SUBJECT TO REVISION

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Ground Water Branch

GEOLOGY AND GROUND-WATER HYDROLOGY OF THE MILL CREEK AREA, SAN BERNARDINO COUNTY, CALIFORNIA

By

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59-38

Prepared in cooperation with the
City of Redlands, California

Open-file report

Long Beach, California

1959

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GEOLOGY AND GROUND-WATER HYDROLOGY OF THE MILL CREEK AREA, SAN BERNARDINO COUNTY, CALIFORNIA

By L. C. Dutcher and W. L. Burnham

ABSTRACT

The Mill Creek area, in the upper Santa Ana Valley, California, is bounded on the north by the Santa Ana River, on the east by the San Bernardino Mountains, on the south by the Crafton Hills, and on the west by the west edge of the city of Redlands. Large alluvial fans underlie most of the area, but other landforms include alluvial benches, dissected alluvial hills, plains, terraces, and bedrock hills which locally protrude above the floor of the alluviated valley.

The water-bearing deposits include channel deposits of Recent age, which principally underlie the channels of the Santa Ana River and Mill Creek, younger alluvium of Recent age beneath flood plains and in fans, older alluvium and bench deposits of Pleistocene age, and the San Timoteo beds of Frick (1921), of Pliocene and early Pleistocene age.

The younger alluvium attains a known maximum thickness of about 140 feet beneath Mill Creek upstream from the mouth of Mill Creek Canyon; elsewhere in the area it ranges in thickness from a featheredge to about 130 feet in Mill Creek basin. The older alluvium locally may exceed 800 feet in thickness; and the San Timoteo beds of Frick (1921) locally may exceed 2,000 feet, but their thickness and extent beneath the valley areas are imperfectly known.

The virtually nonwater-bearing rocks include the Potato sandstone of Vaughan (1922) which crops out in the San Bernardino Mountains, and crystalline and metamorphic rocks of pre-Tertiary age, which form the bedrock of the area.

Faults strike across the valley area and form barriers that restrict the movement of ground water through all deposits older than those of Recent age. The approximate positions of several ground-water barriers in the area are shown for the first time. Major barriers include the Crafton, Redlands, and Oak Clen faults; in addition, other barriers, believed to be minor faults, subdivide previously established ground-water basins.

The area of Bunker Hill Basin, as previously established by Eckis (1934), is separated into Mill Creek, Mentone, and Redlands basins. The area of San Timoteo Basin, as previously established by Eckis (1934), is further subdivided into several smaller basins, including Reservoir basin and the Sand Canyon and Redlands Heights areas.

Mill Creek is the largest tributary of the Santa Ana River in the Mill Creek area. The flow at the mouth of the canyon where the stream emerges from the San Bernardino Mountains and just downstream from the intake of power canal 1, which is the third and final diversion point on the stream, averaged about 8,700 acre-feet per year during the periods of record, 1920-38 and 1948-55. The records include 20 years in a dry and 6 years in a wet climatic period. The combined flow of the three power canals, which divert water from Mill Creek upstream from the gage at the mouth of the canyon, averaged about 15,200 acre-feet per year during the period of record, 1920-55, which included 13 years in a wet and 22 years in a dry climatic period. A part of the water diverted from Mill Creek is returned to ground water through spreading basins in Mill Creek and Mentone basins each season. During the period of record, 1922-55, which included 11 years in a wet and 22 years in a dry climatic period, it is estimated that a total of about 170,000 acre-feet, or an average of about 5,000 acre-feet per year, was conserved in this manner. The flow of Mill Creek near its juncture with the Santa Ana River also was gaged after 1939. The outflow in Mill Creek during the period 1939-55 averaged about 2,000 acre-feet per year. The period included 7 years in a wet and 10 years in a dry climatic period.

Seasonal water-level fluctuations of as much as 50 feet are recorded in Mill Creek basin; long-term fluctuations in response to wet and dry climatic cycles of as much as 120 to 140 feet are recorded in Reservoir, Redlands, and Western Heights basins.

Pumping tests were made in Mill Creek basin to determine the coefficients of transmissibility, permeability, and storage of the younger and the older alluvium and the distances to aquifer boundaries. The estimated coefficient of permeability of the younger alluvium in Mill Creek basin is about 1,400 gpd/per (gallons per day) square foot; the coefficient of storage, practically the same as the specific yield, is about 0.05; and the transmissibility locally is nearly 100,000 gpd per foot. The estimated coefficient of permeability of the older alluvium in Mill Creek basin is about 50 gpd per square foot; it may be as much as 300 gpd per square foot locally in Mentone basin.

Recharge to Mill Creek basin occurs principally by seepage from Mill Creek and from artifical spreading basins, subsurface inflow from the mouth of Mill Creek Canyon and from the Triple Falls Creek area, and from deep penetration of rain. During the period for which records of both inflow and outflow of surface water in Mill Creek are available, 1948-55, recharge to Mill Creek basin from seepage losses averaged at least 800 acre-feet per year and may have been somewhat greater. These years, however, were entirely within a dry period. Ground-water inflow at the mouth of Mill Creek Canyon and from the Triple Falls Creek area may be on the order of 1,000 and 2,000 acre-feet a year, respectively. The long-term average deep penetration of rain may be on the order of 200 acre-feet a year. Estimated total recharge for the 8-year dry period 1948-55 was 35,000 to 40,000 acre-feet.

Ground water is discharged from the ground-water reservoir of Mill Creek basin principally by pumping and subsurface outflow to Mentone basin; a very small amount is transpired by plants, and infrequently a very small amount discharges as "rising water" in Mill Creek; the latter two items were not estimated. Metered and estimated pumpage during the period 1941-55 totaled about 29,000 acre-feet. The estimated subsurface outflow to Mentone basin through the younger and older alluvium during the period 1936 to 1955, which included 10 years in a wet and 10 years in a dry climatic period, was about 115,000 acre-feet, or an average of about 5,700 acre-feet per year. Estimated total discharge for the period 1941-55, which included 5 years in a wet and 10 years in a dry climatic period was 110,000 acre-feet.

The estimated gross ground-water storage capacity of Mill Creek basin is about 8,000 acre-feet, based on a specific yield of 5 percent estimated from pumping tests. The estimated usable capacity is about 6,400 acre-feet. In December 1951 only about 2,000 acre-feet of the usable storage remained in the basin, and in March 1955 about 2,800 acre-feet of usable storage remained.

Because the usable storage capacity is small, the dependable yield of Mill Creek basin is limited to the supply available during severe droughts. During the 6-year dry period 1946-51 the short-term yield was estimated to be 1,600 acre-feet. The existing wells in the basin have combined yields capable of depleting the available supply during a 6-year drought, but their efficiency was low and the pumping costs were large at the end of the drought period. The short-term yield could be increased substantially by additional water-spreading operations in the eastern part of the basin, and by salvage of a part of the subsurface outflow from the basin by drilling supply wells or constructing a collection gallery or a large water tunnel near the western margin of the basin.

The chemical quality of ground water in the Mill Creek area is excellent. The waters are mainly of the calcium bicarbonate type, have about 160 to 230 parts per million of dissolved solids, and generally are suitable for agricultural and domestic uses.

INTRODUCTION

LOCATION AND EXTENT OF THE AREA

The Mill Creek area is in the easternmost part of the upper Santa Ana Valley in San Bernardino County, Calif. (pls. 1 and 2). It is about 80 miles east of Los Angeles

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Plate 1.- Generalized geologic map of the South Coastal Basin in the Los Angeles area, Calif.

Plate 2.- Geologic map of the Mill Creek area, Calif.

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and is bordered by the San Bernardino Mountains on the east, the Santa Ana River on the north, and the Crafton Hills on the south. The area has an east-west length of about 12 miles and an average north-south width of about 5 miles. The area is shown in detail on the Yucaipa and Redlands topographic quadrangle maps of the U. S. Geological Survey at a scale of 1:24,000. The area is readily accessible from Los Angeles and from the California desert area to the east by way of U. S. Highways 70 and 99.

Hydrologically the area includes all or parts of Mill Creek, Mentone, Western Heights, San Timoteo-Beaumont, Reservoir, Redlands, and Bunker Hill basins and the Mill Creek Canyon, Triple Falls Creek, Greenspot, Sand Canyon, and Redlands Heights areas. The geologic and hydrologic complexity of the area has necessitated the establishment of these numerous basins and areas. The report is concerned specifically with Mill Creek basin.[1]

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[1] Except for the South Coastal Basin, the term "basin" is used throughout this report to indicate a ground-water basin, the boundaries of which do not necessarily coincide with topographic features. In this report the previously established Bunker Hill, Yucaipa, San Timoteo, Beaumont, and Lytle Basins (pl. 2) are differentiated by capitalization of the letter <u>B</u> in the word basin from the newly described Mill Creek, Mentone, Redlands, Reservoir, Western Heights, and San Timoteo-Beaumont basins, which are indicated by use of the lowercase letter <u>b</u> in the word basin.

The basins are filled with alluviums and they are extensively cultivated except locally on the steeply sloping alluvial fans near streams. Citrus fruits are the principal crop, and irrigation is necessary because of low rainfall. The district around Redlands contains some of the oldest orange groves in California and reportedly produces more navel oranges than any other area of comparable size in the world. The citrus trees grow best on the deep reddish-brown soils developed on the older alluvial deposits which crop out near the borders of the area, particularly in and near the city of Redlands.

The city of Redlands, population 18,429 in 1950, is the largest community in the area. The economy is based primarily on the production and marketing of citrus fruits, but light industry has grown during recent years.

PURPOSE AND SCOPE OF THE REPORT

The Geological Survey, in cooperation with the city of Redlands, began the ground-water study of the Mill Creek area in July 1954. The objective of the study was to investigate the so-called Mill Creek basin in order to determine the geologic and hydrologic conditions of ground-water supply and movement, to ascertain whether the basin is separated hydrologically from Bunker Hill Basin, to estimate the magnitude of the ground-water storage capacity, to furnish information relating to the yield of the basin, and to select areas and to comment on methods most favorable for withdrawing the available supply.

The investigation was made by the Geological Survey, U. S. Department of the Interior, under the direction of G. F. Worts, Jr., formerly district geologist for the Ground Water Branch, Sacramento, Calif. The work was under the direct supervision of Fred Kunkel, geologist in charge of the Long Beach subdistrict office. This report is under the combined authorship of L. C. Dutcher and W. L. Burnham; the field location of wells and the geologic mapping south of Redlands is largely the work of Burnham. The pumping tests were made by both authors; the geologic and hydrologic interpretations and text were prepared by Dutcher.

CLIMATIC FEATURES

The climate of the area is of the Mediterranean type, having moderate precipitation in the winter and little or none in the summer. The mean annual precipitation ranges from about 14 inches to more than 23 inches, according to the location and altitude. Extremes have occurred when precipitation was as low as 45 percent of the average in 1898-99 or as high as 223 percent of the average in 1883-84. Pronounced wet and dry periods occur in cycles of nonuniform length.

The city of San Bernardino is about in the center of the San Bernardino Valley, and the period of record of rainfall at that station is the longest for the area. The precipitation for the period 1871-1952 is given in table 1, together with the annual and cumulative departure from average. The average annual precipitation for the period was 16.79 inches. Based on records from weather stations at San Bernardino and Redlands, respectively, the average yearly mean temperature is about 62°F. The temperature has ranged from a maximum of about 116°F to a minimum of 18°F.

Table 1.- Yearly rainfall at San Bernardino during the 82-year period 1871-1952 (in inches)

(For the seasonal year of the U. S. Weather Bureau, July 1 to June 30)

Seasonal year ending June 30	Rainfall	Departure (a)	Cumulative departure	Seasonal year ending June 30	Rainfall	Departure (a)	Cumulative departure
1871	13.94	-2.85	-2.85	1896	8.11	-8.68	-7.17
72	8.98	-7.81	-10.66	97	16.74	-.05	-7.22
73	15.10	-1.69	-12.35	98	8.24	-8.55	-15.77
74	23.81	+7.02	-5.33	99	7.49	-9.30	-25.07
75	13.65	-3.14	-8.47	1900	8.64	-8.15	-33.22
1876	19.90	+3.11	-5.36	1901	17.36	+.57	-32.65
77	9.52	-7.27	-12.63	02	11.15	-5.64	-38.29
78	20.33	+3.54	-9.09	03	17.42	+.63	-37.66
79	11.54	-5.25	-14.34	04	9.37	-7.42	-45.08
80	20.36	+3.57	-10.77	05	20.78	+3.99	-41.09
1881	13.50	-3.29	-14.06	1906	19.88	+3.09	-38.00
82	11.54	-5.25	-19.31	07	23.17	+6.38	-31.62
83	9.17	-7.62	-26.93	08	15.62	-1.17	-32.79
84	37.51	+20.72	-6.21	09	17.36	+.57	-32.22
85	10.81	-5.98	-12.19	10	15.02	-1.77	-33.99
1886	21.93	+5.14	-7.05	1911	16.34	-.45	-34.44
87	14.50	-2.29	-9.34	12	13.84	-2.95	-37.39
88	17.76	+.97	-8.37	13	11.08	-5.71	-43.10
89	20.97	+4.18	-4.19	14	21.45	+4.66	-38.44
90	25.08	+8.29	+4.10	15	19.64	+2.85	-35.59
1891	18.08	+1.29	+5.39	1916	24.72	+7.93	-27.66
92	14.35	-2.44	+2.95	17	13.79	-3.00	-30.66
93	19.82	+3.03	+5.98	18	13.33	-3.46	-34.12
94	8.13	-8.66	-2.68	19	13.62	-3.17	-37.29
95	20.98	+4.19	+1.51	20	19.28	+2.49	-34.80

Table 1.- Yearly rainfall at San Bernardino for the 82-year period 1871-1952 (in inches)--Continued

(For the seasonal year of the U. S. Weather Bureau, July 1 to June 30)

Seasonal year ending June 30	Rainfall	Departure (a)	Cumulative departure	Seasonal year ending June 30	Rainfall	Departure (a)	Cumulative departure
1921	16.46	-0.33	-35.13	1936	17.10	+0.31	-43.48
22	27.75	+10.96	-24.17	37	31.93	+15.14	-28.34
23	11.04	-5.75	-29.92	38	25.36	+8.57	-19.77
24	11.34	-5.45	-35.37	39	16.17	-.62	-20.39
25	10.89	-5.90	-41.27	40	18.33	+1.54	-18.85
1926	20.40	+3.61	-37.66	1941	35.90	+19.11	+ .26
27	20.55	+3.76	-33.90	42	16.70	-.09	+.17
28	14.05	-2.74	-36.64	43	27.53	+10.74	+10.91
29	12.21	-4.58	-41.22	44	21.91	+5.12	+16.03
30	14.06	-2.73	-43.95	45	18.32	+1.53	+17.56
1931	15.31	-1.48	-45.43	1946	12.61	-4.18	+13.38
32	21.98	+5.19	-40.24	47	17.02	+ .23	+13.61
33	13.16	-3.63	-43.87	48	10.95	-5.84	+7.77
34	12.98	-3.81	-47.68	49	14.41	-2.38	+5.39
35	20.68	+3.89	-43.79	50	11.84	-4.95	+.44
				1951	9.35	-7.44	-7.00
				52	23.92	+7.13	+.13

a. Based on a seasonal average of 16.79 inches for the 82-year period.

PREVIOUS INVESTIGATIONS

Several publications contain valuable data concerning the use of water for irrigation, the occurrence and movement of ground water, and the ground-water storage capacity of the alluvial deposits of the report area. However, most deal with the Mill Creek area only as a small part of a larger area investigated. So far as is known the first inventory of wells in the vicinity of Redlands was made by Lippincott (1902a and 1902b) in 1900; the tabulation includes, among other things, the year drilled, depth, land-surface altitude, and a water-level measurement.

A few years later, a report by Mendenhall (1905) on the San Bernardino artesian area included a tabulation of wells in the Mill Creek area and briefly discussed the geology and ground-water hydrology. Additional work on the geologic and hydrologic features in the area was done by Sonderegger (1918), who discussed the water-spreading operations on the alluvial fans.

In a report by Eckis (1934) the geology, hydrology, and ground-water storage capacity of the various ground-water basins in the San Bernardino Valley, as well as in other areas in the South Coastal Basin are discussed. In addition to other useful data that report contains a geologic map of the area, a map showing basin boundaries and water-level contours, and a map showing lines of estimated equal specific yield of the deposits in the ground-water basins.

In a report by Gleason (1947) inflow, outflow, overdraft, and other factors related to the Hydrologic equation for each of the several ground-water basins in the upper Santa Ana Valley are discussed. No appraisal of overdraft in Mill Creek basin was included in that report.

Several publications by the U. S. Geological Survey and the California Department of Water Resources contain useful records of basic data on hydrology, chemical quality of ground waters, and water levels in wells. Chief among these are (1) the U. S. Geological Survey annual water-supply papers (table 7) on surface-water supply and on water levels and artesian pressure in wells; (2) the California Division of Water Resources Bulletin 39 (Gleason, 1932) on water levels in the Santa Ana River basins, and Bulletin 40-A (Gleason, 1947), which contains data on the chemical quality of ground and surface waters in the area; and (3) U. S. Geological Survey Hydrologic Investigations Atlas HA-1 (Troxell, 1954), which discusses the surface-water hydrology of the San Bernardino Mountains.

A report by the Geological Survey (Dutcher and Garrett, 1958, prepared in cooperation with the San Bernardino County Flood Control District, describes the geology and hydrology of the San Bernardino area and includes general information on the occurrence and movemement of ground water in the Mill Creek area. The appendix to that report contains a comprehensive tabulation of wells and well data, selected logs of wells, and chemical analyses of ground and surface waters. The numbers assigned to wells in that investigation are, in a few instances, different from the well numbers assigned during this investigation. The number changes were necessary because the wells in the Mill Creek area were not field located by the Geological Survey during the San Bernardino area investigation. They were plotted and assigned numbers on the basis of existing records. The numbers assigned in this report are based on field-checked locations and are more accurage.

Another report is now being written by the Geological Survey based on an investigation made by W. L. Burnham and L. C. Dutcher in the Redlands - Beaumont area, in cooperation with the San Bernardino County Flood Control District. In it certain features of the geology and ground-water hydrology in the Mill Creek area are discussed, as the investigation in the Redlands-Beaumont area includes the Mill Creek area also. The basic data on water wells in both the Redlands-Beaumont area and the Mill Creek area are to be included in a separate report being prepared by Mr. Dutcher.

In addition to the above reports, a private mimeographed report by Finkle (1923), outlining the findings of a ground-water investigation of the Mill Creek basin area, was made available to the Geological Survey by the city of Redlands. That private report estimated the average annual yield of Mill Creek basin to be about 4,500 gpm (gallons per minute) or about 7,300 acre-feet per year.

ACKNOWLEDGMENTS

Prior to the fieldwork by the Geological Survey in the Mill Creek area, a large number of basic information was obtained from the Los Angeles office of the California Department of Water Resources. The data included logs of wells, chemical analyses of well waters, and records of water levels. In addition, similar information was supplied by the city of Redlands and by Mr. E. F. Dibble, Engineer, San Bernardino Valley Water Conservation District.

The assistance of private well owners and operators in supplying many additional data is gratefully acknowledged. Chief among the water companies supplying information were the East Highlands Orange Co., through Mr. D. L. Alexander, foreman; and Western Fruit Growers, through Mr. Earl Morgan, foreman. The assistance of Mr. George Rawlins, who supplied information relative to ground-water conditions, well locations, history of development, and sites of former tunnels in the Greenspot area, is gratefully acknowledged.

The extensive work and cooperation of the city of Redlands' Water Department, through Mr. Claude Ritchie, former superintendent, is gratefully acknowledged. Also, the firm of Boyle Engineering, through Messrs J. R. Boyle and J. A. Bradley, engineers, kindly supplied information on well yield, drawdown, specific capacity, pumpage, and other data.

WELL-NUMBERING SYSTEM

In the Mill Creek area two local well-numbering systems were formerly in use. One was a location number based on a projection of parallels and meridians spaced at intervals of 6 minutes of latitude and longitude. The other system is based on the use of a serial number for each well. Of the two systems the one using the serial number has been adopted more widely by the public water agencies for filing and tabulating well data.

The well-numbering system used by the Geological Survey in this area conforms to that used in nearly all ground-water investigations made by the Geological Survey in California since 1940. It has been adopted as official by the California Department of Water Resources and by the California Water Pollution Control Board for use throughout the State.

The wells are assigned numbers according to their locations in the rectangular system for the subdivision of public land. For example, in the number 1S/2-30B1 the part of the number preceding the bar indicates the township (T. 1 S.), measured from the San Bernardino base line; the part between the bar and the hyphen is the range (R. 2 W.), measured from the San Bernardino meridian; the number between the hyphen and the letter is the section (sec. 30); and the letter indicates the 40-acre subdivision of the section as shown in the accompanying diagram.

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

30

Within each 40-acre tract the wells are numbered serially as indicated by the final digit. Thus, well 1S/2-30B1 is the first well to be listed in the NW¼NE¼ sec. 30. Because of possible confusion with well numbers assigned by the Geological Survey during the San Bernardino area investigation (Dutcher and Garrett, 1958), which extended across the San Bernardino base line, the well numbers all bear the symbol S. The entire area is west of the San Bernardino meridian and therefore the range number is sufficient and the symbol W has been omitted.

For wells not field located by the Survey and for purposes of plotting wells from unverified location descriptions, the 40-acre tract letter has been replaced by a dash. Thus, well 1S/2-19-3 is the third well plotted in sec. 19 from an unverified location description.

This numbering system has been used also as a convenient means of locating a feature described in the text. Thus, an area or feature within the NE¼SW¼ sec. 21, T. 1 S., R. 2 W., may be identified as being in 1S/2-21L.

In part of the Mill Creek area the township, range, and section grid has been established by Federal surveys; in the remainder of the area it was necessary to project the grid in order to assign numbers to wells. Where the section net has been established by Federal surveys, the sections are shown on plates 2 and 5 as solid lines; where the section grid is projected, they are shown as dashed lines.

GEOLOGY

LANDFORMS

The physiographic history of the eastern part of the upper Santa Ana Valley is extremely complex and is closely related to the structural history. The present landforms, however, are chiefly the result of structural activity, probably beginning in middle-Pleistocene time, but they have been modified somewhat by deposition and erosion in late Pleistocene and Recent time.

San Bernardino Mountains

The San Bernardino Mountains rise steeply at the east margin of the Mill Creek area along the San Andreas fault zone. The crest of the relatively straight southwest-facing mountain front, which is the dissected scarp of the San Andreas fault zone, rises about 5,500 feet above the valley edge at the mouth of the Santa Ana River Canyon. East of the area the crestline of the mountains is interrupted by several isolated peaks, one of which is San Gorgonio Mountain, the highest in southern California--11,485 feet. Rain and melting snow in the mountains supply runoff to the Santa Ana River, Mill Creek, and other streams which, when reaching the alluvial fans and plains at the base of the mountains, contribute most of the ground-water recharge to the area. The geologic structure, rock types, topography, vegetation, soil and mantle rock, and surface and ground-water supplies of the various streams draining the San Bernardino Mountains are discussed in considerable detail by Troxell (1954).

Crafton and Reservoir Canyon Hills

The Crafton Hills, which are east of Redlands, are separated from the San Bernardino Mountains by the structural trough formed by the San Andreas and Oak Glen fault zones. These hills rise abruptly about 1,100 feet above the valley floor on the north and south and are composed of crystalline rocks. The Crafton Hills constitute a barrier to ground-water movement and effectively prevent ground-water underflow from Yucaipa Valley, which lies to the east, to Mill Creek basin, except at the northeast end through the narrow trough between the Crafton Hills and the San Bernardino Mountains.

