variations in annual rainfall for a single station within the project area can be very large. For example, only 12 inches of precipitation was recorded at St. Helena during the 1924 water year, whereas 59 inches was recorded during the 1914 water year.

Significant temperature variations also occur in the project area, largely as a result of the uneven topography. The lower valley troughs and the higher elevations of the surrounding mountains are generally cooler in the summer, and have the lower winter temperatures. The foothills and the alluvial plain are generally warmer, having a frost-free season at least a month longer than the colder zones. The less extreme temperatures in these areas result partly from the thermal insulating properties of night and morning fog blown in from San Pablo Bay. This fog, common during all seasons of the year, decreases the amount of heat received from the sun in summer and decreases radiation from the earth in winter. The mean annual temperature of the project area is about 60°F (15.5°C); there is a seasonal variation about this mean of approximately ±30 degrees. Temperature extremes of 115°F (46°C) and 10°F (-12.0°C) have been recorded at St. Helena.

During the winter months, temperatures below freezing (32°F or 0°C) occur infrequently. The average frost-free season in the valley proper spans 250 days from March 18 to November 22. This time period varies considerably, however, from year to year and from place to place within the valley. For example, frost has occurred at Napa as late as May 26 and as early as October 12. The period from March 15 to May 15 is especially critical to the grape industry because a frost at this time of year seriously reduces crop yields. Statistical information concerning the severity, distribution, and occurrence of frost periods is available from the Napa County Flood Control and Water Conservation District (1972).

GEOLOGY

The geologic formations in the project area were mapped by Weaver (1949), Taliaferro (1951), Kunkel and Upson (1960), and Koenig (1961, 1963). A brief description of the geologic formations, their history, their relation to one another, and their water-bearing properties is considered sufficient for purposes of this report. More detailed information may be obtained in the references cited above.

The floor of the Napa Valley consists of a relatively thin cover of alluvium of Quaternary age overlying a thick section of Sonoma Volcanics of Pliocene age, consolidated sedimentary rocks of Cretaceous age, sedimentary and metamorphic rocks of the Franciscan Formation, and ultrabasic plutonic rocks and serpentine of Jurassic age. As shown in figure 3, the Sonoma Volcanics and the older sedimentary, metamorphic, and ultrabasic rocks crop out in Napa Valley and constitute the bedrock in the project area.

Geologic History

The geologic activities that have had the most direct bearing on the hydrologic system of present-day Napa Valley began during the Miocene epoch. In early and middle Miocene time, the area now known as Napa Valley was part of a structural depression occupied by the Miocene sea. During that time, severe erosion from land masses which bordered the sea caused thousands of feet of sediment to be deposited in the depression.

During late Miocene and early Pliocene time, a general uplift occurred and the Miocene sea regressed. The Napa Valley area probably was above sea level during most of early Pliocene time and was modified by crustal movements, volcanic activity, and erosion. Large areas of the uplifted marine deposits were blanketed by pumice and volcanic ash or covered by flows of basalt, andesite, and rhyolite. In quiet periods between the volcanic episodes, stream valleys and topographic depressions were partly filled with deposits of gravel, sand, and clay, and diatomaceous deposits were formed in fresh or brackish-water lakes. In middle and late Pliocene time, volcanic activity increased and large areas were covered by pumice, welded tuff, and flows of primarily rhyolitic composition.

In early Pleistocene time the region was again uplifted and subjected to extensive erosion. During this time several oscillations of the sea level, accompanied by crustal movements, placed the land surface alternately above and below water. With each of these oscillations, the hydraulic gradients of streams draining the Napa Valley area were altered and readjusted. Stream channels shifted, gradients were changed, and sediments were deposited and eroded at varying rates. Hence, local deposits of early Quaternary age in Napa Valley are highly variable with respect to their lithology, thickness, and hydrologic properties. In middle Pleistocene time a general downwarping of the Napa Valley and surrounding areas forced the streams draining the basin to make further adjustments.

The general topographic form of the present-day Napa Valley area is the result of erosion and deposition that has taken place since the middle Pleistocene downwarping and the last great sea-level rise that occurred following the end of the last Ice Age.

Geologic Units and Their Water-Bearing Properties

For this report, the geologic units of the Napa Valley area have been divided into ultrabasic rocks of Jurassic age; the Franciscan Formation and its metamorphic equivalents of Jurassic and Cretaceous ages; consolidated sedimentary rocks of Cretaceous age; Sonoma Volcanics of Pliocene age; and alluvium of Quaternary age. Figure 3 shows the areal distribution and relative ages of the geologic units.

Ultrabasic Rocks

The ultrabasic rocks of Jurassic age include serpentine, peridotite, dunite, pyroxenite, and minor amounts of silica-carbonate rock derived from alteration of serpentine. The rocks occur as lenses, sheets, and irregularly-shaped masses within, or along, the boundaries of Jurassic equivalents of the Franciscan Formation. The serpentine masses probably were formed by alteration of original igneous intrusive material. Chemical analyses of the serpentinized intrusions (Bailey, Irwin, and Jones, 1964) indicate that the rock is composed of almost equal parts of silica and magnesium with residual amounts of other rock-forming minerals. These rocks are poorly permeable and not important as a source of water supply.

Franciscan Formation

The Franciscan Formation of Jurassic and Cretaceous ages is a heterogeneous assemblage of graywacke, altered volcanic rocks and associated metamorphic rocks, shale, chert, limestone, and conglomerate. In the Napa Valley area, the Franciscan Formation is chiefly consolidated graywacke and shale with minor amounts of greenstone, chert, and conglomerate. All of the units have been more or less metamorphosed and altered by pronounced changes in the physical and chemical environment in which the rocks originated.

Chemical analyses of the sandstone and shale of the Franciscan Formation (Bailey, Irwin, and Jones, 1964) indicate that silica and aluminum are the dominant constituents, followed by iron, magnesium, and calcium, respectively.

Except where fractured or deeply weathered, the Franciscan Formation is poorly permeable. Wells penetrating the rocks may yield enough water for minimum domestic or stock requirements but the water may be of poor quality for domestic uses.

Consolidated Sedimentary Rocks of Cretaceous Age

The consolidated sedimentary rocks of Cretaceous age are chiefly mudstone and siltstone with minor beds of thin-bedded sandstone. The rocks are well consolidated and poorly permeable. Where penetrated by wells, they yield small quantities of water that may be sufficient for minimum domestic or stock requirements but the water may be too mineralized for human consumption.

Yield of Wells Tapping the Consolidated Sedimentary Rocks of Cretaceous Age, the Franciscan Formation, and the Ultrabasic Rocks

Logs of wells and pump-test information supplied by drillers, pump companies, and land owners indicate that the consolidated sedimentary rocks of Cretaceous age, rocks of the Franciscan Formation, and the ultrabasic rocks generally yield small quantities of water to wells. However, significantly larger quantities of water may be obtained from highly fractured or deeply weathered zones. Well-test information from 36 wells drilled into these rocks show an average yield of 19 gpm (gallons per minute) with most wells yielding 10 gpm or less. Most of the well tests for which both yield and drawdown information are available show a specific capacity less than or equal to 0.1 gallon per minute per foot of drawdown.

Sonoma Volcanics

The Sonoma Volcanics constitute a thick and highly variable series of volcanic rocks including andesite, basalt, and minor rhyolite flows with interbedded and discontinuous layers of tuff, tuff breccia, agglomerate and scoria. Redeposited tuff and pumice, diatomite, diatomaceous mud, silt, sand, and gravel, and a prominent body of rhyolite flows and tuff with some obsidian and perlitic glass are also included in this group of rocks.

Redeposited, water-laid pyroclastic materials, diatomite, silt, sand, and gravel are exposed in roadcuts along the Silverado Trail east and southeast of St. Helena. In the vicinity of Calistoga, prominent bodies of rhyolite and rhyolitic tuff have been altered by hydrothermal processes to a hard, dense, fine-grained rock. Thin-section and X-ray diffraction analyses indicate that the altered rhyolitic rocks now consist mostly of quartz and kaolinitic and montmorillonitic clays.

Well-test information from 140 wells tapping the Sonoma Volcanics show an average yield of 32 gpm and an average specific capacity of 0.6 gallon per minute per foot of drawdown.

Alluvium

In this report, deposits described as alluvium or as the alluvial aquifer, include the older alluvium, terrace deposits, older alluvial-fan deposits, and younger alluvium as mapped and described by Kunkel and Upson (1960).

The alluvium underlies and forms the floor of Napa Valley and consists mostly of lenticular, unconsolidated, poorly sorted, and imperfectly bedded deposits of gravel, sand, silt, and clay. Individual lenses of gravel, sand, and clay generally are not more than 10 feet thick but may extend laterally over large areas.

The floor of the Napa Valley is formed mainly by the flood plains and channels of the Napa River and its tributaries. Mechanical analyses by Carpenter and Cosby (1938) show that flood-plain materials consist mostly of silt and clay with a small percentage of gravel and sand. Channel deposits were shown to consist mostly of sand and gravel.

The yield of wells tapping the alluvium ranges from about 50 gpm to about 3,000 gpm depending on the number and thickness of gravel and sand lenses penetrated at the particular well. Well-test information supplied by drillers, pump companies, and land owners for 100 wells perforated in the alluvium indicate that this unit is by far the best aquifer in the project area. The average yield of these 100 wells is about 220 gpm and the average specific capacity is about 10 gallons per minute per foot of drawdown.

Geothermal Activity

Geothermal activity, in the form of "geyser" wells, hot springs, and wells that discharge warm to hot water, occurs at several places in the project area. Ground water associated with geothermal activity is termed "hydrothermal" because the water temperature is unusually high. A standard definition (White, 1957) is used in this report and states that water at a temperature of 5°C or more above the mean annual temperature of the surrounding environment is considered hydrothermal. Thus, for the project area, a well or spring containing water at a temperature equal to, or greater than, 20.5°C (69°F) is said to yield hydrothermal water.

The most notable occurrence of hydrothermal water in the project area is in the vicinity of Calistoga. Kunkel and Upson (1960) reported that several wells in sec. 26, T. 9 N., R. 7 W. periodically discharged hot water and steam in the manner of a geyser. Health resorts featuring hot springs and hot mineralized water have been developed near wells 9N/6W-21M3 and 9N/7W-26R1, 2, (fig. 3). Most wells in the Calistoga area that contain hydrothermal water penetrate confined or semiconfined aquifers and many of these wells flow at the land surface. Drillers' logs indicate that "cool" water occurs at shallow depth throughout most of the Calistoga area; however, at depths ranging from 50 to 100 feet below land surface drillers generally encounter confined, hydrothermal water. Water temperatures in the deeper wells are reported to range from 29.5°C (85°F) to 120°C (248°F). Hydrothermal water and artesian conditions also occur in wells south and east of Calistoga in T. 8 N., R. 6 W., secs. 3, 4, 9, and 25 and in the Rutherford-Oakville area in T. 7 N., R. 5 W., secs. 3, 14, 15, 25, and 26.

Figure 3 shows the location of wells that yield hydrothermal ground water. Table 4 shows chemical analyses of water samples taken from wells that yield hydrothermal water.

GROUND-WATER HYDROLOGY

Ultrabasic Rocks, Franciscan Formation, and Sedimentary Rocks of Cretaceous Age

The ultrabasic rocks, Franciscan Formation, and the sedimentary Cretaceous rocks are saturated below the water table, but yield very little water to wells. This restricted ability to yield water to wells results from a very low average hydraulic conductivity which, for these rocks, is probably on the order of 10^{-4} fpd (feet per day) or less. Ground-water flow patterns in these units generally conform to the topographic slopes except where interrupted by faults or other barriers that impede ground-water movement. The few well records available indicate that confined conditions occur locally within this group of rocks.

Sonoma Volcanics

The tuff breccia, scoriaceous material, and sedimentary deposits that compose a relatively small part of the Sonoma Volcanics generally are more permeable than the older ultrabasic, Franciscan, and sedimentary Cretaceous rocks and yield, on the average, greater quantities of water to wells. The hydraulic conductivity of the breccia, scoria, and sedimentary deposits is probably on the order of 10^{-2} to 10^{-3} fpd. Other units of the Sonoma Volcanics, most notably the andesitic, basaltic, and rhyolitic flow rocks and the hydrothermally altered material, yield little water to wells and probably have a hydraulic conductivity on the order of 10^{-4} fpd or less.

Water in the Sonoma Volcanics commonly is confined, though few wells penetrating this unit actually flow at land surface. Of the wells that do flow, most are located in the Calistoga area and the majority of these discharge hydrothermal water (fig. 3, table 4). Density differences between the hydrothermal water and the cooler ground water are caused by high subsurface temperatures and pressures and probably contribute to the upward movement of hydrothermal water and to the potentiometric heads observed at flowing, hot-water wells and "geyser" wells in the Calistoga area. On the other hand, the relation of depth to the occurrence of confined, hydrothermal water in wells in the Calistoga area (p. 15) suggests that the occurrence of hydrothermal water may be associated with a confining zone.[1] The fact that flowing wells, discharging hydrothermal water, occur in the project area is probably due to the combined influence of a local confining zone and the geothermally induced density differences of ground water.

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[1] A possible mechanism for the development of such a confining zone in hot-water dominated, hydrothermal systems is described on page 53.

Intermittently flowing wells in the Sonoma Volcanics that do not discharge hydrothermal water are located in sec. 16, T. 7 N., R. 5 W. and in secs. 6 and 7, T. 8 N., R. 6 W.

Alluvium

Spatial and Hydrologic Properties

The alluvium is by far the best aquifer in the project area and is locally capable of providing water to wells at rates of more than 3,000 gpm. The average hydraulic conductivity of the alluvium, as determined from drillers' logs and from specific-capacity data ranges from 10 to more than 100 fpd, depending on the percentage of sand and gravel in the alluvial deposits. The distribution of sand and gravel is irregular and variable but, as indicated in figure 4, the average values of hydraulic conductivity follow a general pattern; increasing from north to south and from the peripheries of the valley toward the Napa River. Thus, along any section that crosses the valley, the average hydraulic conductivity near the Napa River is virtually always the highest, and ranges from approximately 40 fpd near Calistoga to more than 110 fpd near Oak Knoll Avenue.

Except for small localized areas of semiconfinement, water in the alluvium is unconfined and moves under a natural hydraulic gradient that conforms in a general way to the surface topography. However, wells in the alluvium ranging in depth from 10 to 56 feet flow continuously or seasonally in secs. 22, 23, and 26, T. 7 N., R. 5 W. Most of these wells contain confined, hydrothermal water similar to wells in the Calistoga area, and the high potentiometric heads are probably the result of geothermally related phenomena such as described on page 16.

The thickness of the alluvium increases progressively from north to south, and from the periphery of the valley toward the Napa River. Figure 5 shows that the thicker sections of alluvial materials are beneath the Napa River and its major tributaries. The alluvium nearly everywhere thins toward the edges of the valley, except in the area immediately east and southeast of St. Helena. Here the thicker sections of alluvium occur at the eastern edge of the valley and abut directly against redeposited material of the Sonoma Volcanics. Also, a thick section of alluvium abuts the Sonoma Volcanics that form the Yountville Hills.

Kunkel and Upson (1960, table 8) used specific-yield values that ranged from 5 to 8 percent to estimate the volume of water in the alluvial aquifer. Because most of the values were in the 6-percent range in the areas of concern to this report, that value was used in conjunction with historical water-level data and estimated aquifer thicknesses (fig. 5) to determine that, as of 1972, the available quantity of water in the alluvial aquifer of northern Napa Valley was about 190,000 acre-feet.

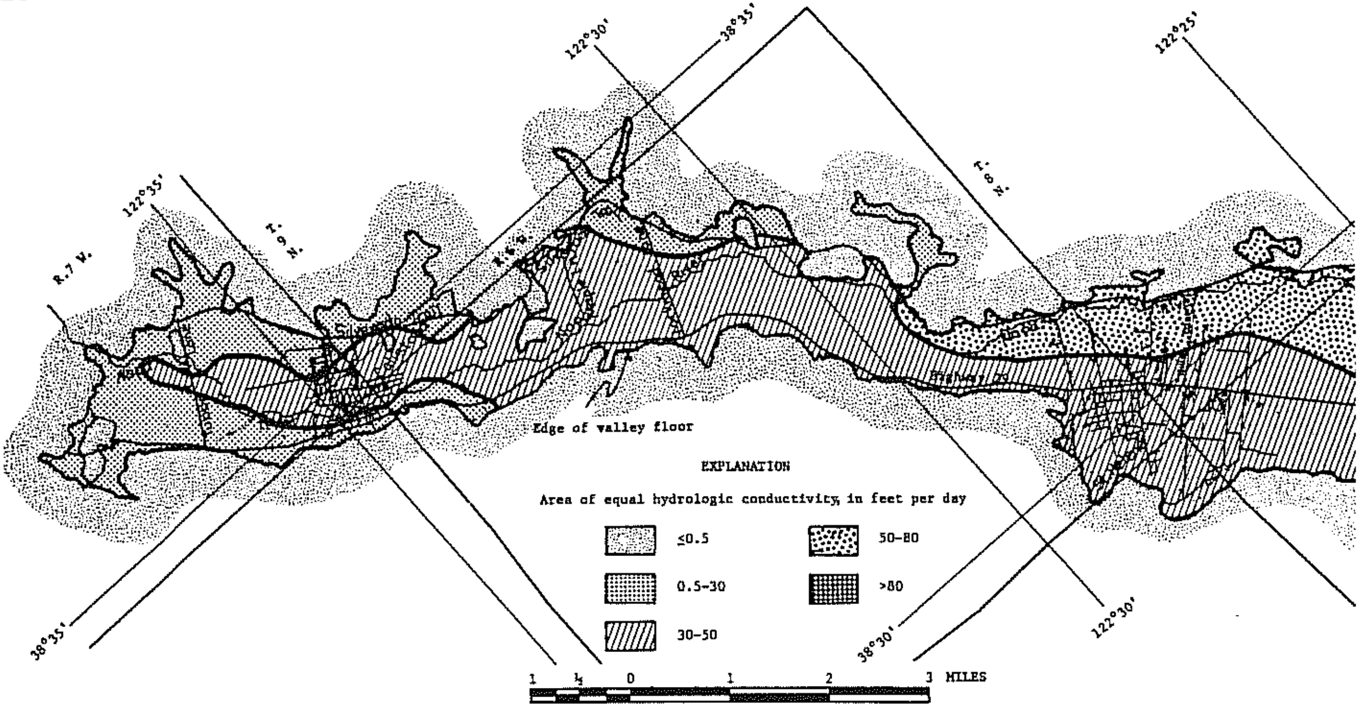
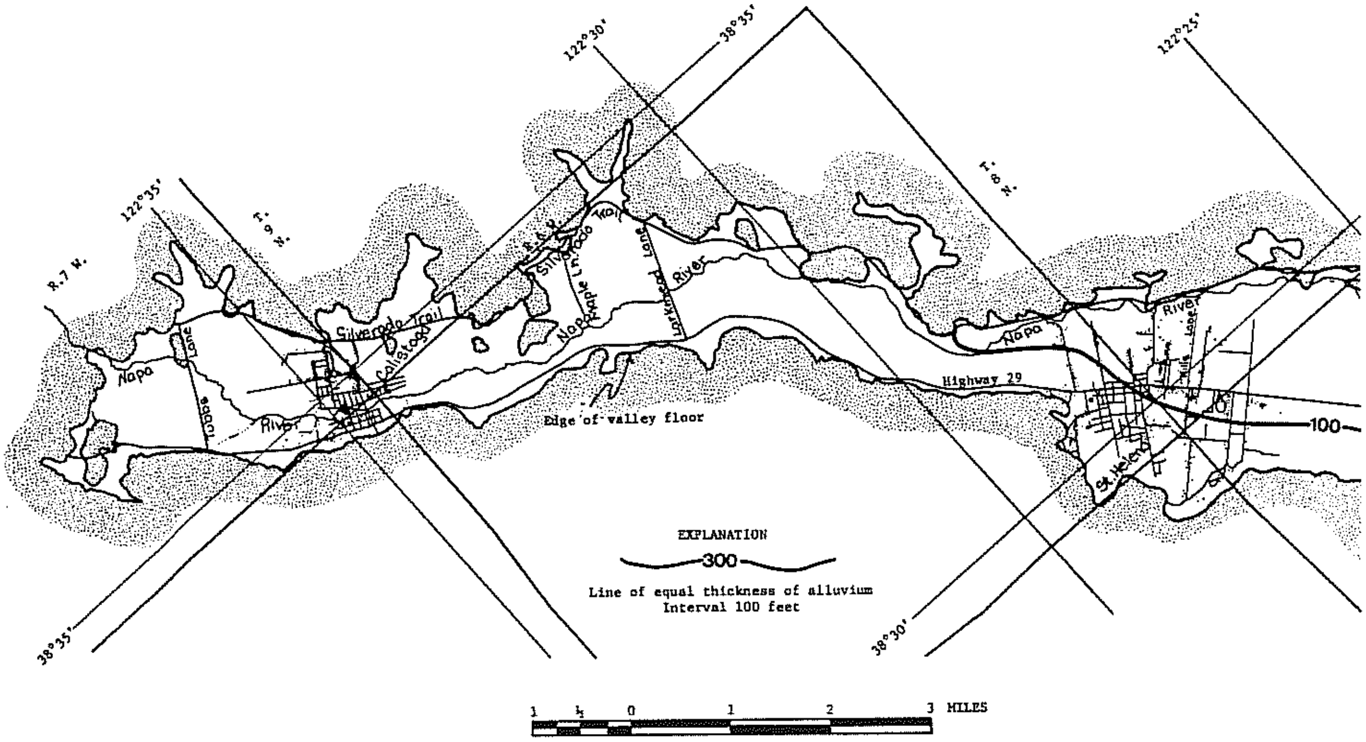


FIGURE 4.--HYDRAULIC CONDUCTIVITY OF THE ALLUVIUM IN NORTHERN NAPA VALLEY.



Base from U.S. Geological Survey 15' topographic series:
Calistoga, 1959, St. Helena, 1960; Sonoma, 1951; and
Santa Rosa, 1954

FIGURE 5.--THICKNESS OF ALLUVIUM IN NORTHERN NAPA VALLEY.

