ARTIFICIAL RECHARGE IN THE UPPER SANTA ANA RIVER AREA

SAN BERNARDINO COUNTY CALIFORNIA

U.S. GEOLOGICAL SURVEY, Water Resources Division.

Water-Resources Investigations 15-75

Prepared in cooperation with the
San Bernardino Valley Municipal Water District

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16. Abstracts By 1990 the San Bernardino Valley Municipal Water District will be receiving 102,000 acre-feet (1.3×10^8 cubic metres) per year of imported northern California water to be used for artificial recharge to the local ground-water system. The upper Santa Ana River area is suited for artificial recharge because it is largely underlain by permeable river-channel deposits. Some sandy clay, silt, and cemented sand and gravel layers may locally retard downward percolation of recharge water. However, test drilling indicates none of these is extensive enough to impede recharge in the spreading grounds. Analyses of ground-water movement during current spreading operations, test-drilling data, and application of Baumann's (1965) equation for calculating the theoretical recharge mound indicate that (1) barriers to ground-water movement are not evident in the river-channel deposits, (2) depth to basement complex is less in the area of the eastern spreading basins than in the western basins, (3) the spreading grounds are capable of accepting as much as 80,000 acre-feet (9.9×10^7 cubic metres) per year, and (4) the water being recharged should move through the aquifer toward the areas of pumpage.

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UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONVERSION FACTORS

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

English	*Multiply by*	*Metric*
acres	4.047×10^3	m^2 (square metres)
acre-ft (acre-feet)	1.233×10^3	m^3 (cubic metres)
acre-ft/yr (acre-feet per year)	1.233×10^3	m^3/yr (cubic metres per year)
ft (feet)	3.048×10^{-1}	m (metres)
ft/d (feet per day)	3.048×10^{-1}	m/d (metres per day)
ft/hr (feet per hour)	3.048×10^{-1}	m/hr (metres per hour)
ft^3/hr (cubic feet per hour)	2.832×10^{-2}	m^3/hr (cubic metres per hour)
ft/s (feet per second)	3.048×10^{-1}	m/s (metres per second)
in (inches)	2.540×10	mm (millimetres)
mi (miles)	1.609	km (kilometres)
mi^2 (square miles)	2.590	km^2 (square kilometres)

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ABSTRACT

The San Bernardino Valley Municipal Water District began receiving its initial entitlement of 46,000 acre-feet (5.7×10^7 cubic metres) per year of imported northern California water in December 1972. By 1990, the district will be receiving 102,000 acre-feet (1.3×10^8 cubic metres) per year. Plans are to distribute this imported water for artificial recharge to the local ground-water system.

The upper Santa Ana River area is well suited for artificial recharge because it is largely underlain by permeable river-channel deposits. Some sandy clay, silt, and cemented sand and gravel layers occur that may locally retard downward percolation of recharge water. However, test drilling indicates none of these is extensive enough to impede recharge in the spreading grounds.

Analyses of ground-water movement during current water-spreading operations, test-drilling data, and application of Baumann's (1965) equation for calculating the theoretical size of the recharge mound indicate that (1) barriers to ground-water movement are not evident in the river-channel deposits, (2) depth to the basement complex is less in the area of the eastern spreading basins than in the western basins, (3) the spreading grounds would be capable of accepting a combined total of as much as 80,000 acre-feet (9.9×10^7 cubic metres) per year, and (4) the water being recharged should move through the part of the aquifer composed of river-channel deposits toward the areas of pumpage.

INTRODUCTION

The San Bernardino Valley Municipal Water District was formed in 1954 primarily to provide supplemental water for the San Bernardino Valley area. To meet the growing water needs of the area, the district entered into a contract with the California Department of Water Resources to receive water from northern California by way of the State Water Project. The district began receiving water at the rate of 46,000 acre-ft (5.7×10^7 m^3) per year in December 1972. The district's entitlement will be gradually increased to about 102,000 acre-ft (1.3×10^8 m^3) per year by 1990. Plans are to distribute this imported water for artificial recharge to the local ground-water system.

The State Water Project will bring imported water as far south as Devil Canyon (fig. 1). From there the water district transports most of the water by pipeline southeastward along the base of the San Bernardino Mountains. The first phase of the pipeline at present is completed only as far as the Waterman Canyon-East Twin Creek spreading grounds. The initial annual allotment of 46,000 acre-ft (5.7×10^7 m^3) of water is being recharged into the spreading grounds at the mouths of Devil and Badger Canyons and at the Waterman Canyon-East Twin Creek spreading grounds. Of this allotment the district is presently spreading at a rate of more than 30,000 acre-ft (3.7×10^7 m^3) per year in the Waterman Canyon-East Twin Creek spreading grounds (San Bernardino Valley Municipal Water District, written commun., 1973).

The water district's pipeline is planned for extension to the Yucaipa area south of the Crafton Hills by about 1980. Construction of the second phase of the pipeline from the Waterman Canyon-East Twin Creek spreading grounds to the Santa Ana River is presently underway. The water district plans to recharge this water in the spreading grounds located in Sand, City, and Plunge Creeks and in the spreading grounds in the upper Santa Ana River (fig. 1), the purpose being to increase the quantity and improve the quality of water in storage in the San Bernardino Valley area. The upper Santa Ana River spreading grounds are to be the principal area of recharge for the imported water (Bechtel Inc., 1970).

The San Bernardino Valley Municipal Water District entered into a cooperative agreement with the U.S. Geological Survey in 1972 for a two-part study of artificial recharge in the San Bernardino Valley. This is the first study dealing with the feasibility of artificial recharge in the upper Santa Ana River spreading grounds. The second study, which is in progress, deals with the effects of artificial recharge on the confined aquifer underlying the city of San Bernardino.

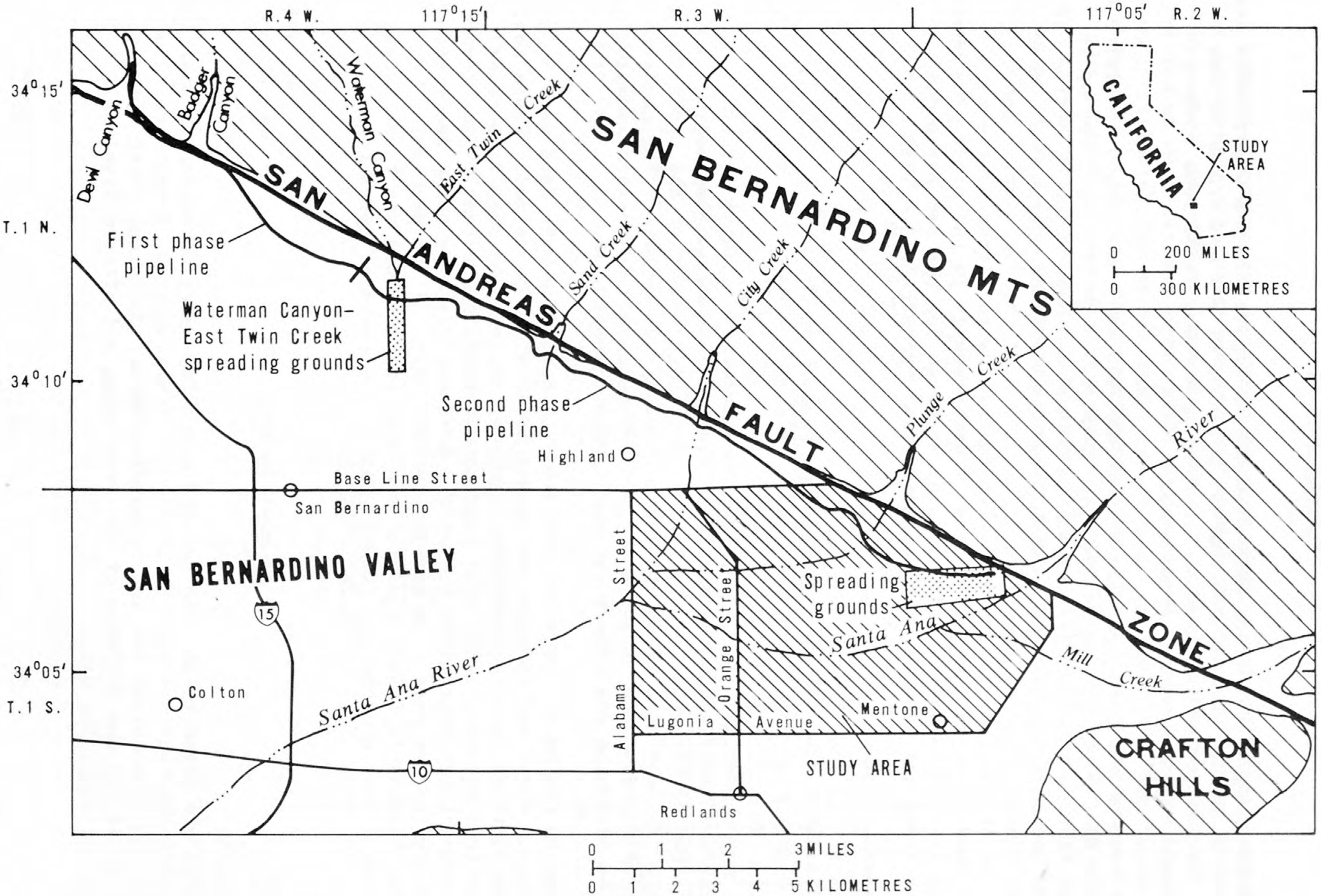


FIGURE 1.--Location of study area.