There is another area of crystalline rock south of Redlands and west of the Crafton Hills. This is termed Reservoir Canyon Hill in this report, and it is nearly buried by the alluvial materials which extend from the Crafton Hills westward about to San Timoteo Creek Canyon. This hill was named for Reservoir Canyon, which bisects it, and was so named because of the large reservoirs maintained near its mouth by the city of Redlands and the Bear Valley Mutual Water Co. Reservoir Canyon Hill also obstructs the movement of ground water from Yucaipa Valley, which lies to the east of the area shown on plate 2, to the ground-water basins of San Bernardino Valley. San Bernardino Valley as defined in this report is restricted to that portion of the upper Santa Ana Valley lying between the San Jacinto and the San Andreas faults and extending from the San Gabriel Mountains on the north to the Crafton Hills and Badlands on the south. There is no ground-water underflow through Reservoir Canyon; therefore, all ground-water underflow must pass through the alluvium-filled gap between the Crafton Hills and Reservoir Canyon Hill or must pass around the western flank of that hill to San Timoteo Canyon, and thence northwestward to San Bernardino Valley.

The Crafton Hills and Reservoir Canyon Hill are bounded on the northwest by the Crafton fault and on the south and southeast by other faults (pl. 2).

A minor bedrock hill lies north of Mill Creek and north of the Crafton Hills. This small hill is known locally as Brown Butte. Together with several small mounds which trend northwest along the north side of Mill Creek, it is discussed in greater detail in the section on the buried bedrock surface in the Mill Creek area.

Lowlands

The lowlands constitute the valley areas underlain by the river-channel deposits, younger alluvium, and the older plain and bench deposits (pl. 2). The principal features include the channels, fans, and flood plains of Mill Creek and the Santa Ana River. Other features include the terraces and benches of these streams, which were forme largely during late Pleistocene time.

Mill Creek rises in the San Bernardino Mountains, enters the east end of San Bernardino Valley at the trace of the San Andreas fault at an altitude of about 2,720 feet, flows about 5 miles westward across a steep fan, and joins the Santa Ana River at an altitude of about 1,680 feet. The average channel gradient in this reach is about 200 feet per mile; near the apex of the Mill Creek fan the gradient is as much as 265 feet per mile.

The Santa Ana River, one of the largest streams in the South Coastal Basin of southern California, also rises in the San Bernardino Mountains and enters the valley at the trace of the San Andreas fault, but at an altitude of about 1,670 feet. It leaves the area at its west edge at an altitude of about 1,190 feet and discharges into the Pacific Ccean, about 70 miles southwest of this area (pl. 1).

East of the Crafton Hills, Yucaipa Creek rises on the south flank of the San Bernardino Mountains, flows southwestward from the Triple Falls Creek area, crosses Western Heights basin, and joins San Timoteo Creek south of the area. San Timoteo Creek flows northwestward and joins the Santa Ana River about 5 miles west of the area.

The channel of Mill Creek ranges in width from 300 to 1,300 feet and is 5 to 40 feet below the adjacent alluvial plain. At times of flood Mill Creek has overtopped its channel banks and inundated most of the alluvial plain south of Mill Creek and the Santa Ana River. For example, during the flood of March 1938 the water extended as far south as the city of Redlands and caused extensive damage to agricultural lands and to dwellings within the city.

Terraces, benches, and fans occur between the alluvial plains and the bordering hills and mountains and often are referred to as "mesas" or "highlands." These are stream-formed features. Along Mill Creek the surfaces of these benches are 20 to 60 feet above the adjoining alluvial plains and channels. In Redlands and to the east an old fan surface slopes northward and merges with the alluvial plain. Along the north edges of secs. 26 and 27, T. 1 S., R. 3 W., the surface of an elongate, east-trending ridge rises above the surrounding plain to a height of 30 feet at the east end but only a few feet at the west end.

DESCRIPTIONS AND WATER-BEARING PROPERTIES OF THE ROCKS AND DEPOSITS

The stratigraphic units of the Mill Creek area can be divided into two groups according to their lithologic and water-bearing properties, as follows: (1) the consolidated, practically nonwater-bearing rocks of pre-Tertiary age and (2) the unconsolidated deposits of late Tertiary and Quaternary age, which include both permeable and impermeable types.

The consolidated rocks include the basement complex of pre-Tertiary age, which includes the igneous and metamorphic rocks that form the mountain masses and underlie the area at depth, and the Potato sandstone of Vaughan (192 of Miocene(?) and Pliocene age, which crops out in the San Bernardino Mountains along Mill Creek Canyon south of the Mission Creek fault.

From oldest to youngest the unconsolidated deposits include the San Timoteo beds of Frick (1921) of Pliocene and early Pleistocene age; the older alluvium of middle (?) and late Pleistocene age; the older plain and bench deposits of late Pleistocene age; the younger alluvium of Recent age underlying the Santa Ana River, Mill Creek, the Mill Creek fan, and smaller streams and fans; and the river-channel deposits of Recent age in and beneath the principal stream channels.

Mapping and study of the unconsolidated deposits were carried on in considerable detail, whereas the consolidated rocks were mapped only to the extent of defining the structural features that extend into the unconsolidated deposits. The areal extent of the rocks and deposits is shown on plate 2; their subsurface extent in the Mill Creek area is shown on plate 4; and structural contours on bedrock underlying the

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Plate 4.- Map and geologic sections showing extent, thickness, and character of the deposits water-level profiles and contours for March 1955 in the Mill Creek area, Calif.

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unconsolidated deposits in the Mill Creek area are shown on plate 3. Table 2 shows the sequence, probable age, general lithologic character, and water-bearing properties of the stratigraphic units in the Mill Creek area.

Table 2.--Geologic units of the Mill Creek area, San Bernardino County, Calif.

Geologic age	Unit and symbol on plate 2	Thickness (feet)	General lithologic character	Water-bearing properties
RECENT	River-channel deposits (Qrc)	0-140±	Unconsolidated boulders, coarse gravel, sand, and silt, in channels of the Santa Ana River and Mill Creek. Generally progressively finer grained and better sorted away from the mountains.	Highly permeable; largely unsaturated but transmit large seepage losses from streams to ground water.
	--LOCAL UNCONFORMITY--			
	Younger alluvium (Qyal)	0-140±	Unconsolidated boulders, gravel, sand, and silt; very poorly sorted in Mill Creek basin but better sorted with increasing distance from mountains; underlies fans and flood plains of principal streams.	Highly permeable in the San Bernardino Valley; locally unsaturated but yields water to wells in Mill Creek basin at rates up to 500 gpm. In Mill Creek basin, permeability about 1,400 gpd per sq. ft. and specific yield about 5 percent, as estimated from pumping tests.
	UNCONFORMITY			

QUATERNARY	PLEISTOCENE	Older plain and bench deposits (Qpb)	0-100±	Unconsolidated gravel, sand, silt, and clay, generally moderately to highly weathered; underlie older dissected flood plains, terraces, benches, and fans; not distinguished from older alluvium in logs of wells or on cross sections.	The two deposits are not distinguishable in logs of wells. Collectively they are highly to poorly permeable; where saturated they yield water to wells at rates up to 3,000 gpm. Permeability about 50 gpd per sq. ft. in Mill Creek basin, locally about 300 gpd per sq. ft. in Mentone basin, and may increase with distance from the mountains.
		--LOCAL UNCONFORMITY--			
		Older alluvium (Qoal)	0-700±	Unconsolidated gravel, sand, silt, and clay, generally moderately to highly weathered; contains numerous soil zones; cut by most faults and barriers shown on plates 2 to 6.	
		--LOCAL UNCONFORMITY--			

Table 2.--Geologic units of the Mill Creek area, San Bernardino County, Calif.--Continued

Geologic age		Unit and symbol on plate 2	Thickness (feet)	General lithologic character	Water-bearing properties
TERTIARY(?)	PLEISTOCENE --?--?--?--?-- PLIOCENE	San Timoteo beds of Frick (1921) (TQs)	2,000±	Semiconsolidated gravel, sand, silt and clay, locally moderately indurated; cut by numerous faults and locally folded.	Poorly to moderately permeable; where saturated, yield small to moderate quantities of water to wells.
		UNCONFORMITY			
TERTIARY	PLIOCENE --------------- MIOCENE(?)	Potato sandstone of Vaughan (1922) (Tps)	2,000?	Consolidated interbedded sandstone, shale, conglomerate, talus breccia, and limestone; locally contains a fossil flora.	Practically non-water-bearing and not tapped by wells.
		UNCONFORMITY			
PRE-TERTIARY		Basement complex (bc)		Crystalline igneous and metamorphic rocks: granite, quartz monzonite, dioritic gneiss, and mica schist, undifferentiated.	Not water-bearing, except for minor amounts of water in weathered zones and fractures.

Consolidated Rocks

Basement Complex (pre-Tertiary)

The oldest rocks in the area are schist, gneiss, and instrusive igneous rocks which are shown as the basement complex on plate 2. The rocks forming the basement complex in the San Bernardino Mountains are granite, dioritic gneiss, and metamorphosed sedimentary rocks; those in the Crafton Hills, Brown Butte, and Reservoir Canyon Hill are mica schist, siliceous dioritic gneiss, and quartz monzonit. The age of these rocks may range from Precambrian in the Crafton Hills to early Late Cretaceous in the San Bernardin Mountains (Eckis, 1934, pl. C). Their age has been designated simply as pre-Tertiary in this report.

Because the igneous and metamorphic rocks do not have numerous void spaces to contain ground water, as do the unconsolidated deposits, they are considered to be virtuall nonwater-bearing; except locally where they are penetrated by wells which intersect fractures at depth, they do not yield economic quantities of water (pl. 2).

Potato Sandstone of Vaughan (1922) (Miocene? and Pliocene)

The Mill Creek Canyon area south of the Mission Creek fault is underlain by the Potato sandstone of Vaughan (1922, p. 374). (See pl. 2.) Where observed the formation was everywhere in fault contact with the granitic rocks of the basement complex. The minimum exposed thickness was estimated to be 1,500 feet by Vaughan (1922), and the deposits tentatively were considered to be of Miocene age. On the basis of a moderately abundant fossil flora discovered by the authors near the crest of the ridge (1S/1-17D) south of Mill Creek Canyon, the uppermost part of the formation tentatively was assigned to the "middle part of the early Pliocene" by Dr. Daniel Axelrod (University of California at Los Angeles, personal communication, February 24, 1956). The relation of the rock types and discussion of the age determination of the formation will be given in greater detail in the report being prepared on the Redlands-Beaumont area.

The Potato sandstone of Vaughan (1922) was not mapped in detail during the present investigation, but several brief reconnaissance traverses across the exposures were made. The formation is composed of indurated sandstone, shale, conglomerate, talus breccia, and limestone beds, which probably contain water only in fractures. Although the formation is not penetrated by wells, it is believed that production of economic quantities of water from the formation would not be possible.

Unconsolidated Deposits

Because the unconsolidated deposits are extremely variable in character and are not everywhere well exposed, the thickness, stratigraphy, and lithology were determined chiefly from well logs. The cross sections show graphically the logs of several wells tapping the unconsolidated deposits and show the stratigraphic position of the several deposits beneath Mill Creek.

San Timoteo Beds of Frick (1921)
(Pliocene and early Pleistocene)

Alluvial deposits designated by Frick (1921) as of Pliocene and early Pleistocene age crop out in the southwestern part of the Mill Creek area and are believed to underlie younger alluvial deposits beneath a large part of San Bernardino Valley south and west of Mentone basin. In logs of wells the contact between the San Timoteo beds of Frick (1921) and the older alluvial deposits could not be determined.

Only the upper part of the San Timoteo beds of Frick (1921) crops out in the area (Eckis, 1934). South of Redlands the beds are gently to moderately folded and generally dip 10° to 25° NE, more steeply than does the land surface. The maximum thickness of the beds is unknown; locally they probably exceed 2,000 feet.

In the area south of Redlands and east of the San Jacinto fault the San Timoteo beds of Frick (1921) include only the uppermost part of the alluvial deposits of Pliocene and early Pleistocene age (pls. 1 and 2).

The exposed deposits consist of an alternating sequence of thick and thin lenticular beds of coarse sand, gravel, and cobbles contained in a matrix of yellow to pink very poorly sorted clay, silt, and fine sand. The sand and coarser particles were derived from granitic and metamorphic rocks, similar in composition to those supplying the materials composing the older and the younger alluvium and the channel deposits. The subrounded sand grains and cobbles, the fresh, gray, unweathered appearance of many sand and gravel beds, the abundant fresh mica, the presence of gypsum in fractures and as cementing material in outcrops, and especially the poor sorting suggest that the beds are a fanglomerate. The depositional environment probably was arid, and the beds are not typical of the locally derived stream-deposited alluvium found elsewhere in the area.

Deeply weathered brown to red residual soil is exposed at irregular horizons within the unit, but the typical weathered and reddish appearance of the materials composing the older alluvium generally is lacking. The uppermost soil zone within the San Timoteo beds of Frick (1921) in the Smiley Heights area in places contains many calcareous nodular masses, and nearly spherical concretions of similar size and shape. The concretionary soil zone locally is a valuable aid in distinguishing between the older alluvial deposits and the San Timoteo beds of Frick (1921).

The San Timoteo beds of Frick (1921) do not constitute a major source of water supply in this area. However, wells south of the Redlands and Crafton faults derive some of their supply from the San Timoteo beds. Deep wells elsewhere in the area, particularly in the western part may penetrate these deposits at depth and derive a part of their supply from them.

The specific capacities of the wells in San Timoteo-Beaumont Basin, which derive practically all their supply from the upper part of the San Timoteo beds of Frick (1921), range from 20 to 25 gpm per foot of drawdown. These wells yield up to 500 gpm and have drawdowns ranging from 20 to 25 feet. Because the water-bearing sand and gravel lenses in the San Timoteo beds are discontinuous and because the deposit is mildly deformed, closely spaced wells of comparable depth may penetrate different thicknesses of permeable material and may have a wide range in yield. With regard to well construction the uncemented loose sand and silt, which compose a large part of the beds, make it necessary to exercise great care in selecting the proper size of perforations and in developing the well to avoid "sanding" and related difficulties.

Older Plain and Bench Deposits and Older Alluvium
(Middle and Late Pleistocene)

In the upper Santa Ana Valley the older plain and bench deposits are closely associated with the older alluvium. These two units can be distinguished by careful geologic mapping, but they cannot be identified in logs of wells, and their water-bearing properties appear to be similar. Accordingly, the two units are distinguished on the geologic map (pl. 2) but the contact is shown diagrammatically in the cross sections (pl. 4), and the two are discussed together in this section of the report.

Thick accumulations of older alluvium nearly everywhere underlie the deposits of Recent age and crop out to form well-weathered, reddish-brown alluvial benches, hills, terraces, and plains which generally are topographically above the flood plains and other areas whose alluvium is now being deposited. Eckis (1928, p. 228, 235-236) named deposits of this age the San Dimas formation in the area near the town of San Dimas north of Pomona (west of this area). In later work, however, because of well-established local usage, the term "older alluvium" was substituted for the San Dimas formation of Eckis (1928) and its equivalents throughout the region, and such usage has been maintained by most workers in the area.

In this area the older alluvium of Eckis (1934) is that part of the early alluvium of Mendenhall (1905) which accumulated after the deposition of the "badlands clays"--the San Timoteo beds of Frick (1921). Structural activity during late Pleistocene time disrupted the drainage systems and locally elevated the oldest part of the older alluvium. These deposits locally were eroded while alluviation continued elsewhere in the area.

The elevated, slightly folded basal part of this sequence now makes up Morton Ridge and the ridge extending westward from the Crafton Hills to Smiley Heights (pl. 2). For the purposes of this report, the older unit of the two alluvial deposits is called the older alluvium. The younger unit, which is about 50 to 100 feet thick and which underlies the extensive benches, terraces, and dissected fans around the Crafton Hills and westward beneath Redlands and the Greenspot and Triple Falls Creek areas, is called the older plain and bench deposits. Combined, these two units constitute the older alluvium of Eckis (1934).

The older alluvium of this report was deposited during and after the Pleistocene time of major structural activity in southern California and therefore is cut by many faults and other features which act as barriers to ground-water movement. The younger deposits of Recent age are not appreciably affected by the faults.

Character, extent, and thickness of the older alluvium.--The older alluvium is well exposed along Sand Canyon Road in the Sand Canyon area, in the canyons south of Redlands Heights and Smiley Heights, and along Morton Ridge in the Greenspot area. It is composed of strongly weathered residual clay, silt, sand, gravel, and some boulders. Thick horizons of dark-reddish-brown gritty clay, marking buried soil zones, are separated by beds of poorly to moderately sorted sand and gravel. An outstanding characteristic of most of the older alluvium is the degree of weathering of the majority of the rock particles (clasts) and the coating of most of the gravel clasts with an iron oxide stain. The clasts that compose most of this deposit are gneissic hornblende-biotite diorite, biotite schist, and some granite. These rock types produce an alluvium which weathers readily in response to alternate wetting and drying in the zone above and within the range of water-table fluctuation. Oxidation of the iron-rich minerals and weathering of the feldspars weaken the clasts, most of which crumble readily under a hammer blow.

Along Morton Ridge, between Mill Creek and the Santa Ana River, the older alluvium underlies the older plain and bench deposits. The materials making up Morton Ridge and the narrow outcrop along the San Andreas fault zone east of Mill Creek (pl. 2) probably are not a true alluvial deposit, in that they appear to represent an accumulation of debris related to the uplift of the San Bernardino Mountains as they rose along the San Andreas fault zone. The upper part of the detrital material, composed of angular blocks and boulders in an earthy to clayey matrix, has little or no stratification. In the basal part of the exposures the material is more typical of the bedded older alluvium found elsewhere in the area. The clasts are of the same composition as the rock types forming the mountains immediately north and east of the exposures.

Wells drilled through the older alluvium penetrate alternate beds of gravel, boulders, sand, and clay which are progressively better sorted and more distinctly bedded at increasing distances from the mountain front. Except in the deeper parts of the buried valleys, where the San Timoteo beds of Frick (1921) may be present, the several hundred feet of alternating beds of reddish clay, sand, and gravel reported in logs of wells throughout the area probably represents the older alluvium and (or) older plain and bench deposits.

The contact between the older alluvium and the older plain and bench deposits usually cannot be distinguished in logs of wells. Furthermore, the contact between the older alluvium and the San Timoteo beds of Frick (1921) usually cannot be determined from well logs. In surface exposures the older alluvium rests with local unconformity on the San Timoteo beds.

Extent, character, and thickness of the older plain and bench deposits.--The older plain and bench deposits are widely exposed in the area near Redlands, in Mill Creek basin, and in the Triple Falls Creek and Greenspot areas. Throughout the area the unit is deeply weathered to a reddish brown, and the exposed surface characteristically is a well-developed, deep-reddish-brown residual soil. Where exposed in road cuts and banks of stream channels, the soil is underlain by alternating thick beds of residual soil separated by thin beds of weathered sand and gravel. In many exposures the transition from a sand and gravel bed upward into the residual soil above can be seen, as well as faint outlines of the residual clasts in the soil zones.

In general, the older plain and bench deposits probably represent the final stages in the long period of alluviation in late Pleistocene time. The unit ranges in thickness from a few feet where it laps onto older rocks and alluvial deposits to possibly 100 feet or more in the locally depressed areas where it represents simply an upward extension of the older alluvium. Along the north banks of Mill Creek and locally elsewhere the older plain and bench deposits rest unconformably on the older alluvium.

Detritus derived from the Potato sandstone of Vaughan (1922) makes up a large part of the older plain and bench deposits in the Triple Falls Creek area; elsewhere the materials were derived from the basement complex, which also was the source of the older alluvium, and from reworked older alluvium and San Timoteo beds of Frick (1921).

Water-bearing properties.--Except in Mill Creek basin where the younger alluvium is the principal water-bearing unit, the older alluvium supplies most of the water to wells in the area. Throughout most of the area the older plain and bench deposits are above the zone of water-level fluctuations. The deepest wells in Western Heights basin and in the western part of Reservoir and Redlands basins obtain most of their supply from the older alluvium, although some water may be obtained from the underlying San Timoteo beds of Frick (1921).

Major changes in the depositional environment of these alluvial deposits resulted from structural activity which continued to elevate the surrounding mountain areas throughout the depositional period and caused the deposition of an alluvial sequence which varies greatly stratigraphically, geographically, and, hence, hydrologically. Changes in lithology and corresponding changes in the hydrologic properties of the deposits are related directly to the downstream distance from the mountain front. Eckis (1934, pl. C) recognized that the specific yield of the deposits gradually increases from the mountains toward the San Jacinto fault (pl. 1).

Data from aquifer tests and on specific capacities of wells indicate that the permeability of the older alluvial deposits is about 50 gpd per square foot in Mill Creek basin and locally is about 300 gpd per square foot in Mentone basin (table 12).

In Western Heights and Reservoir basins the specific capacities of wells range up to 20 to 30 gpm per foot of drawdown, and yields from wells range about from 400 to 600 gpm.

Younger Alluvium (Recent)

In the Mill Creek area the younger alluvium is mostly undissected, and in most places its subsurface character cannot be observed. Because of this, the thickness, lithology, and water-bearing properties of the deposit were determined from well logs and aquifer tests. Along the south bank of the Santa Ana River and locally along Mill Creek, where the stream channels are entrenched, a study of the outcrops aided in determining the lithology of the upper part of the younger alluvium.

Areal extent and thickness.--The areal extent of the younger alluvium is shown on plate 2. It includes deposits underlying the flood plains of the Santa Ana River, Mill Creek, and San Timoteo Creek, and the alluvial fans. The extent and thickness of the younger alluvium locally was controlled during deposition by the existence of old stream channels which were downcut into older deposits and (or) bedrock, probably at the end of Pleistocene time. These old channels, now backfilled with younger alluvium of Recent age, are not everywhere visible, and their existence and extent have been determined approximately by examination of well logs and data from aquifer tests.

In logs of wells the base of the younger alluvium beneath Mill Creek can be established fairly accurately where the alluvium overlies bedrock; it is recognizable also throughout most of the area where the alluvium overlies older plain and bench deposits and older alluvium of Pleistocene age. (See geologic sections shown on pl. 4.) The depth to the base ranges from about 60 to 140 feet below the land surface. By comparing logs in areas where the position of the base of the younger alluvium is known with logs of nearby wells where the base is not known and by projecting upstream the slope of the contact, the base can be determined fairly accurately. The thickness of the younger alluvium is about 70 to 80 feet downstream from the Crafton fault and ranges from 70 to about 140 feet between the Crafton and San Andreas faults (pl. 4, sec. A-A').

<u>Lithology and stratigraphy</u>.--The younger alluvium includes all the materials, except the most recent channel deposits, laid down during the present cycle of alluviation by streams. It is composed principally of unweathered crystalline-rock debris derived from the surrounding highlands and contains minor amounts of detritus from consolidated sedimentary rocks. So far as can be determined the deposits are unfaulted and are composed principally of boulders, gravel, sand, and silt. Even where the younger alluvium is weathered, the decomposition and red or yellow iron staining so characteristic of the older alluvium are not present.

Water-bearing properties.--The younger alluvium supplies water to public-supply and irrigation wells, and to one water tunnel during years when the deposits penetrated by the tunnel are saturated. According to a private report by Finkle (1923, p. 6), the younger alluvium when nearly saturated supplied water to wells at rates up to 810 gpm (gallons per minute). During 1955 the younger alluvium yielded water to wells at rates up to 500 gpm. The water tunnel extends from the filter plant of the city of Redlands about to well 1S/2-22C1--a distance of about 1,500 feet. Wells 1S/2-22C1 and 22C2 were drilled at the tunnel, which reportedly is about 45 feet below the land surface at well 22C1. The reported yield of the tunnel was about 2,000 gpm when the younger alluvium at well 22C1 was saturated to within 30 feet of land surface. During 1944 the tunnel produced 3,200 acre-feet of water (table 13), but in 1955 it was in very poor condition and was entirely above the zone of saturation.

In order to determine the coefficients of transmissibility, permeability, and storage of the younger alluvium in Mill Creek basin, aquifer tests were made at three wells in the basin (table 11). The data obtained from the tests indicate a range in transmissibility from 92,000 to 120,000 gallons per day per foot. The estimated permeability of the younger alluvium in Mill Creek basin is about 1,400 gallons per day per square foot (table 11).