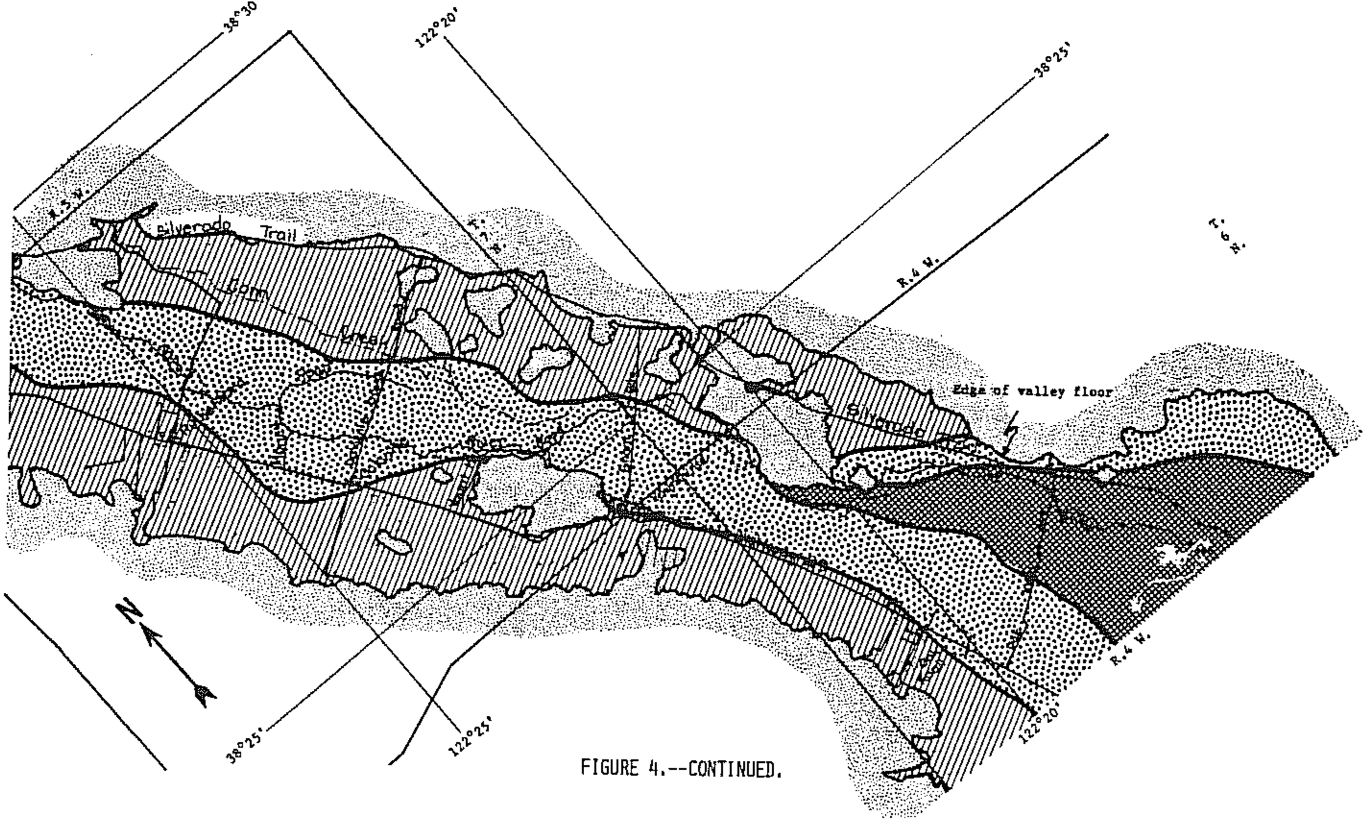


FIGURE 4.--CONTINUED.

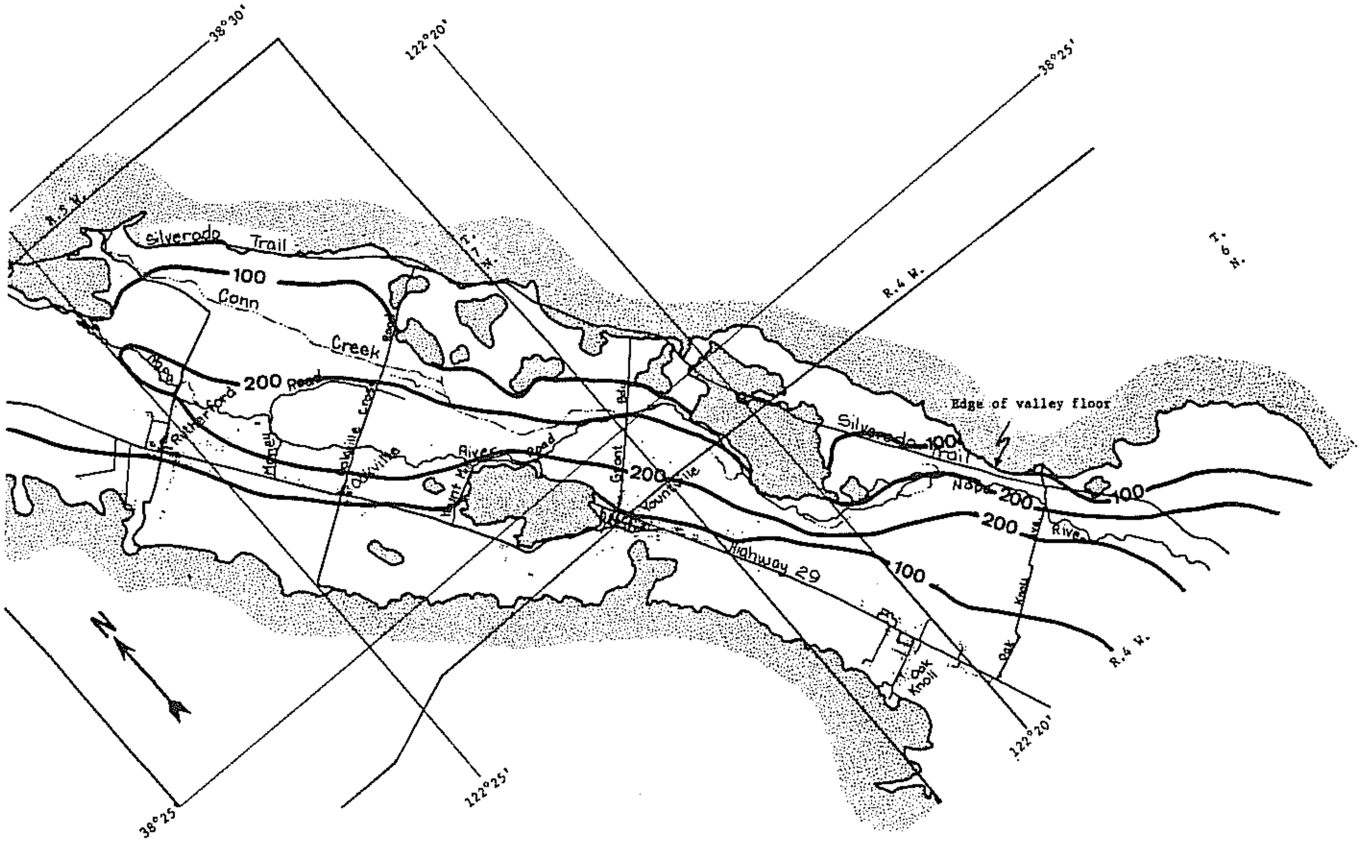


FIGURE 5.--CONTINUED.

Recharge and Discharge

Recharge to the alluvium occurs by infiltration of rain, percolation from streams, and subsurface inflow from older rocks. Discharge from the alluvium occurs by evapotranspiration, ground-water flow to the Napa River, pumping from wells, and subsurface outflow across the southern boundary of the project area.

At the present time (1972), the Napa River is a gaining stream and contributes little recharge to the water table. Even during years of limited rainfall, when the river flows intermittently, water is discharged from the aquifer in those reaches where the river is flowing and water recharges the alluvium in reaches where the river channel is dry; thus, net recharge to the alluvial aquifer is negligible.

Subsurface outflow occurs across the southern boundary of the project area as underflow in the alluvial deposits beneath and directly adjacent to the Napa River and is considered to be relatively constant over time. Using Darcy's law, known values of the hydraulic gradient, and estimated values of hydraulic conductivity, the subsurface discharge is calculated to be between 1 and 2 cfs (cubic feet per second). Subsurface inflow along the periphery of the valley is insignificant except in the area east and southeast of St. Helena. Here, relatively permeable redeposited volcanic materials abut thick sections of alluvium and provide an estimated constant inflow to the alluvial aquifer of 0.50 cfs.

Fluctuation of Water Levels and Streamflows and the Response of Water Table and Streamflows to Annual Rainfall

Historically, ground-water levels and streamflows in the Napa Valley have varied considerably from season to season and from year to year and have been most critically influenced by winter and early spring precipitation. Seasonal fluctuations of the water table and seasonal changes in streamflows are relatively large because of large seasonal variations in rainfall. Consequently, streamflows and ground-water levels are highest in the spring, decline progressively through the summer and autumn, and are lowest before the onset of winter rains.

Fluctuations of the water table and total streamflows from water year to water year are also directly dependent upon rainfall. During most water years, rainfall is sufficient to meet soil-moisture requirements and to replace ground water lost by pumping and by natural discharge. During years of limited rainfall, however, soil-moisture requirements are not met, some depletion from ground-water storage occurs, and surface runoff and ground-water discharge to the Napa River are reduced. Several consecutive dry years in succession would aggravate the problem of decreased streamflows to a degree commensurate with the length and severity of the drought and the amount of ground-water pumping. During years when rainfall is significantly below average, there may be no flow in the Napa River during most of the summer and autumn months. If significant storage depletion occurs as the result of pumping during a dry period and if the water is replaced as a result of recharge during a subsequent wet period, the total discharge of the Napa River at Oak Knoll Avenue during the wet period will be reduced by the amount of storage gained after flow begins.

Water-level data indicate that during the last 42 years (1929-70) seasonal and annual water-table fluctuations caused by periods of below average rainfall and pumping from wells have not exceeded 30 feet.

Water-table response to annual rainfall is a reflection of the annual recharge to the aquifer and indicates the ability of the aquifer to receive further recharge. The three curves in figure 6 show annual water-table recovery in three observation wells in the alluvium plotted against total annual rainfall for the same year. The graphs show that annual recharge to the water table is sensitively controlled by total annual rainfall up to a threshold value of 35 to 40 inches at St. Helena. Beyond this amount, significant increases in rainfall do not cause a corresponding recovery of water levels, and the excess rainfall becomes rejected recharge. Consequently, the threshold value of 35 to 40 inches indicates the average annual rainfall required at St. Helena to meet soil-moisture requirements and to replace ground-water storage previously depleted as a result of pumping and natural aquifer discharge.

Several wells some distance from the Napa River and the three wells for which the general response curves (fig. 6) were calculated, indicate that long-term rainfall trends rather than annual rainfall may influence water-table response for a particular water year. For example, several consecutive years of rainfall well below the threshold value, followed by a year of rainfall well above the threshold value, can produce a water-table response for the last year considerably above that indicated by the general response curve. Similarly, several consecutive years of rainfall above the threshold value can produce a water-table response for the last such year considerably below that indicated by the response curve. Such extreme variations in precipitation and recharge have influenced water-table response through the years. However, repetition of precipitation-recharge conditions has also occurred, and the response data generated from these events, coupled with long-term rainfall and water-level records, were used to damp the influence of extreme climatologic variations on the water-table response curves. Thus, the curves do define valid relations and become a useful aid in estimating precipitation-recharge relations.

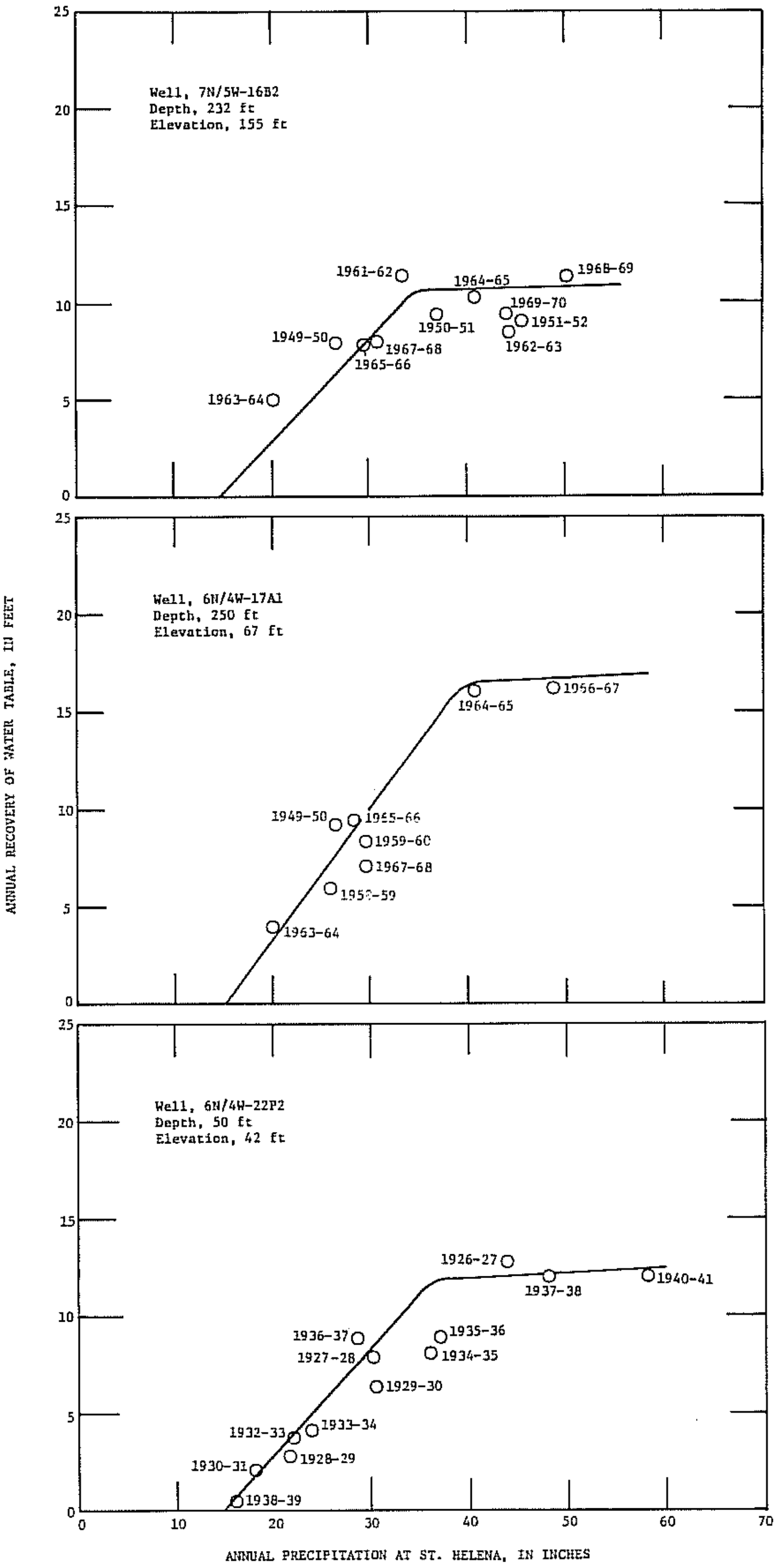


FIGURE 6.--WATER-TABLE RESPONSE CURVES.

Only three response curves are shown in figure 6 because sufficient long-term water-level data were not available for other observation wells. However, comprehensive water-level data for short periods of record from Bryan (1932) and Kunkel and Upson (1960) indicate that the magnitude of water-table response to annual rainfall generally is the same in most parts of the alluvial aquifer. Thus, the "threshold" values shown in figure 6 can be extrapolated to most of the project area. The exception to this rule is in the narrow part of the alluvium north of St. Helena, near Barro, where aquifer geometry and the requirements of flow continuity maintain high ground-water levels and dampen response to rainfall.

Total annual stream discharge from the project area is also directly dependent upon annual rainfall. This relation is indicated by the curves in figure 7 where the total annual streamflow for Conn Creek, Dry Creek, and the Napa River is plotted against total annual rainfall at St. Helena. These curves indicate that the annual discharge of tributary streams decreases with decreasing rainfall and becomes negligible when annual rainfall at St. Helena is 20 inches or less.

Relation of Annual Recharge to Annual Rainfall

Subsurface inflow was discussed previously (p. 20) and is considered to be nearly constant over time. Recharge to the alluvial aquifer from rainfall and streamflow, on the other hand, is not independent of annual precipitation; in fact, recharge amounts vary considerably when annual rainfall is less than the threshold value (fig. 6).

For example, net annual recharge[1] to the alluvial aquifer from percolation of rain is estimated to be 3 inches per unit area during water years when the threshold value of rainfall is equalled or exceeded. This recharge is progressively reduced when rainfall departs negatively from the threshold value, and it probably becomes virtually zero during water years when total rainfall at St. Helena is less than 12 inches.

Net recharge from streamflow is similarly dependent on annual rainfall. Most of this recharge is derived from streams tributary to the Napa River and occurs near the valley margins where the tributary flows leave the older, impermeable rocks and pass over permeable channel deposits in the alluvium. Net annual recharge from streamflows is at a maximum when annual rainfall equals or exceeds the threshold value, becomes progressively less when rainfall is less than the threshold value, and for most years probably is negligible when annual rainfall at St. Helena is 20 inches or less.

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[1] Net recharge to the alluvium is defined as the total amount of water recharged to the water table minus the losses from the water table attributed to evapotranspiration.

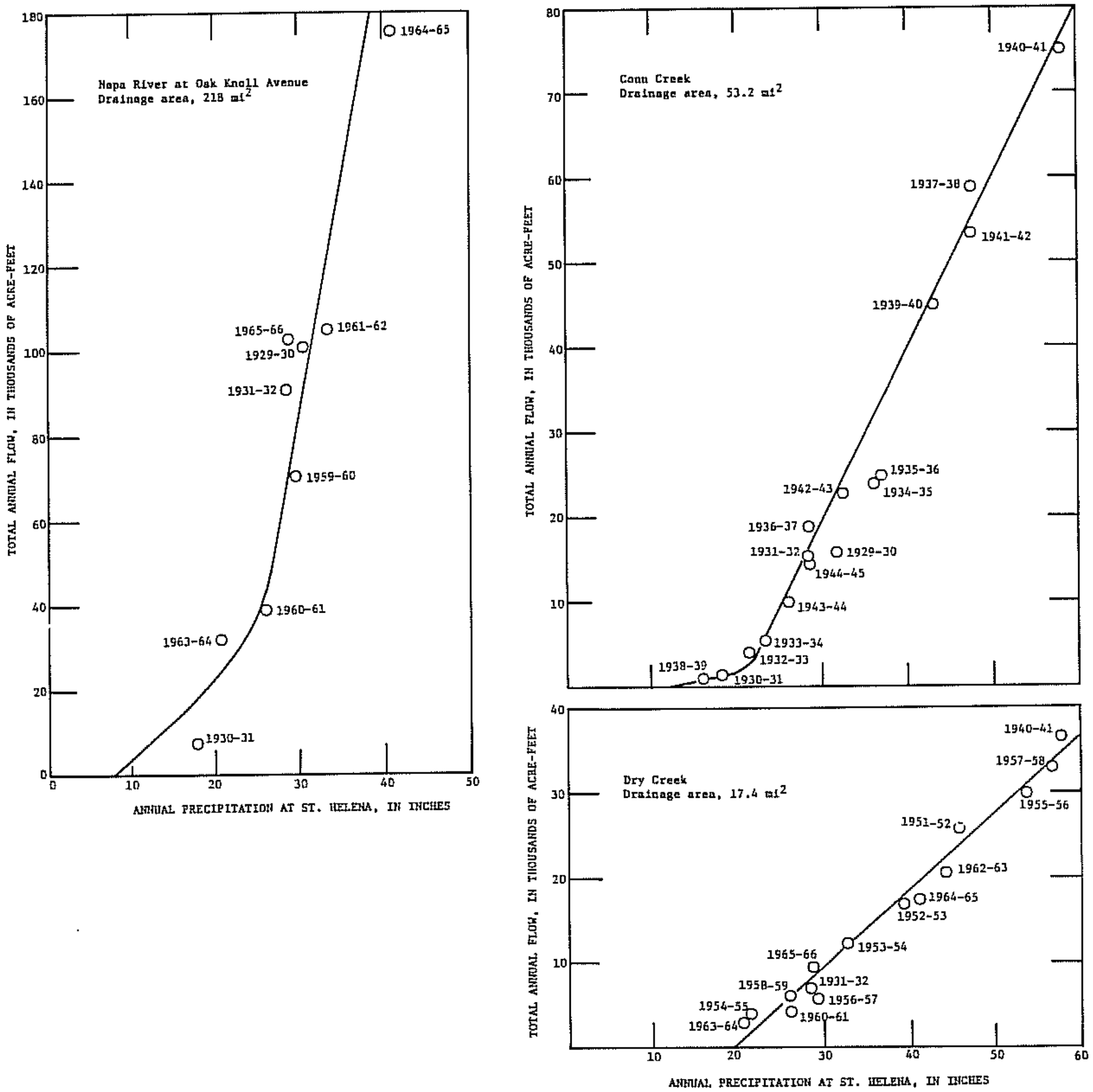

FIGURE 7.--STREAMFLOW RESPONSE CURVES.

Ground-Water Pumpage

Faye (1972) calculated the annual agricultural use of ground water in the project area from power records for the years 1964-70 (table 2). Domestic use of ground water in the project area for the same period is estimated to have been 300 acre-feet per year. Annual agricultural pumpage for the 1964-67 period (table 2) varied inversely with the rainfall at St. Helena After 1967, however, annual pumpage increased significantly and no longer varied in a way sensitive to rainfall. The 1967-70 period coincides with the increasing use of ground water to provide frost protection for vineyards. Thus, future ground-water withdrawals probably will reflect the length and severity of spring frosts and the amount of acreage devoted to vineyards.

TABLE 2.--*Calculated agricultural pumpage from the alluvial aquifer in northern Napa Valley for water years 1964-70 (Faye, 1972)*

Water year	Pumpage (acre-feet per year)
1964	4,500
1965	4,050
1966	4,650
1967	3,300
1968	5,150
1969	5,600
1970	5,700

Definition of Steady-State and Transient-State Conditions in the Alluvial Aquifer

The flattening of the water-table response curves in figure 6 indicates that the distribution of ground-water levels in the alluvial aquifer is about the same during those water years when rainfall equals or exceeds the threshold value. A statistical evaluation (table 1) of the rainfall record at St. Helena indicates that the threshold value of rainfall has a recurrence interval of less than 3 years. On the average, then, approximately the same distribution of water-table elevations, and, by inference, the same quantities of aquifer recharge and discharge, occur throughout the alluvial aquifer every 3 years. Thus, for purposes of this study, steady-state conditions are said to occur in the alluvial aquifer during those years when rainfall equals or exceeds the threshold value (p. 21). The quantities of water recharged to, and discharged from, the alluvial aquifer during those years and the spring water-table surface that develops as a result of that recharge and discharge are said to define those steady-state conditions.

The fact that long term, water-table elevations in the alluvial aquifer are generally static indicates that very little storage depletion or storage accumulation has occurred with time. Thus, in order to satisfy continuity, net discharge[2] from the alluvial aquifer must equal net recharge when steady-state conditions prevail.

Rainfall and water-level records indicate that steady-state conditions occurred in the alluvial aquifer during the 1963 water year. Using unpublished water-level data and estimated quantities of recharge and discharge, a water-level contour map for the spring of 1963 (fig. 8) was prepared and a ground-water budget (table 3) was computed. The ground-water budget and the water-level contour map are considered representative of the water body in the alluvial aquifer during most of the 1929-70 period.