Area of Study

The boundary of the study area is shown in figure 1. The upper Santa Ana River area is about 8 mi (13 km) east of the city of San Bernardino at the base of the San Bernardino Mountains. The San Andreas fault zone forms the northeastern boundary of the study area.

The area of study is approximately 20 mi^2 (52 km^2) and ranges in altitude from 1,200 ft (360 m) above sea level to about 2,000 ft (610 m). The upper Santa Ana River area, formed from erosion of the San Bernardino Mountains, is generally uneven ground scattered with large boulders and sparse brush cover. The river channel in the study area is about 2 mi (3 km) in width. Land development in the area is primarily agricultural with citrus as the main crop. Ground water is the main source of water supply in the area. The upper Santa Ana River area is the major area of recharge for the San Bernardino Valley area and has been the site of artificial recharge since 1911.

Purpose and Scope

The purpose of this study was to (1) evaluate the feasibility of increasing the recharge in the San Bernardino Valley area, by spreading water imported from northern California in the spreading grounds of the upper Santa Ana River, (2) determine if any faults that might impede artificial recharge extend into the Santa Ana River area, and (3) develop a water-level monitoring program to determine the effects of the spreading operation.

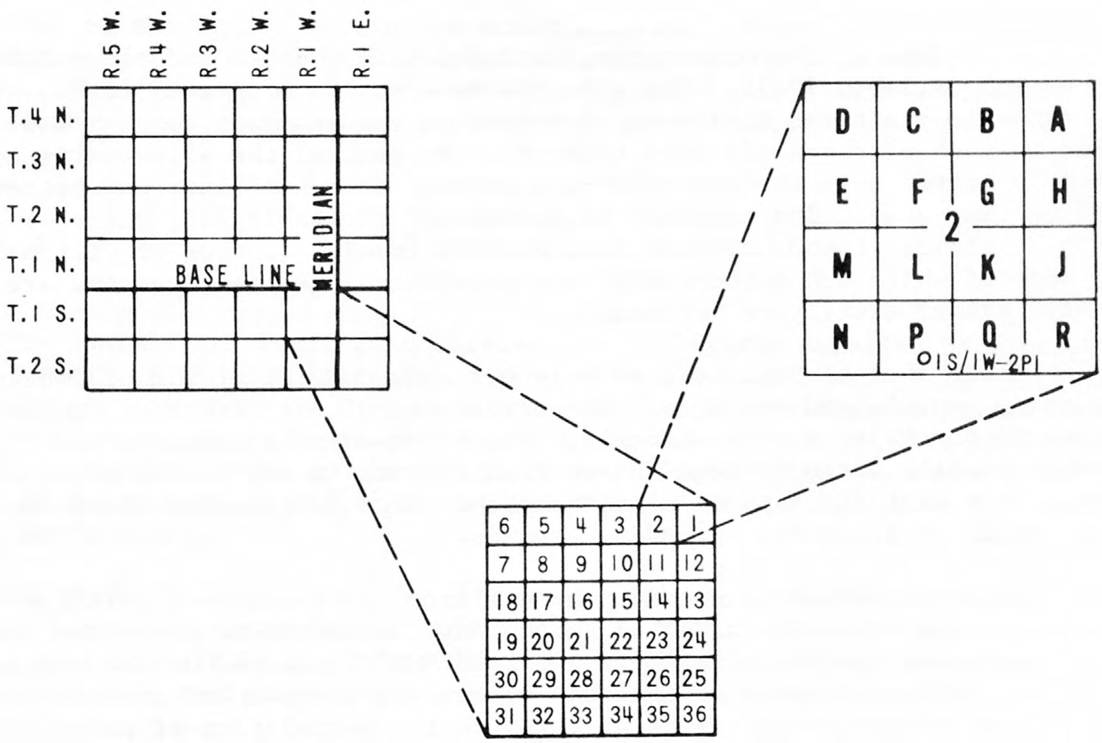
Wells in the study area were canvassed to determine what data were available and where additional observation wells might be needed. Three test holes were drilled near the spreading grounds. Lithologic logs from these holes and from existing wells were used to determine the extent of any layers of low permeability that might impede the movement of water being recharged. A seismic survey was made to determine the thickness of the permeable sediments. Baumann's (1965) equation was used to calculate the theoretical size of the recharge mound that would result from recharge operations.

Acknowledgments

Thanks are given to the San Bernardino Valley Water Conservation District for allowing the test holes to be drilled on its property. Thanks are also given to the personnel at the San Bernardino Valley Municipal Water District who contracted for the drilling of the test holes and offered invaluable assistance in supplying data.

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public land. For example, in the well number 1S/1W-2P1, that part of the number preceding the slash indicates the township (T. 1 S.); the number and letter following the slash indicate the range (R. 1 W.); the number following the hyphen indicates the section (sec. 2); the letter following the section number indicates the 40-acre (1.6×10^5 m^2) subdivision of the section according to the lettered diagram below. The final digit is a serial number for wells in each 40-acre (1.6×10^5 m^2) subdivision. The area lies entirely in the southwest quadrant of the San Bernardino base line and meridian.



GEOLOGY

Lithology

For this study the lithologic units have been modified from those mapped by Dutcher (Dutcher and Garrett, 1963) to include only three units (fig. 2)--basement complex, alluvium, and river-channel deposits.

The basement complex underlies the alluvium and river-channel deposits and makes up the surrounding hills and mountains. It is composed of igneous and metamorphic rock of pre-Tertiary age. These rocks are nearly impermeable except where fractured or weathered and are not an important source of ground water. For purposes of this study, the basement complex is considered to be non-water bearing.

The alluvium, of Quaternary age, includes both younger and older alluvium (Dutcher and Garrett, 1963). The alluvium is composed of gravel, sand, silt, clay, and some scattered boulders. It overlies the basement complex and is exposed in much of the study area (fig. 2). In general the alluvium is coarse and poorly sorted near the mountains and becomes somewhat finer and better sorted farther away. The alluvium is moderately permeable and, where saturated, yields ground water of good quality freely. Lenses of silt or clay, some of which are quite sandy, are generally local features and are not extensive either areally or vertically.

The river-channel deposits, of Holocene age, consist of unconsolidated silt, sand, gravel, and boulders. The river-channel deposits overlie the alluvium in the major stream channels. The river-channel deposits are highly permeable causing large seepage losses from streams to the ground-water system. This fact is of particular importance because it makes these deposits highly useful as sites for spreading grounds.

Lithologic information provided by drillers' logs and test drilling indicates fairly permeable material throughout the length of the river channel in the study area--sections A-A' (fig. 3) and B-B' (fig. 4). Local lenses of sandy clay, silt, and cemented sand and gravel are present but are not extensive and should not significantly reduce the percolation of water at the recharge facilities. Section C-C' (fig. 5) indicates extensive clay deposits south of the river channel near Mentone (fig. 2). These clay deposits occur at a depth of about 200 ft (60 m) below land surface and should not impede recharge in the Santa Ana River channel.