The aquifer tests also were analyzed to derive the coefficient of storage of the younger alluvium in Mill Creek basin. A coefficient of storage of 0.05 was interpreted, which indicates that the specific yield of the deposits is approximately 5 percent.

Both the permeability and the specific yield of the younger alluvium are believed to increase in the downstream direction in a manner similar to those of the older alluvium. A short distance downstream from the San Jacinto fault, about 6.5 miles west of Redlands, the permeability of the younger alluvium was interpreted (Dutcher and Garrett, 1958) from pumping tests to be about 2,700 gpd per square foot. Thus, the indicated permeability of the younger alluvium in Mill Creek basin is about half as great as the indicated permeability of the younger alluvium beneath the flood plain of the Santa Ana River a distance of 12 to 13 miles downstream. Probably the increase in permeability with increased distance from the mountains is releated to the better soiling of the materials downstream. However, a systematic determination of the rate of increase in permeability downslope is not practical because the younger alluvium is completely above the zone of saturation in much of the area between the canyon mouths and the central part of the valley (pl. 4).

The yields of wells that tap the younger alluvium in Mill Creek basin decrease during the summer and in prolonged dry periods and increase during the winter and in wet periods. These changes in yield have been and are critical to the supply for the city of Redlands and other water users. Accordingly, the following discussions briefly outline the reasons for the range in well yield.

Well data indicate that existing wells yield about 4 to 5 gpm per foot of drawdown for each 10 feet of saturated younger alluvium penetrated by the well. Thus, for a typical well that penetrates 70 feet of saturated younger alluvium the specific capacity will be about 30 to 35 gpm per foot of drawdown and the well will yield about 300 to 350 gpm with a 10-foot drawdown for a short time before the drawdown increases substantially. If an attempt is made to increase the yield, the specific capacity is lowered because the drawdown is increased and the thickness of saturated material through which the water moves toward the well is reduced. Moreover, the yield of the well decreases as the water level declines during the pumping season, even if no attempt is made to increase the initial pumping rate. And, decline in yield is caused also by the effect of the increased pumping lift on pump capacity. Both observations and theoretical considerations indicate that, if the nonpumping water levels decline 20 feet during the pumping season or during a drought, causing a reduction in the saturated thickness of younger alluvium from 70 to 50 feet, the yield of the well will decrease from about 300 or 350 gpm to about 200 or 250 gpm, if a constant 10-foot drawdown is maintained.

River-Channel Deposits (Recent)

The river-channel deposits underlie the active and inactive channels of all streams and dry washes in the area. They underlie a large part of the entrenched channel of the Santa Ana River along the northern margin of the area. Their extent locally is poorly defined, especially where Mill Creek crosses the extensive alluvial fan upstream from its juncture with the Santa Ana River and in the area just downstream from the Santa Ana River canyon where extensive water-spreading operations are practiced. Here the two stream courses are only temporary and change from time to time, usually during each major flood. The surface extent of the river-channel deposits is shown on plate 2.

The river-channel deposits consist of boulders, gravel, sand, and silt. These deposits extend downward to and rest with local unconformity on the younger alluvium. The maximum thickness is not known but locally may be on the order of a few tens of feet. Because the deposits are indistinguishable from the younger alluvium in wells, the base of the deposits is shown diagrammatically on the sections (pl. 4).

In general these deposits consist of debris derived from the surrounding mountains and generally are very coars containing many boulders up to 3 feet in diameter near the mountains, but consisting mainly of gravel and sand at lower altitudes.

For the most part the deposits are above the zone of ground-water saturation and do not yield water to wells. Locally in Mill Creek canyon, in parts of Mill Creek basin, and in the central part of Bunker Hill Basin northwest of Redlands the deposits periodically are saturated to the land surface and yield water to wells at rates equal to those from equivalent thickness of the younger alluvium. Except in times of extreme flood when the younger alluvium is inundated, all seepage loss from the streams to ground water occurs through the river-channel deposits. Martin (1951a, p. 157) determined that, when the water in the Santa Ana River was clear and the channel deposits were free from silt, the rate of water loss through these deposits to the underlying ground-water body was as much as 20 inches per hour, or 40 acre-feet per day per wetted acre. These determinations involved small test plots which were kept covered by clear water to a depth of 4 inches for a period of 72 hours. Similar short-term tests conducted elsewhere in the San Bernardino Valley indicated that infiltration rates ranged from about 6 to 23 inches per hour (Martin, 1951b). These tests demonstrate the high permeability of the deposits and their ability to transmit large quantities of recharge to the underlying ground-water reservoirs, even during short periods of runoff.

GEOLOGIC STRUCTURE

Regional Structural Features

In this report the area between the San Jacinto and San Andreas faults is termed the San Bernardino block. It is characterized by several major structural features and numerous secondary faults which trend more or less parallel to the two major faults. In a broad aspect the southern part of the block, including the San Jacinto Mountains (pl. 1), is uplifted, but the northern part of the block, principally the San Bernardino Valley, is depressed. The Mill Creek area is in the depressed northern part of the block.

Numerous faults cross the area, and in the past movements along them have resulted in relatively depressed and uplifted areas that received differential sedimentation. Moreover, structural movements locally have produced barriers to the movement of ground water. These features commonly are along known faults and are shown on the geologic map (pl. 2). The barrier effect of these features is shown on the geologic sections (pl. 4) and on the water-level contour map (pl. 5).

The San Andreas fault, the longest and probably the most publicized structural feature in California, borders the area on the east where it extends along the west margin of the San Bernardino Mountains as a broad, complex fault zone. Another large-scale structural feature, only partly shown on the geologic map (pl. 2), is the Banning fault which strikes east-southeastward across the extreme southwest corner of this area. That fault is of regional significance and will be discussed in detail in the report being prepared on the Redlands-Beaumont area.

Structural Features Related to Ground Water

The Mill Creek area contains several small but hydrologically critical structural features. These include the Oak Glen fault, which strikes roughly parallel to the San Andreas fault zone and is approximately a mile to the southwest and several curving cross faults which trend approximately at right angles to and lie between the Banning and Oak Glen faults. The Greenspot area is the site of a graben, locally depressed to a depth greater than 1,000 feet between the San Andreas and Oak Glen faults.

The curving cross faults greatly influence the occurrence and movement of water. From southeast to northwest they include the Chicken Hill fault, two unnamed faults near the southwest margin of the Crafton Hills, and the Crafton and Redlands faults (pls. 2, 3, 5, 6). The area between the Chicken Hill fault and the smaller faults near the north margin of Western Heights basin is depresse(the block represented by the Sand Canyon area, Reservoir Hill, and the Crafton Hills and bounded on the north by the Crafton fault is uplifted relative to the surrounding areas. The area between the Crafton and Redlands faults is downdropped relative to the area on either side. The magnitude of the displacements along these faults is not known, but locally it may be as much as several hundred feet. Elsewhere only minor movements are believed to have occurred, as shown by the structural contours on bedrock (pl. 3).

The ground-water barriers shown on the maps probably mark extensions of known faults or the approximate positions of concealed faults. These include the Redlands, Mentone, and Bryn Mawr barriers, which are discussed in detail in the section on ground-water barriers.

Buried Bedrock Surface

Sufficient well data were obtained locally in the Mill Creek area, principally in Mill Creek and Mentone basins, to show that the alluvial materials beneath the valley floor overlie an old, eroded bedrock surface developed prior to the deposition of the alluvial deposits. Structural contours on the basement complex are shown on plate 3. The contours have been drawn only where logs

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Plate 3.- Map showing structural contours on bedrock in the Mill Creek area, Calif.

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of wells indicate that bedrock was encountered, and in general the absence of structural contours from broad areas indicates that wells have not been drilled to sufficient depth to encounter bedrock.

The configuration of the bedrock surface beneath Mill Creek has an important bearing on the occurrence and movement of ground water, the yields of wells drilled into the overlying alluvial deposits, the position of actual or potential aquifers, and the magnitude of the ground-water storage capacity, and locally it largely controls the hydraulic gradient of the contained ground water.

The buried bedrock surface beneath Mill Creek begins in the mountains several miles upstream from the east edge of the area (pl. 3). Downstream from the mouth of the canyon, between the San Andreas fault zone and the Oak Glen fault (pl. 2), the bedrock locally is about 1,000 feet below the land surface and little is known concerning the buried topography. In the area extending about 4 miles downstream from the Oak Glen fault, however, sufficient data were collected to compile structural contours with reasonable accuracy.

The bedrock surface shows several distinct features. A ridge extends westward from Brown Butte and diverges southward from the south side of the extension of the Oak Glen fault to the bedrock inliers cropping out in 1S/2-16 and 17 (pl. 2). This feature forms the northern margin of the aquifer in the Mentone area (pl. 4, sections C-C' and D-D'). A distinct canyon carved in bedrock crosses the area (pl. 3) from east to west along the south margin of the bedrock ridge. The canyon probably begins at the Oak Glen fault beneath the present course of Mill Creek. The general trace of the axis of this buried canyon trends westward between the Crafton Hills and Brown Butte. At about Garnet Street it appears to curve southwest about to the center of sec. 20; then it curves northwest and probably extends to the Mentone barrier.

Another probable canyon trends westward along the north side of the Redlands barrier, starting about at 1S/2-30A and terminating at the Mentone barrier. This canyon is shown on plate 4 (section C-C'). A minor canyon appears to trend northwest from about well 1S/2-30C1 to the Mentone barrier. A buried bedrock hill, about 1,650 feet above sea level at 1S/2-19Q, at times protrudes above the regional water table in Mentone basin (pl. 5). Its top may be about 50 to 70 feet below the land surface, and the buried hill forms a part of the southern boundary of the aquifer in Mentone basin (pl. 4, sections C-C' and D-D'). A second smaller bedrock hill is present about at well 1S/3-25-1 just north of the Redlands barrier.

West of Mentone barrier, the buried bedrock surface appears to be displaced downward by structural movements along a possible fault about at the position of the barrier (pls. 3 and 4, section A-A'). Except for a short distance just downstream from the barrier, wells do not penetrate bedrock in Bunker Hill or Redlands basins. Between the Redlands barrier and the Crafton fault, wells do not penetrate bedrock, which probably is downdropped by structural movements along the two features.

Structural contours drawn on a buried bedrock surface in the Sand Canyon area between the Crafton Hills and Reservoir Canyon Hill also are shown on plate 3. Here, however, the altitude control is poor and the position of the contours is subject to considerable error. The meager data suggest a buried canyon whose axis extends northwest from well 2S/2-5A1 to the Crafton fault.

SURFACE-WATER FEATURES OF MILL CREEK

DIVERSIONS AND CAGING STATIONS

Mill Creek is the largest tributary of the Santa Ana River in the Mill Creek area. It drains about 40 square miles of the western slopes of the San Bernardino Mountains where it has cut a deep gorge; in the valley it flows in indistinct channels across an alluvial fan to join the Santa Ana River about 6 miles downstream from the mountains. Records of daily flow of Mill Creek at the mouth of the canyon began in January 1919. At that time a gage was installed in the NE¼ sec. 13, T. 1 S., R. 2 W., 5¼ miles northeast of Mentone.

It is of historical interest to note that in 1892 a flume or pipeline was constructed from the mouth of the canyon to the zanja (Mill Creek water ditch, constructed in 1819) intake in the southwest corner of sec. 14, T. 1 S., R. 2 W. The purpose of the 7,250-foot pipeline, which has a capacity of 18,000 gpm (40.5 cfs), was to supply water diverted from Mill Creek for use in the generation of electric power at the zanja intake (1S/2-14N). Powerhouse 1 of the Southern California Edison Co. still is operating at the site (pl. 2), and according to Beattie (1951, p. 58):

> "...Mill Creek Power House No. 1 ...was the first power house ever built which used three-phase generation and transmission of electric power."

Powerhouse 2, at the mouth of Mill Creek Canyon, was completed in 1898 and was supplied with water diverted from Mill Creek about 3 miles upstream. Soon after powerhouse 2 was completed another flume was built high on the hillside which conveyed water from an intake about 6 miles upstream from the canyon mouth for the operation of powerhouse 3 (pl. 2).

The canals, flumes, and pipelines that supply water to the powerhouses are Power Canals 1, 2, and 3. Canals 2 and 3 lead to powerhouses 2 and 3, which are located near the mouth of the canyon near the intake of canal 1. The tailrace of powerhouses 2 and 3 discharges into canal 1, for use at powerhouse 1. Water is diverted from Mill Creek to canal 1 only when the water discharged from the combined powerhouses is insufficient to operate powerhouse 1 to full capacity.

Much of the natural flow of Mill Creek, therefore, is diverted at points upstream from the gaging station at the canyon mouth. During the summer months the entire flow of the stream frequently is diverted for beneficial use. After the water diverted from the creek passes through powerhouse 1 it is used as follows: Part of the flow is piped to a water-filtration plant owned by the city of Redlands from which it enters the city distribution system, during the irrigation season the remainder of the water enters the canals and pipelines and is used for irrigation outside Mill Creek basin, and during the winter season the water is spread in the several channels of Mill Creek downstream from powerhouse 1 or is used to recharge wells in several basins adjoining Mill Creek basin.

The gaging station at the mouth of Mill Creek canyon was operated from January 1919 to March 1938 at which time the station was destroyed. No further observations were obtained until October 1947 when a new gage was established. The observations have continued to the present.

In February 1939 a gage was installed on Mill Creek north of Mentone just upstream from the junction with the Santa Ana River (pl. 5). Observations of flow at the Mentone gage have continued to the present, although during much of the period of record the stream was dry along its lower reaches.

INFLOW

The surface-water inflow to Mill Creek basin, which is the principal potential source of ground-water recharge, is measured at the gaging station, "Mill Creek near Yucaipa (prior to October 1954 called Mill Creek near Craftonville)." The annual runoff for this station is given in table 3. In addition to the inflow at this gage, the total flow of Mill Creek includes the diversions upstream or the combined flow of power canals 1, 2, and 3, which are given in table 4. Table 4 also includes the discharge of three wells which pump into the flume and are in Mill Creek canyon upstream from powerhouses 2 and 3. Although the flow of the power canals is diverted for use, during the winter months a part of the flow ordinarily is returned to the basin as artificial recharge in specially constructed spreading basins.

Table 3.- Annual flow of Mill Creek near Yucaipa (prior to October 1954 published as "near Craftonville") for the periods 1920-38 and 1948-55[1]

Year ending September 30	Total (acre-feet)	Year ending September 30	Total (acre-feet)
1920	13,500	1934	590
1921	3,020	35	2,530
22	56,900	36	2,290
23	1,380	37	36,590
24	809	38	65,440
25	0	1939-47	no records
1926	6,850	1948	97
27	17,500	49	302
28	155	50	514
29	596	1951	169
30	2,610	52	7,520
1931	205	53	479
32	11,600	54	2,300
33	22	55	519

1. Records from U. S. Geological Survey Water-Supply Papers 1315-A (compilation through 1950), 1215, 1245, 1285, 1345, and 1395.

Table 4.- Annual flow of Mill Creek power canals 1, 2, and 3 near Yucaipa (prior to October 1954 published as "near Craftonville"), 1920-55[1]

Year ending Sept. 30	Power canal 1 (acre-feet)	Power canals 2 and 3 (acre-feet)	Year ending Sept. 30	Power canal 1 (acre-feet)	Power canals 2 and 3 (acre-feet)
1920	829	17,300	1938	1,660	11,990
21	2,130	18,800	39	2,800	17,490
22	2,330	21,000	40	1,870	16,330
23	3,780	21,000	1941	2,710	18,530
24	1,780	15,000	42	2,220	18,510
25	1,420	10,800	43	2,300	17,610
1926	1,140	13,900	44	3,150	18,140
27	3,390	17,600	45	2,360	18,200
28	1,350	12,300	1946	1,650	17,130
29	1,050	11,600	47	1,080	16,200
30	774	14,800	48	180	11,440
1931	704	12,200	49	715	10,530
32	5,330	16,100	50	95	11,260
33	1,210	13,600	1951	54	8,150
34	496	9,740	52	829	15,560
35	1,940	14,630	53	1,120	14,050
1936	1,170	16,280	54	630	14,920
37	7,400	17,170	55	471	12,570

1. Records from U. S. Geological Survey Water-Supply Papers 1315-A (Compilation through 1950), 1215, 1245, 1285, 1345, 1395, and unpublished data.

The larger permanent spreading basins are at sites 1S/2-21B, 21D, and 20B, and smaller basins are at sites in 1S/2-13 and 1S/2-14 (pl. 5). The reported annual quantity of Mill Creek water and water from the Santa Ana River, piped to Mill Creek basin via the Bear Valley highline, spread in this manner is given in table 5; the data were supplied by the San Bernardino Valley Water Conservation District (Martin, 1951a, p. 208). During the early period of record, only extremely crude estimates of the quantity spread are available. During recent years the estimates are believed to be improved but still are somewhat crude. Part of the water is spread in Mill Creek basin, and part enters spreading basins downslope from Garnet Street and consequently recharges ground water in Mentone basin. No data are available as to the relative quantity of water recharged in each spreading basin because the overflow from the upstream basins is unmetered and flows through gravel channels to successive spreading basins downstream. Based on discussions with Mr. E. F. Dibble, engineer for the San Bernardino Valley Water Conservation District, however, probably about 50 percent of the total was spread east of Garnet Street after 1950.

The surface-water inflow to Mill Creek basin from Triple Falls Creek and from small streams which drain a part of the north side of the Crafton Hills is not gaged.

Table 5.- Estimated annual quantity of water recharged in the Mill Creek spreading basins, 1922-55[1]

Year ending September 30	Recharge (acre-feet)	Year ending September 30	Recharge (acre-feet)
1922	29,000	1939	6,400
23	4,300	40	6,600
24	690	1941	11,000
25	340	42	5,200
1926	2,400	43	8,900
27	6,700	44	7,500
28	3,700	45	8,600
29	230	1946	1,400
30	3,200	47	3,000
1931	480	48	630
32	7,200	49	190
33	1,200	50	210
34	100	1951	50
35	9,100	52	5,000
1936	5,000	53	2,700
37	22,000	54	2,300
38	4,200	55	1,100

For the 34-year period 1922-55

Total	170,000	Average	5,000

For the 20-year period 1936-55

Total	about 100,000	Average	about 5,000

1. The data were supplied by the San Bernardino Valley Water Conservation District and are based on infrequent visual inspections of water flowing in irregular shallow stream channels; the values reported are very crude approximations and for later years are believed to be very conservative. All data rounded to two places by Geological Survey.

OUTFLOW

The surface-water outflow from Mill Creek basin and the upstream part of Mentone basin is measured at the gagi station "Mill Creek near Mentone," which is about 1.1 miles downstream from the Crafton fault and nearly 5 river miles downstream from the gage at the mouth of Mill Creek Canyon. The annual flow for this station is given in table 6 which shows that for the 17-year period 1939-55 the annual runoff exceeded 1,000 acre-feet in 7 years, was less than 500 acre-feet in 8 years or for nearly one-half the period of record, was less than 50 acre-feet in 4 years, and exceeded 10,000 acre-feet only in 1941 when the runoff was 14,720 acre-feet.

Of the total flow for the station, part previously was gaged at the mouth of Mill Creek Canyon but part was runoff from the Triple Falls creek drainage area, from the Crafton Hills, and from the valley lands between the gages at Mentone and the mouth of Mill Creek Canyon.

Table 6.- Annual flow of Mill Creek near Mentone, 1939-55[1]

Water year ending September 30	Flow (acre-feet)	Water year ending September 30	Flow (acre-feet)
1939	a1,010	1948	5.6
40	2,590	49	0
1941	14,720	50	48
42	326	1951	8.9
43	5,840	52	3,820
44	147	53	350
45	1,390	54	963
1946	2,440	55	292
47	902		

1. Data from U. S. Geological Survey Water-Supply Papers 1315-A(compilation through 1950), 1215, 1245, 1285, 1345, and 1395.

a. Incomplete.

GROUND-WATER HYDROLOGY

The ground-water hydrology of Mill Creek basin is related closely to the occurrence of ground water in the nearby basins. In connection with the study and the investigation being made of the Redlands-Beaumont area detailed studies of the occurrence and movement of ground water were made. As a result of this work the Mill Creek area was divided into six ground-water basins and five hydrologic areas. Mill Creek, Reservoir, Mentone, Redland Western Heights, and Beaumont-San Timoteo basins are described herein for the first time (pl. 2). The area also includes part of the Bunker Hill Basin, described in several other reports. Of these basins, Mill Creek basin is of primary concern in this report. The poorly defined hydrologic areas are referred to by area names rather than basin names and include the Triple Falls Creek, Mill Creek Canyon, Greenspot, Redlands Heights, and Sand Canyon areas.

In this report the ground-water hydrology of the Mill Creek basin area is developed in two parts: (1) The subdivision of the area into several ground-water basins and hydrologic areas, critical analysis of the barrier features and basin boundaries which impete ground-water movement and delimit the basins and areas, and the occurrence and movement of ground water; and (2) the quantitative aspects of ground-water inflow and outflow, aquifer tests, ground-water storage capacity, yield, and finally the general chemical quality of water in Mill Creek basin.

In earlier reports on the area the positions of many of the ground-water barriers were determined only approximately or their presence was unknown. Of the newly defined basins, Mill Creek, Mentone, Reservoir, and Redlands basins in part comprise sub-basins of the much larger hydrologic unit called Bunker Hill Basin in earlier reports. Because future studies may show that the area of Bunker Hill Basin, even as presently outlined, contains additional sub-basins or areas, no decision was made by the writers to establish definitely whether Mentone, Redlands, and Reservoir basins should be considered as subdivisions of Bunker Hill Basin or as separate ground-water basins bordering Bunker Hill Basin on the south and east. The complexity of the geologic structure and hydrology of the area suggest that the area presently included in Bunker Hill Basin ultimately will be proved to contain additional basins separated by faults and (or) ground-water barriers.

GROUND WATER BASIN

Mill Creek Basin

Mill Creek basin extends from the Mill Creek Canyon area on the east to Mentone basin (Crafton fault) on the west and from the Crafton Hills and the Triple Falls Creek area on the south to Brown Butte and Greenspot area on the north. It is about 3 miles long, 0.3 to 0.7 mile wide, and covers an area of about 1.4 square miles (pl.5).

Plate 5.- Map of the Mill Creek area, Calif., showing location of wells and water-level contours for March 1955.

Northeast of the Oak Glen fault the boundaries between the basin and the Greenspot and Triple Falls Creek areas are poorly defined. In this area the extent of Mill Creek basin is taken arbitrarily as about the same as that of the younger alluvium and river-channel deposits (pl. 2). The small subbasins between Mill Creek barrier and the San Andreas fault zone are considered a part of the Mill Creek Canyon area because both may be separated hydrologically from the area downstream.

As herein considered, Mill Creek basin is a subdivision of a larger hydrologic unit called Bunker Hill Basin in most earlier ground-water reports. Although Mill Creek basin formerly was considered a part of Bunker Hill Basin, geologic and hydrologic data indicate that the Crafton fault forms a ground-water barrier that separates Mill Creek basin from the area downstream.

The ground-water hydrology of Mill Creek basin is intimately associated with that of the Mill Creek Canyon area and the Triple Falls Creek area, because both areas are upstream from and are tributary to the basin. Moreover, the ground-water hydrology of Mill Creek basin also is related to that of Mentone basin, which is downstream from and receives discharge from Mill Creek basin.

Other Basins and Areas

Mill Creek Canyon Area

The Mill Creek Canyon area is a long, very narrow valley extending from the Mill Creek barrier upstream beyond the area shown on plate 2. It is bounded by the consolidated rocks of the San Bernardino Mountains, except for the small area along Mill Creek between the mouth of the canyon and the Mill Creek barrier. Ground-water and surface-water outflow from the Mill Creek Canyon area enters Mill Creek basin as it crosses the Mill Creek barrier.