Separation of the streamflow hydrograph into quantities of base flow and surface runoff for the Napa River at Oak Knoll Avenue indicates that the average ground-water discharge to the Napa River and subsequently out of the project area, during the 1963 water year was 18.0 cfs. Net pumpage of ground water during that water year was estimated to have been 4.0 cfs, after allowing for an estimated 10 percent irrigation return flow. Subsurface outflow across the southern boundary of the project area was estimated to be 1.5 cfs (p. 20). Thus, the total average net discharge from the alluvial aquifer for 1963 water year is computed to have been 23.5 cfs, and is considered to be the steady-state discharge from the project area.

Net recharge from direct rainfall penetration is estimated to be 3 inches per unit area during periods when the total rainfall at St. Helena equals or exceeds the threshold value. Rainfall thus contributes about 12.5 cfs of net recharge to the alluvium under steady-state conditions. Nearly all the remaining 11.0 cfs of net recharge required to maintain steady-state ground-water conditions is contributed by tributary streams along the periphery of the valley.

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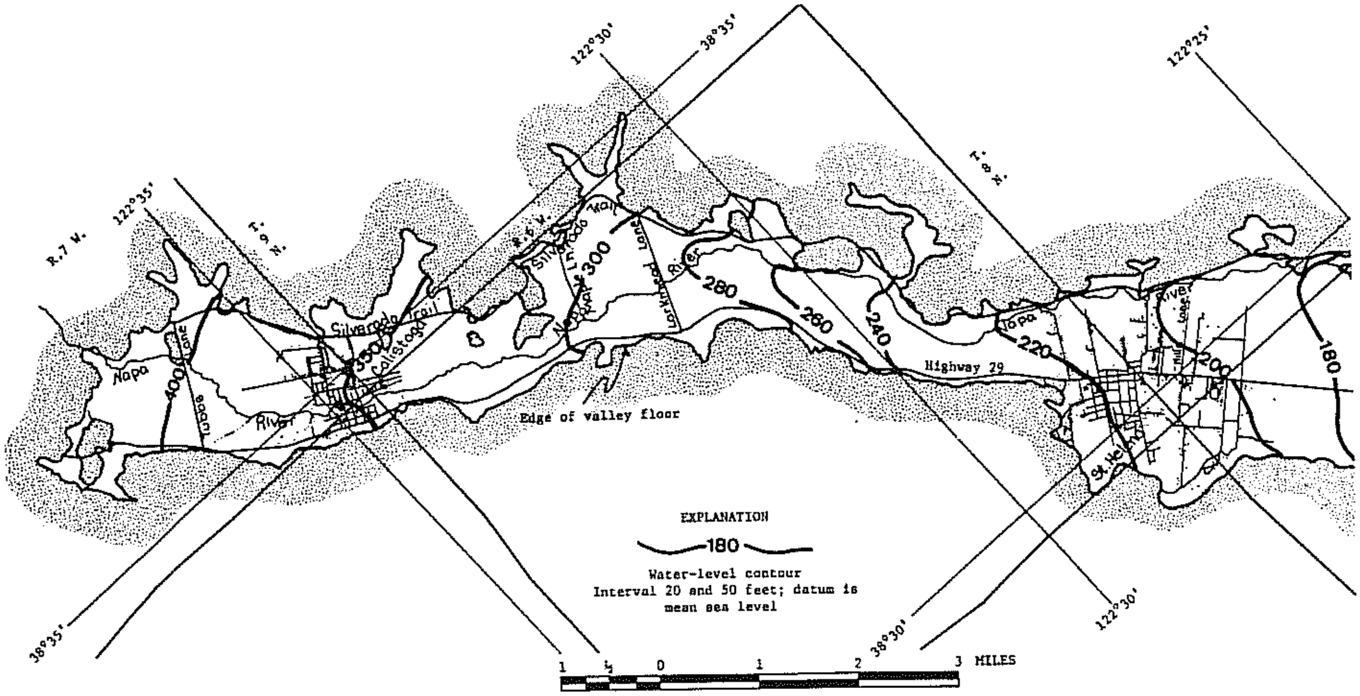
[2] Net discharge is defined as all water discharged from the saturated zone except evapotranspiration.

Even though steady-state conditions generally have prevailed in the project area during the past 40 years, the rainfall record indicates that dry periods have occurred during which the annual rainfall was less than the threshold value for several consecutive years. During these periods, steady-state conditions did not prevail in the alluvial aquifer, some storage depletion occurred, and in extreme cases--most notably during the 1930 and 1931 water years--the Napa River did not flow for a considerable period of time. At the end of such periods, the water-level contours were generally 20 to 30 feet below steady-state levels. For this study, whenever rainfall at St. Helena is significantly below the threshold value for several consecutive water years, ground-water conditions are defined as undergoing change and a transient-state situation is said to prevail. Water-level contours in, and quantities of recharge to and discharge from the alluvial aquifer under transient-state conditions are defined as transient-state parameters.

Bryan (1932) reported water-level records and streamflow hydrographs for 1929-32 water years, during which a total of 77.1 inches of rainfall was measured at St. Helena. Transient-state conditions prevailed throughout that period, most notably from the spring of 1930 through the summer of 1931. Water-level contours at the beginning and end of this period are shown in figures 9 and 10. Figure 9 shows that in the spring of 1930, water levels were 5 to 10 feet below steady-state water levels (fig. 8). Figure 10 shows that in June of 1931, water levels were generally 15 to 25 feet below steady-state levels (fig. 8).

The period April 1930 to June 1931 is considered most representative of transient-state conditions as defined in this report, and will henceforth be referred to as the transient period. Separation of streamflow hydrographs for base flow and surface runoff indicates that from April 1930 to June 1931, the base flow of the Napa River averaged 10.5 cfs. No flow was recorded in the Napa River at Oak Knoll Avenue from June 5 to November 26, 1931. The total ground-water withdrawal from the alluvial aquifer during the transient period was estimated to be 3,700 acre-feet. This amount was about 200 acre-feet more than the annual average withdrawal rate of 3,000 acre-feet reported by Faye (1972) as representative of this period. The difference reflects an estimated increase in the use of ground water to supplement deficient rainfall. Bryan (1932) indicated that during the transient period approximately 1,100 acre-feet of base flow was diverted from the Napa River and from Conn Creek for irrigation purposes upstream from Oak Knoll Avenue. Thus, the total net discharge from the alluvial aquifer during the transient period was estimated to have been 18.0 cfs, after allowing for an estimated 10 percent irrigation return flow and assuming that subsurface discharge across the southern boundary of the project area remained unchanged at 1.5 cfs.



Base from U.S. Geological Survey 15' topographic series:
Calistoga, 1959; St. Helena, 1960, Sonoma, 1951; and
Santa Rosa, 1954

FIGURE 8.--WATER-LEVEL CONTOURS IN NORTHERN NAPA VALLEY, SPRING 1963.

Recharge to the alluvial aquifer in the transient period occurred during seasonal rains of the 1931 water year when approximately 18 inches of precipitation was measured at St. Helena. Relating this annual precipitation to the water-table response curves in figure 6, indicates that total recharge to the water table for the 1931 water year was 11 to 16 percent of the steady-state value. Considering that evapotranspiration from an unusually low water table was minimal, the net recharge to the alluvial aquifer during the transient period was estimated to be 14.5 percent of the steady-state recharge, or 3.6 cfs. Net recharge to the water table from streams tributary to the Napa River is estimated to be zero when annual rainfall at St. Helena is 20 inches or less. Thus, the total net recharge during the transient period was estimated to consist of 0.5 cfs of subsurface inflow and 3.1 cfs of direct infiltration of rainfall. Table 3 summarizes the steady-state and transient-state water budgets for the alluvial aquifer.

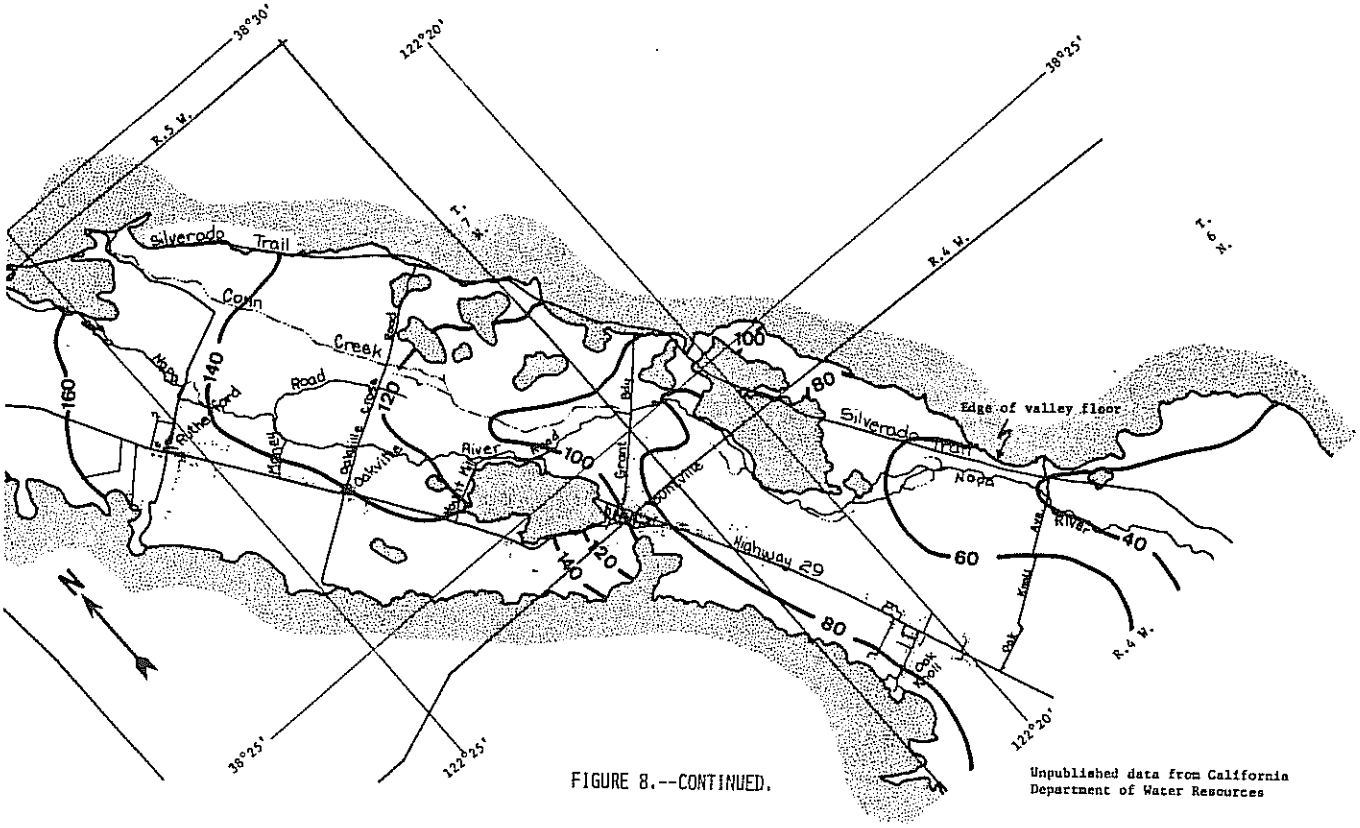


FIGURE 8.--CONTINUED.

Unpublished data from California Department of Water Resources

TABLE 3.--*Water budgets for steady-state and transient-state conditions in the alluvial aquifer of northern Napa Valley*

Steady-state conditions				Transient-state conditions			
Discharge (cfs)		Recharge (cfs)		Discharge (cfs)		Recharge (cfs)	
Base flow in Napa River	18.0	Rainfall	12.5	Base flow in Napa River	10.5	Rainfall	3.1
Net pumpage	4.0	Tributary streams	10.5	Net pumpage	6.0	Tributary streams	0
Subsurface outflow	1.5	Subsurface inflow	.5	Subsurface outflow	1.5	Subsurface inflow	.5
Total	23.5		23.5		18.0		3.6

Gross change in storage = 0 cfs

Gross change in storage = 14.4 cfs

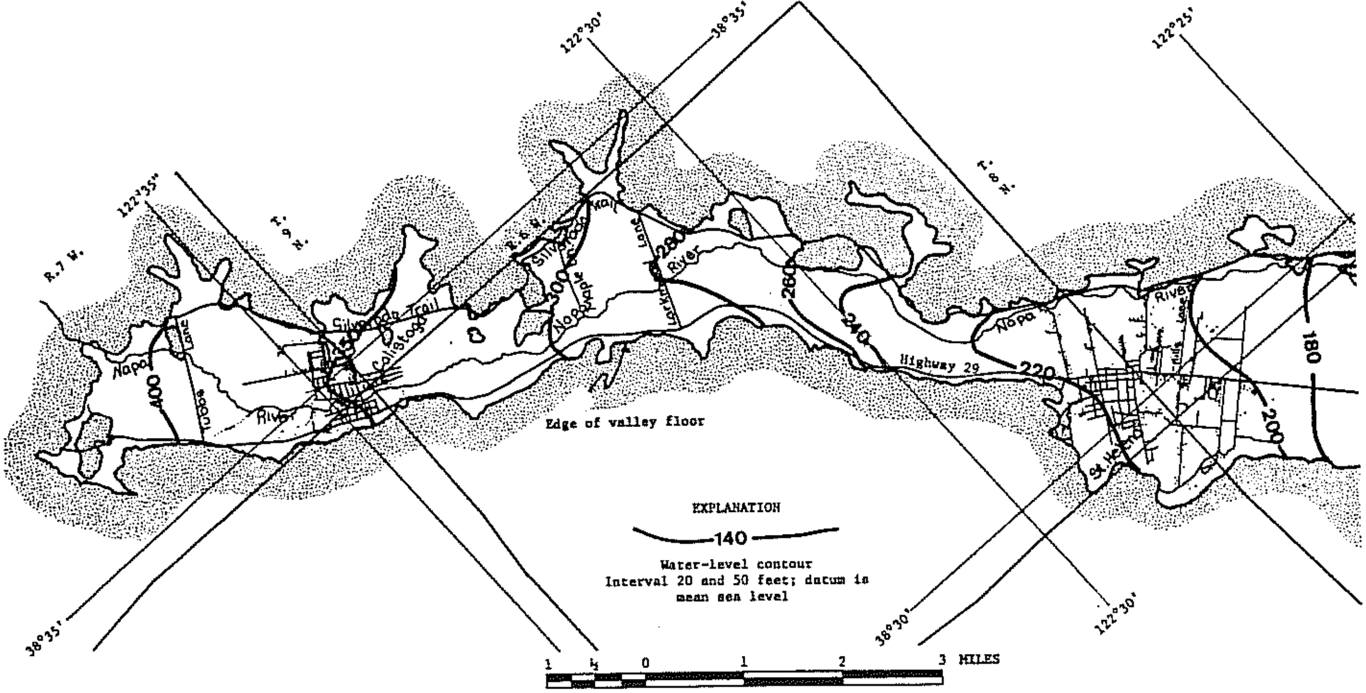
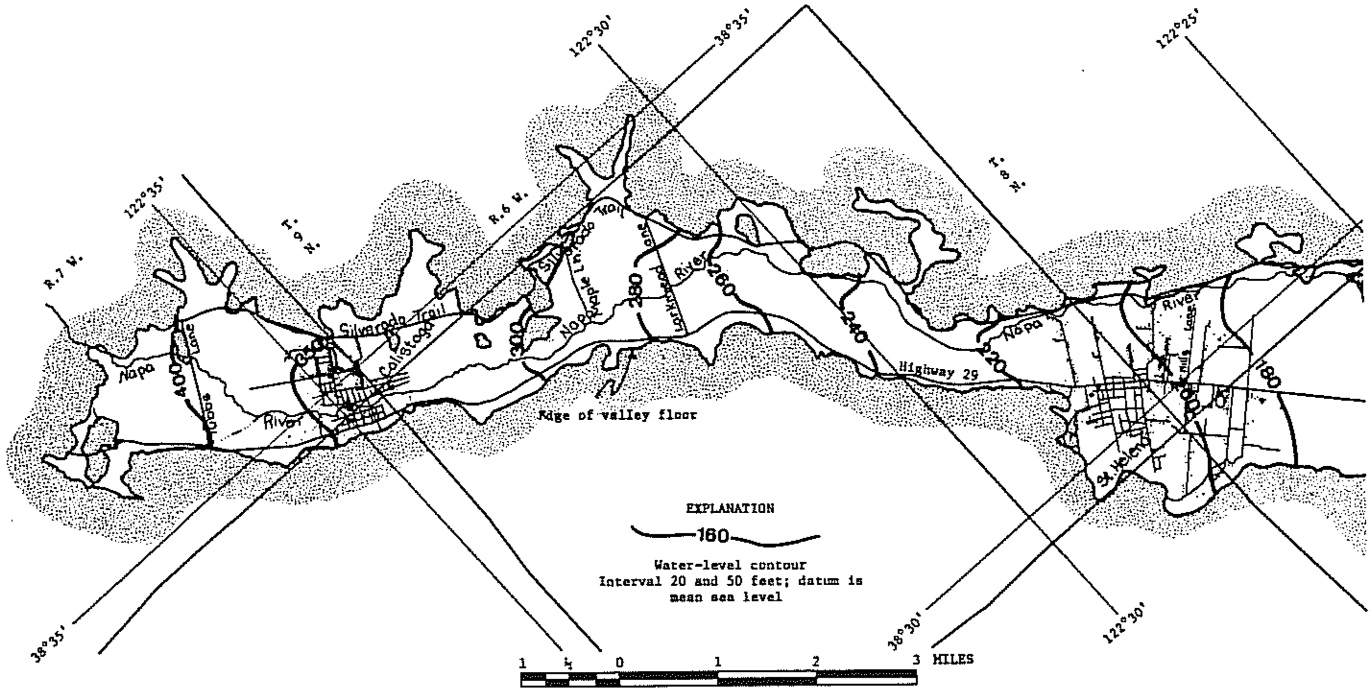
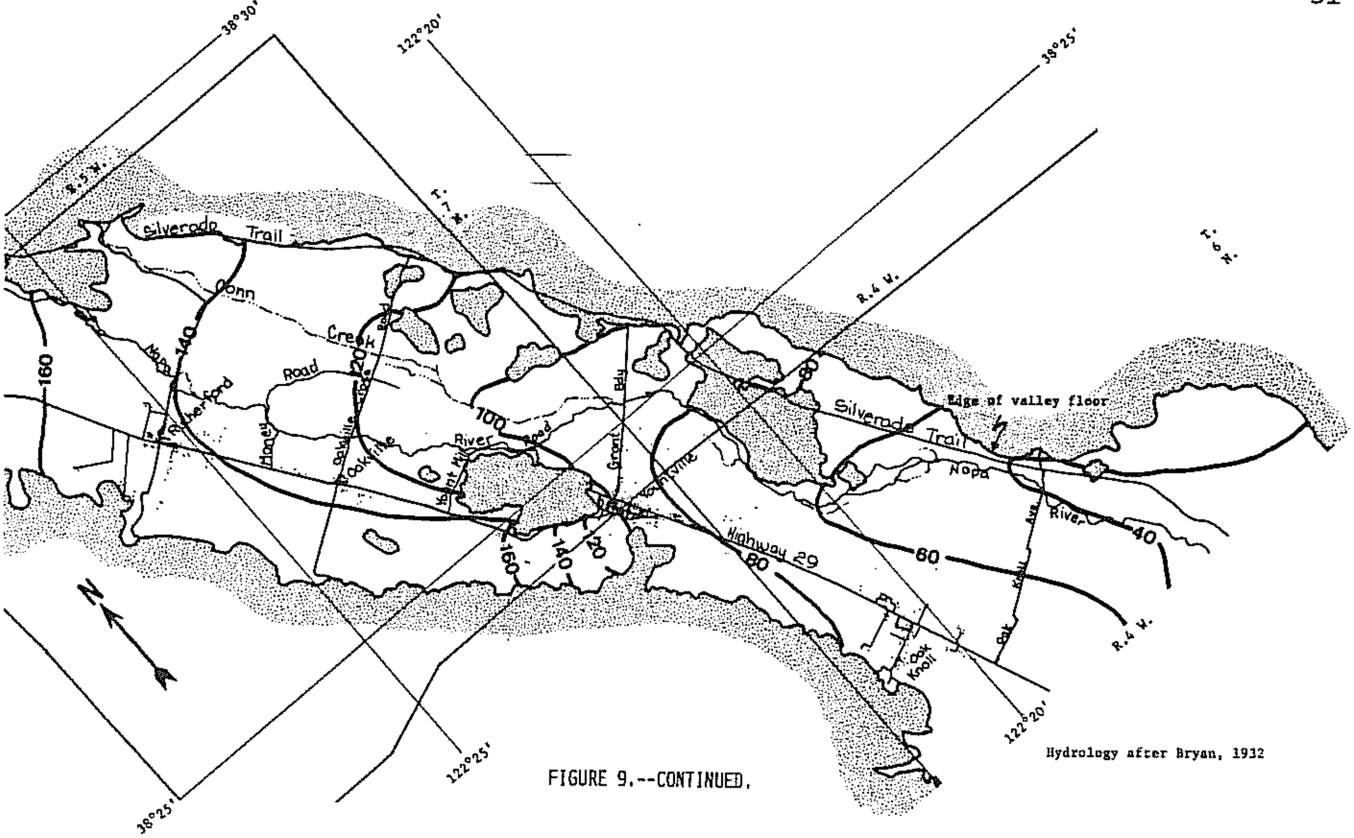


FIGURE 9.--WATER-LEVEL CONTOURS IN NORTHERN NAPA VALLEY, SPRING 1930.