Faults and Ground-Water Barriers

Geophysical and hydrologic data from previous studies indicate that several faults occur within the study area. Fault zones in consolidated rocks commonly consist of a series of fissures that may serve as conduits for ground-water flow. Conversely, faults in unconsolidated deposits commonly act as barriers to ground-water flow. Although the cause and nature of the barrier effects of faults are not completely understood, ground-water movement across faults may be impeded because of one or more of the following conditions: (1) The offsetting of permeable beds against less-permeable beds; (2) the presence of clayey fault gouge, which is less permeable than the aquifer; (3) local deformation of beds near the fault; and (4) cementation of the fault zone and material immediately adjacent to the fault by deposition of minerals from ground water.

Most of the faults within the study area are concealed by alluvium. Apparently, unfaulted alluvial deposits overlie faulted alluvium. Data are not available in most areas to determine the depth below land surface at which the faults become effective as a barrier to ground-water movement.

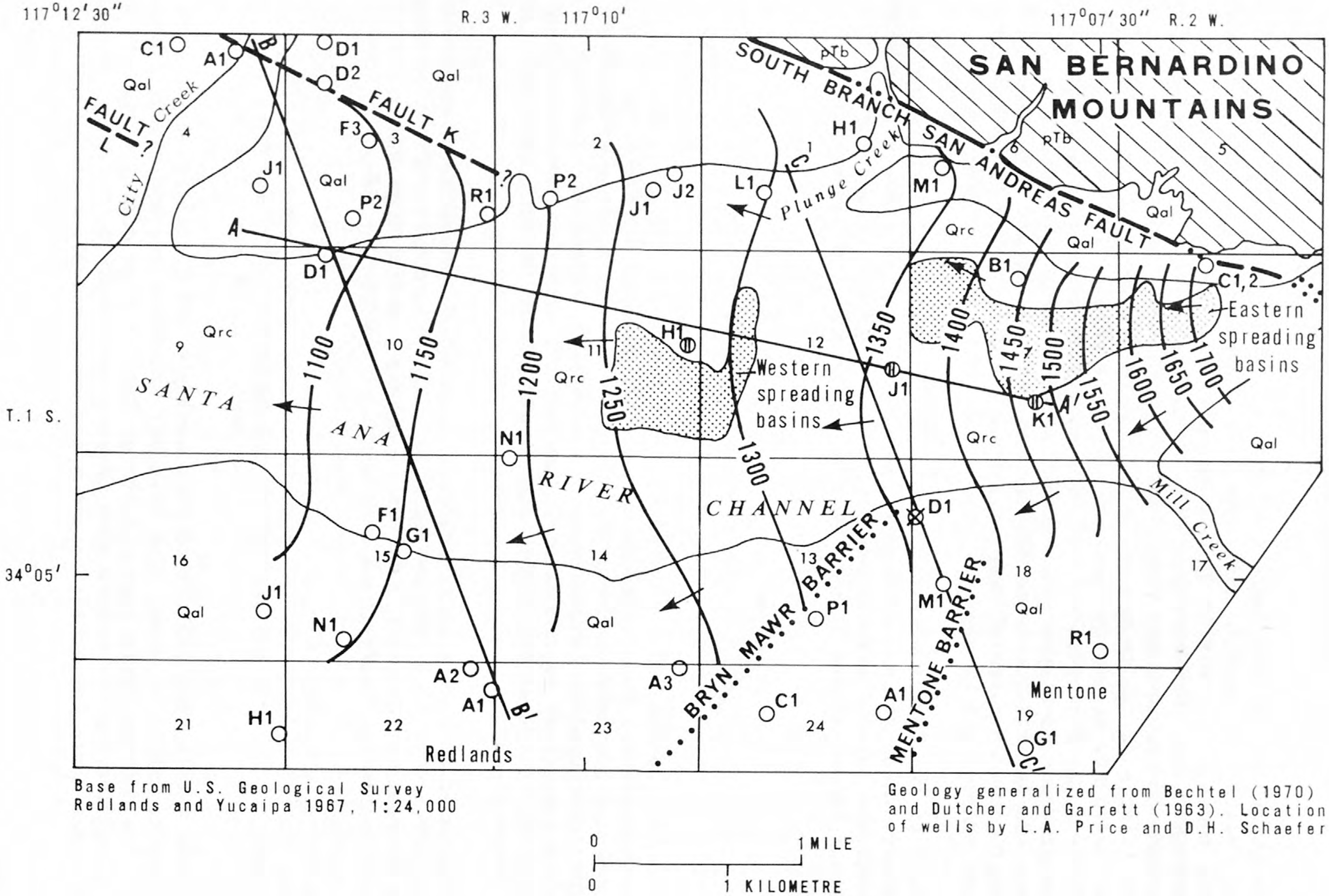
San Andreas Fault Zone

The San Andreas fault zone consists of two nearly parallel branches through most of the San Bernardino area. The southern branch (fig. 2) forms the northeast boundary of the study area, and along its trace alluvium is faulted either against basement complex or against alluvium. The fault zone is easily recognized by truncated ridges and offset beds. Movement along the fault is both vertical and right-lateral throughout the area with the south block downdropped.

The fault acts as a nearly complete barrier to ground-water movement in the San Bernardino area (Warner and Moreland, 1972, p. 7). Offset of water levels in wells across the fault has been noted, and springs and heavy vegetation mark the fault trace across the mouths of many canyons.

Fault K and Fault L

Fault K (fig. 2), postulated from geologic and hydrologic data (Dutcher and Garrett, 1963), is about 1 mi (1.6 km) southwest of, and nearly parallel to, the San Andreas fault zone. Although fault K does affect ground-water movement in the San Bernardino area (Warner and Moreland, 1972), it does not seem to have a similar effect in the upper Santa Ana River area.


117°12′30″
R. 3 W.
117°10′
117°07′30″
R. 2 W.
T. 1 S.
34°05′
SAN BERNARDINO MOUNTAINS
SOUTH BRANCH SAN ANDREAS FAULT
FAULT K
FAULT L ?
City Creek
Plunge Creek
Mill Creek
SANTA ANA RIVER CHANNEL
BRYN MAWR BARRIER
MENTONE BARRIER
Western spreading basins
Eastern spreading basins
Mentone
Redlands
Qal
Qrc
pTb
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
A
A′
B
B′
C
C′
Base from U.S. Geological Survey
Redlands and Yucaipa 1967, 1:24,000
Geology generalized from Bechtel (1970)
and Dutcher and Garrett (1963). Location
of wells by L.A. Price and D.H. Schaefer
0
1 MILE
0
1 KILOMETRE

EXPLANATION

QUARTERNARY

Holocene

Qrc

River-channel deposits

Unconsolidated boulders, coarse gravel, sand, and silt in major river channels; highly permeable; transmits large seepage losses from rivers and streams to the main water body

Qal

Alluvium

Unconsolidated gravel, sand, silt, and clay containing some boulders; overlies basement complex; moderately permeable and yields water freely to wells

PRE-TERTIARY

pTb

Basement complex

Consolidated metamorphic and igneous rocks; underlies alluvium and forms bordering hills and mountains; non-water bearing except where fractured

Contact

?

Fault

Dashed where approximately located; dotted where concealed; queried where doubtful

A A'

Line of section

Ground-water barrier

(Modified from Dutcher and Burnham, 1960)

1300

Water-level contour

Shows altitude of water level; Contour interval 50 feet (15 metres). Datum is mean sea level. Arrow indicates general direction of ground-water flow

A1

Well and number

See text for explanation of well-numbering system

J1

Test hole and number

D1

Destroyed well and number

FIGURE 2.--Geology, location of selected wells, and water-level contours, April 1974.