Triple Falls Creek Area

The Triple Falls Creek area occupies that part of the structural trough, 0.6 to 0.9 mile wide, between the San Andreas and Oak Glen faults that extends eastward from the contact between the younger alluvium and the older plain and bench deposits at the east side of Mill Creek basin. This area formerly was considered to be partly within Bunker Hill Basin and partly in Yucaipa Basin (Eckis, 1934, pl. E). Because of a paucity of wells in the area and because of the extreme structural complexity of the trough along the San Andreas fault zone, the eastern extent of the area is unknown. In the western half of the area the principal ground-water movement is toward Mill Creek basin (pl. 5). In the eastern part the direction of movement is not known.

Creenspot Area

The Greenspot area also occupies a part of the structural trough between the San Andreas and Oak Glen faults and formerly was considered to be a part of the Bunker Hill Basin (Eckis, 1934, pl. E). The area is bounded on the northeast by the San Bernardino Mountains, on the west by the Greenspot fault, on the south by the Oak Glen fault and Brown Butte, and on the east by the northwest edge of younger alluvium in Mill Creek basin. It is about 2.5 miles long and 1 mile wide (pl. 2). The area is named for a cienaga (swamp) which formerly existed on the east side of the Greenspot fault. The swamp supported a considerable growth of vegetation which was visible to early settlers as they came over the mountains and was referred to as the "greenspot" on the eastern margin of the San Bernardino Valley. During the early period of development two wells drilled just up-stream from the Greenspot fault flowed at land surface.

Ground-water outflow from the area may enter either the northern part of Mentone basin or the eastern end of Bunker Hill Basin. However, the bedrock ridge extendin westward from Brown Butte may impede movement of ground water from the area west of the Greenspot fault to Mentone basin. It is known that ground-water outflow from the western-most part of the Greenspot area does not enter Mill Creek basin.

Mentone Basin

Mentone basin is roughly triangular, is about 2 miles across at the north end, and narrows to a point on the southwest in a distance of about 2.8 miles. It extends from the Crafton fault and Mill Creek basin on the east to the Mentone barrier on the west. It is bounded on the south by the Redlands barrier and, at least along most of its reach on the north, by the subsurface bedrock ridge extending westward from Brown Butte. The basin is mainly a subdivision of what formerly was considered to be part of Bunker Hill Basin, but the southernmost part of the basin formerly was considered to be in the San Timoteo Basin (north part) (Eckis, 1934, pl. E).

Most of the ground-water outflow from Mentone basin enters Redlands basin, but a small amount may cross the Redlands barrier and enter Reservoir basin on the south.

Western Heights and San Timoteo-Beaumont Basins

Western Heights and San Timoteo-Beaumont basins are southeast of Redlands. They are remote from the hydrologi problems of Mill Creek basin and were not studied in this investigation. The source of water in Reservoir basin was determined to be mainly from ground-water outflow from Western Heights basin through the Sand Canyon and Redlands Heights areas, and possibly in small part from ground-water outflow from San Timoteo-Beaumont basin. The bulk of the discharge from San Timoteo-Beaumont basin enters Redlands basin.

Sand Canyon and Redlands Heights Areas

The Sand Canyon and Redlands Heights areas are southeast of Redlands and the Crafton fault (pl. 2). The Sand Canyon area is bounded on the northeast by the Crafton Hills, on the southwest by Reservoir Canyon Hill, and on the northwest by the Crafton fault. The southeastern boundary of the area is imperfectly known but may be along the faults at the northwest side of Western Heights basin. The Redlands Heights area is bounded on the northwest by the Crafton fault and on the northeast by Reservoir Canyon Hill. As now delimited, it is bounded on the southwest and south by the Banning fault, but other barrier features not now known may necessitate revision of this boundary when more data become available. Insufficient data are available to determine whether the area largely in sec. 3, T. 2 S., R. 3 W., is in the Redlands Heights area or in Reservoir basin.

The Sand Canyon and Redlands Heights areas may prove to be westward extensions of the Western Heights basin. Because of the paucity of wells, both east and west of Reservoir Canyon Hill between the Crafton fault and the wells in the central part of Western Heights basin and in San Timoteo Canyon, the boundary and hydrologic relation between Western Heights and San Timoteo-Beaumont basins and the Sand Canyon and Redlands Heights areas are unknown. The complexity of the relations is described in greater detail in a report being prepared on the Redlands-Beaumont area.

The ground-water outflow (pl. 5) from the Sand Canyon area enters Reservoir basin and most of that from the Redlands Heights area also enters Reservoir basin but part probably enters San Timoteo-Beaumont basin.

Reservoir Basin

Reservoir basin of this report is a subdivision of the northern part of the former San Timoteo Basin (Eckis, 1934, pl. E). Reservoir basin is bounded on the east and southeast by the Crafton fault and the Sand Canyon and Redlands Heights areas, on the north and northwest by the Redlands fault and Redlands barrier, which is believed to extend northeastward from the Redlands fault and to intersect the Crafton fault near the west margin of the Crafton Hills. The southwest boundary of the basin is not known. Because of the paucity of wells between the city of Redlands well field in Reservoir Canyon and San Timoteo Canyon, it cannot be determined whether the area largely in sec. 3, T. 2 S., R. 3 W., is in Reservoir basin, in the Redlands Heights area, or in San Timoteo-Beaumont basin.

Ground-water outflow from Reservoir basin mostly enters Redlands basin across the Redlands fault, but a very small part may cross the Redlands barrier into the southwest corner of Mentone basin and thence cross the Mentone barrier into Redlands basin.

Redlands Basin

Redlands basin of this report is a subdivision of the larger areas formerly included in Bunker Hill Basin and in northern San Timoteo Basin (Eckis, 1934, pl. E). Redlands basin is a long narrow basin trending northeast beneath the city of Redlands from San Timoteo Creek toward the Santa Ana River. It is about 1.5 miles wide on the southwest and narrows to about 0.5 mile on the northeast. It is at least 6 miles long, as shown on plate 5, but its northeastern extent is unknown. Redlands basin is bounded on the southeast by the Redlands fault and the Mentone barrier, on the northwest by the Bryn Mawr barrier, and on the southwest by the Banning fault.

Ground-water outflow from Redlands basin enters Bunker Hill Basin. The ground water in Redlands basin is recharged mainly by ground-water outflow from Mentone, Reservoir, and San Timoteo-Beaumont basins, but the Santa Ana River and possibly Mill Creek contribute recharge during periods of runoff from the San Bernardino Mountains.

Bunker Hill Basin

One of the largest and most highly developed ground-water basins in the upper Santa Ana Valley is Bunker Hill Basin, which includes most of the San Bernardino Valley (Dutcher and Garrett, 1958). As a part of this investigation the occurrence and movement of water in the easternmost part of the basin south of the Santa Ana River was studied in relation to the hydrologic problems of the Mill Creek basin area.

The subsurface outflow from Bunker Hill Basin is described in an open-file report by Dutcher and Garrett (1958), and the quantitative aspects of ground-water inflow to Bunker Hill Basin from the Redlands-Beaumont area are described in a report being written by W. L. Burnham and Mr. Dutcher.

Effectiveness of the Ground-Water Barriers

The effectiveness of the ground-water barriers and faults, which impede or restrict the movement of ground water, is critical to the hydrology of Mill Creek basin. The criteria by which the presence of the barrier features is recognized or is postulated and the limits of accuracy in the locations of these features are discussed for each barrier in the following pages.

The physical nature of the barrier-producing materials developed along the faults is beyond the scope of this report, but in general the barriers occur along and are genetically related to faults. The barriers are not considered to be entirely impermeable, however, and water leaks to some degree through all of the barriers, except possibly those barriers associated with the regional faults that have very large displacements, such as the San Jacinto fault. Ground water crosses these large barriers chiefly through unfaulted materials of Recent age.

Mill Creek Barrier

Downstream from the mouth of Mill Creek Canyon several faults strike nearly parallel to the San Andreas fault zone (pl. 2). One of these features, herein called the Mill Creek barrier, is believed to impede ground-water movement (pl. 5). This fault locally is well exposed, and the location of the barrier shown on the water-level contour map is based principally on geologic data. Other subsidiary faults nearby also may impede ground-water movement.

The Mill Creek barrier probably is not effective in the younger alluvium, and consequently it does not impede the flow of ground water into Mill Creek basin. However, it appears to restrict the flow of water through the older alluvium and older plain and bench deposits, causing ground water upgradient from the barrier to move upward into the younger alluvium as it crosses the barrier. Downstream from the barrier ground water "cascades" downward into the older alluvial deposits. The displacement of water levels across the barrier locally may be as much as 150 feet (pl. 5).

Test well 1S/2-14H2, drilled for the city of Redlands in December 1955, upstream from the Mill Creek barrier, penetrated younger alluvium to a depth of 112 feet and the Potato sandstone of Vaughan (1922) between 112 and 145 feet but did not encounter ground water. The altitude of the base of the younger alluvium is about 2,540 feet. However, well 14H1, also upstream from the Mill Creek barrier and only 480 feet west of well 14H2, had a static water level that stood at an altitude of about 2,630 feet at the time well 14H2 was drilled. The explanation for this disparity is not known, but the high water level in well 14H1 may be related to a perched water body, to ground water moving southwestward from the older alluvial deposits nearby, or to other causes controlled by the unnamed fault nearby. It seems likely that the younger alluvium in this vicinity upstream from Mill Creek barrier was unsaturated and ground water was below the level of the base of the younger alluvium encountered in well 14H2.

Oak Glen Fault Barrier

The Oak Glen fault strikes nearly parallel to the San Andreas fault and, as shown on the geologic map (pl. 2), forms the south side of the graben between the Crafton Hills and the San Bernardino Mountains. East of the Crafton Hills the Oak Glen fault is offset by the Chicken Hill fault and constitutes the Oak Glen fault barrier. A pronounced scarp is present in the older plain and bench deposits north of wells 1S/2-24R1 and 1S/1-19P1.

The altitude of the water surface south of the Oak Glen fault barrier in wells 1S/1-19P1 and 1S/2-24R1 in March 1955 was 2,553 and 2,529 feet, respectively. The altitude of the water surface in the Triple Falls Creek area at that time, however, was considerably higher--about 2,915 feet at well 1S/1-19G1. The water-level contours, although incomplete in this area, suggest that in March 1955 the displacement in water level across the Oak Glen fault barrier ranged from about 200 to 350 feet. At well 1S/1-20Q1 the altitude of the water level was 3,336 feet, nearly 800 feet higher than that at well 19P1, suggesting that the Oak Glen fault acts as a barrier to ground water everywhere along its trace east of the Chicken Hill fault.

West of the Crafton Hills, however, the fault does not constitute a barrier to ground-water flow through the younger alluvium in Mill Creek basin. Data are lacking to determine whether the fault acts as a barrier to ground water movement in the area west of Brown Butte.

Greenspot Fault Barrier

The Greenspot fault is believed to be a barrier to ground-water movement everywhere along its trace (pls. 2 and 5). Wells 1S/2-9M1 and 16F1 were drilled east, or upgradient, from the Greenspot fault barrier and reportedly flowed at land surface when first drilled. A natural swamp, caused by ground water rising to the surface along the upstream side of the fault, formerly existed; springs were present in the small canyons which drain the Greenspot area, and an extensive area of black organic soil has developed along the upstream side of the barrier. A water tunnel was driven through the fault zone from the downstream side near well 1S/2-9M1, but because of constructional difficulties, it was not extensively used and now is destroyed.

In 1900 the water level in well 1S/2-16E1, now destroyed, was about 300 feet lower than the level at well 16F1 (Mendenhall, 1905, pl. 12).

Crafton Fault Barrier

The Crafton fault forms a barrier to the northward movement of ground water between the Sand Canyon and Redlands Heights areas and Reservoir basin, and to westward movement from Mill Creek to Mentone basin. The fault displaces the older alluvium and the older plain and bench deposits, but it is believed not to displace the younger alluvium. Consequently, the fault does not act as a barrier to the movement of ground water through the younger alluvium from Mill Creek basin to Mentone basin.

The barrier action of the Crafton fault is most clearly demonstrated where it passes between wells 1S/2-29N1 and 29P1 only 450 feet apart, in Reservoir basin and the Sand Canyon area, respectively. Here the water-level displacement across the barrier was about 170 feet in March 1955 (pl. 5). The disparity between the level in well 2S/3-1D1, which is just south of the Crafton fault barrier in the Redlands Heights area, and the poorly controlled water-level contours in Redlands basin suggests that the water-level displacement along that reach of the barrier may be about 120 feet.

The barrier action of the Crafton fault is less clearly evident but is none the less persistent along the western limit of Mill Creek basin. Here ground-water outflow from Mill Creek basin crosses the Crafton fault barrier principally through the unfaulted younger alluvium. As shown by the water-level profiles on plate 4, however, a barrier action probably caused by the faulting of the older deposits, is indicated by the greatly increased gradient downstream from the barrier as compared to the relatively uniform and much flatter gradient upstream from the barrier.

Other evidence for the fault barrier includes the displacement of bedrock (pl. 3), rapidly increasing thickness of saturated older alluvium and older plain and bench deposits between wells 1S/2-21B1 and 21E1 without a corresponding decrease in hydraulic gradient. No major change in the saturated cross-sectional area occurs west of Mill Creek basin where the water-level gradient is nearly constant and about parallels the slope of the bedrock surface. If any part of the latter two items were reversed, then a change in water-level gradient at about the position of the barrier could be accounted for. Because the cross-sectional area of younger alluvium remains about constant and that of the older alluvium and older plain and bench deposits decreases with distance upstream from well 1S/2-21E1 and remains about constant downstream from well 1S/2-21D1, and because of the other reasons outlined above, it is concluded that the Crafton fault extends northeastward across Mill Creek and forms a barrier to ground-water movement in the older alluvium and older plain and bench deposits.

Data derived from test well 1S/2-21D1, drilled for the city of Redlands at a site suggested by the Geological Survey, in large part made it possible to determine the presence of the Crafton fault barrier in that the geologic and water-level data obtained confirmed the position of the barrier and the magnitude of the water-level drop across the barrier.

Finally, further evidence for the Crafton fault barri between Mill Creek and Mentone basins was supplied by long-term residents who reported that a swampy area former existed south of Mill Creek Road in the vicinity of well 1S/2-21M1 on the upgradient side of the fault barrier. This area was known locally as German Springs cienaga (projected north to section A-A', pl. 4), and doubtless existed at times when there was considerably more ground-water underflow than in 1955.

The barrier was instrumental in causing water levels at those times to rise to land surface and to form the cienaga on the upstream side of the barrier.

Other Barriers

Other barriers that form the common boundaries between basins include the Redlands fault barrier, Redlands barrier, which probably is an extension of the Redlands fault, Mentone barrier, and Bryn Mawr barrier (pls. 2 to 6). These are critical to the ground-water outflow from the Redlands-Beaumont area and are discussed in detail in another report (Burnham and Dutcher, in preparation).

OCCURRENCE OF GROUND WATER

The occurrence of ground water is discussed separatel for Mill Creek and Mentone basins and for the Mill Creek Canyon and Triple Falls Creek Areas. The water body in ea basin is considered to extend from the margin of the area or from the bordering uplands, faults, or barriers on the upstream side of the basin to the bordering barrier featur on the downstream side of the basin or to the downstream margin of the area herein considered. The water body in each basin is contained within the alluvial deposits which underlie the area between the bordering barriers or faults. The bottom of the water body is considered to be at the ba of the alluvial deposits in the basin, but in several basi and areas the base of the water body has not been encounte in wells. The thickness of the water body in each basin is dependent not only on the depth to water below land surface (pl. 6) but also on the depth to the consolidated rocks below land surface.

Plate 6 is a map showing the approximate depth to the

Plate 6.- Map showing depth to water in the Mill Cree area, Calif., in March 1955.

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water level in these basins and areas in March 1955, and plate 3 is a map showing contours on the buried bedrock surface, where data are available. By using plate 5 to determine the water-surface altitude and plate 3 to determ the depth to bedrock, the approximate thickness of the wat bodies can be estimated. The depth to water differs from place to place in each basin, depending upon the topograph and the slope of the water surface.

The water body in each basin or area is confined, semiconfined, or unconfined. Where the type of occurrence is known, it is described for each basin or area, but in several of the basins and areas the extent of confinement is not known.

Mill Creek Basin

The water body in Mill Creek basin extends from the Mill Creek barrier to the Crafton fault barrier and is contained in the younger alluvium and in the older plain and bench deposits and older alluvium. Between the San Andreas and Oak Glen faults the water body extends to a depth of about 900 feet below the land surface, but between the Oak Glen and Crafton faults the depth decreases from about 130 feet at the Oak Glen fault to about 100 feet half a mile to the west, then increases to about 210 feet on the west beneath the deepest part of the basin (pl. 4). It terminates on the south at the Crafton Hills and on the north at Brown Butte and its westward subsurface extension. The depth to water in March 1955 ranged from about 170 feet below land surface just west of the Mill Creek barrier to about 25 feet at well 1S/2-21B1 near the west margin of the basin (pl. 6). In the younger alluvium ground water is unconfined; in the eastern part of the basin the deeper part of the water body is semiconfined or locally confined by silt and clay beds in the older alluvial deposits.

Mill Creek Canyon Area

The water body in the Mill Creek Canyon area extends downslope from a point in the canyon east of the eastern border of plate 5 to the Mill Creek barrier and probably is contained entirely in younger alluvium. It extends to a depth of 130 feet below land surface at well 1S/1-7L1; elsewhere in the area the base of the water body is probably between 30 and 140 feet below land surface (pls. 4 and 6). Plate 4 shows the water-level profiles in the canyon area for December 1951 and for March 1955 and also shows the approximate thickness of the water body along the canyon reach. The water body in the Mill Creek Canyon area is believed to be everywhere unconfined.

Triple Falls Creek Area

The water body in the Triple Falls Creek area is contained in the older plain and bench deposits and older alluvium except for a few canyon areas east of the San Andreas fault where water is contained in the younger alluvium. At well 1S/2-24C1 the water body extends to a depth of at least 400 feet below land surface, but at well 1S/1-19G1 bedrock was encountered at a depth of 384 feet below land surface.

In 1955 the depth to water in the area ranged from about 100 feet near the Oak Glen fault to about 250 feet near the north margin of the area (pl. 6). Based on data from other areas where wells penetrate deposits similar to those in Triple Falls Creek area, ground water is probably semiconfined.

Greenspot Area

The water body in the Greenspot area probably is contained wholly in the older alluvium, except for the uppermost part just east of the Greenspot fault which may be contained in the older plain and bench deposits. At wells 1S/2-9P1 and 9Q1 the water body extends to a depth of at least 600 feet below land surface; at wells 1S/2-14L1, 14E1, and 15G1 it extends to a depth of about 1,000 feet.

The depth to water in March 1955 ranged from about 50 feet or less just east of the Greenspot fault to about 200 feet near the east margin of the area. Based on well logs and on the former existence of flowing wells just east of the fault, the water body in the Greenspot area locally is confined.

Mentone Basin

The water body in Mentone Basin extends from the Crafton fault barrier on the east to the Mentone barrier on the west and from the Redlands barrier on the south to the bedrock ridge, which is the westward subsurface extension of Brown Butte, on the north. It completely underlies Mentone basin, except for the areas beneath Mentone where the buried bedrock surface protrudes above the water body (pl. 5). The water body is contained entirely within the older alluvium and the older plain and bench deposits except near the Crafton fault barrier where the water body in March 1955 extended upward into the younger alluvium. The available data indicate that the water body is largely unconfined and locally semi-confined.

The altitude of the base of the water body is shown on plate 3 and the depth to water is shown on plate 6. The depth to water in March 1955 was from about 50 feet below land surface in the eastern part of the basin to about 300 feet below in the western part (pls. 5 and 6).

Reservoir Basin

The water body in Reservoir basin is contained principally in the older alluvium and locally in the older plain and bench deposits. It is semi-confined to confined; the degree of confinement increasing with depth. The thickness of the water body is unknown because wells have not been drilled to bedrock. However, the water body is known to extend to a depth of 750 feet below land surface at the Reservoir Canyon well field in 1S/3-35. The depth to water in March 1955 was locally only 50 feet below land surface in that area, but because the slope of the water table was much less than the slope of the land surface, the depth to water probably was about 300 to 350 feet near the Crafton fault. (See pl. 4, section B-B', and pl. 6.)

Redlands and Bunker Hill Basins

The water bodies in Redlands and Bunker Hill Basins are contained in the older alluvium and probably in the San Timoteo beds of Frick (1921). The water body in Bunker Hill Basin locally extends upward into the younger alluvium. The maximum thicknesses of the water bodies are unknown because wells do not encounter bedrock in the different parts of the basins. The water body in Redlands basin extends to a known depth of 850 feet below land surface; that in Bunker Hill Basin locally extends at least to 1,400 feet. The depth to water in March 1955 in Redlands basin was locally only about 100 to 150 feet below land surface, but near the Redlands fault and Mentone barrier it was about 300 to 350 feet below land surface (pls. 4 and 6).

Wells in Redlands and Bunker Hill Basins penetrate only the upper part of the water body, but these locally disclose differences in head within the range of penetration. In Bunker Hill Basin several generalized water-bearing zones were recognized by Dutcher and Garrett (1958) east of the Loma Linda fault (pl. 1). The zones of differing head and the zone of semiperched water in the deposits overlying the main water bodies of Redlands and Bunker Hill Basins are discussed in greater detail in a report being prepared on the Redlands-Beaumont area.

Other basins and areas

The water bodies in Western Heights and San Timoteo-Beaumont basins and in the Sand Canyon and Redlands Heights areas were not studied during this investigation. The occurrence of ground water in those basins and areas however, is discussed in detail in another report by Burnham and Dutcher.

Minor Water Bodies

Minor water bodies occur in the Mill Creek area but were not studied in detail during the present investigation. These consist of: (1) A shallow very thin water body overlying bedrock immediately around the flanks of the Crafton Hills. It is penetrated locally by windmill-powered wells used mainly for stock; (2) a water body of small extent between the bedrock outcrops of the San Bernardino Mountains and the San Andreas fault zone (pl. 5). It is penetrated locally by small water tunnels used to supply domestic water to ranch homes in the Morton Ridge area; and (3) a shallow semi-perched water body which overlies local clay beds or lenses in Redlands and Bunker Hill Basins. This water body is recharged chiefly by percolation of irrigation water and direct recharge of precipitation. Discharge from the minor water bodies contributes to the recharge of the main water bodies in the several basins in which they occur.

SOURCE AND MOVEMENT OF GROUND WATER

Ground water, like water in streams, moves from areas of high head to areas of lower head, but at a much slower rate. The water-level contours for March 1955 (pl. 5) show that the lowest water levels, about 1,100 feet above sea level, are those in the northwest part of the Mill Creek area in Bunker Hill Basin. Eastward and southward from this part of Bunker Hill Basin the water levels are progressively higher in altitude, indicating that ground water is moving toward the area of lower levels from all the ground-water basins in the area. All ground water in the area, therefore, tends to flow toward Bunker Hill Basin, but the barrier features and the operation of large capacity irrigation and public-supply wells have a pronounced effect on the direction and character of the movement. The barriers are such that ground water, either by flowing through barrier zones of greatly reduced permeability or by spilling over the top, is able to move downgradient from one basin to the next, finally reaching Bunker Hill Basin.

WATER-LEVEL FLUCTUATIONS IN WELLS

In the Mill Creek area periodic depth-to-water measurements have been made in more than 100 observation wells by the San Bernardino Valley Water Conservation District, the city of Redlands, and many private water companies. Records that have been published are contained in the reports listed in table 7. In addition, numerous water-level measurements made by the Geological Survey are tabulated in a separate report being prepared by L. C. Dutcher.

The contours show that two sources of subsurface inflow occur at the east end of the Mill Creek area: The Mill Creek Canyon and Triple Falls Creek areas supply subsurface inflow to Mill Creek basin, and Western Heights basin and the Sand Canyon and Redlands Heights areas supply inflow to Reservoir basin. The movement from Mill Creek basin is westward to Mentone basin, then to Redlands basin, and finally to Bunker Hill Basin. The movement from Reservoir basin is principally northwestward to Redlands basin, where it joins the flow from Mentone basin, then to Bunker Hill Basin.