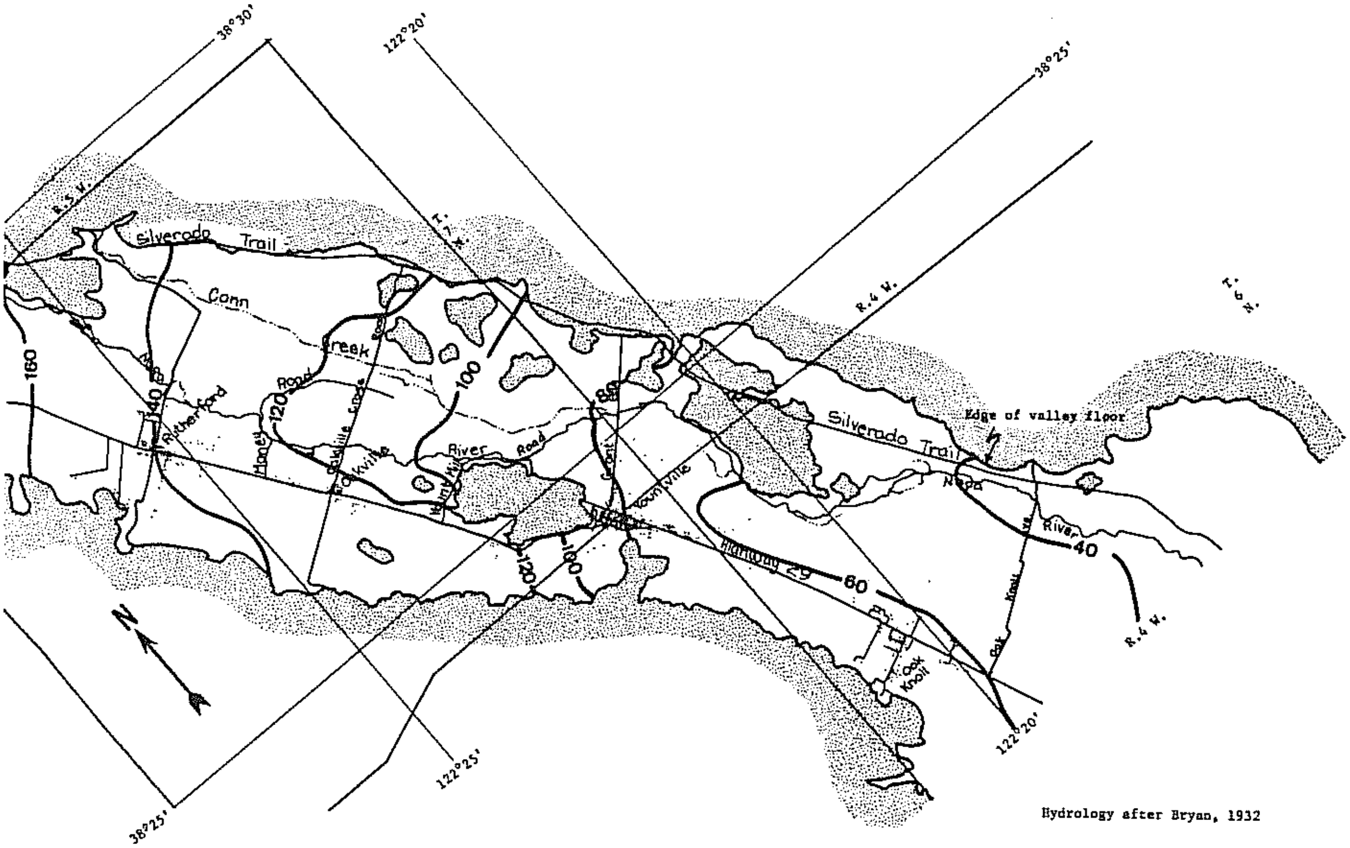
Base from U.S. Geological Survey 15' topographic series:
Calistoga, 1959; St. Helena, 1960, Sonoma, 1951; and
Santa Rosa, 1954

FIGURE 10.--WATER-LEVEL CONTOURS IN NORTHERN NAPA VALLEY FOR JUNE 1931.



Hydrology after Bryan, 1932

FIGURE 9.--CONTINUED.



Hydrology after Bryan, 1932

FIGURE 10.--CONTINUED.

MATHEMATICAL SIMULATION OF THE ALLUVIAL AQUIFER

Discussion of the Mathematical Model

The linear mathematical model used in this study is an expression of two-dimensional flow through porous media in the form of a computer program designed to simulate the response of an unconfined aquifer to constant rates of recharge or discharge. A detailed discussion of model theory and the analytical approach to model development is given in Pinder and Bredehoeft (1968).

A mathematical model, such as the one mentioned above, is an idealized representation of a ground-water system and is designed to describe, in concise quantitative terms, the response of the aquifer system to various conditions of stress. Such a quantitative response is necessary for even a general understanding of the complex hydrologic relations that occur in an aquifer system and it facilitates a description of the combined influences that climate, geology, hydrology, and man have on a ground-water basin.

Hydrologic relations are seldom simple and, generally, cannot be exactly described. Model simulation, therefore, requires assumptions and approximations that simplify conditions in the so-called "real world." Models are only as accurate as the assumptions used in their construction, and these assumptions should be kept in mind when model results are evaluated. The simplifying assumptions used in the model designed for this study are:

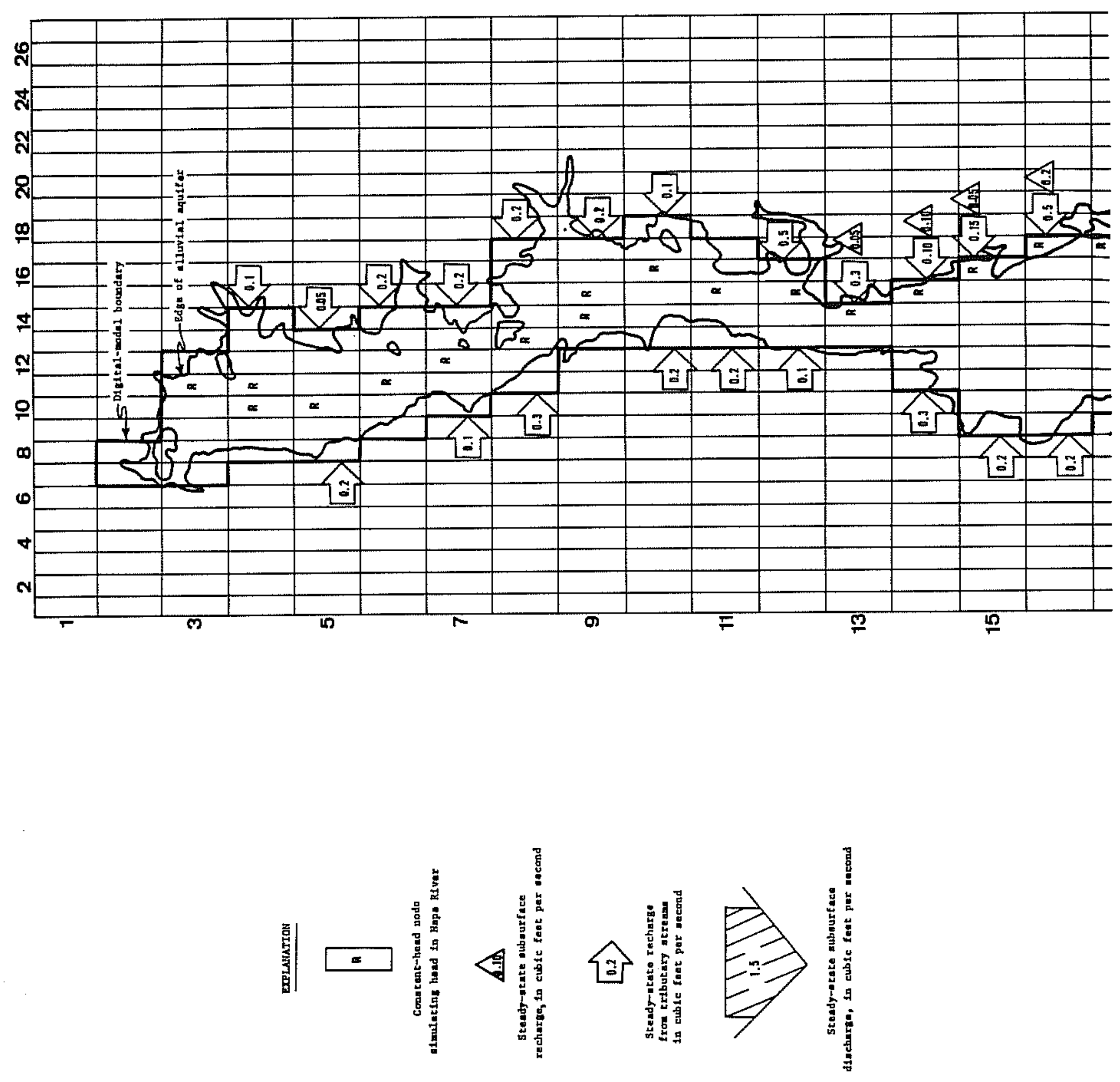
1. The alluvial aquifer is the only significant source of ground water;
2. Ground water occurs under water-table (unconfined) conditions;
3. The hydraulic head in the aquifer and the thickness, hydraulic conductivity, and specific yield of deposits are areally distributed and sufficiently uniform that each of these parameters can be represented by an average value per unit area;
4. Values for specific yield do not change with time;
5. Within the alluvial aquifer, vertical flow components are negligible compared with horizontal flow components; and
6. Recharge and discharge occur at constant rates over specified periods of time.

Before the model can be used to predict future ground-water levels, the model parameters used to describe the alluvial aquifer must be verified and checked against known geologic and hydrologic data. When the model-generated water levels for a particular set of conditions approximate the historic water levels within some predetermined limit of accuracy, the model is considered verified and ready for use in predicting future ground-water levels under various patterns and rates of pumping.

For this study, a uniform rectangular grid network of 35 rows and 27 columns was superposed on a plan view of the alluvial aquifer. Each unit area, or node, represents 6,750,000 square feet or nearly 155 acres. Model-control points were designated at the center of each node. A model boundary was then placed on the grid by tracing along the individual rectangular areas, or nodes, where they approximated the alluvial contact described in figure 3. The grid network, model boundary, alluvial contact, and other elements used in the model analysis are shown in figure 11. All hydrologic parameters communicated to, or computed by, the model were referred to the various nodes in units of feet and seconds. An individual node is designated by the number of the row and column. For example, the tenth node of the fifth row is designated (5-10).

At each node the following information was recorded:

1. The size of the grid interval, 1,500 x 4,500 feet;
2. Initial hydraulic-head values in the alluvial aquifer, in feet;
3. Elevation of the base of the alluvial aquifer, in feet;
4. Hydraulic-conductivity values for the alluvial aquifer, in feet per second;
5. Specific-yield values for the alluvial aquifer;
6. Recharge or discharge rates, in cubic feet per second, at each node designated as a recharge or discharge point. Negative values indicate a recharge point.


2
4
6
8
10
12
14
16
18
20
22
24
26
1
3
5
7
9
11
13
15
Digital-model boundary
Edge of alluvial aquifer
R
0.1
0.05
0.2
0.3
0.5
0.15
0.10
EXPLANATION
R
Constant-head node simulating head in Napa River
0.10
Steady-state subsurface recharge, in cubic feet per second
0.2
Steady-state recharge from tributary streams in cubic feet per second
1.5
Steady-state subsurface discharge, in cubic feet per second

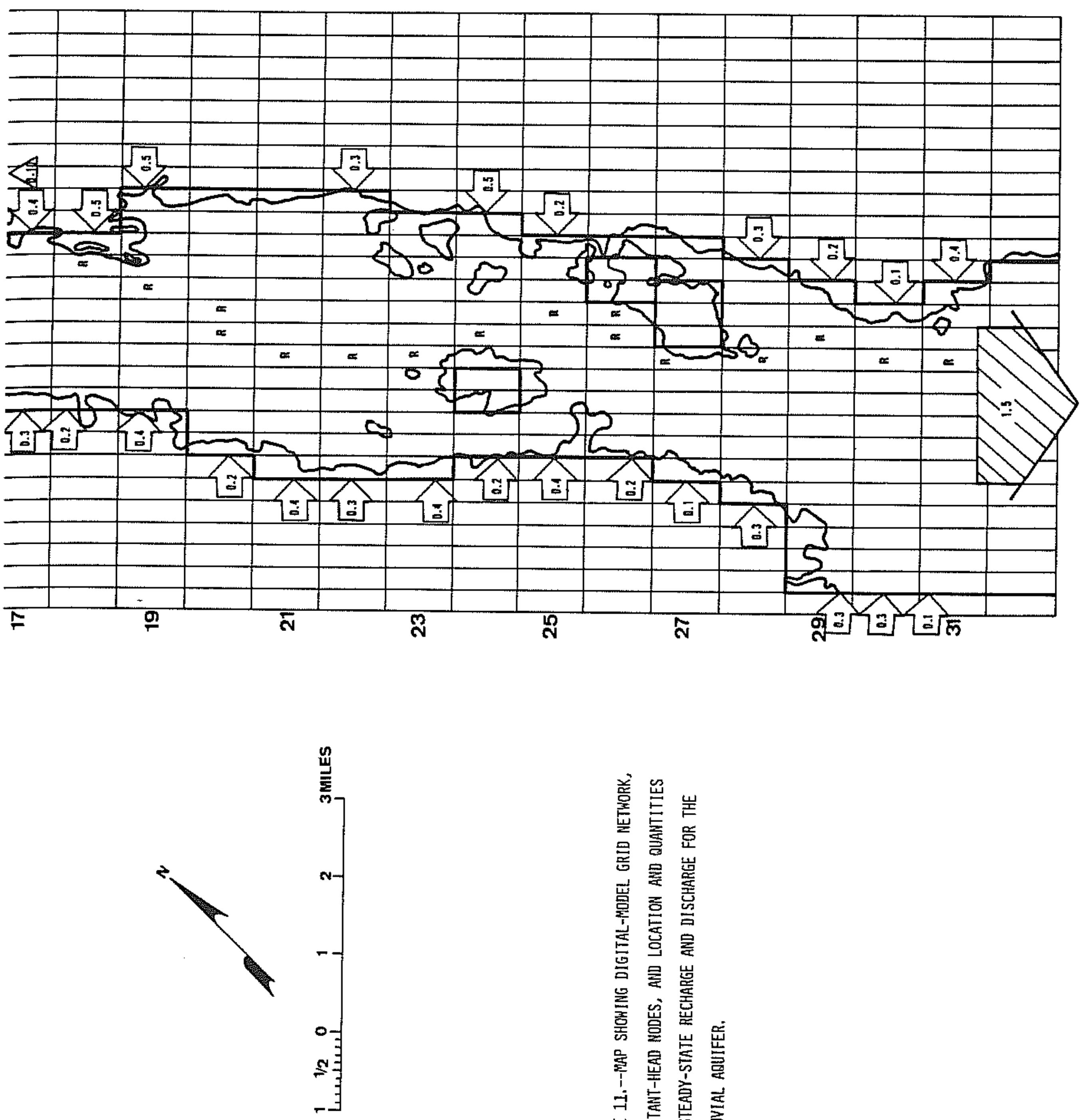


FIGURE 11.--MAP SHOWING DIGITAL-MODEL GRID NETWORK, CONSTANT-HEAD NODES, AND LOCATION AND QUANTITIES OF STEADY-STATE RECHARGE AND DISCHARGE FOR THE ALLUVIAL AQUIFER.

Simulation of Steady-State and Transient-State Conditions in the Alluvial Aquifer

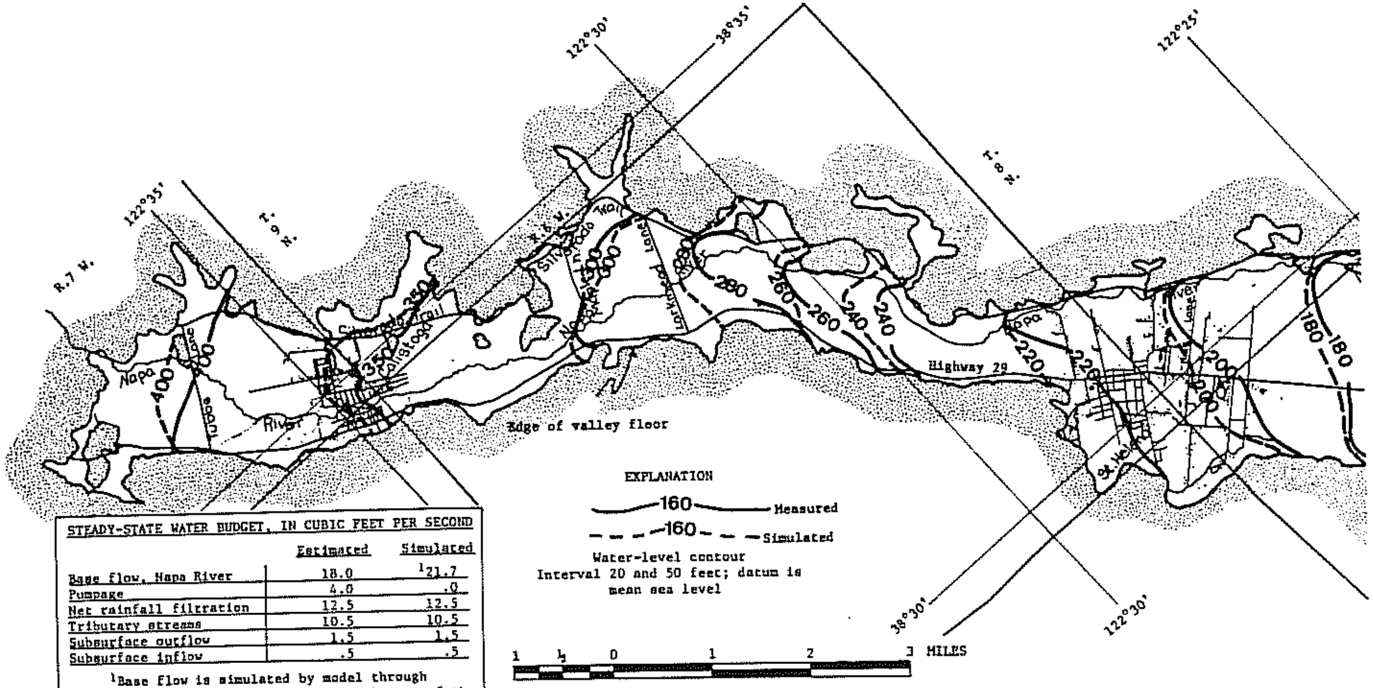
For this study, steady-state and transient-state conditions in the alluvial aquifer were simulated using the Pinder-Bredehoeft digital model and the assumptions discussed earlier. Net recharge to the model aquifer was simulated by postulating recharge wells at appropriate nodes; a constant rate of vertical recharge was postulated at every node in order to simulate infiltration of rainfall to the water table. Data for pumping rates at individual wells were unavailable. Consequently, total net discharge from the aquifer under both steady-state and transient-state conditions was assumed to have occurred as flow to the Napa River and subsurface flow out of the area. The Napa River was simulated by using constant heads at appropriate nodes that act as points of discharge from or recharge to, the aquifer, depending on the water-table elevations at adjacent nodes. Net quantities of water entering or leaving constant-head nodes were calculated by the model and were not specified by the model operator.

The model was calibrated by matching computed water-level contours and aquifer-discharge data with measured water levels and estimated aquifer-discharge data. Proper calibration of the model aquifer required adequate simulation of both steady-state and transient-state conditions; utilizing, in each case, the same nodal distribution of constant-head nodes, hydraulic conductivity, aquifer thickness, and specific yield.

Steady-state conditions were simulated using the steady-state water-level contours (fig. 8) and the recharge and discharge data given in table 3. Figure 11 shows the nodal distribution and quantities of steady-state peripheral recharge from tributary streams, subsurface discharge, and the distribution of the constant-head nodes simulating the Napa River. Approximately 3 inches of water per unit area was recharged to the model at an average rate in order to simulate net infiltration of rainfall to the water table. Quantities of peripheral recharge from tributary streams were distributed at appropriate nodes (fig. 11) according to the size, number, and location of tributary streams entering the valley. Subsurface recharge from redeposited materials in the Sonoma Volcanics totals 0.5 cfs and was distributed at nodes 13-14, 14-15, 15-16, 16-17, and 17-17 (fig. 13). Subsurface discharge across the southern boundary of the project area was estimated at 1.5 cfs and was distributed at nodes 31-7, 31-8, 31-9, 31-10, 31-11, 31-12, and 31-13. Other steady-state discharge was simulated as aquifer discharge to the Napa River and was calculated by the model as flow to constant-head nodes. The model aquifer was operated under simulated steady-state conditions for a period of time corresponding to a real time difference of 35 years. At the end of that time, water-table elevations were calculated by the model at each appropriate node and compared to historical data. Figure 12 shows the simulated steady-state water-level contours, contours constructed from historical water-level data, and estimated and simulated water budgets for the steady-state condition.

Transient-state conditions brought about by large variations in rainfall and runoff were simulated using the initial water-level contours shown in figure 9 and the transient-state recharge and discharge data given in table 3. Approximately 0.75 inch of water per year per unit area was recharged to the model in order to simulate net infiltration of rainfall to the water table. No peripheral recharge from tributary streams was provided for; however, subsurface recharge from redeposited materials in the Sonoma Volcanics totals 0.5 cfs and was distributed at nodes 13-14, 14-15, 15-16, 16-17, and 17-17. Subsurface discharge across the southern boundary of the project area was maintained at 1.5 cfs and distributed at nodes 31-7, 31-8, 31-9, 31-10, 31-11, 31-12, and 31-13. Other transient-state discharge was simulated as aquifer discharge to the Napa River and was calculated by the model as flow to constant-head nodes. The model aquifer was operated under simulated transient-state conditions for a simulation period corresponding to the 14-month dry period from April 1930 to June 1931. At the end of this period, water-table elevations were calculated by the model at each appropriate node and compared to historical data. Figure 13 shows simulated water-level contours and contours constructed from historical data for June 1931 and compares the estimated and simulated transient-state water budgets. The differences between the calculated and simulated values of aquifer discharge and gross storage change in the alluvial aquifer for the transient period were considered to be within acceptable limits of error.

The aquifer response under both transient and steady-state conditions was simulated by the model using the same nodal distributions of hydraulic conductivity, aquifer thickness, and specific yield. Successive simulations of transient conditions for time periods of 31, 78, 148, 254, and 412 days, indicated a progressive water-table decline throughout most of the model aquifer. This water-table decline was accompanied by a progressive decrease in model-aquifer discharge to constant-head nodes at the Napa River. Similar declines in the water table and in aquifer discharge to the Napa River were described as representative of the alluvial aquifer's response to transient conditions (p. 21). At the end of the transient period, flow directions at approximately one-third of the constant-head nodes had reversed; indicating, in effect, that dry reaches had occurred along the Napa River. Such transient response from the model aquifer and the properly simulated water-level contours and water budgets (figs. 12 and 13) indicated that the model aquifer was properly calibrated and is sufficiently accurate to be used as a tool to predict future ground-water levels. The above statement should be qualified with respect to response of the constant-head nodes when simulating short-term, transient conditions of less than a year. Reliable short-term simulations require a much more sensitive response to model-aquifer conditions at the constant-head nodes than can now be achieved. It was not within the scope of this project to provide a model of such sensitivity, nor would it have been possible to do so within the limitations of time and money alloted. However, future efforts to provide refinements of the model should include attempts to simulate more accurately the alluvial aquifer's response to rapidly changing flow conditions in the Napa River.