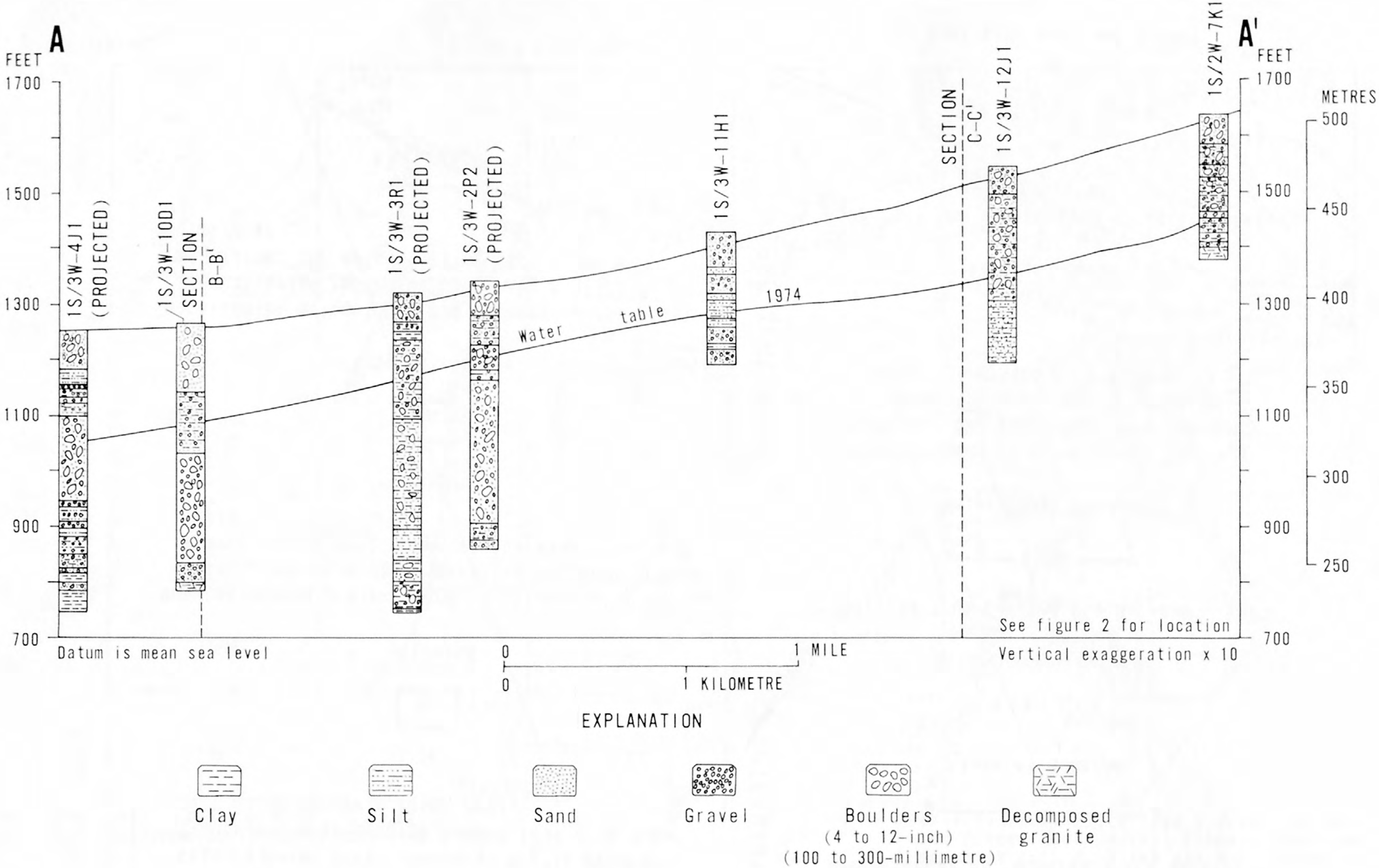


FIGURE 3.--Generalized section A-A'.

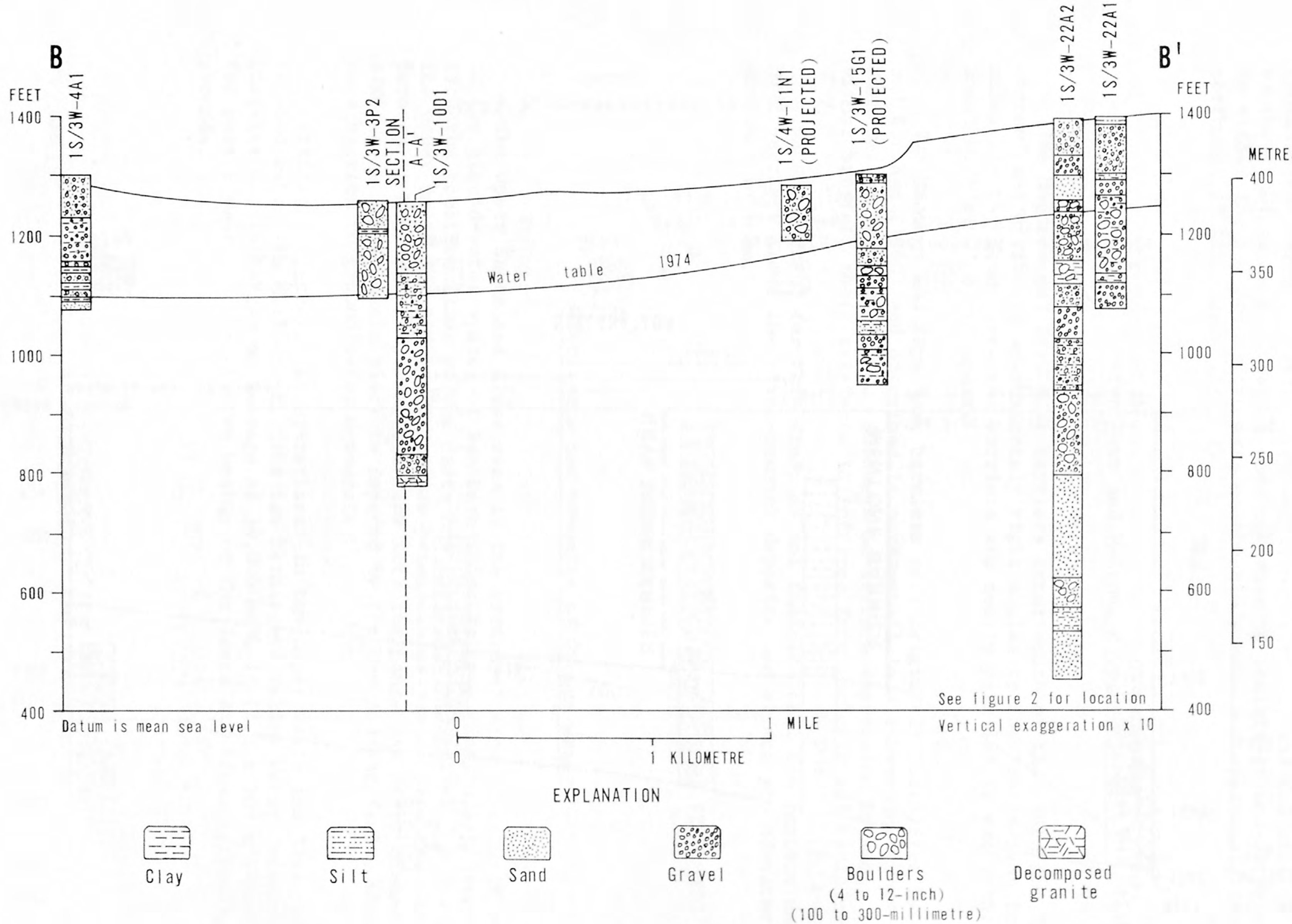


FIGURE 4.--Generalized section B-B'.