The contours do not show directly the other principal sources of recharge, which include seepage loss from streams, deep penetrations of rain and imported irrigation water, and artificial recharge in stream channels and through wells. Nevertheless, although they are not individually distinguishable, these sources of recharge have a pronounced effect on the position of the contours.

Finally, the contours show that subsurface discharge occurs at the west edge of the area in Bunker Hill Basin where movement is chiefly westward toward the San Jacinto fault (pls. 1 and 5).

Table 7.- Published records of water-level measurements in the Mill Creek area, California

Year	U. S. Geological Survey Water-Supply Paper number	Year	California Division of Water Resources Bulletin
1905	142	1932	39 and 39-A
21	468	33	39-B
36	817	34	39-C
37	840	35	39-D
38	845	36	39-E
1939	886	1937	39-F
40	911	38	39-G
41	941	39	39-H
42	949	40	39-I
43	991	41	39-J
1944	1021	1942	39-K
45	1028	43	39-L
46	1076	44	39-M
47	1101	45	39-N
48	1131	46	39-O
1949	1161	1947	39-P
50	1170	48	39-Q
51	1196	49	39-R
52	1226	50	39-S
53	1270	51	39-T
54	1326	52	39-U
		1953	39-V
		54	39-W

The records of water-level fluctuations in wells are utilized to interpret past and present hydrologic conditions. The records show several types of fluctuations caused by the conditions and forces at work in the water bodies of the several basins. These fluctuations are related principally to seasonal pumping effects and to natural ground-water depletion and replenishment.

Plates 7 to 12 show hydrographs for 9 selected wells in Reservoir, Redlands, Mill Creek, Mentone, and Bunker Hill Basins. The locations of these wells are shown on plate 5. The hydrographs show that the water-level fluctuations are of two general types: Long-term fluctuations caused not only by cyclic periods of greater or less than average rainfall and runoff but also by changes in pumping regimen, and seasonal fluctuations resulting from variations in draft from ground water and the amount of the annual recharge. During the winter and spring when the runoff is not diverted for irrigation or domestic supply, the ground-water bodies beneath the stream beds ordinarily are recharged in a magnitude determined by the duration and intensity of the runoff. On the other hand, during the summer and autumn, the pumping draft for irrigation and domestic supply usually is larger than in the winter.

Long-Term Fluctuations

The long-term water-level trend in most of the ground water basins of the area has been one of decline for the period of record. In 1955 the levels locally were the lowest for the period of record. Long-term hydrographs for representative wells in the several basins show that the recharge during periods of large surface runoff is not equal; they also show that the rates of water-level declines, following periods of greater than average recharge, are not equal. The rate and magnitude of recovery during a wet cycle or period of large runoff and the rate and magnitude of decline during a dry cycle depend largely on the geographic location of the observation wells in relation to sources of recharge from streams, to pumped wells, and the storage capacities of the basins.

In general the hydrographs (pls. 7 to 12) reflect the cyclic pattern of precipitation and hence runoff and recharge. In some areas or basins the size of the basin, amount of pumpage, situation in relation to large streams, and the type of natural recharge and discharge are less obvious but equally important factors which influence the nature of the water-level fluctuations. Most of the graphs show a decline to 1935 or 1936 in response to below-average recharge, a rise to peak levels in the period 1937-45 in response to above-average recharge, and a decline, starting about 1945 or 1946 and ending at or near record-low levels in 1951, caused mainly by a severe drought and little recharge. The above-average recharge in 1952 caused a halt in water-level decline in some wells. However, some levels continued to decline to record low levels, and in others levels rose.

The magnitude of the response to variations in recharge from precipitation and runoff ranged widely from one basin to another. In general the water-level fluctuations in the larger basins that receive recharge from major streams were similar and of one type; those in Mill Creek basin which is small but receives recharge from Mill Creek were of a different type; those in the larger basins that receive little recharge from streams but are mainly recharged by subsurface flow were similar and of a third type.

In relatively large basins, such as Bunker Hill, Redlands, and Mentone, which contain much ground water in storage and receive little annual recharge during periods of drought compared to the volume in storage, the long-term range in water levels was large, generally between 60 and 100 feet. The hydrographs for wells 1S/3-14P1 (pl. 9), in the eastern part of Bunker Hill Basin, 1S/2-19D1 (pl. 10) and 1S/3-24C1 (pl. 9), in the northeast part of Redlands basin, and 1S/2-19G1 (pl. 7), in Mentone basin, demonstrate the long-term fluctuations in these localities.

In Mill Creek basin, which is small and has limited storage capacity, the annual recharge received from Mill Creek during periods of drought, although reduced in volume, is sufficient to replenish a considerable percentage of the total storage capacity of the basin. For that reason the long-term range in water levels was roughly only about 40 to 50 feet. The hydrographs for wells 1S/2-21B1, 21E1, and 21H2 are shown on plates 7 and 8. For convenience of comparison the hydrograph for well 1S/2-19G1, in Mentone basin, is also plotted on plate 7.

Because both basins are recharged by Mill Creek, the relative size of the two basins is clearly evident by the nature of the long-term fluctuations; only during wet periods is the volume of recharge sufficient to cause substantial water-level recovery in the larger (Mentone) basin.

In general the graph for well 1S/2-21E1 in Mill Creek basin (pl. 7) shows a decline of about 25 feet

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Plate 7.- Hydrographs of wells in Mill Creek and Mentone basins.

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during the period 1932-36, a rapid rise to nearly a maximum level in July 1937, a period between 1937 and 1945 during which the basin was filled about to capacity each spring, the period of drought from about 1946 to 1951 during which the successive high spring levels were progressively lower and during which the levels declined about 40 to 60 feet, and a rapid rise during the 1951-52 fall-to-spring season. In general the hydrographs of wells in Mill Creek basin show a period of little change after 1952, except at well 1S/2-21E1 where the overall decline was nearly 30 feet during the period 1952-55.

The fluctuations of water levels in well 1S/2-19G1 in Mentone basin (pl. 7) and wells 1S/3-24C1 and 1S/2-19D1 in Redlands basin (pls. 9 and 10) are typical of water-level fluctuations in basins

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Plate 9.- Hydrographs of wells in Redlands and Bunker Hill Basins.

Plate 10.- Hydrograph of well in Redlands basin.

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that are recharged mainly by intermittent streams; the water-level fluctuations closely correspond to the stream hydrographs and (or) a graph showing cumulative departure from normal rainfall (Dutcher and Garrett, 1958). The relatively slow water-level decline at those wells after about 1945 illustrates that the ground-water storage capacity of those basins is relatively large in relation to average annual discharge and recharge. The water-level fluctuations in well 1S/2-21E1 (pl. 7), and wells 21B1 and 21H2 (pl. 8) in Mill Creek basin,

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Plate 8.- Hydrographs of two representative wells in Mill Creek basin.

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however, are typical of fluctuations of water levels in basins recharged by an intermittent stream but where the ground-water storage capacity is relatively small compared to the annual discharge.

The long-term fluctuations in Reservoir basin are of a type somewhat different from those in Bunker Hill, Redlands, and Mentone basins, also from those in Mill Creek basin or in Western Heights basin. Plate 11 shows a graph of water-level fluctuations in well 1S/3-36M1.

Plate 11.- Hydrograph of well in Reservoir basin and graph of cumulative pumpage.

In general the graph shows essentially no net change during the period 1927-31, a gradual rise to peak levels in the period 1932-44, and a decline, starting about 1945 to record-low levels in 1955.

In order to show the general relation between the pumpage and the water-level decline in Reservoir basin during the drought beginning in 1946 a graph of the cumlative pumpage from the city of Redlands well field, beginning in June 1944, is also shown on plate 11. The major part of the water withdrawn from the basin is pumped at the well field, which is less than half a mile west of well 1S/3-36M1. The annual pumpage for the city is shown in table 8.

Table 8.- Metered pumpage at city of Redlands in Reservoir basin during the water years 1941-53[1]

Water year ending September 30	Pumpage[2] (acre-feet)	Water year ending September 30	Pumpage[2] (acre-feet)
1941	290	1948	5,720
1942	1,320	1949	5,560
1943	1,390	1950	4,900
1944	1,640	1951	5,430
1945	2,130	1952	2,500
1946	3,440	1953	3,380
1947	4,330		

1. Compiled from data supplied by the city of Redlands, rounded to the nearest 10 acre-feet by the Geological Survey.

2. Includes pumpage from city wells 10, 11, 12, 14, 15, and 16 from 1941 through 1949; includes city well 13 during 1949-51; includes city well 17 during 1952-53.

The parallelism between the hydrograph of well 1S/3-36M1 and the graph of city pumpage (pl. 11) during the period June 1944 to December 1951 is evident. Throughout this period the water level in the well declined approximately in direct proportion to the cumulative pumpage. The pumpage was about 34,000 acre-feet and the water level declined about 120 feet. The average ratio of pumpage to water level was 280 acre-feet per foot of drawdown. After 1951, however, the water level flattened considerably, whereas the cumulative pumpage graph continued downward at a slope nearly equal to that for the period 1944 to 1951. For the period January 1952 to August 1954 the pumpage was about 9,000 acre-feet and the water-level decline about 18 feet. Thus, the ratio of pumpage to water-level decline was about 500 acre-feet per foot of drawdown.

The change in the ratio of pumpage to water-level decline in 1952 may be related to one or more of the following: Recharge in that wet year from penetrations of rain or imported irrigation water, or imported water recharged through wells; a decrease in subsurface outflow or an increase in inflow directly resulting from pumping at the well field; or ground water withdrawn from storage outside the basin boundary shown on the water-level contour map and at a considerable distance from the well field. The geology and hydrology of the area near the well field in 1S/3-36 are complex, and sufficient data are not available to determine which of the above causes the long-term fluctuations of water level in Reservoir basin to be significantly different from those in all nearby basins and areas except immediately downstream in Redlands basin. (See graph for well 1S/3-35B1, pl. 12, which shows that

Plate 12.- Hydrograph of well in Redlands basin.

the fluctuations in Redlands basin immediately downstream from well 1S/3-36M1 are essentially the same as the fluctuations in Reservoir basin except for the sudden drop in water level in 1950.) For the drought period 1946-51, water levels probably would have declined somewhat as a result of natural discharge from the basin even if there had been no pumping from the city wells. Thus, of the overall decline of 120 feet for the period 1945-51 an unknown part was caused by natural discharge and the remainder, and probably the major part, was caused by pumping. The above-average precipitation in 1952 probably was in part responsible for the decrease in the rate of water-level decline, which might account for the rather abrupt increase in the ratio of pumpage to water-level decline.

It is of interest to note, however, that graphs similar to those shown on plate 11 showing drawdown at an observation well caused by pumping a nearby well at a constant rate and cumulative pumpage from that well will invariably show an increase in the ratio of pumpage to water-level decline with time after pumping started in the vicinity of the wells; this will occur even though no change in the natural recharge-discharge regimen of the aquifer results from pumping. Based on the incomplete data available, therefore, it appears possible Reservoir basin may extend some distance southwest of the area where water-level contours are shown on plate 5. It will not be possible to determine whether changes in the rate of recharge to the basin, salvage of subsurface flow, or withdrawal of water from storage at a considerable distance from the well field is mainly the cause for the increase in the ratio of pumpage to water-level decline at the well field since 1952, until complete and accurate records of future pumpage and change in water level in the basin are available.

Seasonal Fluctuations

In addition to the general long-term rises and declines of ground-water levels due to depletion and replenishment of ground water in storage, the water levels in most areas exhibit a marked seasonal decline caused mainly by pumping during the late spring, summer, and autumn, and a marked seasonal rise caused by cessation of pumping and recharge in the winter and early spring. The hydrographs for wells near areas of heavy withdrawals show an annual fluctuation of as much as 50 feet, whereas the graphs for wells more remote from areas of pumping show fluctuations of only a few feet. Each spring, usually in April, water levels in most wells begin to decline as pumping for the irrigation season begins, reach the deepest levels usually in October and November, and recover through the winter.

The hydrographs on plates 7 to 12 show the seasonal fluctuations in representative wells in the several basins and areas in the Mill Creek area. In general, during periods of drought the spring peaks each year are successively at lower levels; during wet periods the converse is true. Exceptionally wet years, such as 1937 and 1938, cause large water-level rises. In Redlands, Reservoir, Mentone, Mill Creek, and Bunker Hill Basins the rises during wet periods ranged from 20 feet to more than 90 feet.

The hydrographs on plates 7 and 8 show the large seasonal fluctuations in representative wells in Mill Creek basin. In general the water levels reflect pronounced periods of drought to a lesser degree than are reflected by levels in the larger basins. The seasonal fluctuations of water levels in Mill Creek basin reflect seasonal recharge to and discharge from the relatively small basin to a greater degree than do the fluctuations in most larger basins where the storage capacity is greater. The autumn to spring recoveries during 1936-37, 1940-41, 1942-43, and 1951-52 are most pronounced and at well 1S/2-21E1 (pl. 7) the spring recovery was about 50 feet in 1951-52. The autumn to spring recoveries for each year of the period 1946-51, however, were much less and averaged about 10 to 20 feet. As shown by the graphs for wells 1S/2-21B1, 21E1, and 21H2 (pls. 7 and 8) the minimum seasonal fluctuation of water level occurred during the very wet year 1941. The summer decline at well 1S/2-21B1 was only about 5 feet. The summer decline during 1942, however, was about 30 feet at that well and was about 50 feet at well 21E1. The amount of recharge during the winter and spring as well as the pumpage from the basins during the following summer and fall months influence the magnitude of the seasonal fluctuations.

PUMPING TESTS

Pumping or aquifer tests are made to determine the coefficients of transmissibility and storage of an aquifer. The coefficients are used in making quantitative estimates of water available in an aquifer, in computing the amount of ground-water outflow and inflow through the aquifer, and in estimating the future water-level decline that will result from pumping from the aquifer. The coefficient of transmissibility may be defined as the number of gallons of water that will move in 1 day through a vertical strip of the aquifer 1 foot wide, having a height equal to the full thickness of the aquifer, under a hydraulic gradient of 100 percent (1 foot per foot); it is expressed as gallons per day per foot.

The coefficient of storage may be defined as the volume of water released or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. A simple way of visualizing this concept is to imagine an artesian aquifer which is elastic and is uniform in thickness and which is assumed, for convenience, to be horizontal. If the head of water in that aquifer is decreased, there will be released from storage a finite volume of water that is proportional to the change in head. Because the aquifer is horizontal, the full observed head change is evidently effective perpendicular vertically from the top to the bottom of the aquifer, and extends laterally so that its cross-sectional area is coextensive with the aquifer-surface area over which the change occurs. The volume of water released from storage in that prism, divided by the product of the prism's cross-sectional area and the change in head, results in a dimensionless number which is the coefficient of storage. If this example were revised slightly, it could be used to demonstrate the same concept of coefficient of storage for a situation in which the head of water in the aquifer is increased or for a horizontal water-table aquifer.

A formula developed by Theis (1935, p. 519-524), commonly referred to as the nonequilibrium formula, is one of the basic mathematical means of deriving the coefficients of transmissibility and storage. The determinations are based on the rate of decline and recovery of the water levels in observation wells caused by pumping a nearby well for a period of time, then shutting off the pumped well. Or, by use of modifications of that formula, the determinations are based on the rates of drawdown and (or) recovery in the pumped well.

In Mill Creek basin pumping tests were made at several sites. These tests were of different types, and several methods were used to compute the coefficients of transmissibility and storage. The tests, methods, and results are described below.

Tests at Wells 1S/2-22C1, 22C2, and 15P2

Before the pumping tests were started at the city of Redlands wells which are in the Mill Creek channel near Brown Butte, automatic water-level recorders were installed in pumped well 1S/2-22C2 and observation well 1S/2-22C1. During one of the tests, a recorder was operated also in well 1S/2-15P2. Three tests were made at this site: One was for 48 hours in which well 1S/2-22C2 was pumped at an average rate of 460 gpm; the second was a 10-day test in which well 22C2 was pumped at an average rate of 430 gpm; and the third was a 32-day test in which well 1S/2-15P2 was pumped at an average rate of 210 gpm. During the first two tests, water-level measurements were made at the two nearby observation wells and in the pumped well; measurements of both drawdown and recovery were recorded. These measurements were made at 5-second intervals for several minutes immediately before and after the pumping started or stopped and at progressively greater intervals as the tests progressed.

The basic formula was developed on the basis of six physical assumptions: (1) That the aquifer is infinite in extent; (2) that it is homogeneous; (3) that its transmissibility is constant at all places and in all directions; (4) that it is confined between impermeable beds; (5) that the coefficient of storage is constant; and (6) that water is released from storage instantaneously with a decline in artesian head. An examination of the geologic map (pl. 2) in the vicinity of the tests plainly indicates that the aquifer is not of infinite extent and, therefore, assumption (1) above is not satisfied. There are no recognizable confining beds in the area of the test and assumption (4) is not satisfied. The degree to which assumptions (2), (3), (5), and (6) are satisfied in the test area remains to be examined. Geologic data indicate that, if pumping continues for a long enough time, the younger alluvium in most respects is sufficiently homogeneous to meet assumptions (2), (3), (5), and (6). However, the younger alluvium varies slightly in thickness along the cross section.

Although several of the assumptions of the equation are not satisfied at the test site, the lack of an infinitely extensive aquifer and a constant transmissibility at all places and in all directions can be adjusted by the use of certain formulas. The reasons for and mathematical treatment of the deviations of the field curve from the type curve are explained in the section on the determination of aquifer boundaries. The fact that there are no confining beds in the area was compensated for by adjusting the observed drawdowns to theoretical values which would occur in an exactly similar but confined aquifer in which no dewatering of the water-bearing deposits would occur during pumping. These adjustments of the field observations were made by use of a formula derived by Jacob (1944):

$$s' = s - s^2/2m \qquad (1)$$

Where $\underline{s}'$ is the corrected drawdown in feet due to dewatering of the aquifer during pumping; $\underline{s}$ is the observed drawdown, in feet; and $\underline{m}$ is the saturated thickness of the aquifer at the well, in feet.

Coefficient of Transmissibility

The transmissibility at each observation well is derived from the following formula:

$$T = \frac{114.6QW(u)}{s'} \qquad (2)$$

Where T is the coefficient of transmissibility, in gallons per day per foot, Q is the discharge of the pumped well, in gpm; $W(u)$ is the well function of u, derived from the type curve; and s' is the correct drawdown in the observation well, in feet.

Based on the 48-hour test, the transmissibility at well 1S/2-22C2 was about 96,000 gpd per foot and at well 1S/2-15P2 was about 125,000 gpd per foot. These two values suggest that at the time of the test and in the area tested the transmissibility of the aquifer was on the order of 100,000 gpd per foot.

The second test, during which well 1S/2-15P2 was pumped at an average rate of 210 gpm for a period of 32 days, was made after the 48-hour test to check the transmissibility obtained during the 48-hour test and to determine, if possible, whether the coefficient of storage derived from the 48-hour test was representative of the average coefficient of storage of the aquifer. The water-level measurements made at wells 1S/2-22C1 and 22C2 during the 32-day test are given in table 9. From that table it can be seen that, after about 25 days of continuous pumping, approximately steady-state conditions existed in the vicinity of the pumped well and the observation wells, and the rate of water-level decline in observation wells located at different distances from the pumped well was essentially the same. The rate of water-level decline after about 25 days was about 0.07 to 0.08 foot per day at both observation wells.

To compute the transmissibility of an aquifer at steady-state conditions the equation commonly known as the Thiem formula (Wenzel, 1942, p. 81) is used as follows:

$$T = \frac{527.7 \times Q \times \log r_2/r_1}{(s'_1 - s'_2)} \quad \text{--------------} \quad (3)$$

Table 9.- Drawdown in observation wells during aquifer tests in Mill Creek basin

Date 1955	Elapsed pumping time (days)	Drawdown[1] (feet)	Water-level decline (-) or rise (+) (feet per day)
Well 1S/2-22C1 (well 1S/2-15P2 pumping 210 gpm from 8:00 a.m., April 6 to May 8, 1955)			
April 6[2]	0	0.75	--
7	1	.93	-0.18
8	2	1.16	-.23
(Well 1S/2-22C2 started pumping 430 gpm at 10:30 a.m., April 8, 1955)			
April 9	3	2.77	-1.61
10	4	3.68	-.91
11	5	4.32	-.64
12	6	4.78	-.46
13	7	5.20	-.42
April 14	8	5.55	-.35
15	9	5.86	-.31
16	10	6.16	-.30
17	11	6.43	-.27
18	12	6.68	-.25
(Well 1S/2-22C2 shut off at 12:30 p.m., April 18, 1955)			
April 19	13	5.75	+.93
20	14	5.20	+.55
21	15	4.97	+.23
22	16	4.88	+.09
23	17	4.83	+.05

Continued

Table 9.- Drawdown in observation wells during aquifer tests in Mill Creek basin--Continued.

Date 1955	Elapsed pumping time (days)	Drawdown (feet) 1/	Water-level decline (-) or rise (+) (feet per day)
April 24	18	4.84	-0.01
25	19	4.87	-.03
26	20	4.94	-.07
27	21	4.99	-.05
28	22	5.06	-.07
April 29	23	5.15	-.09
30	24	5.23	-.08
May 1	25	5.30	-.07
2	26	5.37	-.07
3	27	5.45	-.08
4	28	5.53	- .08
5	29	5.60	-.07
6	30	5.68	-.08
7	31	5.75	-.07
(Well 1S/2-15P2 shut off at 8:00 a.m., May 8, 1955)			
May 8	32	5.76	--
9	33	5.63	+.13
10	34	5.45	+.18
11	35	5.28	+.17
12	36	5.11	+.17

Continued

Table 9.- Drawdown in observation wells during aquifer tests in Mill Creek basin--Continued.

Date 1955	Elapsed pumping time (days)	Drawdown [1/] (feet)	Water-level decline (-) or rise (+) (feet per day)
May 13	37	4.95	+0.16
14	38	4.79	+.16
15	39	4.65	+.14
(Well 1S/2-15P2 started pumping at about 4:00 a.m., May 16, 1955)			
Well 1S/2-22C2 (well 1S/2-15P2 pumping 210 gpm from 8:00 a.m., April 6 to May 8, 1955)			
April 6 [3/]	0	.57	--
7	1	1.53	-.96
8	2	1.81	-.28
(Well 1S/2-22C2 started pumping 430 gpm at 10:30 a.m., April 8, 1955)			
April 9	3	26.05	-24.24
10	4	28.75	-2.70
11	5	30.20	-1.45
12	6	31.35	-1.15
13	7	32.35	-1.00

Continued

Table 9.- Drawdown in observation wells during aquifer tests in Mill Creek basin--Continued.

Date 1955	Elapsed pumping time (days)	Drawdown 1/ (feet)	Water-level decline (-) or rise (+) (feet per day)
April 14	8	33.20	-0.85
15	9	33.85	-.65
16	10	34.30	-.45
17	11	34.69	-.39
18	12	35.05	-.36
(Well 1S/2-22C2 shut off at 12:30 p.m., April 18, 1955)			
April 19	13	6.67	+28.38
20	14	5.81	+.86
21	15	5.63	+.18
22	16	5.63	0
23	17	5.67	-.04
April 24	18	5.74	-.07
25	19	5.82	-.08
26	20	5.89	-.07
27	21	5.96	-.07
28	22	6.04	-.08
April 29	23	6.13	-.09
30	24	6.20	-.07
May 1	25	6.27	-.07
2	26	6.35	-.08
3	27	6.43	-.08

Continued

Table 9.- Drawdown in observation wells during aquifer tests in Mill Creek basin--Continued.