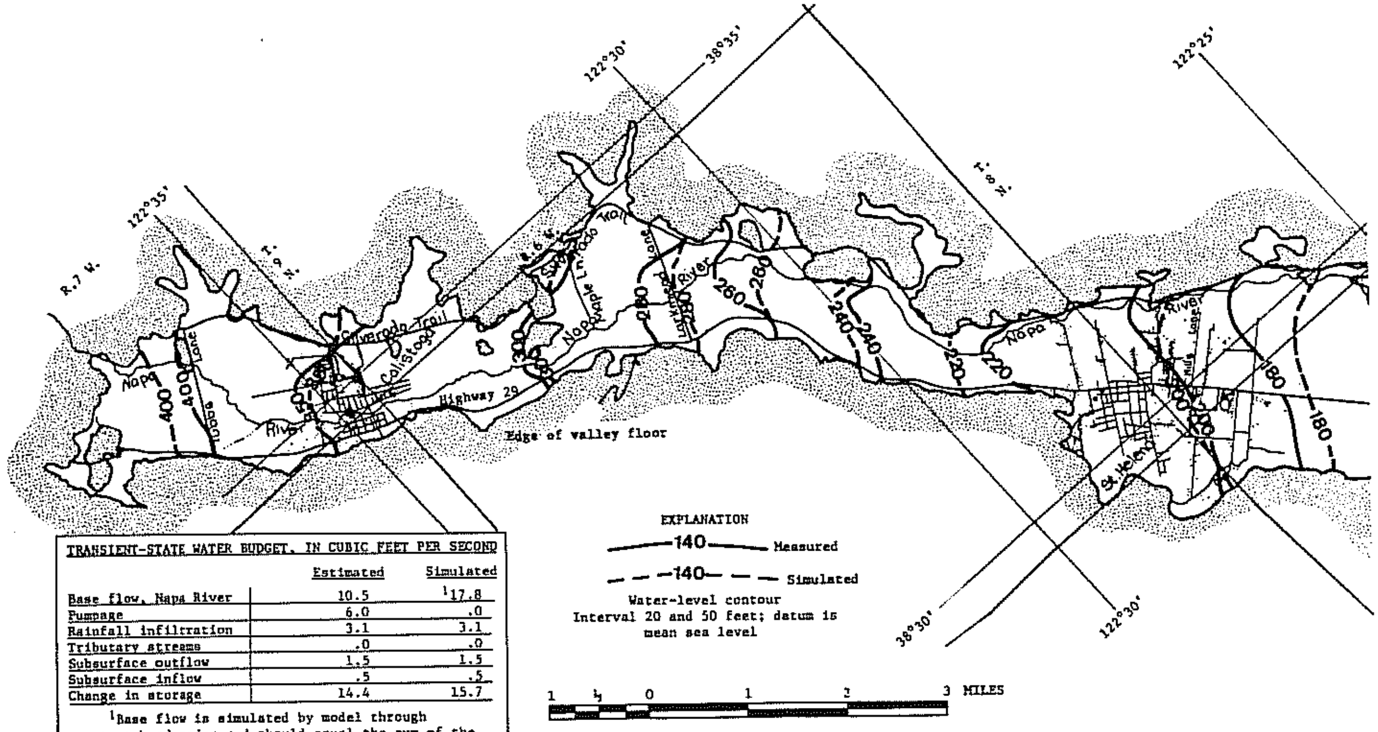


STEADY-STATE WATER BUDGET, IN CUBIC FEET PER SECOND

	Estimated	Simulated
Base flow, Napa River	18.0	[1]21.7
Pumpage	4.0	.0
Net rainfall filtration	12.5	12.5
Tributary streams	10.5	10.5
Subsurface outflow	1.5	1.5
Subsurface inflow	.5	.5

[1] Base flow is simulated by model through constant-head nodes and should equal the sum of the estimated base flow and pumpage.

FIGURE 12.--COMPARISON OF MEASURED AND SIMULATED



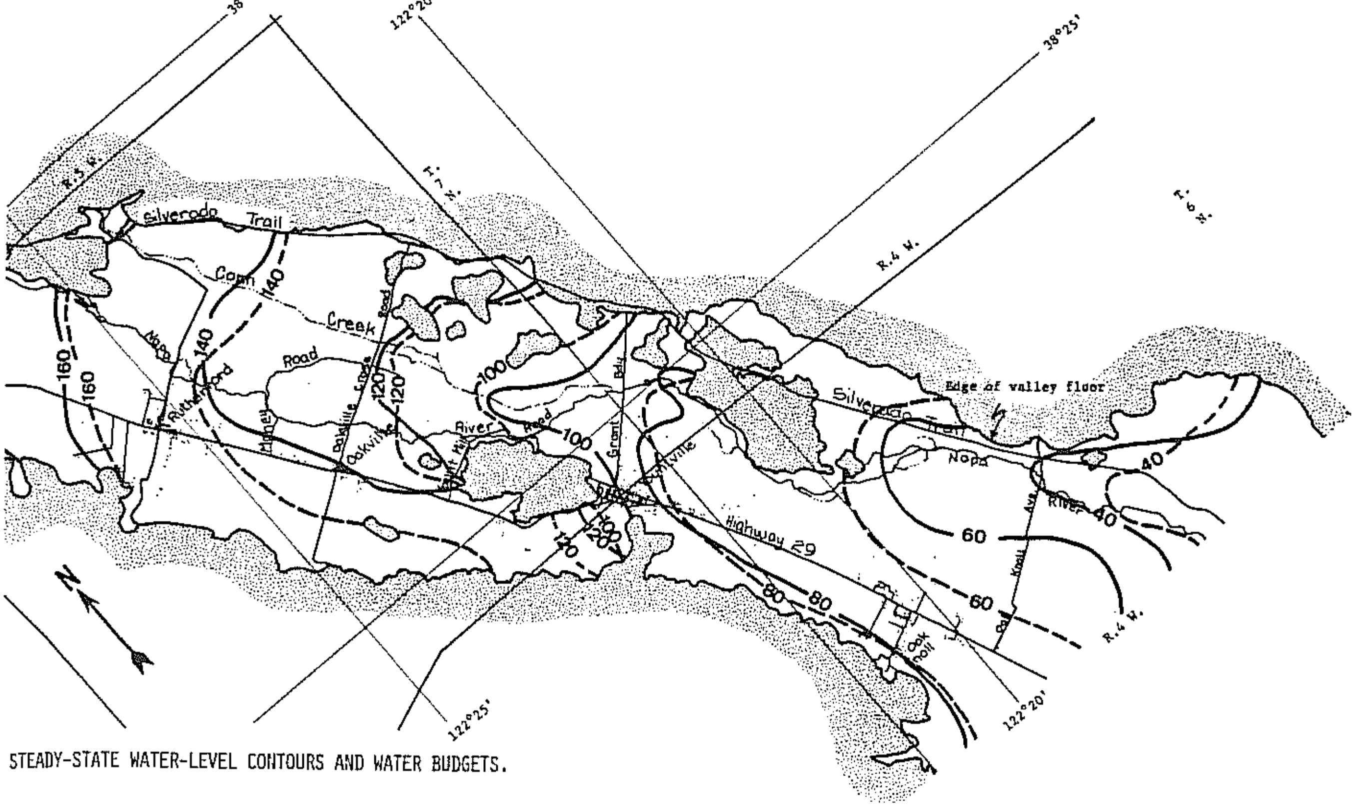
TRANSIENT-STATE WATER BUDGET, IN CUBIC FEET PER SECOND

	Estimated	Simulated
Base flow, Napa River	10.5	[1]17.8
Pumpage	6.0	.0
Rainfall infiltration	3.1	3.1
Tributary streams	.0	.0
Subsurface outflow	1.5	1.5
Subsurface inflow	.5	.5
Change in storage	14.4	15.7

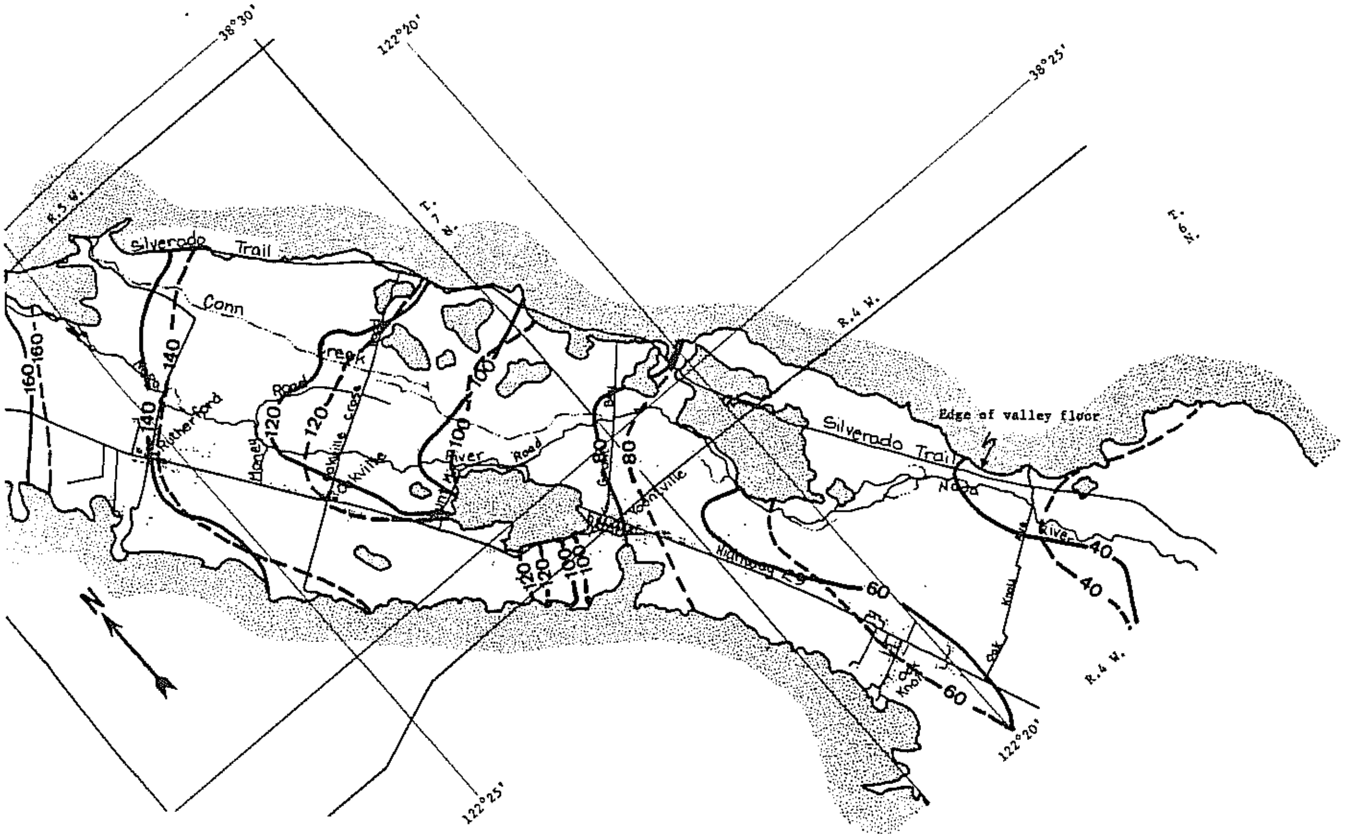
[1] Base flow is simulated by model through constant-head nodes and should equal the sum of the estimated base flow and pumpage.

Base from U.S. Geological Survey 15' topographic series: Calistoga, 1959; St. Helena, 1960; Sonoma, 1951; and Santa Rosa, 1954

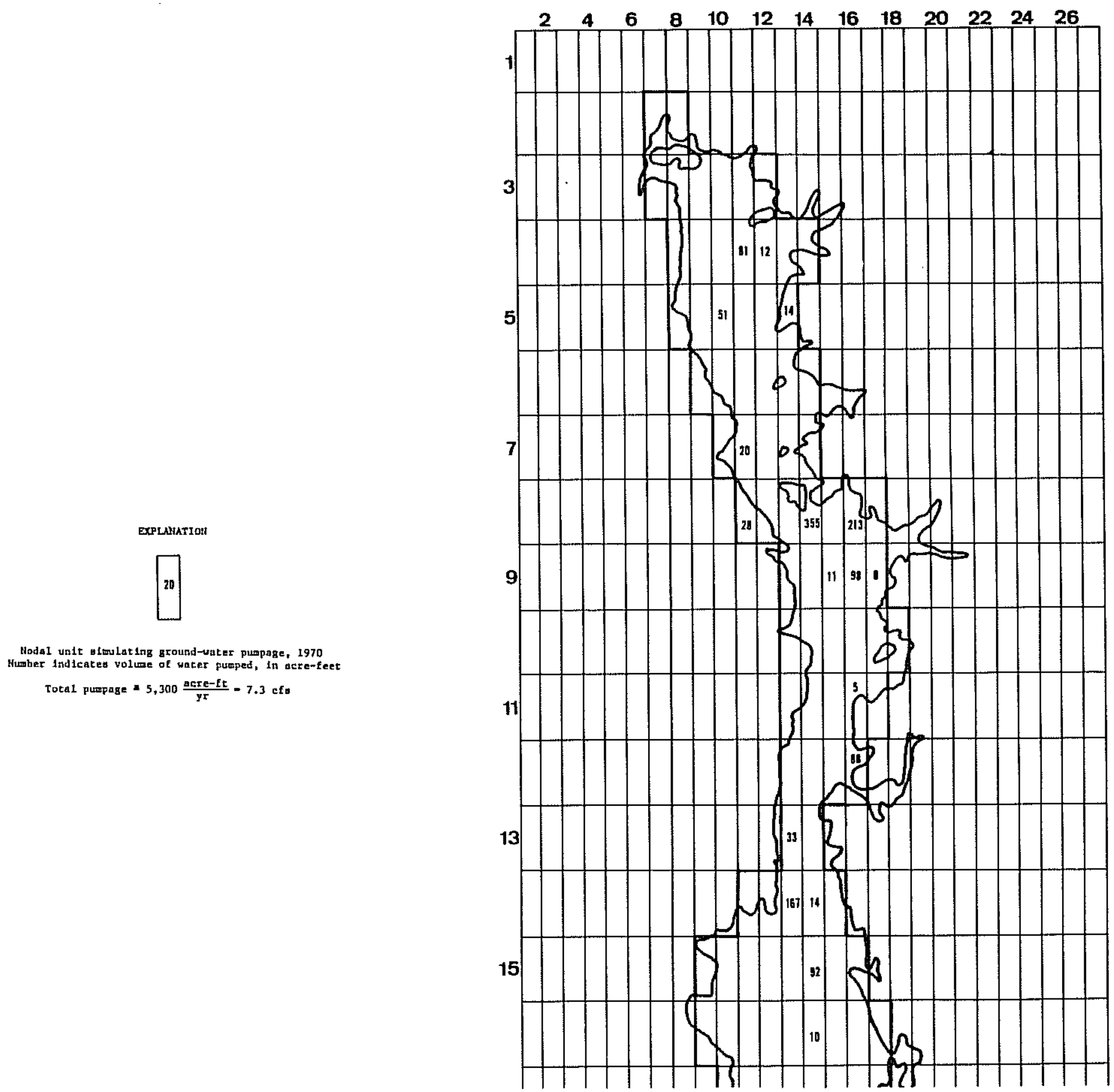
FIGURE 13.--COMPARISON OF SIMULATED AND MEASURED WATER-LEVEL CONTOURS



STEADY-STATE WATER-LEVEL CONTOURS AND WATER BUDGETS.



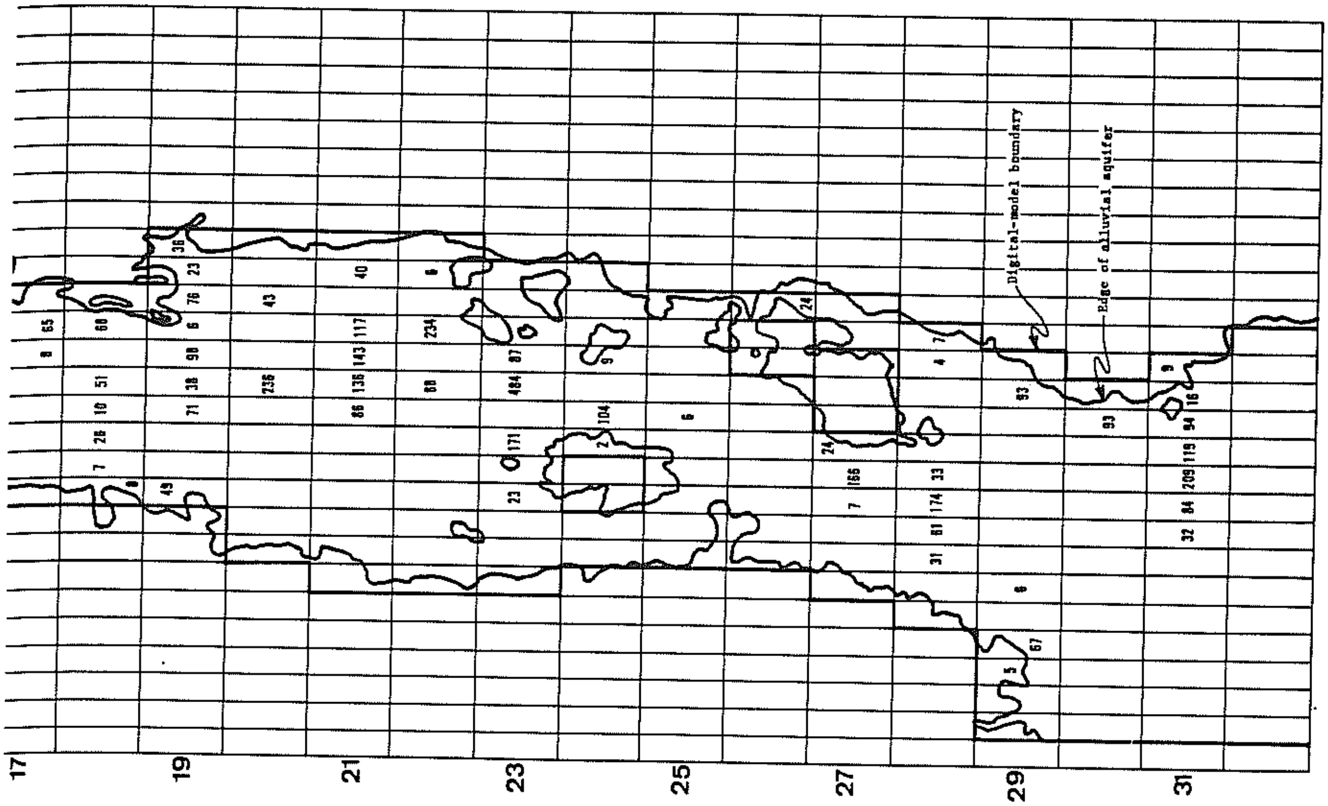
FOR JUNE 1931 AND APPLIED AND SIMULATED TRANSIENT-STATE WATER BUDGETS.



EXPLANATION

Nodal unit simulating ground-water pumpage, 1970
Number indicates volume of water pumped, in acre-feet

Total pumpage = 5,300 $\frac{\text{acre-ft}}{\text{yr}}$ = 7.3 cfs



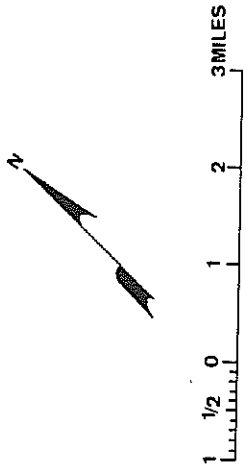


FIGURE 14.--NET GROUND-WATER PUMPAGE FROM ALLUVIAL AQUIFER IN NORTHERN NAPA VALLEY, 1970.

SIMULATION OF CRITICAL DROUGHT CONDITIONS IN THE PROJECT AREA

The Napa County Flood Control and Water Conservation District (1970) estimated that by the year 2020 the annual use of ground water in the project area could range from 12,000 to 35,000 acre-feet. The ability of the alluvial aquifer to provide such large withdrawals, without imposing serious limitations on well users, depends for the most part on the amount of net recharge available every year. During water years when precipitation is equal to or above the threshold value, net recharge to the aquifer is expected to be sufficient to replace the storage depleted during the previous season(s). On the other hand, if several consecutive years occur, during which precipitation is significantly less than the threshold value; the net aquifer recharge will be small or entirely lacking and drought conditions may result. The effect of such drought conditions, measured in terms of their impact on ground-water users, will depend on the distribution of pumping centers in the project area; the rate and timing of pumping from large capacity wells; and the length and severity of the drought. The most critical situation will develop when large quantities of water are pumped from the alluvial aquifer during a year or series of years, when net aquifer recharge is practically zero. For this study, a period of critical drought is said to occur when large-scale ground-water pumpage takes place after a water year or series of water years when recharge to the alluvial aquifer is negligible. Table 1 indicates that the probability of occurrence of critical drought conditions is about 3 percent annually and only 0.09 percent for the occurrence of two such years in sequence.

The response of the alluvial aquifer to critical drought conditions for periods of 1 and 2 years was simulated by the aquifer model. Initial conditions were taken to be the same as those simulated for June 1931; that is, no flow in the Napa River and no simulated net recharge occurring from tributary streams or from precipitation. Subsurface recharge and discharge were simulated using the same values as used for the steady-state and transient-state conditions described above. Withdrawal rates from the alluvial aquifer were estimated using data from Faye (1972), the 1970 distribution of irrigation wells, assumed total lifts and pumping times, and the design capacity of pumps in the project area during the 1970 water year. Figure 14 shows the calculated net pumpage from the alluvial aquifer during the 1970 water year. This pumpage represents total calculated pumpage (5,900 acre-feet) less an estimated 10 percent irrigation return flow. In order to simulate future ground-water conditions the 1970 nodal distribution of pumping was maintained, but pumping rates were doubled and quadrupled. Critical drought conditions were then simulated for 2 years using twice the 1970 rate of pumping and for 1 and for 2 years using 4 times the 1970 rate of pumping. The results of these simulations are shown in figures 15, 16, and 17. These figures show the probable distribution of water-level contours in the alluvial aquifer after a simulation of what probably are the most adverse conditions to which the aquifer will ever have to respond.

Simulation of twice the 1970 pumpage for 2 years (fig. 15) and quadruple the 1970 pumpage for 1 year (fig. 16) indicated little depletion of the aquifer. A significant pumping depression did develop just north of Maple Lane in the center of the valley. South of St. Helena, many wells 30 feet or less in depth would be dry under these drought conditions and pumping lifts at deeper wells would be increased.

Figure 17 indicates that significant declines in the water table would occur after 2 years of critical drought conditions with quadruple the 1970 pumping rates. The pumping depression near Maple Lane would expand and another depression would probably develop directly east of it. In the center of the valley, between Rutherford and Oakville, much of the upper 50 to 70 feet of the alluvial aquifer would be dewatered and a cone of depression would extend northward toward the periphery of the valley. Also, dewatering of the upper part of the alluvial aquifer would occur between Yountville and Oak Knoll Avenue. In the vicnity of Oak Knoll Avenue, large simulated withdrawals made between Highway 29 and the Napa River would cause a cone of depression to extend westward toward the periphery of the valley. South of St. Helena, relatively shallow wells having depths of 60 feet or less would be dry under such conditions.