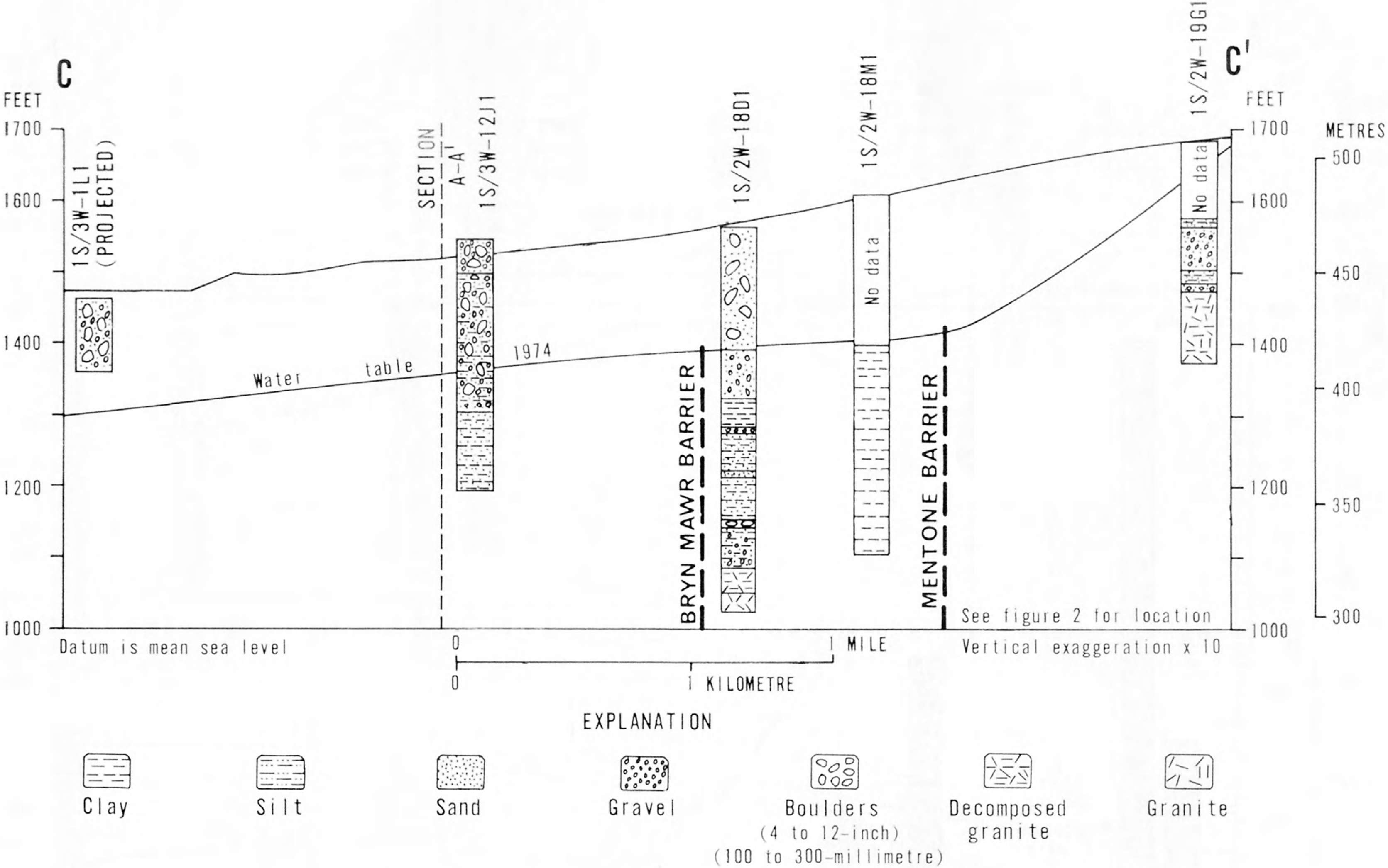


FIGURE 5.--Generalized section C-C'.

Fault L (fig. 2), also postulated from hydrologic and geologic data (Dutcher and Garrett, 1963), lies nearly parallel to, and 0.5 mi (0.8 km) southwest of, fault K. Fault L does not seem to inhibit ground-water movement in either the San Bernardino area or the study area and apparently terminates northwest of City Creek (fig. 2).

Bryn Mawr and Mentone Barriers

The Mentone and Bryn Mawr barriers occur south of the Santa Ana River channel and strike at approximately right angles to the San Andreas fault zone. In the study area the barriers are nearly parallel to each other and about 0.75 mi (1.2 km) apart.

The Mentone and Bryn Mawr barriers were originally postulated by Dutcher and Burnham (1960) and described in more detail in a subsequent study by Burnham and Dutcher (1960). Although no surface expression is known for either barrier, their existence is inferred from geologic and hydrologic data.

Data collected for this study do not indicate that the Mentone and Bryn Mawr barriers cross the river-channel deposits and affect ground-water movement in them.

HYDROLOGY

Occurrence and Movement of Ground Water

The upper Santa Ana River area is the principal area of natural recharge to the ground-water system of San Bernardino Valley. The bulk of recharge is from the combined flows of the Santa Ana River and Mill Creek. Recharge to the upper Santa Ana River area occurs primarily as runoff from the San Bernardino Mountains. Subsurface flow into the Santa Ana River channel from streams in the mountain block is impeded by the San Andreas fault, which acts as a barrier to ground-water movement.

Artificial recharge is operational in the upper Santa Ana River area and to some extent in Mill Creek. The San Bernardino Valley Water Conservation District has recharged an average of 10,000 acre-ft (1.2×10^7 m^3) per year in the past 9 years in the eastern basins of the Santa Ana River spreading grounds.

Figure 2 shows the movement of ground water under recharge conditions to be generally westward paralleling the Santa Ana River. Figure 2 also shows some ground-water movement laterally out of the channel along its length during recharge conditions. There is no indication that any of the postulated faults act as barriers to ground-water movement in the river-channel deposits. Presumably post-faulting scour and deposition by the Santa Ana River have eradicated any near-surface barrier effects of the faults. Ground-water flow north of the Santa Ana River moves southwestward in response to recharge from the San Bernardino Mountains. South of the river channel, ground-water flow is northwestward in response to natural recharge from the highland areas to the south.

Water-Level Fluctuations

The water supply of the San Bernardino Valley is almost entirely from wells. The depth to ground water in the study area ranges from about 70 ft (20 m) to about 250 ft (75 m) below land surface. The upper Santa Ana River area, like the rest of San Bernardino Valley, has experienced periodic long-term water-level declines. Water-level fluctuations in four wells shown in figure 6 demonstrate this long-term decline.

Between 1945 and 1965 the water level in the area declined at a rate of about 10 ft (3 m) per year. This was due to a combination of increased pumpage and less-than-average precipitation. Between the years 1965 and 1970 the water level in wells rose as much as 200 ft (61 m), with an average increase of about 20 ft (6 m) per year. This rise in water level was due to a general increase in precipitation that resulted in a decrease of pumpage and an increase in natural recharge coupled with artificial recharge in the area. This period of greater-than-average precipitation culminated in the heavy precipitation of 1969. Since about 1970 the water levels have again declined at a rate of about 10 ft (3 m) per year.

FEASIBILITY OF INCREASING ARTIFICIAL RECHARGE

One method of storage and distribution of water is through artificial recharge of surface water to the ground-water system. Underground storage of water under proper conditions is often preferable to surface storage for many reasons including reducing losses from evaporation, less expensive storage space, and water-quality protection. However, several important conditions must be met for a ground-water basin to be considered suitable for artificial recharge. The infiltration rate of the spreading grounds must be high enough to accept the anticipated rate of recharge. The storage capacity of the ground-water basin must be adequate to accommodate the anticipated volume of recharge. The transmissivity of the water-bearing material must be sufficient to transmit the water away from the recharge site to the area of extraction.

Test Drilling

Three test holes (fig. 2) were drilled and logged (table 1) in the Santa Ana River channel near the spreading grounds. The purpose of these test holes was (1) to locate any low-permeability layers that might retard the downward percolation of water being recharged, (2) to determine if any water-level discontinuities exist caused by possible extension of any of the faults into the Santa Ana River channel, and (3) to monitor the planned recharge operations. The holes were drilled at approximately 1-mi (1.6-km) spacings along the river channel. All three holes were drilled using a cable-tool rig, completed as observation wells, and perforated from the bottom of the wells to at least 40 ft (12 m) above the water table. Recorders were installed to continuously monitor water levels in the area. In addition a recorder was installed on well 1S/2W-7B1 (fig. 2). To supplement the monitoring program, wells 1S/2W-6M1, 8C1, 8C2, 18R1, and 1S/3W-1H1, 2J1, 2P2, 13P1, and 24C1 (fig. 2) are measured twice a month.

The results of the test drilling indicated that the subsurface material at the spreading grounds is generally permeable enough to allow water to percolate to the water table. Some sandy clay, silt, and cemented sand and gravel were found that may retard downward percolation of the imported water to the water table and cause local perched ground-water bodies. However, none of these layers of low permeability seems to be extensive. Test drilling indicates a definite trend from coarser-grained material in the east to finer-grained material farther west.

Test hole 1S/2W-7K1 penetrated a layer of sandy clay and decomposed granite beginning at 244 ft (74 m) below land surface that might represent the top of the weathered bedrock zone. The top of this layer was 40 ft (12 m) below the level at which water was found. This would then represent the lower limit of usable storage in the permeable sediments near the eastern spreading basins. Seismic refraction data obtained in the area of well 1S/2W-7K1 show a seismic velocity of about 7,700 ft/s (2,350 m/s) at a depth of about 240 ft (73 m) indicating the weathered zone and a seismic velocity of about 12,300 ft/s (3,750 m/s) at a depth of about 330 ft (100 m) indicating bedrock. Neither of the other test holes penetrated the weathered zone.