Date 1955	Elapsed pumping time (days)	Drawdown (feet) 1/	Water-level decline (-) or rise (+) (feet per day)
May 4	28	6.50	-0.07
5	29	6.57	-.07
6	30	6.65	-.08
7	31	6.73	-.08
(Well 1S/2-15P2 shut off at 8:00 a.m., May 8, 1955)			
May 8	32	6.77	--
9	33	6.34	+.43
10	34	5.97	+.37
11	35	5.68	+.29
12	36	5.45	+.23
13	37	5.26	+.19
14	38	5.10	+.16
15	39	4.96	+.14
(Well 1S/2-15P2 started pumping at about 4:00 a.m., May 16, 1955; the following data are based on an extrapolation of the recovery curve at well 22C2 after May 15, 1955)			
May 16	40	4.85	+.11
17	41	4.73	+.12
18	42	4.65	+.08
19	43	4.56	+.09
20	44	4.50	+.06

Continued

Table 9.- Drawdown in observation wells during aquifer tests in Mill Creek basin--Continued.

Date 1955	Elapsed pumping time (days)	Drawdown 1/ (feet)	Water-level decline (-) or rise (+) (feet per day)
May 21	45	4.44	+0.06
22	46	4.40	+.04
23	47	4.35	+.05
24	48	4.31	+.04
25	49	4.26	+.05

1. Drawdown is computed from static water level at 8:00 a.m., March 29, 1955, prior to the tests and is not corrected for regional water-level trend.

2. Static water level was 59.75 feet below top of recorder floor.

3. Static water level was 52.25 feet below top of recorder floor.

In which *T* is the transmissibility of the aquifer in gallons per day per foot, *Q* is the discharge in gallons per minute of the pumped well, r_2 is the distance from the farthest well to the pumped well, r_1 is the distance from the closest well to the pumped well, s'_1 is the drawdown observed in the observation well closest to the pumped well at any time after steady-state conditions are reached, corrected for dewatering of the aquifer, and s'_2 is the drawdown in the observation well at the greater distance from the pumped well at the same time s'_1 was measured, also corrected for dewatering of the aquifer.

Using: Q = 210 gpm; r_1 (to well 22C2) = 409 feet; r_2 (to well 22C1) = 660 feet; s'_1 (at well 1S/2-22C2) = 6.73 feet after 31 days; and s'_2 (at well 1S/2-22C1) = 5.75 feet after 31 days. *T* was computed as follows:

$$T = \frac{527.7 \times 210 \times 0.206}{0.98} = 23{,}000 \text{ gpd per foot}$$

Because of the aquifer boundaries in the area of the tests, which are explained in detail farther on in this report it can be demonstrated that 23,000 is about a quarter of the true transmissibility of the aquifer. Therefore, the transmissibility of the aquifer tested, as determined after pumping well 1S/2-15P2 for 31 days, was 4 x 23,000 or about 92,000 gpd per foot. This agrees closely with the value determined at well 1S/2-22C1 during the 48-hour test.

Determination of Aquifer Boundaries

The assumptions on which the nonequilibrium formula is based must be met or appropriate adjustments must be made. The assumption of infinite areal extent of the aquifer was not valid for the conditions in Mill Creek basin. A negative boundary exists where impervious formations or deposits limit recharge and expansion of the cone of depression. Computations based on the image-well theory are used to adjust the nonequilibrium formula for the effect of boundaries (Ferris, 1955, p. 92). One negative boundary was encountered during the 48-hour test at observation wells 1S/2-22C1 and 15P2.

The negative boundary can be analyzed by the use of a nonequilibrium log graph. As pumping begins in the real well, the water level in an observation well will draw down at an initial rate determined by the influence of the pumped well only. When the cone of depression of the real well reaches the boundary the rate of drawdown will increase and will be doubled (when $\underline{u}$ becomes small), because the water level at the boundary behaves as though it were under the influence of two pumped wells discharging at the same rate. The water level in an observation well will react in a similar way and the drawdown will be doubled (when u becomes small).

The distance from the observation well to the image well can be calculated from the divergence of the field curve from the type curve--the divergence resulting from the effect of the negative boundary. For a given aquifer the time intercepts at equal drawdown very directly as the square of the distance from the pumped well to the observation well and are independent of the rate of pumping. If the distance from the observation well to the pumped well and the time intercepts for both the real and image wells are known, the distance from the observation well to the image well can be calculated by use of the following equation:

$$r_i = r_p \sqrt{\frac{r^2p/tp}{r^2p/ti}} \text{ ---------- } (4)$$

In which r_i is the distance in feet from image well to observation well, r_p is the distance in feet from pumped well to the observation well, t_p is the time in minutes since pumping began for a particular value of s' to be observed before the boundary becomes effective, and t_i is the time in minutes since pumping began when the divergence of the drawdown curve from the type curve, under the influence of the image well, is equal to the values of s' and t_p.

Drawdown $\underline{s}'$, in feet, varies directly with discharge, $\underline{Q}$, and inversely as the coefficient of transmissibility, $\underline{T}$. The rate of change of drawdown is doubled after the image well becomes effective (and $\underline{u}$ becomes small).

By use of equation (4) and data from the test the distance from well 1S/2-22C1 to an image well was computed to be 1,130 feet. Similarly, the distance from well 1S/2-15P2 to an image well was computed to be 940 feet.

Although it was determined that during the 48-hour test a negative image well existed at a distance of 1,130 feet from well 1S/2-22C1 and at a distance of 940 feet from well 15P2, it remains to be determined whether these image wells were at the same location or whether two image wells existed, and to determine the distance to the hydraulic barrier from each observation well. A method for locating a hydraulic boundary in the vicinity of a discharging well was devised by Moulder (1951). A circle is scribed whose center is at the nearby observation well and whose radius, $\underline{r_i}$, is equal to the computed distance from the observation well to the image well. The image well lies somewhere on this circle. Lines are drawn from any convenient point on this circle to the observation well and to the real discharging well. Another circle, whose center is at the midpoint of a line drawn between the observation well and the pumping well, then is scribed so that its circumference passes through the midpoint of the line drawn from the real pumping well to the selected point on the circle on which the image well lies. The hydrologic boundary will be somewhere on this smaller circle. In areas where the geology is not known this method is useful for locating aquifer boundaries providing at least three observation wells are used.

In Mill Creek basin, where the surface and subsurface geology was approximately known, the tests served to delineate more closely the distances from the test sites to the hydrologic boundaries along the north and south sides of the basin. Thus the data from observation well 1S/2-15P2 were used to establish the position of the boundary along the north side and the data from well 22C1 were used to establish the boundary along the south side (pl. 13, lower figure). Also, the approximate

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Plate 13.- Geometry for locating hydrologic boundaries and image wells from aquifer-test data.

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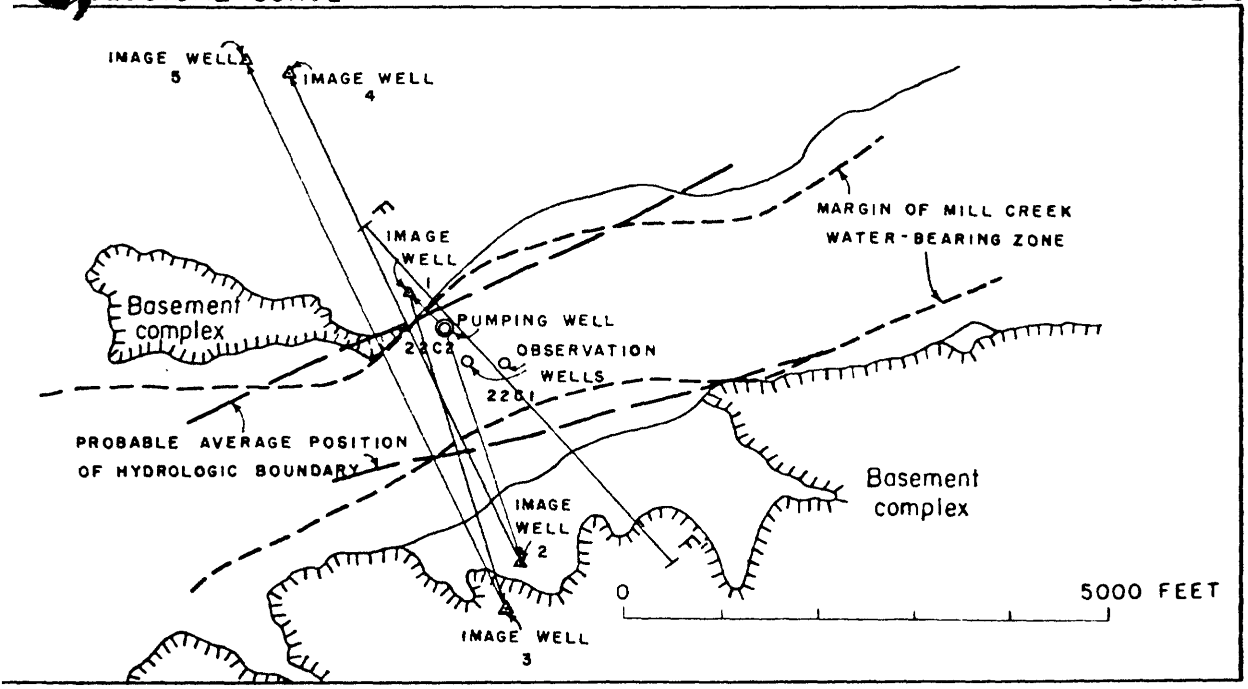
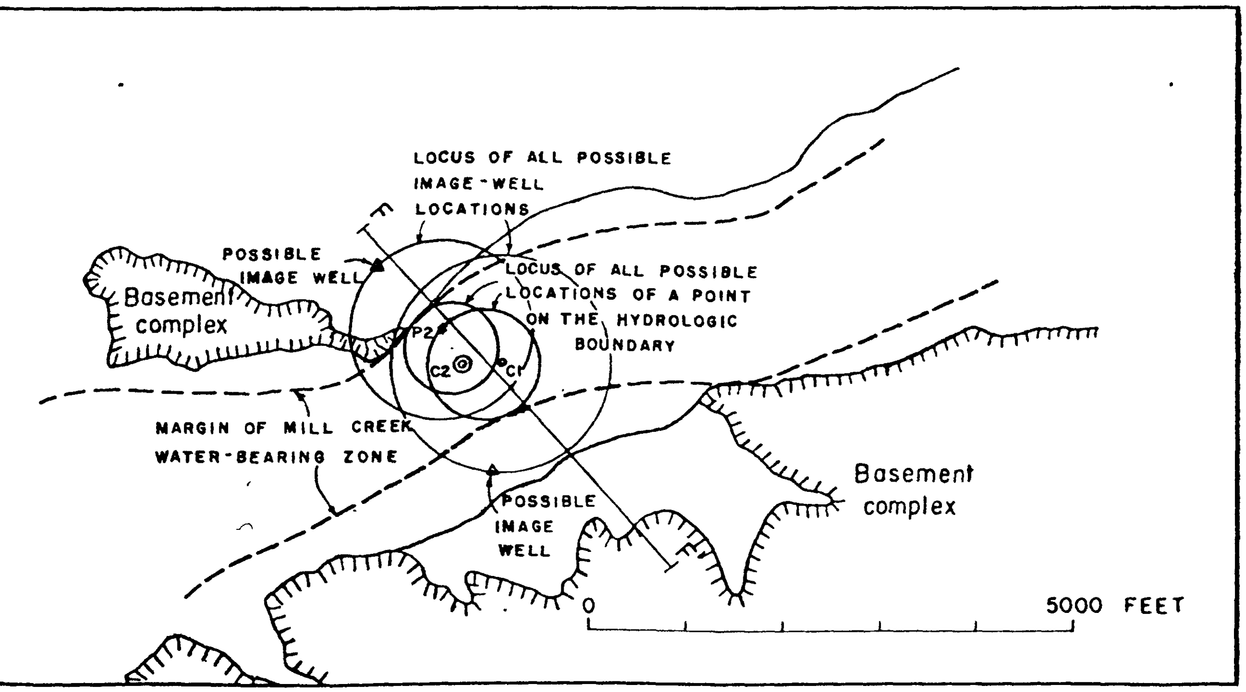
positions of the respective image wells were determined. Thus, the positions of the north and south margins of the saturated younger alluvium, shown on plate 4, section F-F', and the saturated cross-sectional area of younger alluvium were determined from the test results and logs of wells.



Data from 32-day aquifer test; well 1S/2-15P2 pumping



Data from 48-hour aquifer test; well 1S/2-22C2 pumping

GEOMETRY FOR LOCATING HYDROLOGIC BOUNDARIES AND IMAGE WELLS FROM AQUIFER-TEST DATA

In a case where two impervious boundaries exist and strike more or less parallel along the margins of the aquifer, as occurs in Mill Creek basin (pls. 4 and 13), analysis by the image theory requires use of an image-well system extending to infinity. In the case of the 32-day test, when well 1S/2-15P2 was pumped at the rate of 210 gpm, an actual determination of the position of the individual image wells was not possible, because of interference caused by the pumping of well 1S/2-22C2 for a 10-day period shortly after well 1S/2-15P2 began to pump and because the regional water-level trend in the area tested was imperfectly known throughout the 32-day period of the test (table 9). However, by using the data from the 48-hour test and the known geology, the positions of the image wells were postulated. This was done by selecting an average strike for both the northern and southern margins of the channel deposits at about the average position suggested by the 48-hour test (pl. 13) and the geology. Image wells were postulated to exist on the opposite sides of the barriers from the real pumping well, at right angles to the strike of each negati barrier, and at distances from the barriers equal to the distances from the real pumping well to the barriers. Thus, as shown on plate 13, during the 32-day test, image well 1 is the image of the real pumping well north of the aquifer; image well 2 is the image of the real pumping well south of the aquifer; image well 3 is the image of image well 1 reflected at right angles across the south boundary; image well 4 is the image of image well 2 reflected at right angles across the north boundary; and image well 5 is the image of image well 3 reflected at right angles across the north boundary; and so the system would continue to infinity.

Coefficient of Storage

For the period covered by the first (48-hour) test the coefficient of storage at each observation well was derived from the following equation:

$$S = \frac{Tu}{2,693\ r^2/t} \text{ --------------------- } (5)$$

where S is the coefficient of storage, u is derived from the type curve at the match point, 2,693 is a factor (1.87 x 1,440) which must be used to convert time units from days to minutes as plotted on the field curve, r is the distance from the pumped well to the observation well, and t is the time in minutes since pumping began, and T is the coefficient of transmissibility.

The coefficient of storage in the latter part of the test at well 1S/2-22C1 was computed to be:

$$S = \frac{96,000 \times .1}{2,693 \times 1.65 \times 10^2} = 0.022$$

At well 1S/2-15P2 during the later part of the test:

$$S = \frac{125,000 \times .1}{2,693 \times 8.6 \times 10} = 0.054$$

Because different coefficients of storage were obtained at the two observation wells, 0.022 at well 1S/2-22C1 and 0.054 at well 15P2 during the 48-hour test, because a reasonably accurate value is needed to estimate the ground-water storage capacity of the bouldery deposits in Mill Creek basin, and because the values computed from the 48-hour test data are considerably smaller than the values commonly associated with alluvial deposits (Eckis, 1934, pl. E; Poland, 1951), additional analysis of the data was made.

The only available means of checking the determined values was to compute theoretical drawdown curves by using values for the aquifer constants derived from the test data when well 1S/2-15P2 was pumping. Theoretical curves can be drawn that will show the drawdown at any point in the aquifer for any given rate of withdrawal, as affected by existing boundary conditions. It can be seen from the nonequilibrium formulas (Theis, 1935) that $\underline{W(u)}$ depends on $\underline{u}$ only. Drawdown curves for a given rate of withdrawal from the aquifer are readily prepared, therefore, by selecting three convenient values of $\underline{u}$, for example, 1.0, 0.1, and 0.01, and finding the corresponding values of $\underline{W(u)}$ in Wenzel's table (1942, p. 88), which are 0.2194, 1.8229, and 4.0379.

The term $\frac{114.6Q}{T}$ is constant for a given aquifer and given rate of discharge. Three values of s, drawdown in feet, are calculated by using equation (2), the three values of W(u), and a T of 92,000 gpd per foot. The term $\frac{1.87r^2S}{T}$ also is constant for a given aquifer and given distance from the pumped well. Three values of t, time in days, corresponding to the three computed values of s, are calculated by using equation (5), the three selected values of u, the value of r, and an S of 0.05.

$$s = \frac{114.6QW(u)}{T} \quad \text{------------- (6)}$$

and from equation (5)

$$t \text{ days} = \frac{1.87r^2S}{Tu} \quad \text{------------------ (7)}$$

The calculated values of s and t plotted on log-log paper will be on a segment of the type curve (pl. 14).

Plate 14.- Log-log plot showing probable drawdown at well 1S/2-22C2 caused by pumping well 1S/2-15P2.

In addition, s and t coordinates for each probable image-well radius, as mechanically estimated by the method previously discussed, were computed so that five separate segments of the type curve were drawn. The distance r from observation well 1S/2-22C2 to the real pumping well was 409 feet; the distances r_1, r_2, r_3, and r_4, from well 22C2 to the mechanically plotted image wells I_1, I_2, I_3, and I_4, were 900, 2,150, 2,600, and 3,500 feet, respectively (pl. 13, upper sketch). Because the drawdown s, measured at an observation well at any time after pumping starts, is the sum of the individual drawdowns caused by the pumping of each real or image well, the individual drawdown of each image well was added to the drawdown caused by pumping the real well, as shown on plate 14. The resulting curve should duplicate exactly the curve compiled by plotting the individual water-level measurements made in the observation well as pumping progressed. In other words, if the regional trend could be determined accurately during pumping, if well 1S/2-22C2 had not been pumped during the time well 15P2 was pumping, if the coefficients of T and S of the aquifers were 92,000 gpd per foot and 0.05, respectively, and if the image wells were where they are shown on plate 13, the drawdown curve in well 1S/2-22C1 would follow exactly the theoretical curve as constructed.

The reliability of many of the preceding assumptions is imperfectly known, however, and it remains to be determined whether the aquifer constants obtained from the 48-hour and 32-day tests are reasonable. The transmissibility was estimated by use of equation (3) after 31 days of pumping to be 23,000 gallons per day per foot, which multiplied by 4 (the real well and 3 image wells pumping after 31 days), is 92,000 gallons per day per foot. If the transmissibility of the aquifer in the area tested averages 92,000 gallons per day per foot and if the coefficient of storage is 0.05, as the 48-hour test at well 15P2 suggests, the drawdown observed at observation well 22C2 after 31 days would be equal to the sum of the drawdown caused by pumping the real well and three image wells, providing the image wells are at or near the positions postulated on plate 13. This accumulated drawdown was calculated to be 2.70 feet on May 7 at well 1S/2-22C2 after 31 days of pumping from the aquifer (pl. 14).

Plate 14 also shows the extrapolated recovery curve at well 13/2-22C2, after well 15P2 started to pump again on May 16, 1955 (table 9). If the regional water-level trend which was determined prior to starting the tests is projected, the regional static water level on May 7 would be approximately 56.3 feet below the measuring point at well 22C2 after 31 days. This information shows that a drawdown of 2.7 feet, computed by the construction of the theoretical curves (pl. 14, upper diagram), is reasonable and supports the contention that the aquifer constants and boundary conditions are reasonably correct as determined for the 48-hour test.

It can be demonstrated by the construction of theoretical drawdown curves, using a transmissibility of 92,000 gpd per foot and the image distances used, that the real well plus four or more image wells would be influencing the water-level decline at well 22C2 after 31 days, if the coefficient of storage of the aquifer were appreciably less than about 0.05. Also, it can be demonstrated that the postulated positions of the image wells can be moved through a rather broad range, if the positions of the barriers are changed somewhat, before the critical distance between image well 3 and the pumped well would cause either two or four instead of three image wells to be influencing the drawdown at well 22C1 after 31 days. Finally, it can be demonstrated by

construction of theoretical drawdown curves that the pumpin
of one real well and fewer than three image wells would
be influencing the drawdown at wells 1S/2-22C1 and 22C2
after 31 days, if the coefficient of storage of the
aquifer were appreciably greater than 0.05.

It is concluded that on the basis of the above data the coefficient of storage of the younger alluvium in Mill Creek basin is about 0.05 or that the specific yield, which under water-table conditions is approximately equal to the coefficient of storage, is about 5 percent. This value is used elsewhere in this report to compute the ground-water storage capacity of the younger alluvium in Mill Creek basin.

Tests at Other Wells

Aquifer tests were made also at wells 1S/2-21D1, 21E1, 21E2, 20K1, and 30G1 in the Mill Creek area. To derive estimated coefficients of transmissibility at each of the wells, the Theis (1935, p. 522) recovery method was used. This method utilizes the water-level measurements obtained from the pumped well after the pump has been stopped, and the transmissibility is derived from the following formula:

$$T = \frac{264 \times Q \times \log_{10}(t/t')}{s'} \text{------------} (8)$$

Where $\underline{T}$ is the coefficient of transmissibility, in gallons per day per foot; $\underline{Q}$ is the discharge of the pumped well, in gallons per minute; $\underline{t}$ is the time since pumping started, in minutes; $\underline{t}'$ is the time since pumping stopped, in minutes; and $\underline{s}'$ is the residual drawdown of water level corrected for dewatering of the aquifer, in feet.

This method did not always give results consistent with those obtained by use of the nonequilibrium formula, but in general where the two methods could be compared, the coefficient of transmissibility estimated by using the water-level measurements made during the later part of the tests was approximately equivalent to the values determine by the nonequilibrium formula. The transmissibilities of the deposits tested by the recovery method are given in table 10. The wide range in transmissibility obtained fro these tests is related to the range in saturated thickness of the deposits tapped and to the type of deposit tapped, as explained in the next section of the report.

Table 10.- Estimated transmissibility of the younger and the older alluvium based on aquifer tests at five wells in the Mill Creek area, Calif.

Well	Date of test	Time pumped (minutes)	Estimated coefficient of transmissibility (gpd per foot)
1S/2-20K1	March 1, 1955	360	31,000
21D1	December 2	400	18,000
21E1	January 11	300	53,000
21E2	January 12	360	16,000
30G1	November 22	412	29,000

Application of the Test Data

The data obtained from the aquifer tests, described in the preceding paragraphs, pertain only to the materials tested and only to the saturated thickness of the aquifer at the time of the test. However, the area of Mill Creek basin is small and hence the coefficients obtained from the tests probably are applicable throughout the basin.

Because the test data are used elsewhere in this report to compute ground-water underflow, inflow, and outflow at several times when different amounts of younger alluvium and older alluvium (including the older plain and bench deposits) are saturated in the basin, it was necessary to estimate the permeability of the younger and older alluviums in the basin from the test data. The transmissibility divided by the saturated thickness of the water-yielding deposits tested is equal to the average permeability:

$$P = \frac{T}{m} \text{ ---------------------------------- } (9)$$

where P and T are the coefficients of permeability and transmissibility, respectively, and m is the saturated thickness, in feet, of the water-yielding deposits.

The results of all the aquifer tests made in the Mill Creek area are presented in table 11. Because the tests locally were made at wells for which no logs are available, data derived from a study of the log and water-level profiles (pl. 4) were used to determine the saturated thickness of the materials tested.

Table 11.- Estimated coefficients of permeability of the younger and the older alluvium in Mill Creek basin, Calif.