It should be emphasized that the critical drought conditions described above are statistically rare events, and even if pumpage should increase to the projected values, the amount of water stored in the alluvial aquifer would be sufficient for most of the projected needs. During most water years, some recharge to the aquifer will almost certainly take place accordingly to the recharge mechanisms described previously. If significant storage depletion occurs and if the water table drops below the bed of the Napa River, the river will become a major source of recharge to the alluvial aquifer and flow in the Napa River will be reduced accordingly.

It should also be emphasized that in years following critical dry periods, normal rainfall and runoff would cause substantial water-level recovery and steady-state water-level conditions would probably reoccur. Thus, no long-term aquifer depletion should develop in the alluvium under the water-use conditions expected during the 1970-2020 period. If optimum plans for using the alluvial aquifer could be developed so that costs were minimized, significant economic benefits could accrue to the water users in future years.

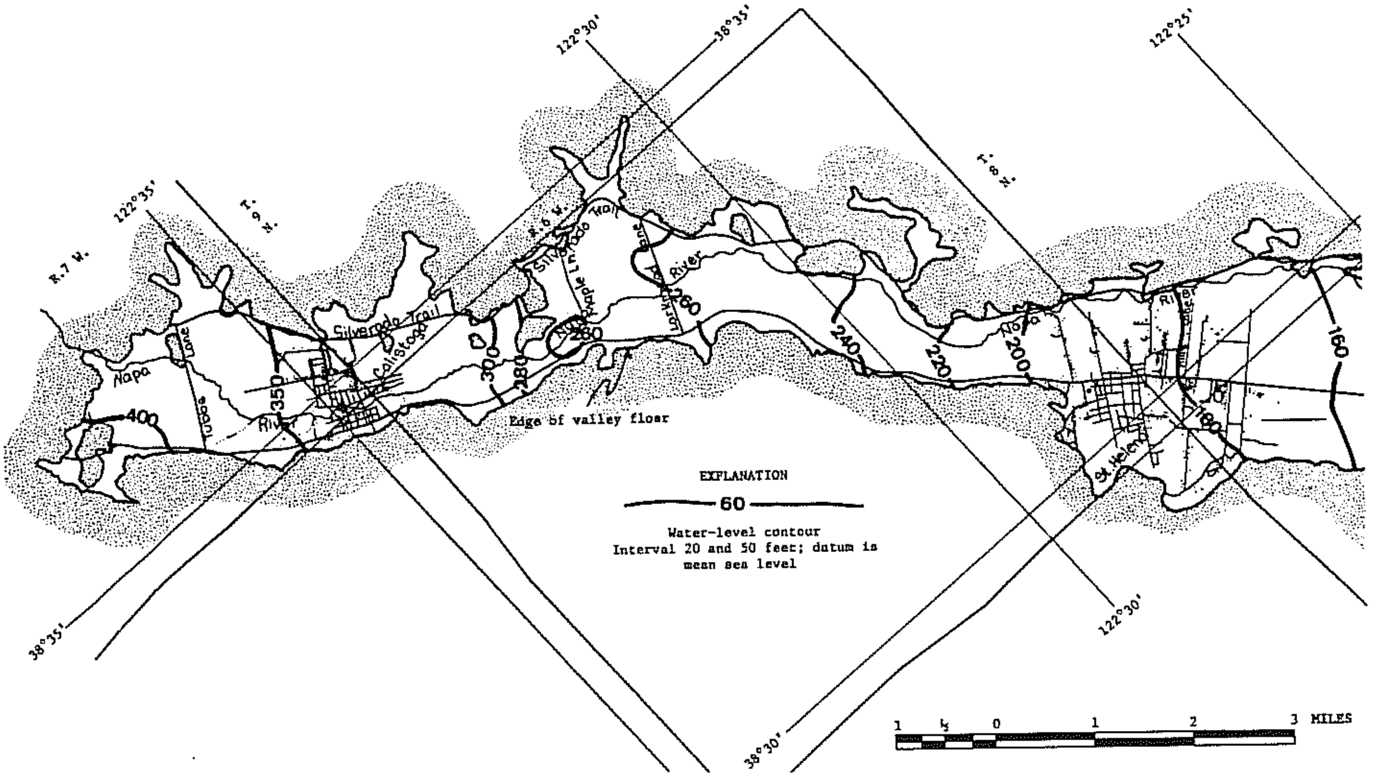
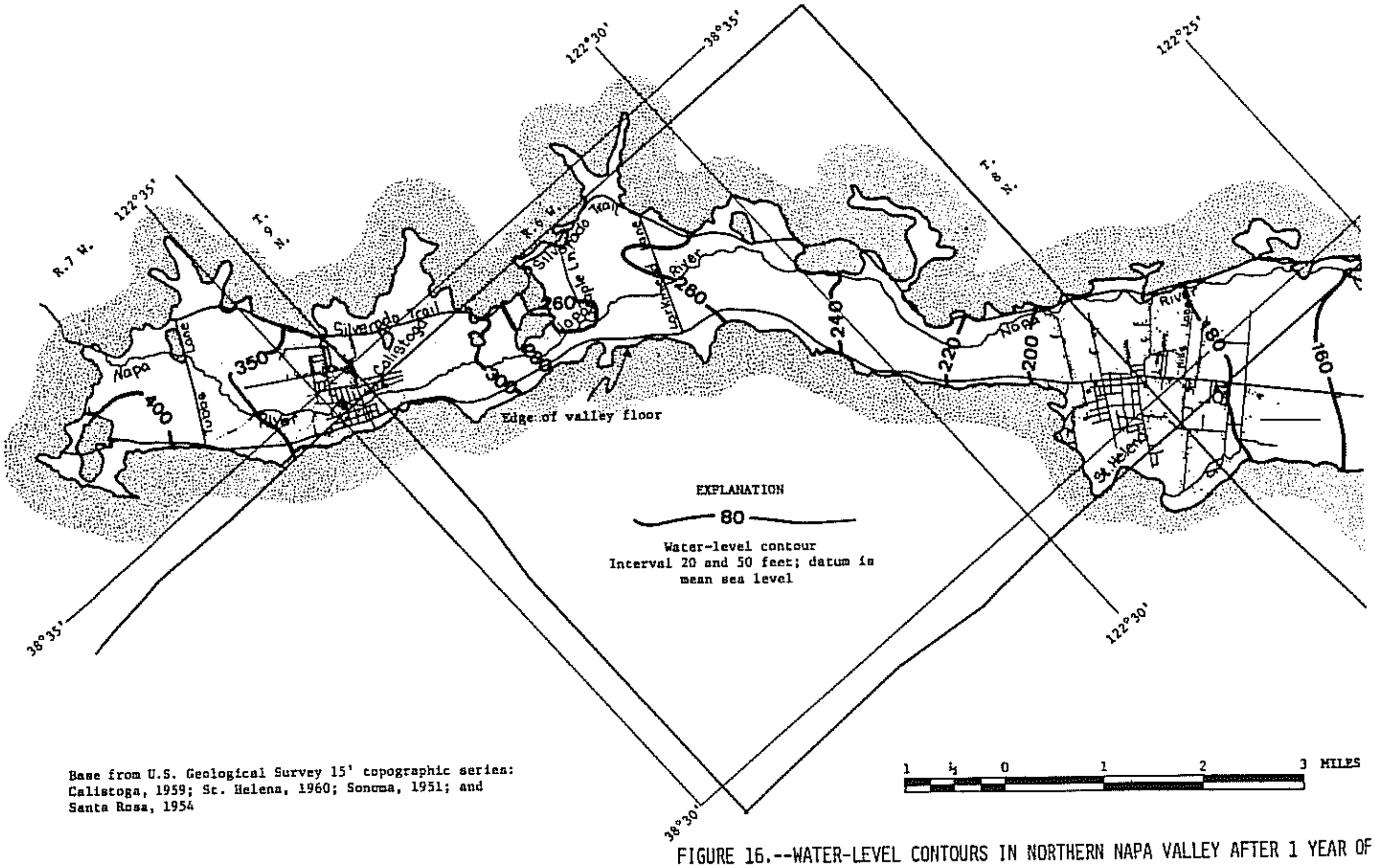
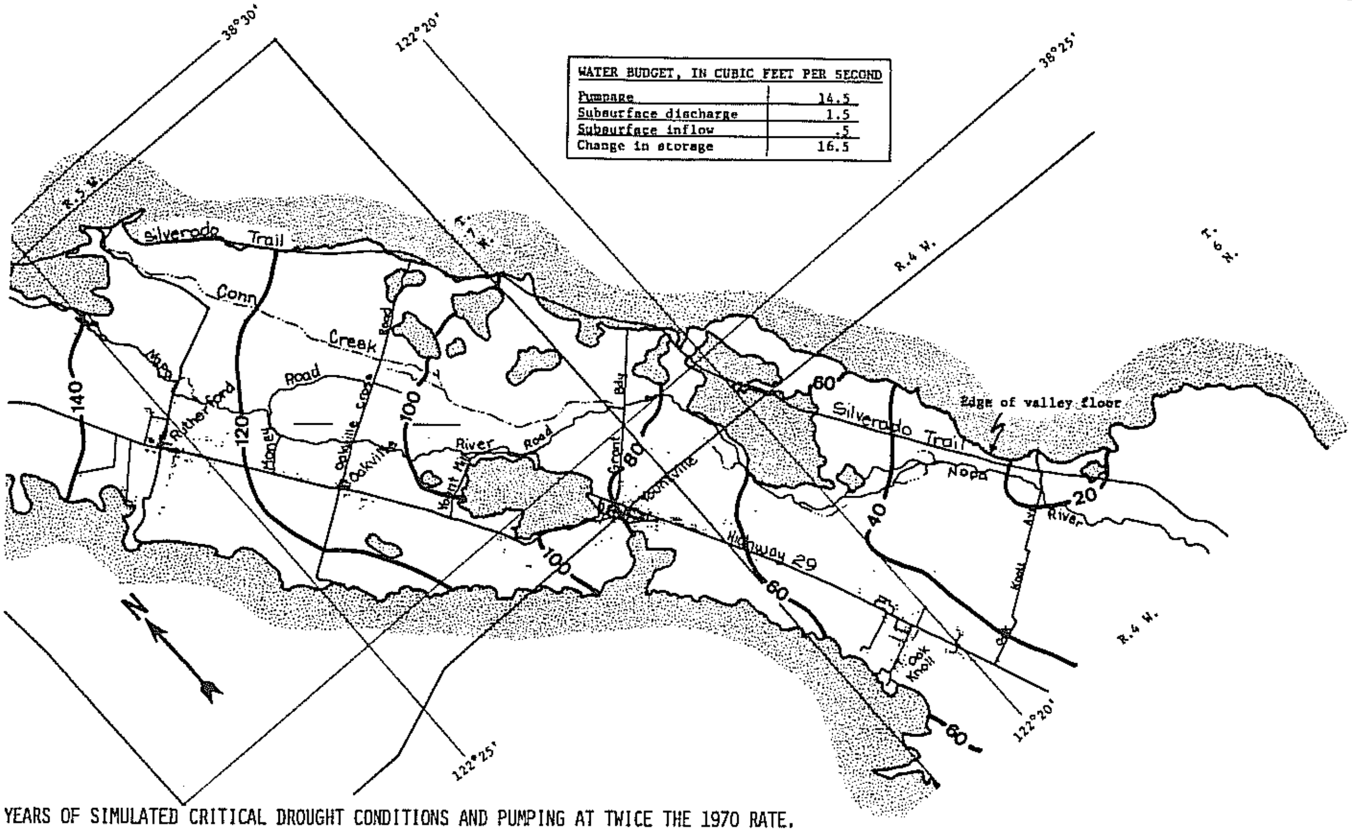


FIGURE 15.--WATER-LEVEL CONTOURS IN NORTHERN NAPA VALLEY AFTER TWO CONTINUOUS



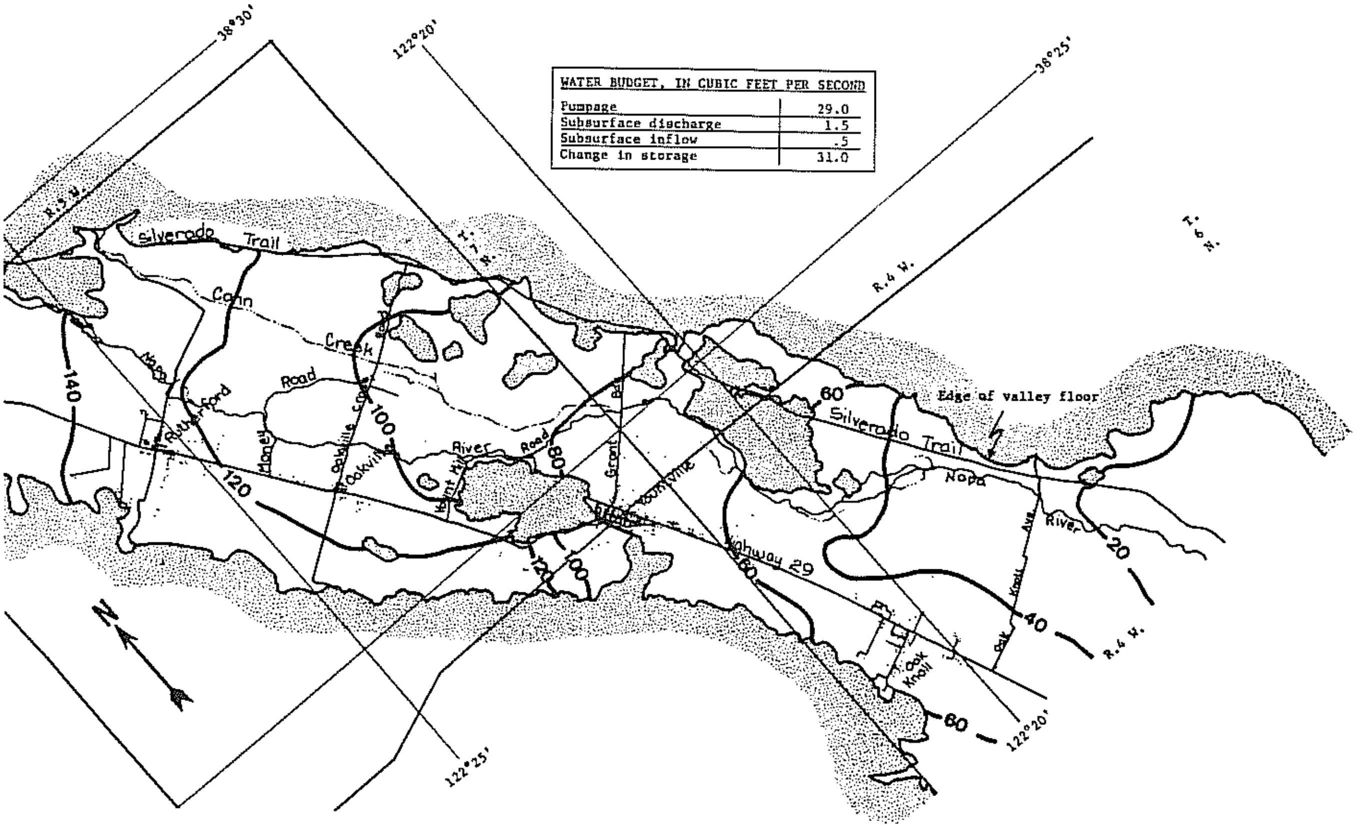
Base from U.S. Geological Survey 15' topographic series: Calistoga, 1959; St. Helena, 1960; Sonoma, 1951; and Santa Rosa, 1954

FIGURE 16.--WATER-LEVEL CONTOURS IN NORTHERN NAPA VALLEY AFTER 1 YEAR OF



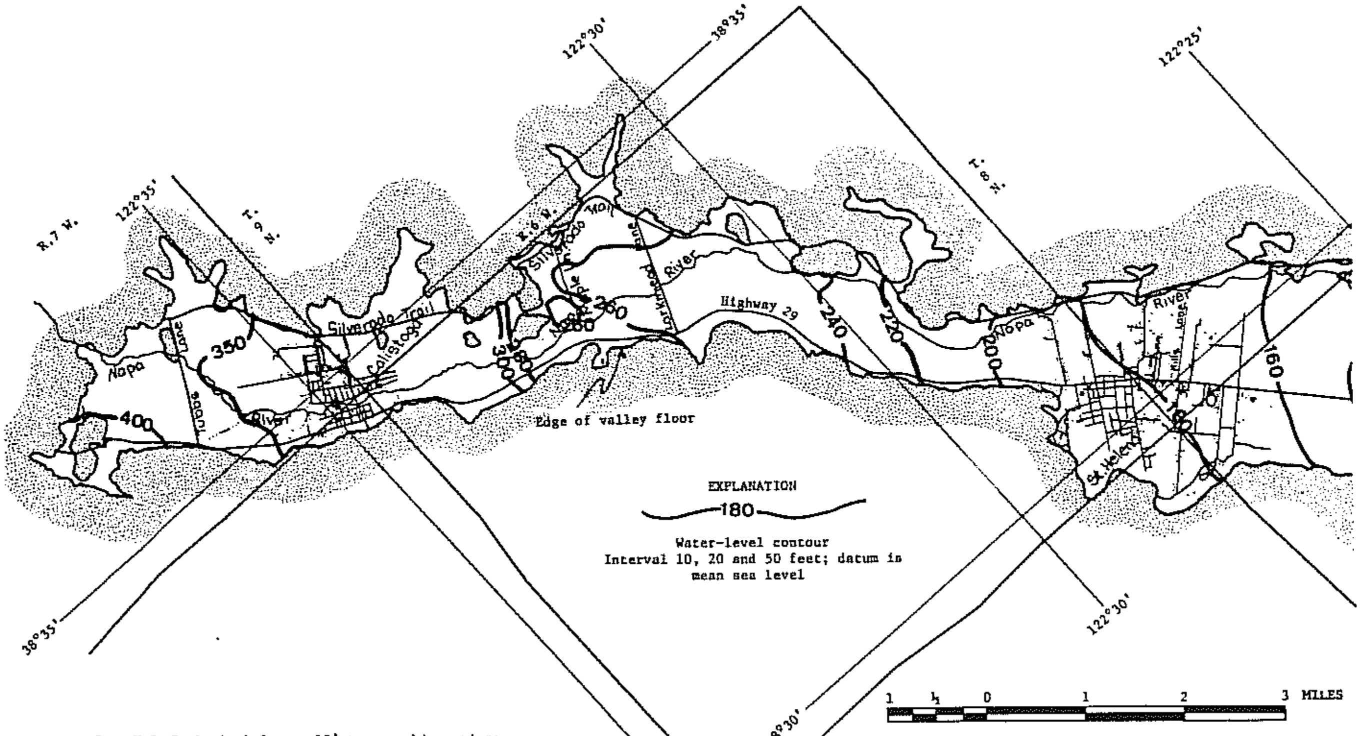
WATER BUDGET, IN CUBIC FEET PER SECOND	
Pumpage	14.5
Subsurface discharge	1.5
Subsurface inflow	.5
Change in storage	16.5

YEARS OF SIMULATED CRITICAL DROUGHT CONDITIONS AND PUMPING AT TWICE THE 1970 RATE.



WATER BUDGET, IN CUBIC FEET PER SECOND	
Pumpage	29.0
Subsurface discharge	1.5
Subsurface inflow	.5
Change in storage	31.0

SIMULATED CRITICAL DROUGHT CONDITIONS AND PUMPING AT QUADRUPLE THE 1970 RATE.

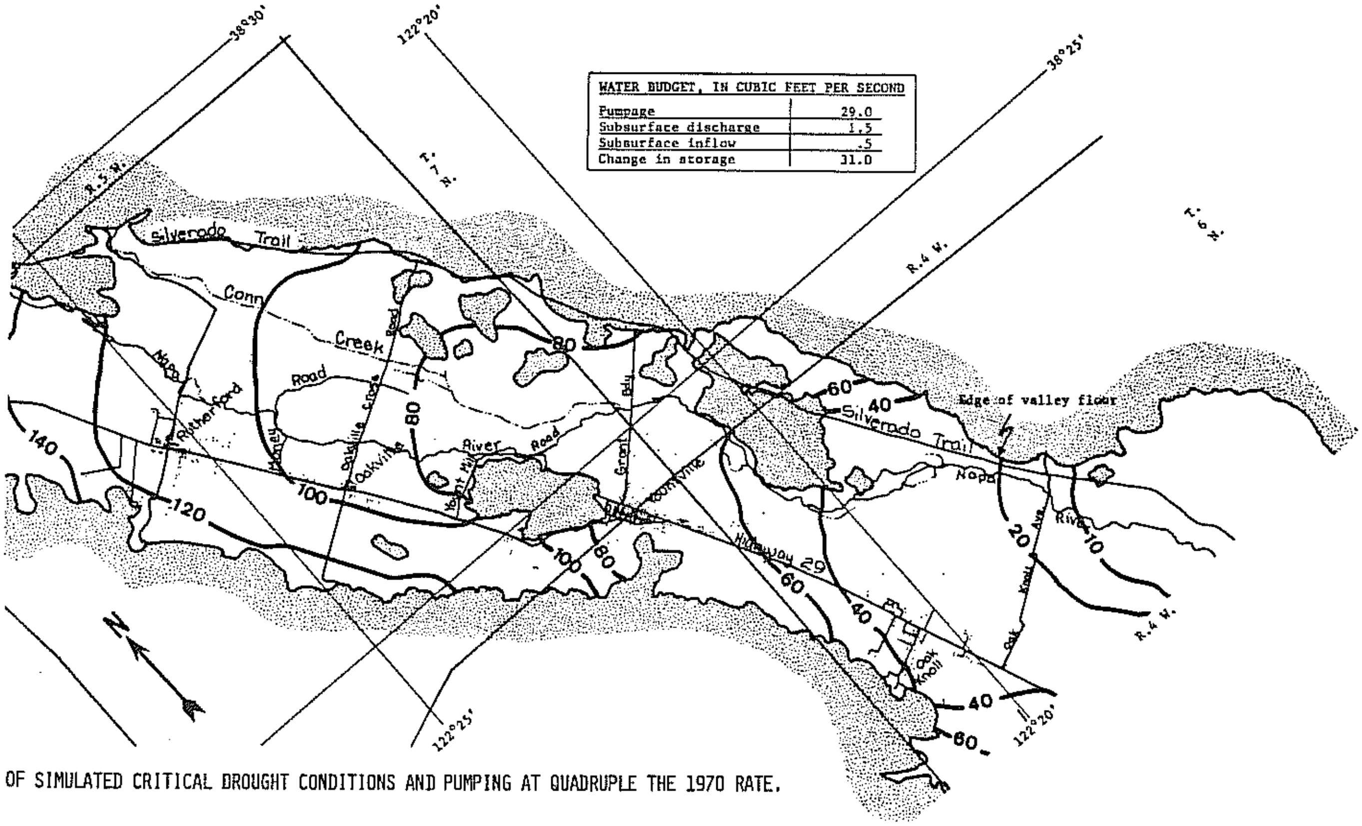


Base from U.S. Geological Survey 15' topographic series:
Calistoga, 1959; St. Helena, 1960; Sonoma, 1951; and
Santa Rosa, 1954

FIGURE 17.--WATER-LEVEL CONTOURS IN NORTHERN NAPA VALLEY AFTER TWO CONTINUOUS YEARS

GROUND-WATER QUALITY

Water-quality criteria are based on the type and amount of dissolved solids (mineral and organic matter) in water and on the intended use of the water. Dissolved matter in water is mostly in the form of electrically charged particles called ions whose concentrations are measured in milligrams per liter (mg/l) or milliequivalents per liter (meq/l). Positively charged ions are called cations; negatively charged ions are called anions. Among the more important factors that influence the quality of water for irrigation are the dissolved-solids concentrations, the ratio of sodium to other positively charged ions, the concentration of bicarbonate ions, and the boron concentration. Domestic water users are generally concerned with the hardness of water and the concentrations of such potentially harmful or distasteful constituents as chloride, nitrate, sulfate, fluoride, iron, and sodium.