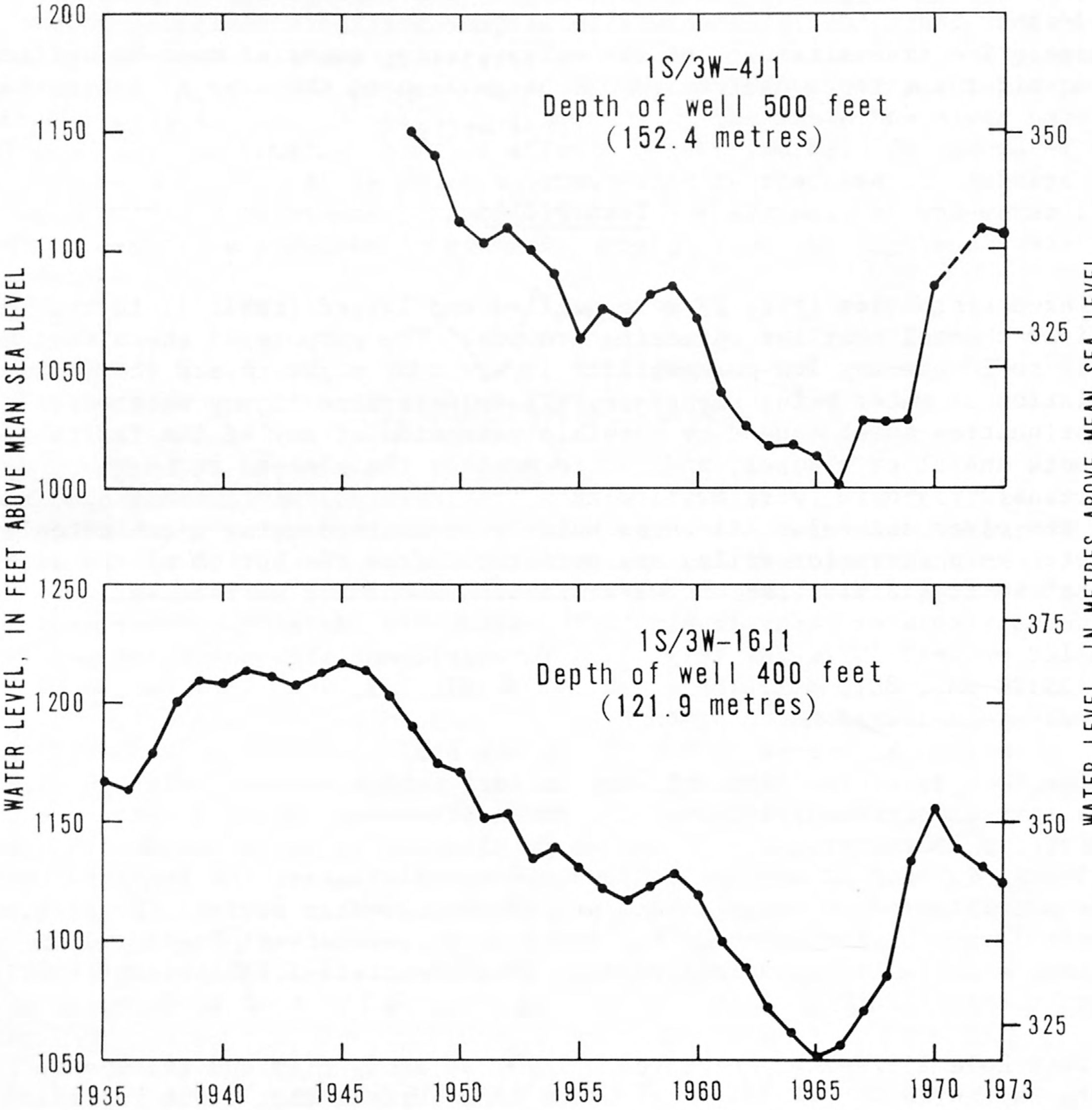


FIGURE 6.--Hydrographs of selected wells.

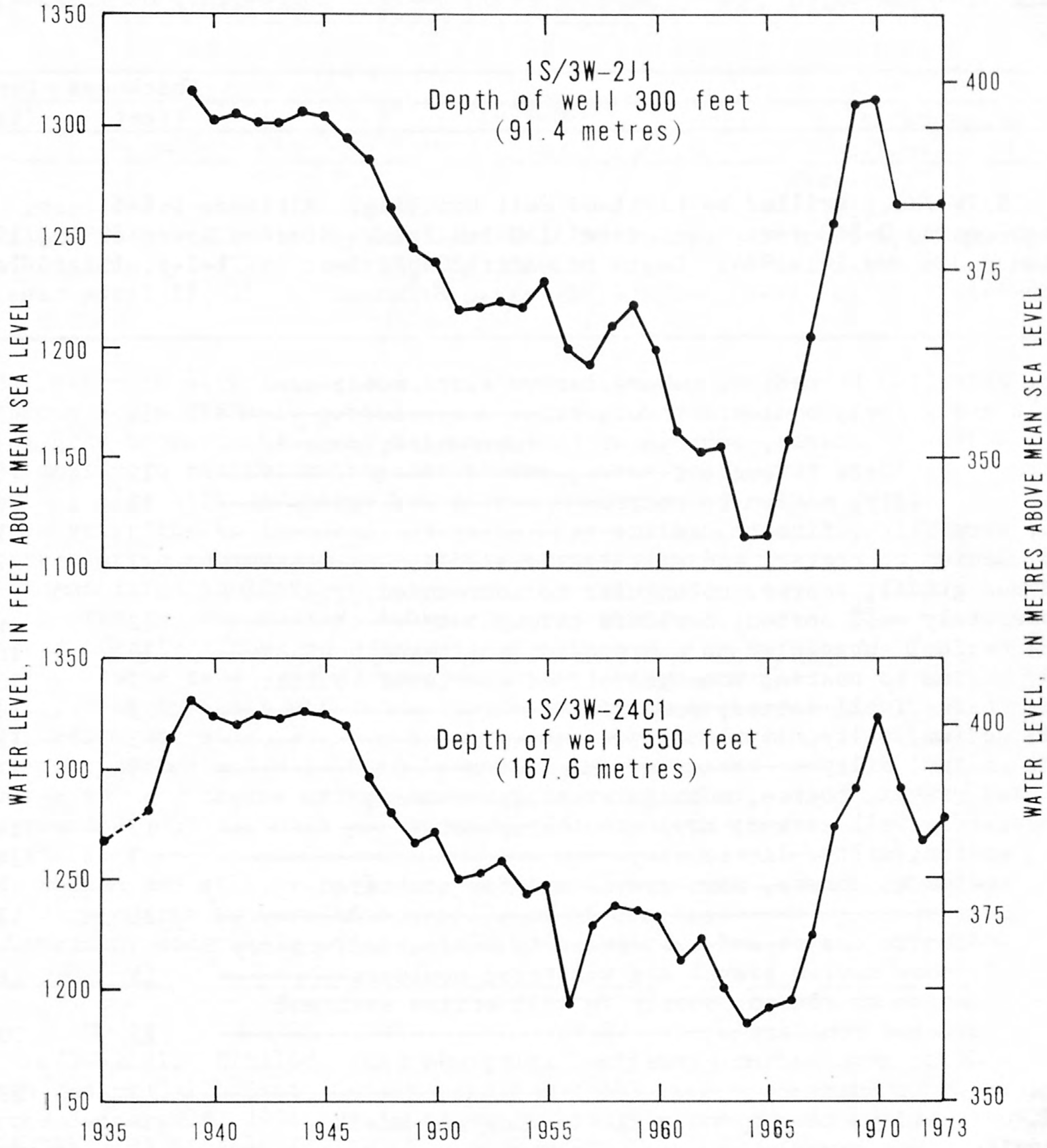


FIGURE 6.--Continued.