Well	Test method and length of test	Estimated transmissibility (gpd/ft.)	Thickness (feet)		Depth to bedrock (feet)	Depth to water at time of test (feet)	Saturated thickness (feet)		Permeability (gpd/sq. ft.)	
			Qyal 1/	Qoal 2/			Qyal 1/	Qoal 2/	Qyal 1/	Qoal 2/
1S/2-15P2	Theis (48 hours)	125,000	a97	a0	a97	34	63	0	2,000	-
22C1	Theis (48 hours)	96,000	a130	a0	a130	60	70	0	1,400	-
22C1	Theim (31 days)	92,000	a130	a0	a130	60	70	0	1,300	-
22C2	Theim (31 days)	92,000	a130	a0	a130	53	77	0	1,200	-
20K1	Recovery (6 hours)	31,000	c100	c150	c250	82	18	150	d1,400	b40
21D1	Recovery (6+ hours)	18,000	a86	a161	a247	77	9	161	d1,400	b35
21E1	Recovery (5 hours)	53,000	e90	e110	c200	54	36	110	d1,400	b30
21E2	Recovery (6 hours)	16,000	c70	c80	c150	63	7	80	d1,400	b75
30G1	Recovery (7 hours)	29,000	a0	a238	a238	140	0	98	-	f300
						Average, about			1,400	50

1. Qyal is the younger alluvium.
2. Qoal is the older alluvium, including the older plain and bench deposits.
a. Determined from well log.
b. Based on $P_2 = (T - P_1 m_1)/m_2$ in which P_1 is permeability of the younger alluvium, m_1 is the thickness of saturated younger alluvium, P_2 is permeability of the older alluvium, m_2 is the saturated thickness of the older alluvium.
c. Based on depth of the well and probable thickness of younger and older alluviums estimated from cross sections and structure contour map (pls. 3 and 4).

d. Based on approximate permeability of the younger alluvium estimated from the 48-hour and 31-day tests at wells 1S/2-22C1, 22C2, and 15P2.

e. Estimated on the basis of logs for wells 21B1 and 21D1.

f. Well at south side of Mentone basin. Excluded from average.

The data in table 11 show that the average permeability of the older alluvium (including the older plain and bench deposits) in Mill Creek basin is on the order of 50 gpd per square foot and that the average permeability of the younger alluvium in the basin is on the order of 1,400 gpd per square foot.

RECHARCE

The four principal sources of recharge to Mill Creek basin are: Seepage loss from Mill Creek; induced recharge by water spreading; subsurface ground-water inflow, both natural and induced by pumping; and deep penetration of rain which percolates downward to become ground water. There is little irrigation on the lands of Mill Creek basin, and hence the return of excess irrigation water to ground water is negligible. Data necessary to make accurate long-term quantitative estimates of the recharge from each source are lacking or incomplete, but the available data relative to each source of recharge are presented in the following sections of the report. Where possible, crude estimates of recharge, or probable magnitude of recharge, from each source are made.

Seepage Loss from Mill Creek

There are insufficient data to appraise fully the average annual seepage losses from Mill Creek in Mill Creek basin. The runoff at the mouth of Mill Creek Canyon for the period 1948-55 is given in table 3. The runoff for the same period at the gage "Mill Creek near Mentone," which is in Mentone basin (pl. 2), is given in table 6. This is the only period for which records of runoff at both stations are available.

No data are available from which to appraise the average annual surface-water inflow to Mill Creek downstream from the Yucaipa gage at the mouth of Mill Creek Canyon. The surface-water inflow to Mill Creek between the Yucaipa and Mentone gages includes the discharge of Triple Falls Creek, the runoff from a part of the Crafton Hills, and runoff from the valley lands upstream from the Mill Creek gage near Mentone. During the 8-year period 1948-55 the average annual flow at the mouth of the Mill Creek Canyon and at the station near Mentone was 11,900 acre-feet and 5,488 acre-feet, respectively. It is of interest to note that during 5 months of the period 1951-55 the total discharge at the Mentone gage exceeded that at the Craftonville gage. An unknown part of the runoff at the Mentone station was not measured at the upper station. Thus, recharge to ground water by seepage losses from Mill Creek was not less than 6,500 acre-feet, or not less than an average of about 800 acre-feet a year during that period, which includes 7 years of below-average rainfall. Probably nearly all of the recharge occurred in Mill Creek basin. If a large part of the discharge at the Mentone gage during the period was contributed by runoff to the stream downstream from the gage at the mouth of Mill Creek Canyon, the recharge to ground water by seepage losses from Mill Creek might have been as much as 11,000 acre-feet during the 8-year period or an average of nearly 1,400 acre-feet a year during that period. More than half, or at least 3,700 acre-feet, of the seepage loss between the two stations occurred in the year 1952, which had above-average rainfall.

Although records of runoff at the mouth of the canyon are not available for the period 1939-47, the period 1937-45 was one of above-average precipitation (table 1), and runoff during that period also was greater than average. The hydrographs of wells 1S/2-21E1 and 21B1 (pls. 7 and 8) show that the ground water in storage in Mill Creek basin was maintained about at capacity during much of the period. Also, because the deposits were saturated to land surface beneath the stream bed during part of the time, potential recharge was rejected.

Induced Recharge by Water Spreading

During most winter and spring months, the water which passes through power canals 1, 2, and 3 (table 5) is not all used for irrigation and domestic purposes, and part of the water is returned to the stream bed or is placed in large gravel-floored spreading basins to recharge ground water. The approximate annual amount of water spread in this manner is given in table 5. However, not all the water spread in this manner recharges the ground-water body of Mill Creek basin. A small amount evaporates and a large part is spread west of Garnet Street and consequently recharges the ground-water body of Mentone basin.

According to figures supplied by the San Bernardino Valley Water Conservation District, the total amount of water conserved by water-spreading operations since 1921 is about 170,000 acre-feet, or an average of about 5,000 acre-feet a year during the 34-year period (table 6). However, during the dry period 1946-55 recharge from this source ranged from only 50 acre-feet in 1951 to 5,000 acre-feet in 1952 and averaged only 1,600 acre-feet per year.

Subsurface Ground-Water Inflow

The two principal sources of subsurface ground-water inflow to Mill Creek basin are the inflows from Mill Creek Canyon through the younger alluvium and from Triple Falls Creek area between the east end of the Crafton Hills and the San Bernardino Mountains through the older alluvium and possibly the older plain and bench deposits.

The annual amount of ground water moving through saturated deposits can be computed by the following equation:

$$Q = 0.00112\ PIA \quad \text{-----------} \quad (10)$$

in which Q is the underflow, in acre-feet a year; P is the permeability of the deposits, in gpd per square foot; I is the average hydraulic gradient for the year, in feet per mile; A is the saturated cross-sectional area, in square feet, of the deposits through which the ground water moves; and 0.00112 is the factor for converting gallons per day to acre-feet per year.

This basic equation is used not only to estimate the ground-water inflow to the area, as described below, but also to estimate the ground-water outflow at the west end of Mill Creek basin.

Inflow from Mill Creek Canyon Area

The boundary between Mill Creek basin and the Mill Creek Canyon area is near the mouth of the canyon about at the Mill Creek barrier. Because of insufficient data at that place, inflow moving through the younger alluvium was estimated at cross section G-G' (pl. 4). This is nearly a mile upstream at a place where the deposits have been saturated to land surface since historic time and therefore the underflow has remained about constant. Rising water in the cienaga or swamp at section C-G' (pl. 4), which reportedly amounts to nearly 500 acre-feet in some wet years, is diverted for power.

Upstream from section G-G', the average saturated thickness of the deposits at well 1S/1-7L1 during the period 1936-55 was about 70 feet, based on water levels and the log of that well, and the average width, assuming a narrow U-shaped cross section (pl. 4, sec. G-G'), was about 250 feet. The saturated cross-sectional area, therefore, was on the order of 17,000 square feet. The hydraulic gradient was essentially the same as the creek channel, or about 270 feet per mile. The permeability of the younger alluvium probably is about the same as that in Mill Creek basin, which was estimated to be about 1,400 gpd per square foot (table 11). Thus, the annual underflow at section G-G' can be estimated by equation (10):

$$Q \doteq 0.00112 \times 1{,}400 \times \frac{270}{5{,}280} \times 17{,}000 \doteq \text{roughly 1,300 acre-feet per year}$$

Most of the rising water is diverted for use downstream and very little returns to the ground-water body. In addition, a thick growth of phreatophytes just upstream from section G-G' transpires ground water. Thus, the inflow to Mill Creek basin is less than the estimated underflow of roughly 1,300 acre-feet per year at the line of section, and is estimated to be on the order of 1,000 acre-feet a year.

Inflow from Triple Falls Creek Area

The water-level contour map (pl. 5) shows that ground water moves into Mill Creek basin from the Triple Falls Creek area between the Crafton Hills and San Bernardino Mountains. In 1955 the gradient was about 300 feet per mile. Owing to the lack of observation wells in the Triple Falls Creek area the permeability of the older alluvium was not determined; but based on the yield characteristics of well 1S/2-24C1, the permeability probably is low and may be about equal to the older alluvium in Mill Creek basin, which was estimated to be about 50 gpd per square foot. During 1955 there was a minimum of 250 feet of saturated older alluvium at well 1S/2-24C1, and the saturated thickness may have been about the same to the north. The width between the south margin of the younger alluvium and the Oak Glen fault, measured north-south through wells 1S/2-13P1 and 24C1, was about 3,000 feet. The saturated cross-sectional area, therefore, may have been roughly 750,000 square feet. Thus, in 1955 the inflow can be estimated by equation (10):

$$Q \doteq 0.00112 \times 50 \times \frac{300}{5,280} \times 750,000 \doteq \text{roughly } 2,000 \text{ acre-feet}$$

The fragmentary water-level records for wells in the Triple Falls Creek area show that there has been only a moderate range in fluctuations, and, therefore, the changes in hydraulic gradient and saturated cross-sectional area also have been only moderate. Accordingly, the crude estimate of subsurface ground-water inflow to Mill Creek basin of 2,000 acre-feet in 1955 probably is ~~magnitude of~~ on the order of the long-term average annual inflow to the basin from that source.

Inflow from the deposits beneath the minor tributary streams on the north flank of the Crafton Hills and on the south flank of the San Bernardino Mountains adjacent to Mill Creek basin probably is very small. The amount supplied is within the limits of error involved in estimates of larger inflow to Mill Creek basin from the Mill Creek Canyon and Triple Falls Creek area, and, therefore, no separate estimate of this increment was attempted in this study.

Finally, during the irrigation season when wells and the water tunnel near Brown Butte are used, inflow to the basin from the Greenspot area may be induced. The amount of recharge to the basin from this source may be small but cannot be determined because of the paucity of wells in the area and because there are few records of water-levels.

Recharge from Precipitation

During years of average or above-average precipitation in Mill Creek basin, some contribution to ground water results from rainfall on the valley floor. According to figures supplied by the U. S. Soil Conservation Service (Muckel and Aronovici, 1952, table 36), the average annual deep penetration of rain during the 21-year period 1928-48 was about 0.25 acre-foot per acre per year in Lytle Basin (Eckis, 1934, pl. C), and was about 0.23 acre-foot per acre per year in the southeast part of Bunker Hill Basin. Because the rainfall, vegetation, alluvial materials, and surface slope in Mill Creek and Lytle Basins are very similar, the long-term average deep penetration of rain probably is about the same in both basins.

The surface area of Mill Creek basin is about 900 acres. Thus, during the period 1928-48, the deep penetration of rain in Mill Creek basin probably supplied an average annual recharge on the order of 200 acre-feet. However, in years of below-average rainfall, such as 1948-51 (table 1), and since 1952 the recharge from this source probably was negligible.

Total Recharge

The total recharge to Mill Creek basin for any selected period is the sum of the recharge by seepage loss from streams, water-spreading operations, subsurface ground-water inflow from Mill Creek Canyon, Triple Falls Creek area, and all other sources, and deep penetration of rain for that period. Owing to lack of records of runoff for the gage, Mill Creek near Yucaipa, for the period 1939-47 and owing to the difficulty of distinguishing between the water spread in Mill Creek basin from that in Mentone basin, an estimate of total recharge can be made only for the years since 1947. Crude estimates of total recharge to Mill Creek basin for the periods 1948-51 and 1948-55 are given in table 12. The values are believed to be conservative because several known sources of recharge are not included. Well data or stream gages are lacking at critical sites and recharge in these areas could not be estimated.

Table 12.- Crude estimates of total recharge to Mill Creek basin, 1948-51 and 1948-55

Period of record	Source of recharge	Estimated recharge (acre-feet)
1948-51	Seepage losses along Mill Creek in Mill Creek basin	
	Discharge of Mill Creek at the mouth of Mill Creek Canyon (table 3)--------------	1,080
	Inflow to Mill Creek from Triple Falls Creek and all other sources downstream from the mouth of Mill Creek Canyon------	(?)
	Discharge of Mill Creek near Mentone (table 6)-------------------------------	62
	Subtotal	1,000+
	Deep penetration of rain-----------------------	0
	Recharge from spreading basins (table 5)--------	a500
	Subsurface ground-water inflow	
	From the Mill Creek Canyon area------------	4,000
	From the Triple Falls Creek area-----------	8,000
	From the Greenspot area during the irrigation season-----------------------	(?)
	Total	14,000±

Continued

Table 12.- Crude estimates of total recharge to Mill Creek basin, 1948-51 and 1948-55--Continued.

Period of record	Source of recharge	Estimated recharge (acre-feet)
1948-55	Seepage losses along Mill Creek in Mill Creek basin	
	Discharge of Mill Creek at the mouth of Mill Creek Canyon (table 3)------------------	11,900
	Inflow to Mill Creek from Triple Falls Creek and all other sources downstream from the mouth of Mill Creek Canyon-------------	(?)
	Discharge of Mill Creek near Mentone (table 6)-----------------------------	-5,500
	Subtotal	6,500+
	Deep penetration of rainfall-------------------	1,000
	Recharge from spreading basins-----------------	a6,000+
	Subsurface ground-water inflow	
	From the Mill Creek Canyon area-----------	8,000
	From the Triple Falls Creek area----------	16,000
	From the Greenspot area-------------------	(?)
	Total	38,000±

a. Based on the belief that about 50 percent of the total quantity was spread in Mill Creek basin; crude estimates supplied by the San Bernardino Valley Water Conservation District.

For the 4 exceptionally dry years 1948-51 total seepage loss amounted to not less than 1,000 acre-feet (tables 3 and 6); spreading operations in Mill Creek basin may have amounted to half of the total, or crudely 500 acre-feet (table 5); subsurface inflow, roughly 12,000 acre-feet; and deep penetration of rainfall, virtually zero. Thus, total recharge for the period was on the order of 14,000 acre-feet, or 3,500 acre-feet per year. For the 8-year period (1948-55) of below-average recharge, which contained 1 wet year (1952), the total accountable recharge to Mill Creek basin may have been on the order of 35,000 to 40,000 acre-feet or 4,500 to 5,000 acre-feet per year, of which possibly a third was supplied in 1952.

DISCHARGE

Types of Discharge, Past and Present

The two types of ground-water discharge from Mill Creek basin are natural discharge and artificial discharge. The natural discharge includes subsurface ground-water outflow to Mentone basin, during very wet years a very small amount of transpiration by plants and trees, and a small amount of effluent ground water, which rises in the channel of Mill Creek just upstream from the Crafton fault during the infrequent periods when the deposits are saturated to land surface and flows across the trace of the Crafton fault to Mentone basin. The artificial discharge includes pumping from wells and gravity flow of water from one water tunnel near well 1S/2-22C1 when the deposits are saturated nearly to land surface.

Before man began to divert the natural flow of Mill Creek and pump water from wells the discharge from Mill Creek basin was entirely by natural means. Originally the natural discharge included subsurface outflow to Mentone basin and probably to the Greenspot area, transpiration by plants which grew in two cienaga (swampy) areas (pl. 4), and rising water in the channels of Mill Creek in the cienagas.

Mendenhall (1905) describes an area of natural rising water in Mill Creek basin, the downstream limit of which was about at the present location of well 1S/2-15P2. Finkle (1923) briefly describes an irrigation ditch, the headgate of which was about at the downstream extent of the reach of the rising water described by Mendenhall (1905). The ditch was constructed to collect the natural rising water and to divert the supply for irrigation and reportedly supplied about 540 gallons per minute for that purpose. Finkle believed that the area of rising ground water existed at the cienaga because of the presence of a fault barrier which extended across Mill Creek just downstream from wells 1S/2-15P2 and 1S/2-22C1. Geologic data and data from the aquifer tests at wells 1S/2-22C1 and 22C2, however, indicate that the area of rising water probably was related directly to the restricted cross-sectional area of the younger alluvium in that area. No evidence for the existence of a barrier at the downstream edge of the cienaga was discovered. Wells 1S/2-22C1, 22C2, and 15P2 and the water tunnel, which extends from the city of Redlands water-filtration plant to well 1S/2-22C2, were constructed along the former reach of the rising water.

Long-time residents of the area report that for a short reach upstream from the Crafton fault water formerly rose in Mill Creek, and the zanja (water ditch) also collected a small amount of effluent ground water from the adjacent swampy area where phreatophytes grew abundantly. Owing to the dry years and depletion of storage since 1945, to the diversions of surface water from Mill Creek, and to the withdrawals of water from wells and the tunnel, neither of the cienagas are now in evidence and no water is derived from them.

Pumpage

In Mill Creek basin the pumping of water for irrigation began about 1879. Mendenhall (1905, pl. 12) shows the locations of three irrigation wells in the basin which were dry prior to 1900. By 1920 several small-capacity wells had been drilled, but the greatest development took place in 1923 when the East Lugonia Mutual Water Co. extended a water tunnel from the central part of the basin to a terminus in the stream channel opposite the east end of Brown Butte. The original tunnel had been constructed by the Mentone Irrigation Co., which was organized in 1887. Three wells also were dug and drilled; two were drilled through the tunnel near its eastern end (1S/2-22C1 and 22C2) and another was drilled downstream (1S/2-21B1). In 1924 the East Highlands Orange Co. also drilled well 1S/2-15-1, now destroyed, near well 1S/2-15P2. By about 1930 several additional small-capacity wells, used mainly for domestic purposes, also had been dug or drilled in the basin, but since that time further development of the basin has not occurred. The water produced in Mill Creek basin by the East Lugonia Mutual Water Co. was used by the stockholders mainly for irrigation of citrus, and some surplus water was sold to the city of Redlands.

In 1941 the city of Redlands acquired the property in Mill Creek basin belonging to the East Lugonia Mutual Water Co., and the city has operated the wells and the tunnel in the basin since that time, acquiring final ownership in 1951. The water right associated with the land in Mill Creek basin is subject to a 121 miners-inch prior-right commitment (nearly 1,100 gpm) which was acquired originally by the Mentone Irrigation Co., and of which a 60-inch right (540 gpm) is owned in the Greenspot area, and a 61-inch right (550 gpm) is owned in the Mentone area. During dry years the total supply yielded from the wells and the tunnel has been less than the 121-inch prior-right commitment.

Table 13 shows the metered pumpage from wells and the tunnel in Mill Creek basin for the period 1941-55. In addition to the metered pumpage, well 1S/2-15P2 was pumped annually for irrigation, wells 1S/2-21L1 and 22E1 were pumped intermittently for domestic supply during the period 1941-55, and wells 1S/2-21E1, 21E2, and 21M1 were pumped intermittently during the period 1941-49. This unmetered pumpage from the basin was estimated on the basis of the discharge of the individual pumps and the approximate period each well was pumped. The estimated total draft from the basin is the sum of the metered pumpage and the estimated unmetered pumpage. The estimated total pumpage during the period 1941-55 is given in table 13.

Table 13.- Draft from wells and the water tunnel in Mill Creek basin, 1941-55

(Metered draft compiled from data supplied by the city of Redlands)

Water year ending September 30	Metered draft (acre-feet)						Estimated unmetered pumpage[1] (acre-feet)	Estimated total draft (acre-feet)
	Tunnel	21B1	21E1	21E2	21M1	Subtotal		
1941	2,540	6				2,545	600	3,145
42	2,630	195				2,825	600	3,425
43	2,280	165				2,445	600	3,045
44	3,200	270				3,470	600	4,070
45	2,820	310				3,130	600	3,730
1946	1,710	380				2,090	600	2,690
47	620	310				930	600	1,530
48	100	315				415	600	1,015
49	0	310				310	500	810
50	40	250	150	3	160	600	350	950
1951	0	80	75	0	165	320	350	670
52	15	200	75	31	70	390	400	790
53	70	370	110	30	120	700	450	1,150
54	0	380	175	100	130	785	450	1,235
55	0	270	115	66	130	580	450	1,030
Total for the 15-year period, 1941-55, about								29,000
Average about								2,000
Total for the 6-year period, 1946-51, about								7,600
Average about								1,300

1. Includes estimated pumpage from wells 1S/2-15P2, 21L1, 22E1, and small domestic wells for the period 1941-55; and from wells 1S/2-21E1, 21E2, and 21M1 for the period 1941-49.

Subsurface Ground-Water Outflow

The principal area where subsurface (ground-water) outflow from Mill Creek basin occurs is across the Crafton fault at the western end of the basin. Possibly a minor amount occurs along the north side of the basin between the Oak Glen fault and the Mill Creek barrier.

Outflow to Mentone Basin

Essentially all the subsurface ground-water outflow from Mill Creek basin occurs at the plane of the Crafton fault, the common boundary between Mill Creek and Mentone basins. The fault has cut and to a minor extent displaced the older alluvium and older plain and bench deposits (pl. 4). The younger alluvium has not been disturbed appreciably by movement along the fault. The outflow across the fault was estimated from data obtained a short distance upstream from the Crafton fault. The data include the coefficient of permeability of the younger and older alluviums and the average annual hydraulic gradient. Values for these three elements were applied at cross section E-E' (pl. 4) to estimate the annual underflow at the line of section, which is a measure of the outflow across the fault, during the period 1936-55.

Average annual hydraulic gradients.--To determine the average yearly gradient at section E-E' (pl. 4) it was necessary to determine the average yearly altitude of water levels in wells and to compute the gradients from these data. The average altitudes were computed from monthly water-level measurements for all wells upstream from the Crafton fault for which records were available; these included wells 1S/2-15P2, 21B1, 21E1, 21E2, 21H2, 21L1, and 22E1. For a few wells, when monthly data were lacking, the altitudes were estimated from the hydrographs, such as those on plates 7 and 8. Water-level contours were drawn, using the computed average annual water-level altitudes in the wells, and the hydraulic gradients were estimated at section E-E' (pl. 4) for each year of the period 1936-55; these are shown in table 14.

Table 14.- Estimated annual subsurface ground-water outflow from Mill Creek basin, 1936-55

Water year ending Sept. 30	Average water-level altitude at section E-E' (feet above sea level)	Average hydraulic gradient (feet/mile)	Saturated cross sectional area (1,000 sq. ft.)		Estimated annual outflow (acre-feet)
			Qyal[1]	Qoal[2]	
1936	2,050	210	75	190	5,100
37	2,070	200	115	210	a7,200
38	2,070	200	115	210	a7,200
39	2,070	200	115	210	a7,200
40	2,065	200	105	200	a6,700
1941	2,070	195	115	210	a7,000
42	2,070	200	115	210	a7,200
43	2,065	195	105	200	a6,500
44	2,070	200	115	210	a7,200
45	2,075	185	125	210	a7,300
1946	2,065	190	105	200	a6,300
47	2,065	190	105	200	a6,300
48	2,050	195	75	190	4,700
49	2,045	195	65	190	4,100
50	2,040	195	55	180	3,600
1951	2,035	195	50	180	3,300
52	2,050	185	75	190	4,500
53	2,050	b195	75	190	4,700
54	2,050	b195	75	190	4,700
55	2,050	b195	75	190	4,700
Total for the 20-year period 1936-55, rounded					115,000
Average for the 20-year period 1936-55, about					5,700

1. Younger alluvium.
2. Older alluvium including the older plain and bench deposits.
a. Includes a small amount of rising ground water that crosses the trace of the Crafton fault as surface flow.
b. Estimated from incomplete water-level records.

Saturated cross-sectional areas of the younger and older alluviums.--The cross-sectional areas of the younger and older alluviums and older plain and bench deposits through which the subsurface flow occurs are shown on section E-E' (pl. 4). To determine the average yearly saturated cross-sectional areas of the younger and older alluviums for the period 1936-55, the contours drawn to compute the average yearly hydraulic gradients were used. The saturated cross-sectional areas for the younger and older alluviums for each year are shown in table 14.

Estimated subsurface ground-water outflow.--To compute the quantity of underflow moving through Mill Creek basin at section E-E', use was made of a modification of equation (10) as follows:

$$Q = 0.00112 \times (P_1 I A_1) + (P_2 I A_2)$$

in which $\underline{Q}$ is the underflow, in acre-feet a year; 0.00112 is the factor for converting gallons a day to acre-feet per year, $\underline{P_1}$ is the estimated permeability of the younger alluvium and $\underline{P_2}$ is the estimated permeability of the older alluvium, in gallons per day per square foot (table 11), $\underline{I}$ is the average yearly hydraulic gradient, in feet per mile, and is assumed to be the same in the younger and older alluviums; and $\underline{A_1}$ is the saturated cross-sectional area of the younger alluvium and $\underline{A_2}$ is that for the older alluvium, in square feet (table 14).