WATER BUDGET, IN CUBIC FEET PER SECOND	
Pumpage	29.0
Subsurface discharge	1.5
Subsurface inflow	.5
Change in storage	31.0

OF SIMULATED CRITICAL DROUGHT CONDITIONS AND PUMPING AT QUADRUPLE THE 1970 RATE.

Because application of mineralized water to land having inadequate drainage may create an adverse nutritional or toxic response in crops (salinity hazard), the dissolved solids of a water should be known before it is used for irrigation. The electrical conductivity or specific conductance of water is commonly used as an indicator of total dissolved solids.

A high percentage of sodium in irrigation water may influence the soil texture by ion exchange and create a sodium hazard. In this process, sodium replaces calcium and magnesium in the soil complex. The sodium-bearing soil particles may cause the soil to deflocculate and become almost impermeable. A decrease in the relative permeability would also increase drainage problems and could result in the formation of a saline topsoil, creating a potential for salinity hazard.

Large concentrations of carbonate or bicarbonate ions in irrigation water increase the potential for sodium hazard. When a soil-water solution becomes increasingly concentrated, water containing high concentrations of carbonate and bicarbonate ions tends to precipitate calcium and magnesium as carbonates. With the progressive removal of calcium and magnesium from the soil solution, the relative proportion of sodium is increased and the potential for sodium hazard is increased proportionately.

Boron is essential to the normal growth of all plants, but the quantity required is very small. Also, the amount of boron that can be tolerated by one plant may be toxic to more sensitive plants. Boron hazard from irrigation water is based on the concentration of boron in the water and the kinds of plants to which the water is applied. Water having a boron concentration of 0.5 mg/l or less is generally safe to use on all types of crops (Wilcox, 1955).

High concentrations of iron in irrigation water may cause the formation of objectionable scale and bacteria growths in wells and pipe lines and iron precipitates tend to coat soil particles and deflocculate the soil during cyclical applications of irrigation water.

The U.S. Department of Agriculture has developed several methods to evaluate the salinity, sodium, and bicarbonate hazard of irrigation water (Wilcox, 1955). Bicarbonate hazard is evaluated by calculating the residual sodium carbonate (RSC) which is defined as:

$$\mathrm{RSC} = (\mathrm{CO_3}^{=} + \mathrm{HCO_3}^{-})-(\mathrm{Ca}^{++} + \mathrm{Mg}^{++})$$

in which the ionic concentrations are expressed in milliequivalents per liter (meq/l). Generally water containing an RSC of 1.25 meq/l or less is safe for irrigation purposes. Salinity and sodium hazards are evaluated using specific conductance (that is, total dissolved solids) and the sodium adsorption ratio (SAR). SAR is based on the absolute and relative concentrations of positively charged major ions in water such that:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\dfrac{\mathrm{Ca}^{++} + \mathrm{Mg}^{++}}{2}}}$$

where the concentrations are expressed in milliequivalents per liter.

The drinking-water standards of the U.S. Public Health Service (1962) are generally used to evaluate the chemical quality of domestic-water supplies. Recommended upper limits for some of the more common constituents, in milligrams per liter, are listed below.

Constituent	Recommended upper limit (mg/l)
Nitrate (NO_3^-)	45
Chloride (Cl^-)	250
Sulfate ($SO_4^=$)	250
Total dissolved solids	500

The Environmental Protection Agency (1971) has recommended that the upper limit of concentration for sodium in drinking water supplies be placed at 270 mg/l.

Excessive hardness of a domestic water supply generally is caused by high concentrations of calcium and magnesium ions in solution. Hardness usually is reported as total hardness as $CaCO_3$ (calcium carbonate) wherein the concentrations of hardness-producing ions are converted to equivalent weights of $CaCO_3$. Water with a total hardness of more than 120 mg/l as $CaCO_3$ is considered hard (Hem, 1970) and may have objectionable scale-forming and soap-consuming properties. Alkaline water containing calcium and carbonate ions in solution also tends to deposit $CaCO_3$ in pipes and tanks.

High concentrations of iron in domestic water supplies may stain glassware, porcelain, and laundered clothes and may impart an unpleasant inky or astringent taste to the drinking water.

Chemical Classification of Ground Water in the Project Area

Four chemically distinct types of ground water occur in the project area. These water types have been identified by comparing relative concentrations of representative chemical constituents in a water and are listed below according to their frequency of occurrence in the project area.

Mixed cation bicarbonate water
Sodium chloride water
Magnesium bicarbonate water
Sodium bicarbonate water

The chemical analyses of ground water from 59 sampling sites in the project area are given in table 4. Figure 3 shows the location of sampling sites, summarizes the chemical characteristics of ground water in different parts of the project area, and indicates places where hydrothermal water has been found.

TABLE 4.—*Chemical analyses of ground water in the northern part of Napa Valley*

Well locations explained in text, page 5.

Geologic units: Qal, alluvium; Tsv, Sonoma Volcanics, undivided; Ku, sedimentary Cretaceous rocks, undivided; KJf, Franciscan Formation; Jsp, Ultrabasic rocks.

SAR; sodium-adsorption ratio, $Na^+/\sqrt{(Ca^{++}+Mg^{++})/2}$, where the ionic concentrations are expressed in meq/l; symbol <, less than value shown.

RSC; residual sodium carbonate, $(CO_3^{=}+HCO_3^{-}) - (Ca^{++}+Mg^{++})$, where the ionic concentrations are expressed in meq/l; symbol <, less than value shown.

Tr, trace

Values for dissolved solids indicate residue on evaporation at 180°C, except those preceded by the letter "a" which have been calculated (sum of determined constituents).

Values for nitrate preceded by the letter "b" were reported as the sum of nitrate and nitrite.

Other constituents expressed in mg/l, in remarks column as follows: Al, aluminum; Li, lithium; PO_4, phosphate, total; N, nitrogen, total; Mn, manganese; As, arsenic.

Water temperature; degrees Celsius (°C) to degrees Fahrenheit (°F), F = 9/5 (°C) + 32.

Well number	Geologic unit	Depth of well (feet)	Date sampled	Water temperature (°C)	Concentration, in milligrams per liter (mg/l)															SAR	RSC	Specific conductance (micromhos at 25°C)	pH	Other constituents and remarks
					Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$					
														MIXED CATION BICARBONATE WATER										
[c]6N/4W-2H1	Tsv		1915	19.5	14	67	61	124	143	Tr		608	8.8	49					663	2.5	7			Spring; Al, 6.7; Li, Tr
6N/4W-17A1	Qal	250	8/27/58	16.5	25	15	29	18	19	2	167		35	5.9	0.1	6.2	0.0	222	146	<1.0	<1.0	363	7.9	
6N/4W-19J2	Qal		8/1/63		24		18	12	11	.7	58		12	12	.1	50	.28	170	95	<1.0	<1.0	248	6.7	
6N/4W-20L3	Qal	50	8/1/63		24		22	14	13	.5	92		18	9.9	.2	49	.32	187	40	<1.0	<1.0	300	7.0	PO_4, 0.03
7N/4W-30L1	Qal	171	4/19/61		29	.09	7.8	6.0	7.7	2.5	58		2.0	9.1	.1	.2	.0	92	44	<1.0	<1.0	136	7.8	Iron precipitate
7N/4W-19E1	Qal, Tsv	210	3/16/59				15	15	16		153	.0	.0	7.0		Tr	2.5		99	<1.0	<1.0	250	7.3	Water has slight yellow color
7N/5W-4A1	Qal, Tsv	244	8/5/71	20.0	100	3.8	16	6.6	18	4.0	95	.0	6.8	13	.0	b.06	.0	215	67	<1.0	<1.0	195	7.4	
7N/5W-5X	Qal	90	3/1/54				25	20	15		180	.0	.2	10			.1			<1.0	<1.0	310	7.4	
7N/5W-9J1	Qal, Tsv	459	7/20/71	21.0	53	.0	25	18	36	3.8	252	.0	17	8.0	.1	b.06	.2	286	140	1.3	1.4	411	7.8	
7N/5W-13N1	Tsv	147	7/20/71	20.0	94	.0	21	12	11	1.5	160	.0	2.0	6.7	.0	b.9	.0	228	100	<1.0	<1.0	250	7.2	
7N/5W-20B1	KJf, Jsp	181	10/9/70				44	36	23		340			10		.0	.22			<1.0	<1.0	620	7.3	
7N/5W-23C1	Qal, Tsv	390	8/2/71		52	.0	21	25	33	2.3	276	.0	13	9.8	.0	b.06	.0	292	160	1.2	1.4	424	7.9	
[c]7N/5W-26E1	Qal	66	3/16/51	29.5	131	.0	27	15	37	8.2	212		13	19	.3	.1	.78	355	129	1.2	<1.0	397	7.3	Flows
[c]7N/5W-26E2	Qal	79	4/28/52				30	15	40		220		10	30			.6		137	1.5	<1.0	410	7.4	Yellow residue
7N/5W-26M2	Qal, Tsv	215	6/18/53				25	20	25		175	.0	20	20			.0		144	<1.0	<1.0	340	7.6	
7N/5W-34H1	Qal, Tsv	200	8/3/71	16.0	87	.2	23	16	16	2.3	175	.0	13	4.4	.1	b.06	.0	248	120	<1.0	<1.0	286	7.4	
7N/5W-36M1	Tsv	104	8/27/58	20.5	96	.0	17	13	15	3.5	143	.0	7.4	6.2	.2	.5	.0	[a]230	96	<1.0	<1.0	265	8.1	
8N/5W-26M1	Tsv	340	7/10/72		93	.0	7.2	8.1	10	4.4	79	.0	3.8	8.9	.1	b6.7	.0	181	51	<1.0	<1.0	157	7.4	
8N/6W-4Q2	Qal, Tsv	232	9/29/55				10	5	10			65	.0	10			.0		46	<1.0	<1.0	130	7.3	
8N/6W-15A2	Qal	125	3/19/51		53	.0	20	10	10	3.4	112	.0	12	7	.2	1.4	.0	[a]170	91	<1.0	<1.0	211	7.4	
8N/6W-23B2	Qal	168	12/6/55				10	5	20		110	.0	.0	10			.11		46	<1.0	<1.0	160	7.2	
8N/6W-25B3	Qal, Tsv	325	5/28/54				15	15	15		130	.0	.0	15			.0		100	<1.0	<1.0	200	7.2	
9N/6W-31Q1	Qal	51	8/27/58		38	.0	8.9	3.9	8.3	.6	54	.0	7.4	3.9	.0	.2	.0	[a]98	38	<1.0	<1.0	118	7.4	
9N/7W-26M2	Qal, Tsv	140	7/10/72		36	.0	14	14	7.5	.2	95	.0	19	6.6	.0	b14	.0	158	93	<1.0	<1.0	222	7.7	
[c]9N/7W-26P1	Qal, Tsv	470	3/27/52		30		15	18	37	2.3	166	6.0	7.7	28	.1	2.8	1.5		111	1.6	<1.0	372	8.3	
9N/7W-27F1	Qal, Tsv	122	8/31/50				15	5	15		75		15	10			.0	[a]98	58	<1.0	<1.0	100	7.2	
[c]9N/7W-36F1	Qal	31	4/8/57				20	10	30		135	.0	.0	20			.3		92	1.3	<1.0	290	6.8	Yellow color

									SODIUM CHLORIDE WATER															
7N/5W-22G1	Qal	56	9/15/50				35	30	190		285		.0	270			14.0	668	212	5.7	<1.0	1,300	7.4	Flows in winter months
7N/5W-22G2	Qal	40	5/18/51				40	40	190		290		.0	300			14.5	730	255	5.0	<1.0	1,300	7.5	
7N/6W-2D1	KJf		5/11/65	32.0	46		4.6	.6	232	3.0	120	64	12	224	5.7	1.3	32	698	14	56	3.8	1,110	8.8	Spring
8N/6W-4F1	Qal, Tsv	207	--	82.0	111		.8	36	176			90.4	2.2	270				[a]690	154					"Geyser" well
8N/6W-5Q2	Qal, Tsv	305	8/5/71	20.0	65	.88	14	4.7	32	3.7	63	.0	17	50	.2	b.06	1.6	220	54	1.9	<1.0	295	7.1	
8N/6W-9D1	Qal, Tsv	165	2/19/51				35	5	85		110	10	55	95			3.2	[a]340	106	3.6	<1.0	690		
9N/6W-31H3	Qal, Tsv		4/17/70	98.0	134	.0	4.0	.0	180	10	122	3	18	211	11.4		10		10	23.6	1.8	995	8.7	
9N/7W-25N1	Qal, Tsv	149	8/27/58	29.5	66	.17	12	5.6	166	9.8	201	.0	.0	173	6.2	1.2	12	551	53	10	2.2	901	7.7	
9N/7W-26G1	Qal, Tsv	305	12/3/52	31.5			25	5	170		210		.0	220			11.6		93	8.0	1.7	1,420	7.7	Flows
9N/7W-26K2	Qal, Tsv	60	4/25/51				5	5	220		170		.0	190			7.0		36	19.2	2.3	900	8.0	Yellow residue
9N/7W-26K3	Qal, Tsv	150	6/30/55				.0	.0	190		145		.0	195			9.9		0	High	2.4	900	7.6	
9N/7W-26K4	Qal, Tsv	75	6/30/55				.0	.0	185		140	Tr	5	195			10.0		0	High	2.3	900	7.9	Flows
9N/7W-26R1	Qal	18	11/16/48				35	5	105		190		10	115			4.6	[a]370	108	4.5	1.0	800	7.3	
9N/7W-26R2	Qal, Tsv	207	1/10/48	43.5			15		170		165			190			10.6	[a]470				926		
9N/7W-35R1	Qal, Tsv	312					.6	.4	100		170			95			4.2			6.1	1.8	550	7.4	
9N/7W-36D2	Qal, Tsv	165	2/4/58				10	5	160		180	.0		165		Tr			46	12.6	1.8	996	7.6	Warm
									MAGNESIUM BICARBONATE WATER															
6N/4W-6P1	Qal	120	7/10/69	16.5			18	26	15	1.0	137	.0	40	12		19	.0	243	153	<1.0	<1.0	361	7.9	
6N/4W-7X	Qal	100	12/15/55				30	35	25		260	.0	40	20			.3		220	<1.0	<1.0	510	7.0	
7N/5W-5A1	Qal	38	9/29/59		27		18	46	17	3.9	235	.0	51	16	.2	4.6	.5		233	<1.0	01.0	512	8.0	
7N/5W-10M1	Qal, Tsv	590	8/3/71	15.5	39	.2		29	14	1.7	224	.0	18	7.1	.1	b16	.2	259	180	<1.0	<1.0	395	7.5	
7N/5W-20J1	Jsp		10/12/48				70	90	35		530		140	15			.4					1,010	7.1	Spring
[c]7N/5W-22K1	Qal	15	3/9/55				35	55	45		245	.0	20	100			2.9		315	1.1	<1.0	840	6.8	
7N/5W-23D2	Qal	139	2/1/51		47	.10	21	30	20	3.0	241	.0	13	8.0	.0	1.5	.21	[a]260	176	<1.0	<1.0	399	7.5	Flows in spring of the year
8N/6W-9F1	Qal	105	1951				20	20	15		135		10	30				[a]160	113	<1.0	<1.0	310	6.7	
									SODIUM BICARBONATE WATER															
6N/4W-4D1	Tsv, Ku	515	7/20/71		30	.0	40	8.4	110	.5	242	.0	130	11	.6	b.06	.0	450	130	4.1	1.4	637	7.8	
6N/4W-15Q1	Qal, Tsv	303	9/29/59	19.0	45		10	5.6	35	4.0	133	.0	2.1	8.4	.3	9.1	.2	185	48	13	1.2	254	8.1	
8N/5W-27H1	Jsp		8/21/59						644								3.5			23		3,040		
8N/5W-32C1	Tsv	132	3/8/63		100		14	13	57	7.0	248	.0	.0	13	.4	2.5	.64	347	89	2.6	2.3	422	7.8	N, 0.56
8N/6W-7F1	Tsv	245	8/5/71	25.0	91	5.1	7.0	2.2	23	4.6	84	.0	13	3.8	.0	b.06	.0	191	27	1.9	<1.0	160	7.3	
8N/6W-13K1	Tsv		5/11/65				3.8	1.3	7.5	2.8	26		4	5	.1	2.4	.0	97	15	<1.0	<1.0	80	6.1	Spring; PO_4, 0.25; As, Tr; Li, 0.03
8N/6W-15H1	Qal, Tsv		3/19/51		59	.8	13	8.4	39	6.6	180		4.1	5.8	.1	.0	.1	[a]230	67	2.1	1.6		7.3	Mn, 0.45
8N/6W-35R3	KJf		7/20/71		13	.6	44	13	150	3.4	450	.0	130	6.7	.1	b.2	.55	583	160	5.1	4.2	895	7.8	

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c. Probably mixed with sodium chloride water.

Mixed Cation Bicarbonate Water

Mixed cation bicarbonate water is characterized by relatively high concentrations of calcium, magnesium, and bicarbonate ions, and commonly contains anomalous concentrations of sodium. This water is generally alkaline with pH values ranging from near 7.0 to as high as 8.3. The specific conductance is low, ranging from less than 100 micromhos to more than 400 micromhos at 25°C (77°F).

Mixed cation bicarbonate water occurs throughout the Napa Valley area and is generally associated with sediments and detrital material from granitic and volcanic sources. In the project area, the water is common to the alluvial aquifer and to several areas of the Sonoma Volcanics (fig. 3 and table 4).

This water is generally suitable for irrigation and domestic uses. SAR and RSC values (table 4) are characteristically low, and the water is generally classified as soft to moderately hard; total hardness as $CaCO_3$ is generally less than 150 mg/l. High concentrations of iron noted in several analyses may limit the use of the water as an irrigation and domestic water supply.

Sodium Chloride Water

In the project area sodium chloride water generally is associated with geothermal activity and contains relatively high concentrations of sodium, chloride, bicarbonate, boron, silica, and sulfate ions. Anomalous concentrations of nitrate were noted in several samples. The sodium chloride water is generally alkaline with pH values ranging from near 7.0 to as much as 8.7. The specific conductance ranges from less than 300 micromhos to more than 1,400 micromhos at 25°C (77°F).

White (1957) and White, Muffler, and Truesdell (1971) describe a process whereby sodium chloride water originates from a hot-water dominated hydrothermal system of volcanic origin. A similar process may account for the occurrence of sodium chloride water in the northern part of Napa Valley. According to White (1957), deep-percolating meteoric water and possibly water of other origins become involved in a hydrothermal system of high terrestrial heat flow associated with a deep magmatic heat source. This water is heated to steam containing alkali halides in solution; is subsequently circulated within the hydrothermal, ground-water system; and, upon condensation at or near the surface of the earth, yields the characteristic sodium chloride water.

Sodium chloride water in the project area is generally hydrothermal and occurs most commonly in the Calistoga area (p. 15). Figure 3 shows that sodium chloride water also occurs along Maple Lane south of Calistoga, in Sulphur Canyon west of St. Helena, and in the vicinity of Oakville. Water of mixed type was found at Napa Soda Springs, in several wells south of Oakville, and in wells 9N/7W-26P1 and 9N/7W-36F in the Calistoga area (table 4).

The occurrence of sodium chloride water may be associated with faults. Barnes (1970) describes water containing high concentrations of sodium, chloride, bicarbonate, and boron ions that issues from springs along known or inferred fault zones in the western Coast Ranges of North America. In northern Napa Valley, a chemical analysis of water from Napa Soda Springs (6N/4W-2N1, fig. 3, and table 4) indicates the occurrence of sodium chloride water. The springs issue from orifices along the inferred strike of the Soda Creek fault. Sterns, Sterns, and Waring (1937) also implied an association between faults and the occurrence of hot springs in the Calistoga area. As more water-quality and geologic data for the Napa Valley area become available, the association between sodium chloride water and faults may become more apparent.

In the project area, sodium chloride water is marginally suited for irrigation purposes. Boron concentrations and SAR values are characteristically high, RSC values are commonly above 1.25 meq/l (table 4), and relatively high iron concentrations were noted in several analyses. Domestic use of sodium chloride water is practical in some instances even though concentrations of some constituents exceed the upper limits recommended by the U.S. Public Health Service (1962). Hardness generally is less than 150 mg/l as $CaCO_3$.

Water from well 9N/6W-31M3 (table 4) was given the most complete analysis of any sodium chloride water from the project area. Of particular interest is the temperature and the concentration of silica (SiO_2) in the water from this well and from well 8N/6W-4F1 (table 4).

Fournier and Rowe (1966), using curves that relate silica solubilities in water to temperature, have developed a method to estimate ground-water temperatures using the silica content of hot water discharging at land surface. This procedure suggests an underground temperature of at least 138°C (280°F) at well 9N/6W-31M3 and 130°C (266°F) at well 8N/6W-4F1.

A general dependence on depth to the occurrence of flowing wells and the possibility of general confinement in the Calistoga area has been previously mentioned (p. 15). Flowing wells in the Calistoga area are with few exceptions, hydrothermal and yield sodium chloride water. Noting the relation of silica solubility to water temperature (Fournier and Rowe, 1966) it is possible that hot sodium chloride water, rising from depth, mixes with downward-percolating cooler water causing the precipitation of silica and the subsequent cementation of material at the mixing interface. White, Muffler, and Truesdell (1971) indicate that such "self-sealing" phenomena are common in hot-water dominated hydrothermal systems with temperatures in excess of 150°C (302°F). Such activity, taking place over an area of several square miles, could produce a zone of relatively impermeable material that would confine sodium chloride water under a potentiometric head.

Magnesium Bicarbonate Water

Magnesium bicarbonate water is characterized by relatively high concentrations of magnesium and bicarbonate ions and lesser concentrations of calcium ions. This water is generally alkaline with pH values ranging from near 7.0 to 8.2. The specific conductance generally is high, ranging from about 300 micromhos to more than 1,000 micromhos at 25°C (77°F).