TABLE 1.--*Lithologic logs of test holes 1S/2W-7K1, 1S/3W-11H1, and 1S/3W-12J1*

	Thickness (feet)	Depth (feet)
1S/2W-7K1. Drilled by Kirkland Well Drilling. Altitude 1,645 feet; 8-inch casing 0-260 feet, perforated 120-260 feet. Started November 15, 1973, finished January 24, 1974. Depth to water 203.22 feet (1-21-74), 152.10 feet (4-16-74).		
Sand, very fine to medium, subangular to subrounded; some silt and gravel, boulders throughout	36	36
Sand, medium to coarse, subangular to subrounded; some gravel, boulders throughout	19	55
Sand, very silty, medium to coarse	13	68
Sand, very silty, fine to medium	3	71
Sand, medium to coarse, and silt	7	78
Sand and gravel, coarse, subangular to subrounded, moderately well sorted; boulders throughout	12	90
Sand, medium, subangular to subrounded; scattered boulders	10	100
Sand, medium to coarse; some gravel and scattered boulders	7	107
Sand, coarse, well sorted; some silt	8	115
Sand, medium, silty, little clay	5	120
Sand, medium, silty	9	129
Sand and gravel, coarse, subangular to subrounded, moderately well sorted; boulders throughout	17	146
Sand, medium, silty, little clay	3	149
Sand, medium to coarse, some gravel and few scattered boulders	21	170
Sand, medium to coarse and subangular to subrounded, poorly sorted, some medium gravel and scattered boulders	15	185
Gravel, medium to coarse, poorly to well sorted sand and few scattered boulders	15	200
Sand, medium; some medium gravel and silt, and few scattered boulders	10	210
Sand, very silty, clayey and a little clay and small grayish-brown gravel	13	223
Sand, medium to very coarse, subangular to subrounded, moderately sorted; medium gravel and some boulders	9	232
Sand, medium to coarse, and some silt	12	244
Clay, sandy, reddish-brown and decomposed granite	16	260

TABLE 1.--*Lithologic logs of test holes 1S/2W-7K1, 1S/3W-11H1, and 1S/3W-12J1*--Continued

	Thickness (feet)	Depth (feet)
1S/3W-11H1. Drilled by Kirkland Well Drilling. Altitude 1,415 feet; 8-inch casing 0-240 feet, perforated 100-240 feet. Started March 30, 1974, finished April 17, 1974. Depth to water 126.40 feet (4-17-74).		
Sand, coarse to very coarse and very fine to fine gravel; subrounded, moderately sorted; some silt, color ranges from gray-brown to black-brown, some large boulders-------	70	70
Sand, medium to coarse, subangular to subrounded, well sorted; some silt and large boulders----------------------	10	80
Gravel, very fine to fine and coarse to very coarse sand; subangular to subrounded, moderately sorted; some silt and large boulders------------------------------------	35	115
Sand, coarse to very coarse, subangular to subrounded, well sorted, fairly clean--	10	125
Silt and coarse sand, runny, some medium to coarse gravel at top, fairly stiff with some clay at bottom-------------	35	160
Sand, medium and silt, loose and runny, some clay at bottom-	15	175
Sand, very coarse and very fine to medium gravel, some coarse to very coarse gravel and small subangular to subrounded cobbles, very poorly sorted; clean with very little silt---	30	205
Sand, medium and silt, very loose---------------------------	10	215
Sand, very coarse to very fine gravel, subangular to subrounded, moderately sorted, fairly clean----------------	25	240
1S/3W-12J1. Drilled by Kirkland Well Drilling. Altitude 1,545 feet; 8-inch casing 0-205 feet, 6-inch casing 201-350 feet; perforated 120-350 feet. Started January 26, 1974, finished March 25, 1974. Depth to water 192.60 feet (3-25-74), 182.54 feet (4-17-74).		
Sand, medium to coarse and very fine to fine gravel, subangular to subrounded, moderately to poorly sorted; some silt and boulders-------------------------------------	19	19
Sand, fine to medium, and silt, some very fine subangular to subrounded gravel; occasional boulders fairly well sorted--	16	35
Sand, medium to coarse and gravel, subangular to subrounded, moderately sorted; little silt and boulders---	15	50

TABLE 1.--*Lithologic logs of test holes 1S/2W-7K1, 1S/3W-11H1, and 1S/3W-12J1*--Continued

	Thickness (feet)	Depth (feet)
1S/3W-12J1.--Continued		
Sand, fine to medium, and silt, a little coarse sand to very fine gravel, subangular to subrounded, moderately sorted, some large boulders	10	60
Gravel, very fine to medium, subangular to rounded, poorly sorted, some silt and large boulders	5	65
Silt and medium to coarse sand, a small amount of clay binder present, occasional large boulders	10	75
Sand, coarse to very coarse and very fine to medium gravel, subangular to rounded, moderately to poorly sorted, mostly fairly clean but contains silt and fine sand; occasional large boulders and small cobbles	75	150
Silt and medium to coarse sand, silt content tends to decrease with depth, occasional clay binder and a few large gray-brown boulders	50	200
Silt and medium to coarse sand, occasional clay binder and a few large reddish-brown boulders	35	235
Sand, medium to coarse, subangular to subrounded, tightly cemented, white; some decomposed granite chips (clay) throughout interval; driller reports frills like bedrock	115	350

Infiltration Rate

The ability of a spreading ground to accept recharge depends on its infiltration rate. Moreland (1972, p. 39) estimated an average long-term infiltration rate of about 3 ft/d (1 m/d) could be obtained for the upper Santa Ana River spreading grounds. The figure was obtained by determining the wetted area of the spreading grounds from aerial photographs and calculating the inflow rate into the spreading ground. The infiltration rate is calculated by dividing the inflow rate by the wetted area. Using this technique, Moreland (1972, p. 18) calculated infiltration rates of 0.7 ft/d (0.2 m/d) in 1967, 3.7 ft/d (1.1 m/d) in 1969, and 3.3 ft/d (1.0 m/d) in 1970.

The infiltration rate depends on many variables within the spreading grounds. One variable is the extent of clogging of the coarse surface material with silt. The low infiltration rate of 0.7 ft/d (0.2 m/d) calculated by Moreland was probably due to silt clogging. Mr. William Hiltgen from the San Bernardino Valley Water Conservation District (oral commun., 1974) stated that if the upper Santa Ana River spreading grounds are well maintained an infiltration rate of between 7 and 10 ft/d (2 and 3 m/d) can be obtained. Periodic scarifying of the spreading grounds is necessary to maintain a high rate of infiltration.

Theoretical Recharge Mound

The transmissivity of the water-bearing materials must be sufficient to transmit the water away from the recharge site, or the resulting recharge mound will increase in size until the recharge site is waterlogged. The shape and extent of the recharge mound will depend on the recharge rate, permeability of the aquifer, the saturated thickness of the aquifer beneath the recharge site, and the distance to the site of discharge. Although the exact shape of the mound cannot be defined with available data, some conclusions can be drawn, if certain assumptions are made, that may be helpful in analyzing the feasibility of increasing artificial recharge in the area.

An approximation of the shape and size of the recharge mound can be made by applying a method developed by Baumann (1965). Basically the method describes mathematically the shape of a mound built on an inclined water table, underlain by an inclined impermeable stratum--in this case, the basement complex. The mound results from constant recharge at rate (Q), evenly spread over the recharge area, which is affected by extraction, discharge, or some other control at a distance (L) from the center of the recharge area. The area of recharge is divided into parallel strips 1-ft (0.3-m) wide with q_o equaling the rate of recharge in each strip. In developing the theory several assumptions were made including:

1. The aquifer is homogeneous and isotropic.

2. Flow is laminar.

3. The water table and base of aquifer are not horizontal.

4. Recharge is spread evenly over the recharge area and occurs at a constant rate.

5. No boundaries occur within the influence of the body of recharged water.

The equation (Baumann, 1965, p. 228, equation 57) that describes the recharge mound is given by:

$$Y = -\tfrac{1}{2}(2a - iX) + \left[\tfrac{1}{4}(2a - iX)^2 - \left(\frac{2q_oX}{K} - \left[(H + a)^2 - a^2\right] - iXH\right)\right]^{\frac{1}{2}}$$

where Y = height of mound, in feet, above the water table at a distance X, in feet, from center of recharge area
X = distance, in feet, from center of recharge area
a = saturated thickness of aquifer, in feet
q_o = recharge rate, in cubic feet per hour, in a 1-ft wide strip of recharge area
K = permeability, in feet per hour
i = slope impermeable stratum underlying aquifer (dimensionless)
H = maximum height, in feet, of recharge mound beneath recharge area.