Thus, the above equation is used to estimate the underflow past section E-E' (pl. 5). For example, during 1936 the estimated underflow at section E-E' was:

$$Q = (0.00112 \times 1{,}400 \times \frac{210}{5{,}280} \times 75{,}000) + (0.00112 \times 50 \times \frac{210}{5{,}280} \times 190{,}000)$$

$$Q = 4{,}700 + 400 = \text{about } 5{,}100 \text{ acre-feet}$$

The estimated subsurface outflow from Mill Creek basin for the period 1936-55 is tabulated in table 14, which shows that the estimated subsurface outflow has ranged from 3,300 acre-feet in 1951 to 7,300 acre-feet in 1945, and averaged about 5,700 acre-feet a year for the 20-year period 1936-55.

Outflow to the Greenspot Area

The water-level contours for March 1955 (pl. 5) show that between the Mill Creek barrier and the Oak Glen fault little or no flow occurred into the Greenspot area. It is believed that ground water in the Greenspot area is derived almost wholly from the mountain area bordering Mill Creek on the north and that only a minor amount of outflow to the area occurs from Mill Creek basin. During the irrigation season, however, when wells 1S/2-15P2, 22C1, and 22C2 are pumped, or when the water tunnel is used, it appears probable that gradients may be recovered and some inflow to Mill Creek basin from the Greenspot area may be induced.

Total Discharge

The total discharge from Mill Creek basin for any selected period is the sum of the discharge by pumping, extractions from the water tunnel, subsurface groundwater outflow to Mentone basin for that period, and during wet years a very small amount of evapotranspiration which is not figured. Estimates of these forms of discharge have been presented in tables 13 and 14; these data are summarized in table 15.

Table 15.- Estimated total discharge from Mill Creek basin, 1941-55

Water year ending September 30	Total discharge[1] (acre-feet)	Water year ending September 30	Total discharge[1] (acre-feet)
1941	10,000	1949	4,900
1942	10,500	1950	4,500
1943	9,500	1951	4,000
1944	11,000	1952	5,300
1945	11,000	1953	5,800
1946	9,000	1954	5,900
1947	7,800	1955	5,700
1948	5,700		
		Total, about	110,000
		Period 1948-55, about	42,000

1. Rounded.

Table 15 shows that the estimated total discharge ranged from nearly 11,000 acre-feet in 1944 and 1945 to only 4,000 acre-feet in 1951. In general, discharge decreased steadily during years 1946 to 1951 and increased thereafter principally as a result of the wet year in 1952 and increased use of the spreading basin in 1S/2-20B after 1951. In the 4-year period 1948-51 and the 8-year period 1948-55, for which crude estimates of total recharge were made (table 12), the estimated total discharges were about 19,000 and 42,000 acre-feet, respectively.

GROUND-WATER STORAGE CAPACITY

Ground-water storage capacity may be defined as the reservoir space in a given volume of deposits. According to Poland and others (1951), to be usable the reservoir must be economically capable of being dewatered during periods of deficient surface supply and capable of being resaturated, either naturally or artificially, during periods of excess surface supply. It must contain usable water, which may be defined as that having a satisfactory quality for irrigation and domestic uses and occurring in sufficient quantity in the underground reservoir to be available without uneconomic yield or drawdown.

In Mill Creek basin, where pumping occurs almost entirely during the season when surface flow in Mill Creek is nearly or wholly lacking, the amount of water available for use at the beginning of any pumping season is dependent entirely upon the amount of water which the deposits will yield by gravity when the water levels are depressed by pumping. Accordingly, in Mill Creek basin the ground-water storage capacity within natural or selected depth zones is critical with regard to the recoverable water supply of the basin.

The storage capacity of a basin is estimated by multiplying the volume of the aquifer or the depth zone selected by the specific yield of the water-bearing material. The ground water in storage at any selected time is estimated by multiplying the volume of saturated water-bearing material by the specific yield.

Storage Units and Depth Zones

In order to estimate the amount of ground water in storage at selected times Mill Creek basin is arbitrarily divided into two storage units. Unit 1 extends from the Crafton fault barrier to the Oak Glen fault and has an area of about 470 acres. Unit 2 extends from the Oak Glen fault to the Mill Creek barrier and has an area of about 320 acres.

The depth zone for storage unit 1 is considered to extend from the surface of Mill Creek channel down to the base of the younger alluvium or, where present, to the base of the older alluvium. The depth zone for storage unit 2 is considered to extend from the surface of Mill Creek channel downward to an altitude of 2,220 feet above sea level, which is the approximate altitude of the bedrock lip on the downstream side of the Oak Glen fault that effectively prevents drainage of water to storage unit 1 from below that depth (pl. 4).

Specific-Yield Values

The specific yield of the younger alluvium in Mill Creek basin was estimated from the aquifer tests already described to be about 5 percent. Although a specific yield of only 5 percent for unconsolidated unconfined alluvial deposits of Recent age is very low, it is believed to be in the correct order of magnitude because the younger alluvium is composed of poorly sorted boulders, gravel, sand and silt. Boulders, many up to 3 feet or more in diameter, constitute a large percentage of the total. A specific yield of 5 percent, therefore, is used for calculating the storage capacity of the younger alluvium.

The aquifer tests provided no data on the specific yield of the older alluvium and the older plain and bench deposits. Although somewhat better sorted, these materials are similar in texture to the younger alluvium. However, they are cemented locally, and the interstitial spaces, where observed in exposures, commonly are nearly filled with clayey materials formed by the decomposition of the feldspars. Eckis (1934, pl. E) indicated that the specific yield of these older alluvial deposits ranged between 4 and 8 percent in Mill Creek basin. Based on his data, on the results obtained for the younger alluvium, on the character of the deposits examined in the field, and on logs of wells, a specific yield of 5 percent is assigned also to the older alluvial deposits.

Estimated Gross Storage Capacity

The estimated gross ground-water storage capacity of the Mill Creek basin was computed by multiplying the area of the basin, in acres, by the average weighted thickness of the deposits (channel surface to base), in feet, by the specific yield. Table 16 shows the estimated storage capacities for storage units 1 and 2.

[illegible]6.--Estimated gross ground-water storage capacity of storage units 1 and 2 and ground water in storage, December 1951 and March 1955

	Area (acres)	Weighted average thickness (feet)	Total volume (acre-feet)	Specific yield (percent)	Storage capacity and ground water in storage (acre-feet)
Gross storage capacity:					
Unit 1	470	150	70,000	5	3,500
2	320	280	90,000	5	4,500
Total	790	-	160,000	-	8,000
Ground water in storage:					
December 1951					
Unit 1	470	95	45,000	5	2,200
2	320	90	29,000	5	1,400
Total	790	-	74,000	-	3,600
Ground water in storage:					
March 1955					
Unit 1	470	110	52,000	5	2,600
2	320	115	37,000	5	1,800
Total	790	-	89,000	-	4,400

Table 16 shows also the estimated ground water in storage in December 1951, the lowest of record, and in March 1955. The quantity of water in storage at these times was derived in a similar manner, except that the average specific yield (5 percent) was multiplied by the approximate volume of saturated deposits.

Table 16 shows that the estimated storage capacity of the basin is on the order of 8,000 acre-feet. It also shows that the estimated ground water in storage in Mill Creek basin in December 1951 and March 1955 was on the order of 3,600 and 4,400 acre-feet, or about 45 and 55 percent of the gross storage capacity, respectively. Of the gross ground-water storage capacity only a part is usable. The relation of gross storage capacity to the usable storage capacity is discussed in the following pages.

Usable Storage Capacity

The usable ground-water storage capacity of a basin containing water of usable quality, may be defined as that part of the gross capacity that can be depleted during periods of deficient surface supply and that can be replenished during periods of excess surface supply. In Mill Creek basin, there is an ample surface supply during wet periods, to replenish the gross storage capacity. However, the runoff is flashy, and additional spreading basins are needed to conserve the supply for recharge. To recharge the basin most effectively spreading basins should be added to the central and eastern parts of the basin upstream from the principal area of pumping.

On the other hand, during dry periods the recharge is relatively small, a total of about 14,000 acre-feet during the 4-year period 1948-51 (table 12). Therefore the magnitude of the usable storage capacity is limited to the supply that can be withdrawn economically by wells or other structures, such as collection galleries and water tunnels. If wells were properly spaced a large part of the storage in the basin could be pumped. However, the number of wells necessary to accomplish the dewatering would be great and the yields from individual wells would be small during the dewatering of the deepest part of the deposits.

Because a water-level gradient is required before ground water will flow toward a pumping well from the surrounding area, the entire aquifer in storage unit 1 cannot be dewatered by pumping from wells; the practical limit to which the aquifer can be dewatered is not known. The limit would be based on the spacing and depth of existing or planned wells and the economic consideration that high costs of pumping water would limit the withdrawal of water from storage when a substantial part of the aquifer was dewatered because the yields from individual wells would progressively decline. A large collection gallery or water tunnel across the channel at the base of the younger alluvium in the downstream part of the basin would increase the usable storage capacity of the basin. During a period of storage depletion the yield of such a structure would decline less than would the yield from wells.

Storage unit 1 contains all the wells in Mill Creek basin and is the logical area in which to construct a collection gallery. Existing wells derive most of their supply from the younger alluvium and therefore, if the younger alluvium were completely dewatered, some of the wells would be dry and others that tap only the older alluvium in the down-stream part of the basin would have very small yields. Thus, the present usable storage capacity of this unit is considerably less than the gross capacity. In 1951 the levels in unit 1 reached a record low, and the yields of some wells were so small that the economic limit for their operation was almost reached. Accordingly, the usable storage capacity is considered to be only slightly more than the total volume of water depleted in December 1951. The maximum average depth to which the deposits could be dewatered economically is considered to be about 80 feet below the creek channel, or an average of about 25 feet above the base of the younger alluvium (pl. 4). The estimated usable storage capacity of storage unit 1 is shown in table 17.

Table 17.--Estimated usable ground-water storage capacity of storage units 1 and 2, and usable ground water in storage in December 1951 and March 1955

	Area (acres)	Weighted average thickness (feet)	Total volume (acre-feet)	Specific yield (percent)	Usable storage capacity and usable ground water in storage (acre-feet)
Usable storage capacity					
Unit 1	470	80	38,000	5	1,900
2	320	280	90,000	5	4,500
Total	790	-	128,000	-	6,400
Usable ground water in storage					
December 1951					
Unit 1	470	25	12,000	5	600
2	320	90	29,000	5	1,400
Total	790	-	41,000	-	2,000
Usable ground water in storage					
March 1955					
Unit 1	470	40	19,000	5	1,000
2	320	115	37,000	5	1,800
Total	790	-	56,000	-	2,800

With regard to the usable storage capacity of storage unit 2, in which there is no pumping, ground water contained in the deposits drains downgradient to storage unit 1 across the consolidated rock lip at the Oak Glen fault. If it is assumed that during a wet period the deposits in unit 2 can be saturated fully by use of additional spreading basins, then essentially all the ground water in unit 2 above an altitude of 2,220 feet (pl. 4) can be considered usable in that the contained water will drain downstream to storage unit 1 where a large part of it can be withdrawn by wells or collection galleries. If wells can be developed successfully in unit 2, the usable storage capacity would be increased somewhat by lowering the levels below the altitude of the consolidated rock lip. Thus, the usable storage capacity of storage unit 2 is considered to be equal to the estimated gross storage capacity of 4,500 acre-feet (tables 16 and 17).

The estimated usable storage capacities of units 1 and 2, therefore, were computed in a manner similar to that for estimating the gross storage capacity. Table 17 shows that the total estimated usable storage capacity of Mill Creek basin is about 6,400 acre-feet. The usable ground water remaining in storage in December 1951 and March 1955 was computed using the volume of saturated materials remaining in the usable reservoir space. The usable storage remaining in unit 1 plus that in unit 2 was estimated to be 2,000 acre-feet in December 1951 and 2,800 acre-feet in March 1955. By this method, the amount of usable storage remaining in the basin could be calculated for any period when sufficient water-level data are available. Based on experiments and (or) other methods of determination, it might be possible to refine the selected depth zones used to compute usable storage. Changing economic conditions and other factors also might cause a part of the gross ground-water storage capacity in unit 1, which herein is not considered usable, to become available for withdrawals from wells or other structures at some future date, and that part of the gross capacity, therefore, would be in addition to the usable storage capacity of the basin shown in table 17.

Accuracy of the Estimates

It has been shown that total recharge and total discharge have been derived by estimating, computing, or measuring the various elements that make up the totals for the water years 1947-48 through 1954-55--the longest period for which all elements can be estimated. A comparison of the two totals with the estimated change in storage for the period provides a method of checking the accuracy of the estimates. For the 8-year period the total recharge was crudely 38,000 acre-feet (table 12) and total discharge was about 42,000 (table 15), indicating a net depletion of roughly 4,000 acre-feet for the period.

The net change in storage from October 1, 1947, to October 1, 1955, is the difference between the water remaining in storage at those times. The estimated amount of water in storage in October 1947 is 5,200 acre-feet; and in October 1955, 3,600 acre-feet. The difference between the two is a net depletion of about 1,600 acre-feet, which is 2,400 acre-feet less than the depletion estimated by use of the crude estimates of recharge and the estimates of discharge.

Relation of Storage Capacity to Recharge and Discharge

The estimated usable storage capacity of 6,400 acre-feet in Mill Creek basin is small compared to recharge and discharge in most wet years. For example, in 1952 the total recharge was crudely 8,000 acre-feet and the total discharge was about 5,000 acre-feet (table 15). As a result of the large recharge, the storage was replenished to near capacity in that year. On the other hand, during a period of drought when recharge is small, natural discharge plus draft cause a relatively rapid depletion of the usable ground water in storage. In the critical 6-year dry period 1946-51 the usable ground water in storage was depleted from about 4,000 acre-feet in March 1945 to only about 2,000 acre-feet of usable water remaining in December 1951 (table 17). It is apparent, therefore, that conservation of surface supplies would be necessary to increase the recharge to the basin.

Because the existing wells are in the western part of the basin and because the natural downstream drainage of ground water through the basin is rapid, it would be desirable to recharge most of the water in the east (upgradient) part of the basin in storage unit 2. Additional recharge there could be accomplished by spreading additional water during periods of runoff, if suitable spreading areas and (or) basins were constructed. As was mentioned previously, water recharged in the eastern part of the basin would flow downgradient to the area of pumping where it could be recovered during the dry months at wells in the western part of the basin. Because of the rapid depletion of storage in the younger alluvium of storage unit 2 by the process of natural downstream drainage of ground water, it might not be possible to utilize effectively supply wells in that area. Thus, storage unit 1 is the most logical area to consider for any additional supply.

CONSIDERATION OF THE YIELD

Short-Term Yield

The perennial yield of a ground-water basin may be defined as the rate at which ground water can be withdrawn year after year without depleting the ground water in storage to such an extent that withdrawal at that rate is no longer feasible because of prohibitive pumping costs or deterioration of the water quality. In areas where precipitation, and hence recharge, are cyclic and for ground-water basins having a small usable storage capacity, the yield commonly is limited to the supply available durii short, severe dry periods. The yield of the basin in such a period is designated the short-term yield.

In Mill Creek basin the usable storage capacity and the recharge during severe periods of drought are small. The period 1946-51 was the driest 6-year period from 1920 to 1955 and probably the period of least recorded runoff after diversions and hence affords a most critical period to consider in estimating the short-term yield. In 1945 the basin was about 70 percent recharged; in the ensuing 6 years the basin was depleted progressively until by December 1951 the estimated usable ground water remaining in storage was only about 2,000 acre-feet (table 17). Similarly, the estimated total annual pumpage from existing wells and the water tunnel decreased from about 3,700 acre-feet in 1945 to only about 700 acre-feet in 1951, the decrease being due largely to the decrease in wells yields as the deposits were dewatered (table 13). For the critical 6 dry years 1946-51 the estimated draft totaled about 7,600 acre-feet (table 13). Because approximately 2,000 acre-feet of usable ground water remained in storage in December 1951, the total draft from the basin during the period could have been increased by this amount, provided it would have been physically possible and economically feasible to withdraw the remaining water in storage. If so, the short-term yield during a similar 6-year drought may be estimated by the following equation:

Short-term yield

$$= \frac{\text{Total pumpage} + \text{water remaining in storage (usable)}}{6}$$

For the 6-year period 1946-51:

Short-term yield $= \frac{7,600 + 2,000}{6}$ = about 1,600 acre-feet

Thus, under the existing regimen of supply and discharge the perennial yield is limited to the short-term yield during short critical dry periods.

The short-term yield could be increased by use of a surface-water detention reservoir in Mill Creek Canyon, by the use of additional spreading basins in the eastern part of the basin, and by drilling additional wells in the downstream part of the basin to salvage a part of the subsurface ground-water outflow that now is lost to Mentone basin. On the other hand, the short-term yield would be decreased if additional wells were drilled in Mentone basin, because the depressed levels would cause a steeper gradient to develop across the Crafton fault barrier through the younger alluvium and hence would increase the subsurface outflow from Mill Creek basin. Because water levels during most of the historic dry periods were depressed a considerable distance below land surface, increased pumping would have induced little, if any, additional recharge by seepage loss from Mill Creek.

During wet periods, such as 1936-45, there is sufficient recharge each year to replenish the basin almost to full capacity (pls. 7 and 8). In these years, pumpage could be as much as the usable storage capacity, or on the order of 6,000 acre-feet. However, it would not be feasible to attempt to pump this amount in any one year because there would be no assurance that the recharge in the following year or years would be sufficient to replenish the basin to full or near-full capacity. Thus, even in wet years it would not be practical to increase the annual pumpage to much more than the estimated short-term yield of 1,600 acre-feet.

Utilization of Storage and Salvage of Outflow

Because it is the purpose of this report to indicate not only information relative to the yield of Mill Creek basin but also areas and methods most favorable for withdrawing the available supply, the following sections outline the possible means of utilizing more effectively the usable storage capacity and possible methods of increasing the short-term yield of the basin by salvaging a part of the subsurface ground-water outflow. The discussion concerns Mill Creek basin only; the effect on water developments in Mentone basin of reducing outflow from Mill Creek basin is not considered.

Adequacy of Present Wells

The total yield of the existing wells and the water tunnel in Mill Creek basin is sufficiently large to deplete fully the estimated usable storage capacity during dry periods. If all had been pumped at capacity during the 6-year dry period 1946-51, the total pumpage probably would have been about equal to the short-term yield. However, well 1S/2-22C2 was not pumped during this period. As was indicated previously, when storage is depleted the yields of the wells decrease accordingly, and hence pumping them approaches the economic limit, particularly when only 1 to 2 thousand acre-feet of usable water remains in storage unit 1 of the basin.

Need for Additional Wells or Collectors

If it were physically possible to prevent discharge of all or part of the subsurface outflow from Mill Creek basin during a dry period, the short-term yield of the basin would be increased by the annual amount of subsurface outflow salvaged. For the period 1946-51 the estimated outflow totaled nearly 32,000 acre-feet and averaged 5,300 acre-feet per year, which was three times the estimated short-term yield for the period. However, it is not possible to intercept all the subsurface outflow from the basin by pumping from existing wells. A substantial part of the subsurface outflow could be salvaged by either or both of the following methods: (1) Drill and develop several properly spaced wells in the younger alluvium across the flood plain of Mill Creek a short distance upstream from and parallel to the Crafton fault. These wells, ranging in depth from about 85 to 100 feet, could be equipped with small pumps which, if properly operated, would intercept a substantial part of the outflow; and (2) construct a large collection gallery or water tunnel across and at the base of the younger alluvium upstream from and parallel to the Crafton fault. If properly constructed and operated, a water tunnel would intercept a large part of the ground-water outflow from the basin. The principal advantage of a water tunnel is that its yield would be relatively large compared to wells when storage was depleted to the extent where only 10 to 15 feet of the younger alluvium remained saturated.

Pumping from the suggested wells or a water tunnel together with properly managed seasonal water-spreading operations in storage unit 2, whereby water conserved there could be recovered later downstream at the wells or tunnel in storage unit 1 for use instead of being lost from Mill Creek basin by subsurface outflow to Mentone basin before the pumping season begins, would increase the short-term yield of Mill Creek basin. The magnitude of the increase would depend on the pumping practices and schedule.

Locations of Additional Wells

The drilling of additional small-capacity wells in the western part of storage unit 1 of Mill Creek basin is suggested as one method of utilizing more fully and increasing the yield of the basin. The determination of the proper spacing of wells for that purpose is not possible with the available data, because the yields from each would vary considerably during each season and during a prolonged drought, and because the quantity and location of water spread and the amount of water diverted from the stream are factors which cannot be predicted. Moreover, pumping from the basin ordinarily is restricted to periods when little or no flow is present in the stream, and the water pumped from wells is derived almost wholly from the supply available in storage.

As outlined in the section on the aquifer tests, curves could be constructed by using the estimated values for the coefficients of storage and transmissibility (table 11), estimated well yields, and proposed well spacing to show the drawdown at any position in the basin relative to all the pumping wells, if the aquifer boundaries and dewatering of the aquifer caused by pumping are considered (pls. 13 and 14). However, before a full-scale program to utilize fully the storage capacity and to salvage ground-water outflow from the basin are undertaken by drilling additional wells near the Crafton fault, additional aquifer tests should be made at one or two wells drilled for experimental purposes. These data would supply information on the spacing of supply wells and on the amount of ground water that could be salvaged for use. If the tests showed that the drilling of the required number of wells was not justified, the construction of a tunnel to salvage a part of the outflow from Mill Creek basin could be considered.

No large-capacity wells have been drilled in storage unit 2. Pumping lifts would be considerably greater than those in storage unit 1 (pls. 4 and 6), and it would be necessary to pump water in most years from the poorly permeable older alluvium. Wells ranging from 500 to 700 feet deep probably would be required, and as previously indicated the deposits would be depleted rapidly by natural downstream drainage of ground water. Accordingly, deep wells drilled in the central part of storage unit 2 would have small yields and large pumping lifts. Based on data for deep wells in the east part of the Greenspot area, where similar conditions exist, deep wells in storage unit 2 might produce 200 to 300 gpm from a depth of about 250 to 360 feet with a drawdown of about 40 to 50 feet; they might have specific capacities of about 2.5 to 3.5 gpm per foot of drawdown.

The dissolved solids in water used for irrigation should be less than 1,400 ppm, although some crops on certain soils have a much higher tolerance. Of the total cations the percent sodium usually should not be greater than 65 if the specific conductance exceeds about 750 micromhos, and should not exceed about 50 if the specific conductance exceeds about 2,000 micromhos. The boron content of well water in Mill Creek basin presents no problem because all known boron concentrations are far below any unacceptable amount for irrigation. Boron when present in irrigation water in excess of about 1.0 ppm is injurious to citrus and other crops sensitive to boron, and a concentration greater than 3 to 4 ppm is harmful to most crops.

The Mill Creek area contains water of good quality and moderate temperature (table 18). Analyses of waters from selected wells in Mill Creek and Mentone basins and the Mill Creek Canyon area are presented in table 18. These analyses show that the water quality in the area is suitable for ordinary domestic, irrigation, or industrial use.

Table 18.- Selected chemical analyses of well waters in the Mill Creek area, Calif.--Continued

	1S/2-13E1	1S/2-19J1	1S/2-21E1
Percent sodium (Na)	21	12	12
Specific conductance (micromhos at 25°C)	440	379	310
pH	8.0	7.6	8.3
Temperature (°F)	65	66	65
Depth of well, feet	54	233	207
Date sampled	7-13-51	10-9-50	8-27-52
Laboratory	DWR	FCD	DWR
Laboratory number	1605	1426	2373

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