Magnesium bicarbonate water is generally of good quality for both irrigation and domestic purposes. SAR and RSC values (table 4) are low. In several analyses, however, boron concentrations were above recommended limits for boron-sensitive plants. Hardness ranges from about 100 mg/l to more than 500 mg/l as $CaCO_3$.

Barnes and O'Neil (1969) associated magnesium bicarbonate water in the Coast Ranges with serpentine and ultrabasic intrusive rocks. Water from a spring (7N/5W-20J1, fig. 3, and table 4) near the Bella Oaks Mine may represent this association. Also, as noted earlier (p. 13), chemical analyses of ultrabasic rocks show high concentrations of magnesium. Thus, these rocks are identified as a possible source of magnesium in ground water in the Napa Valley area. The occurrence of magnesium bicarbonate water within the alluvial aquifer probably is indicative of the infiltration of streamflow that originated as runoff from ultrabasic rocks.

Sodium Bicarbonate Water

Sodium bicarbonate water contains relatively high concentrations of sodium and bicarbonate ions. In Napa Valley several analyses also showed high concentrations of sulfate. This water is characteristically alkaline and pH values range from 7.3 to 8.1. The specific conductance ranges from less than 100 micromhos to more than 3,000 micromhos at 25°C (table 4).

In most places, sodium bicarbonate water is only marginally suited for domestic and irrigation purposes. SAR and RSC values are commonly greater than 2, boron concentrations are commonly too high for boron-sensitive plants, and relatively high iron concentrations may cause objectionable scales and stains on plumbing and other fixtures. Hardness is generally less than 100 mg/l as $CaCO_3$. Sodium concentrations may be above the limits (270 mg/l) recommended by the Environmental Protection Agency (1971) for public water supplies.

The source of sodium bicarbonate water is not well known, but available data suggest an association with the Franciscan Formation and the consolidated sedimentary rocks.

Occurrence and Classification of Sodium Chloride and Sodium Bicarbonate Water

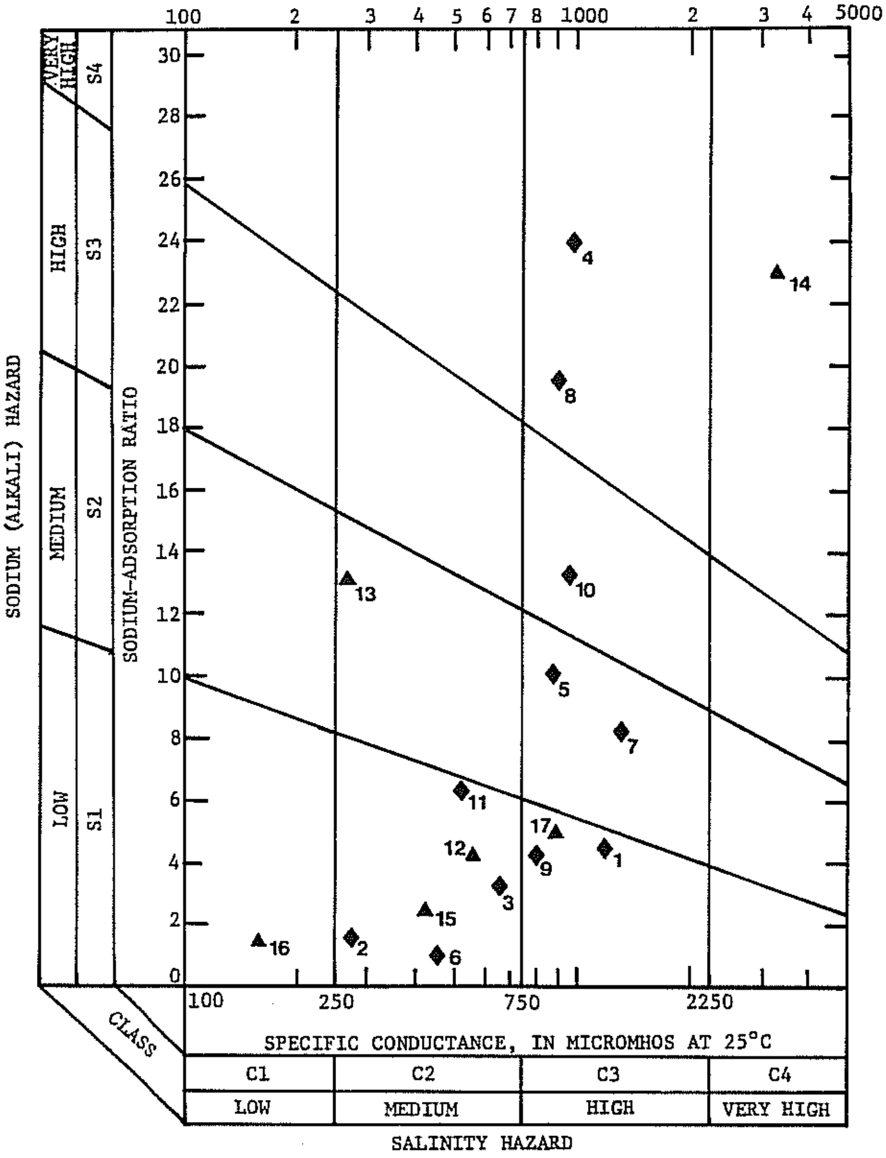
Sodium chloride water and sodium bicarbonate water are the most troublesome mineralized ground waters in the project area. As shown in figure 3, sodium chloride water occurs in the Calistoga area and in the vicinity of Oakville. In the Calistoga area, most wells containing sodium chloride water are located along the topographic axis of the valley from Bennet Lane to Maple Lane. In the vicinity of Oakville, sodium chloride water occurs in the area from Money Road to Yount Mill Road, generally between Highway 29 and the Napa River. Water-temperature records (fig. 3 and table 4) suggest that sodium chloride water may occur in wells located in secs. 3, 15, 25, and 26, T. 7 N., R. 5 W., and in secs. 3 and 25, T. 8 N., R. 6 W.

Sodium bicarbonate water occurs less frequently in the project area than does sodium chloride water and commonly occurs along the periphery of the valley or in the foothills. Wells yielding sodium bicarbonate water are located in secs. 4 and 5, T. 8 N., R. 4 W., in secs. 27 and 32, T. 8 N., R. 5 W., and in secs. 7, 13, 15, and 35, T. 8 N., R. 6 W.

Sodium chloride and sodium bicarbonate water from selected wells were plotted on a diagram (fig. 18) widely used for evaluating water for irrigation. The diagram shows that the sodium chloride water has a medium to high salinity hazard and a low to medium sodium hazard. The sodium bicarbonate water has a low to very high salinity hazard and a low to very high sodium hazard.

Migration of Sodium Chloride Water During Critical Drought Conditions

Sodium chloride water has been identified as the most troublesome and potentially the most harmful type of ground water in the project area. Water-quality data indicate the distribution of sodium chloride water is presently stable. However, critical drought conditions may cause a migration of sodium chloride water into areas of the alluvial aquifer where it does not presently occur. Such a migration would depend, for the most part, on a major change in hydraulic gradients that direct the movement of water in the alluvial aquifer.



EXPLANATION

▲ Sodium bicarbonate water

◆ Sodium chloride water

Number	Location
1	7N/5W-22G1
2	8N/6W-5Q2
3	8N/6W-9D1
4	9N/6W-31M3
5	9N/7W-25N1
6	9N/7W-25N2
7	9N/7W-26G1
8	9N/7W-26K2
9	9N/7W-26R1
10	9N/7W-35R1
11	9N/7W-36D2
12	6N/4W-4D1
13	6N/4W-15Q1
14	8N/5W-27N1
15	8N/5W-32C1
16	8N/6W-7F1
17	8N/6W-35R3

FIGURE 18.--CLASSIFICATION OF SODIUM CHLORIDE AND SODIUM BICARBONATE WATER FOR IRRIGATION. MODIFIED AFTER WILCOX (1955).

Simulation of critical drought conditions in the alluvial aquifer has been discussed in a previous section (p. 42). A comparison of figures 8, 15, 16, and 17 suggests that hydraulic gradients and the direction of ground-water movement probably will not change sufficiently to cause a significant migration of sodium chloride water until critical drought conditions occur and pumping from wells is about four times the volume pumped in 1970. Figure 17 shows simulated water-level contours for northern Napa Valley after 2 years of such conditions. The contours indicate a significant redistribution of hydraulic gradients, and suggest that a major depression caused by excessive pumping in the central part of the valley might extend westward toward Oakville and cause sodium chloride water to migrate toward postulated pumping centers. Because the effects of dispersion and dilution could not be determined, the extent of such a migration or the influences on the ultimate concentrations of sodium and chloride ions in the ground water could not be predicted. On the other hand, migration of undesirable chemical constituents to developed parts of the alluvial aquifer can generally be monitored in the field, and it is recommended that such a monitoring program be estabblished in the near future.

Although the potential for widespread migration of sodium chloride water is small, local problems of this nature can be expected as ground-water development increases. Development of ground water in the Oakville area may be most affected by intrusion of sodium chloride water into local cones of depression.

Evaluation of Quality of Base Flow and Seasonal Runoff in the Napa River

Although the Napa River at the present time is a gaining stream, large annual ground-water withdrawals could significantly alter this condition. For example, if significant storage depletion occurs in the alluvial aquifer during the summer and autumn, recharge from the Napa River will increase during the early part of the rainy season. At the same time, the lowered water levels in the alluvial aquifer may cause base flow to be depleted and no-flow conditions may become common in the Napa River during the later part of the water year. Such a situation would increase the opportunity for inducing recharge from the sewage effluent presently (1972) being discharged to the Napa River by the cities of Calistoga and St. Helena.

In order to evaluate the chemical quality of base flow in the Napa River and to estimate the qualitative impact of water recharged from the Napa River to the alluvial aquifer, two water-quality reconnaissances of the Napa River were made in July and December 1971 at the sampling sites listed below.

Sampling site	Station number	Station name	Local name
1	11-4580	Napa River near Napa	Bridge at Oak Knoll Avenue
2			Bridge at Grant Boundary Lane
3	11-4560	Napa River near St. Helena	Bridge at Zinfandel Avenue
4			Bridge at Lodi Lane
5			Pine Street, Calistoga

The July 1971 data (tables 5 and 6 and fig. 19[3]) are considered indicative of the quality of base flow. The December 1971 data (tables 5 and 6) are indicative of the quality of water most likely to be recharged to the alluvial aquifer by the Napa River after the first significant seasonal rains. These data indicate water of good mineral quality, but high coliform bacteria counts and relatively high concentrations of organic carbon and other nutrients suggest contamination from sewage and fertilizers.

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[3] In figure 19, the rapid rise in water temperature during the late morning of July 27 is probably due to the dissipation of early morning fog and a subsequent sharp rise in air temperature.

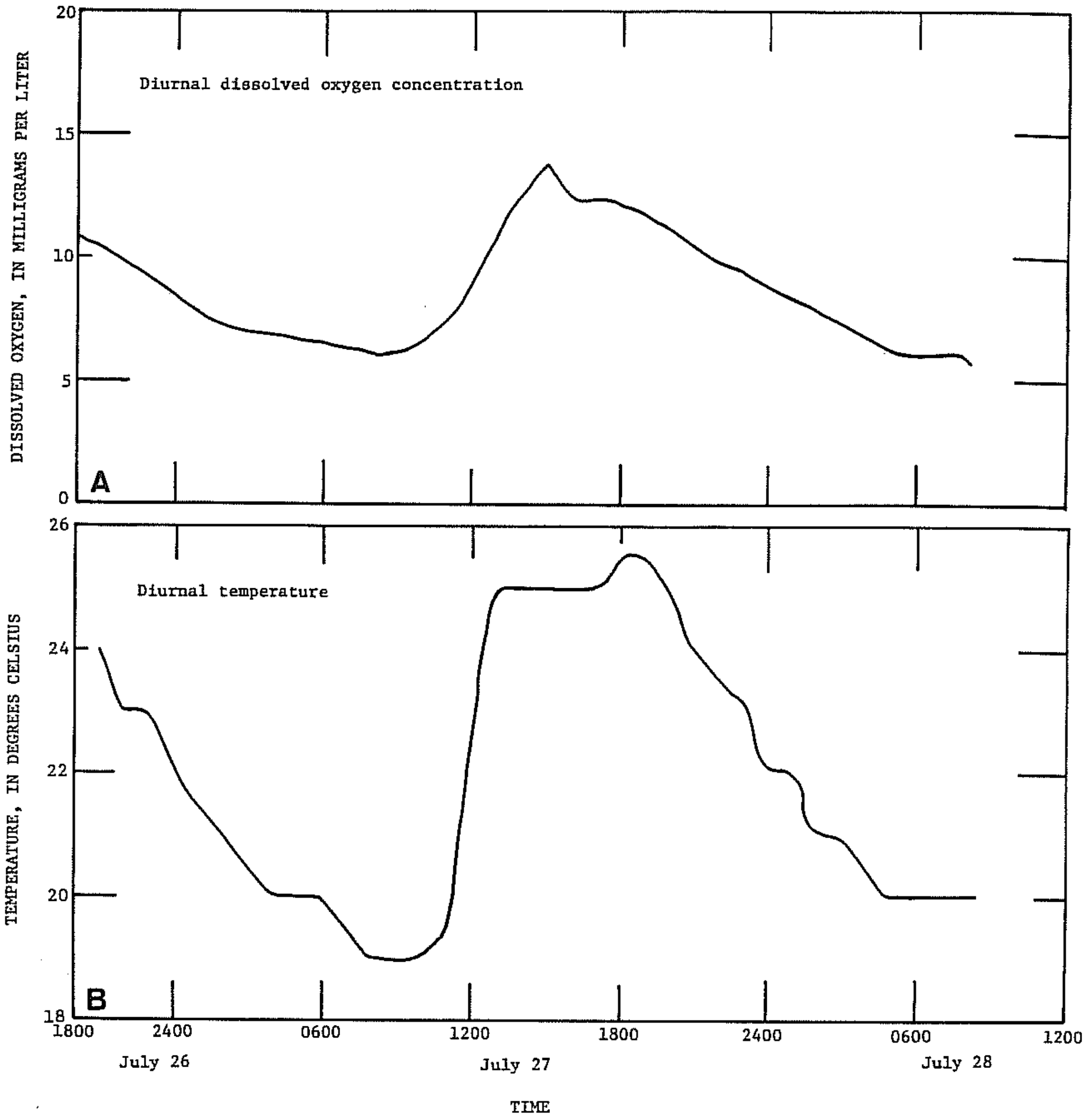

FIGURE 19.--CONTINUOUS DIURNAL DISSOLVED OXYGEN CONCENTRATION AND TEMPERATURE OF WATER IN THE NAPA RIVER AT OAK KNOLL AVENUE, JULY 26-28, 1971.

TABLE 5.—*Chemical analyses of water from the Napa River*

[Sampling sites shown in fig. 3 and explained on p. 58, discharge in cubic feet per second (cfs), computed from stage record at time sample collected]
Nitrate, reported as the sum of nitrate and nitrite.
Dissolved solids, reported as the residue on evaporation at 180°C.

Sampling site and number	Date and time of collection		Discharge (cfs)	Water temperature (°C)	Concentration, in milligrams per liter (mg/l)																	Percent sodium	Specific conductance (micromhos at 25°C)	pH
	Date	Time (hours)			Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate as N	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Total alkalinity as $CaCO_3$			
1 Bridge at Oak Knoll Ave.	7-27-71	1100	2.4	19.0	30	0.02	27	22	21	2.9	198	0.0	27	16	0.1	0.76	0.32	247	160	0.0	162	22	389	7.7
2 Bridge at Grant Boundary Lane	7-27-71	0925		20.0	29	0.03	32	24	19	2.8	228	0.0	21	11	0.1	0.44	0.39	253	180	0.0	187	19	409	7.7
3 Bridge at Zinfandel Ave.	7-27-71	1120	2.0	22.0	27	0.07	32	15	17	2.7	185	0.0	16	11	0.1	0.63	0.37	215	140	0.0	152	20	336	7.6
4 Bridge at Lodi Lane	7-27-71	1330		24.5	47	0.07	11	5	21	3.3	96	0.0	9.3	12	0.3	0.03	0.31	157	48	0.0	79	47	195	7.7
5 Pine St., Calistoga	7-27-71	1435		23.0	49	0.04	17	8.4	36	4.1	142	0.0	23	14	0.5	0.03	1.2	223	77	0.0	116	49	311	7.6
1 Bridge at Oak Knoll Ave.	12-27-71	1500	670	7.0	22	0.16	8.6	5.9	10	3.0	51	0.0	14	9.8	0.4	1.4	0.15	106	46	4	42	31	134	7.1
3 Bridge at Zinfandel Ave.	12-27-71	1330	341	7.0	25	0.11	9.5	4.1	6.4	5.9	44	0.0	11	9.1	0.3	1.3	0.18	99	41	5	36	22	128	7.1

TABLE 6.—*Nutrient, organic, and biological constituents in water from the Napa River*

[Sampling sites shown in fig. 3 and explained on p. 58, discharge in cubic feet per second (cfs), computed from stage record at time sample collected]

Sampling site and number	Date and time of collection		Discharge (cfs)	Water temperature (°C)	Concentration, in milligrams per liter (mg/l)							Remarks
	Date	Time (hours)			Dissolved oxygen (DO)	Organic carbon (TOC)	Nitrogen, total as N	Nitrogen, total Kjeldahl, as N	Ammonia (NH_4) as N	Phosphorus, total as P	Phosphate, ortho as P	
1 Bridge at Oak Knoll Ave.	7-27-71	1100	2.4	19.0	-	6.5	1.1	0.38	0.27	0.45	0.40	Water turbid; large quantities of algae in stream channels; fingerlings and large fish noted; no odor
2 Bridge at Grant Boundary Lane	7-27-71	0925		20.0	7.4		0.85	0.41	0.27	0.09	0.08	Large quantities of yellow-green algae in stream channel; cattle near stream; no odor
3 Bridge at Zinfandel Ave.	7-21-71	1120	2.0	22.0	8.6	5.0	1.0	0.40	0.27	0.08	0.06	Large fish and fingerlings noted. No odor. [1]Total coli, 510 colonies per 100 ml.
4 Bridge at Lodi Lane	7-27-71	1330		24.5	8.6	4.0	0.31	0.28	0.21	0.17	0.15	Considerable algae growth in stream channel; no odor
5 Pine St., Calistoga	7-27-71	1435		23.0	6.8	5.5	0.30	0.27	0.21	0.20	0.15	Water clear; no algae; many aquatic insects and snails
1 Bridge at Oak Knoll Ave.	12-27-71	1500	670	7.0	-	10	2.6	1.2	0.11	0.34	0.08	[2]Total coli, 22,500 MPN per 100 ml; [2]fecal coli, 4,600 MPN per 100 ml
3 Bridge at Zinfandel	12-27-71	1330	341	7.0	-	5.5	2.1	0.75	0.11	0.31	0.28	[2]Total coli, 11,000 MPN per 100 ml; [2]fecal coli, 4,600 MPN per 100 ml

[1] Membrane-filter technique.
[2] Multitube-fermentation technique.

SUMMARY AND CONCLUSIONS

The alluvium is the principal aquifer in the project area and is capable of yielding large quantities of water to wells. The largest yielding wells generally are located along the Napa River and its major tributaries where the aquifer is thickest and most permeable. The total quantity of ground water stored in the alluvial aquifer at the present time (1972) is estimated to be 190,000 acre-feet.

Recharge to the alluvial aquifer occurs chiefly from infiltration of precipitation and percolation from streams tributary to the Napa River. Discharge occurs chiefly by direct discharge to the Napa River, by evapotranspiration, and by pumping from wells. Historically, water levels and stream discharges have been strongly influenced by precipitation. Annual precipitation generally has been sufficient to meet natural and artificial demands placed on the aquifer, and water levels have not changed significantly over time. During periods of limited precipitation, however, water levels have declined and stream discharges have been reduced significantly.

In order to meet increasing demands for agricultural water, users have increased ground-water pumpage since 1967. Projected future ground-water use is estimated to be as much as 35,000 acre-feet per year. Such large annual withdrawals, during critical drought periods, could result in significant aquifer depletion and restrict the availability of ground water to many users. A digital-computer model of the alluvial aquifer simulated critical drought conditions and indicated that (1) ground-water levels should not decline significantly until ground-water pumpage exceeds 24,000 acre-feet per year; (2) after two consecutive years of little or no natural recharge, ground-water withdrawals in excess of 24,000 acre-feet per year could cause significant declines in water levels and significantly redistribute the hydraulic gradients in the valley between Zinfandel Lane and Oak Knoll Avenue; and (3) the alluvial aquifer and the stream system can provide water sufficient to meet most projected ground-water requirements, even under protracted, adverse climatological conditions.

Because of generally low transmissivities in the alluvium, many widely-spaced wells may be required to obtain large rates of withdrawal. The development and operation of large-capacity wells should be managed with respect to placement and coordination of pumping rates and schedules so as to afford the greatest efficiency of operation. Optimum placement and operation of these wells probably cannot be achieved until a ground-water basin management model is developed and coupled to a refined model of the hydrologic system.

The following types of ground water occur in the projected area:

a. Mixed cation bicarbonate water
b. Sodium chloride water
c. Magnesium bicarbonate water
d. Sodium bicarbonate water

Although excessive hardness is common, the quality of most of the ground water is adequate for domestic and stock use. Sodium chloride water is generally unsuitable for irrigation purposes because of high boron concentrations and relatively high SAR values.

The potential for the migration of sodium chloride water under normal conditions of use is slight, but migration could increase locally in the Oakville area, especially during critical drought conditions.

If water levels decline enough to make the Napa River a major source of recharge to the alluvial aquifer, serious biologic and nutrient contamination of the ground water could occur if present (1972) water-quality conditions in the Napa River are maintained.

RECOMMENDATIONS FOR FUTURE WORK

In order to properly manage the water resources in the project area, the following should be considered:

1. The digital model should be refined to include a simulated Napa River that is responsive to withdrawals from the alluvial aquifer under all transient-state conditions.
2. The observation-well network presently operated by the Napa County Agricultural Extension Service should be modified and expanded to include more wells screened in the alluvial aquifer. Efforts should be made to obtain detailed records for existing observation wells, and for new wells that may be added to the network.
3. Pumpage should be compiled annually to provide realistic data for use in refining the digital model and monitoring the potential for critical drought conditions.
4. Hydrologic data from local, State, and Federal agencies should be collected and organized for use in future studies.
5. Wells to monitor the possible migration of sodium chloride water toward pumping centers in the Oakville area should be located and maintained for future sampling. Migrating sodium chloride water can be detected by measuring temperature, chloride, and the specific conductance of the water from wells.

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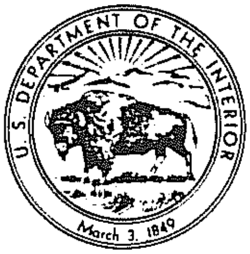

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