To solve for Y the maximum height of the mound must first be computed. This can be done by employing a variation of the preceding equation (Baumann, 1965, p. 228, equation 58).

At $X = L$ and $Y = 0$

$$H = -\tfrac{1}{2}(2a + iL) + \left[\tfrac{1}{4}(2a + iL)^2 + \frac{2q_oL}{K}\right]^{\frac{1}{2}}$$

To analyze the recharge hydraulics of the spreading facilities of the upper Santa Ana River adequately, the eastern and western basins (fig. 2) should be treated separately because of their differing saturated thickness and depth to water.

Eastern Basins

In calculating the size of the theoretical recharge mound of the eastern spreading basins, an initial depth to water of about 200 ft (61 m) and a saturated thickness (a) of 150 ft (45.7 m) were assumed on the basis of test drilling. The permeability (K) was averaged from transmissivity values for the upper Santa Ana River area obtained in a computer-model study of the San Bernardino area by the California Department of Water Resources (1971). The distance to the area of extraction (L) was assumed to be about 8,000 ft (2,438 m). This is the distance to the city of Mentone on the south side of the river and to citrus groves on both the south and north sides of the river, which are major areas of ground-water pumpage.

In the calculations of the maximum height of the recharge mound beneath the recharge area (eastern), the following values were used:

a = 150 ft (46 m)
K = 5 ft/hr (1.5 m/hr)
i = 0.02
L = 8,000 ft (2,438 m)

In the calculation, a range of recharge rates (Q) was used to determine at what point the eastern spreading basins would become waterlogged. The results are:

Recharge rate (Q) (acre-ft/yr)	Recharge per strip (q_o) (ft^3/hr)	Maximum height (H) of mound (ft)
10,000	10.0	62
15,000	14.9	87
20,000	19.9	112
25,000	24.9	134
30,000	29.8	155
35,000	34.8	175
40,000	39.8	194
45,000	44.8	213

It is estimated from these calculations that about 45,000 acre-ft (5.5×10^7 m^3) per year is the maximum rate of recharge which the eastern basins would accept without waterlogging. Figure 7 is a cross section of the recharge mounds resulting from the spreading of 20,000 and 40,000 acre-ft (2.5×10^7 and 4.9×10^7 m^3) per year.

Western Basins

For the western spreading basins an initial depth to water of about 125 ft (38 m) and a saturated thickness (a) of 300 ft (91 m) were assumed from test-drilling data. The permeability (K) was assumed to be the same as that in the eastern spreading basins. The distance to the area of extraction (L) was assumed to be about 8,000 ft (2,438 m) as this is the distance to the city of Redlands, another major area of ground-water pumpage.

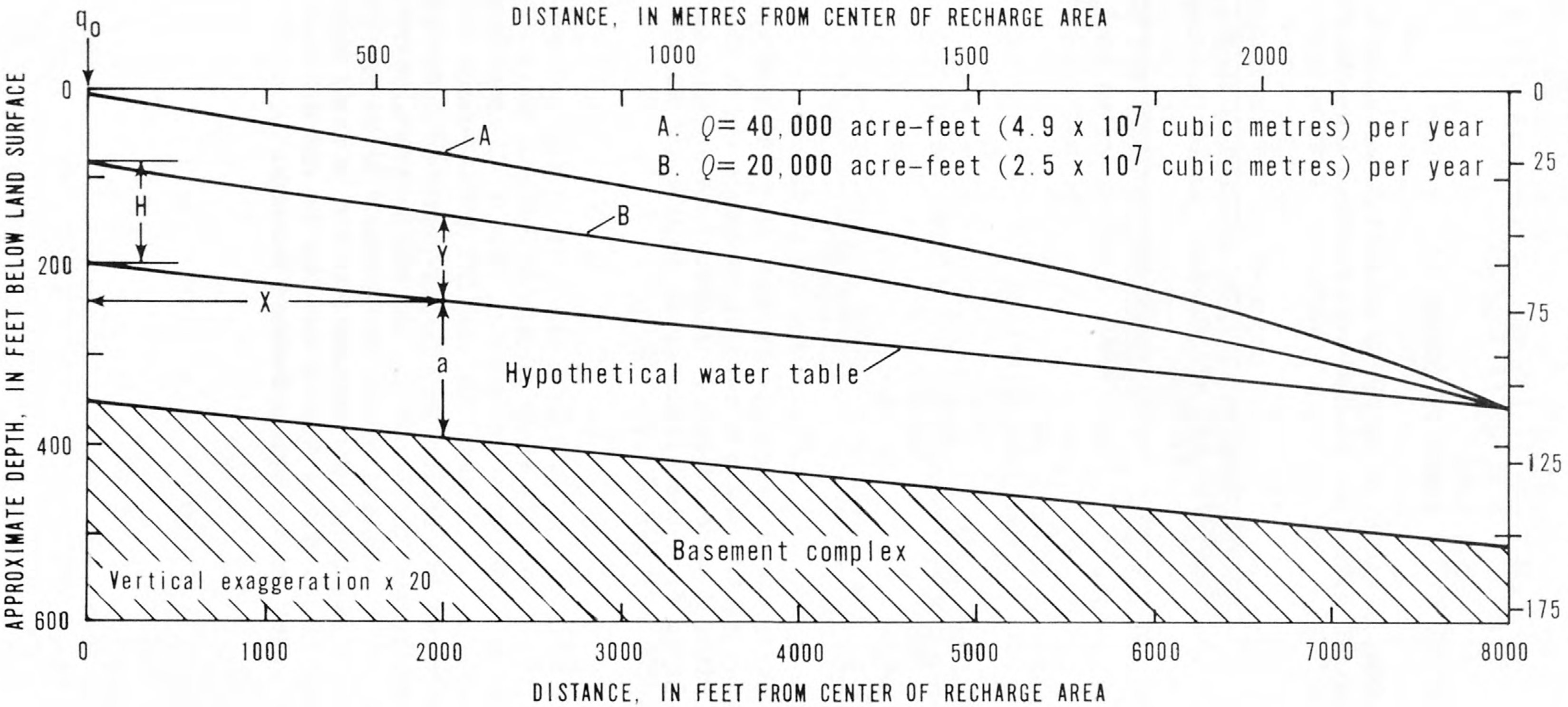


FIGURE 7.--Theoretical recharge mound (eastern basins).

In the calculations of the maximum height of the recharge mound under the recharge area, the following values were used:

$$a = 300 \text{ ft } (91 \text{ m})$$
$$K = 5 \text{ ft/hr } (1.5 \text{ m/hr})$$
$$i = 0.02$$
$$L = 8{,}000 \text{ ft } (2{,}438 \text{ m})$$

In the calculations, a range of possible rates of recharge (Q) was again used. The results are:

Recharge rate (Q) (acre-ft/yr)	Recharge per strip (q_o) (ft^3/hr)	Maximum height (H) of mound (ft)
20,000	19.9	76
25,000	24.9	94
30,000	29.8	110
35,000	34.8	126
40,000	39.8	142

From these calculations, it is estimated that 35,000 acre-ft (4.3×10^7 m^3) per year is the maximum recharge the western basins would accept. Figure 8 is a cross section of the recharge mounds resulting from the spreading of 25,000 and 35,000 acre-ft (3.1×10^7 and 4.3×10^7 m^3) per year.

The recharge mounds shown in figures 7 and 8 are theoretical and approximate because the assumptions required for the use of Baumann's equation are not entirely satisfied. However, conditions in the upper Santa Ana River area are such that these assumptions and calculations give some basis for estimating the magnitude of water-level changes that would result from artificial recharge operations in the area.

The calculations show a combined total of about 80,000 acre-ft (9.9×10^7 m^3) per year as the maximum recharge rate that the eastern and western spreading basins would accommodate together. This is based on present (1974) water levels in the area. Should the water levels decline, producing a greater unsaturated thickness, more water could be spread.

CONCLUSIONS

It is estimated that an artificial-recharge rate of as much as 80,000 acre-ft (9.9×10^7 m^3) of water per year in the upper Santa Ana River spreading grounds is feasible. Analysis of infiltration capacity indicates that the spreading grounds could accept this amount of recharge. The theoretical size of the recharge mound calculated from Baumann's 1965 equation indicates that the transmissivity of the aquifer is sufficient to transmit the

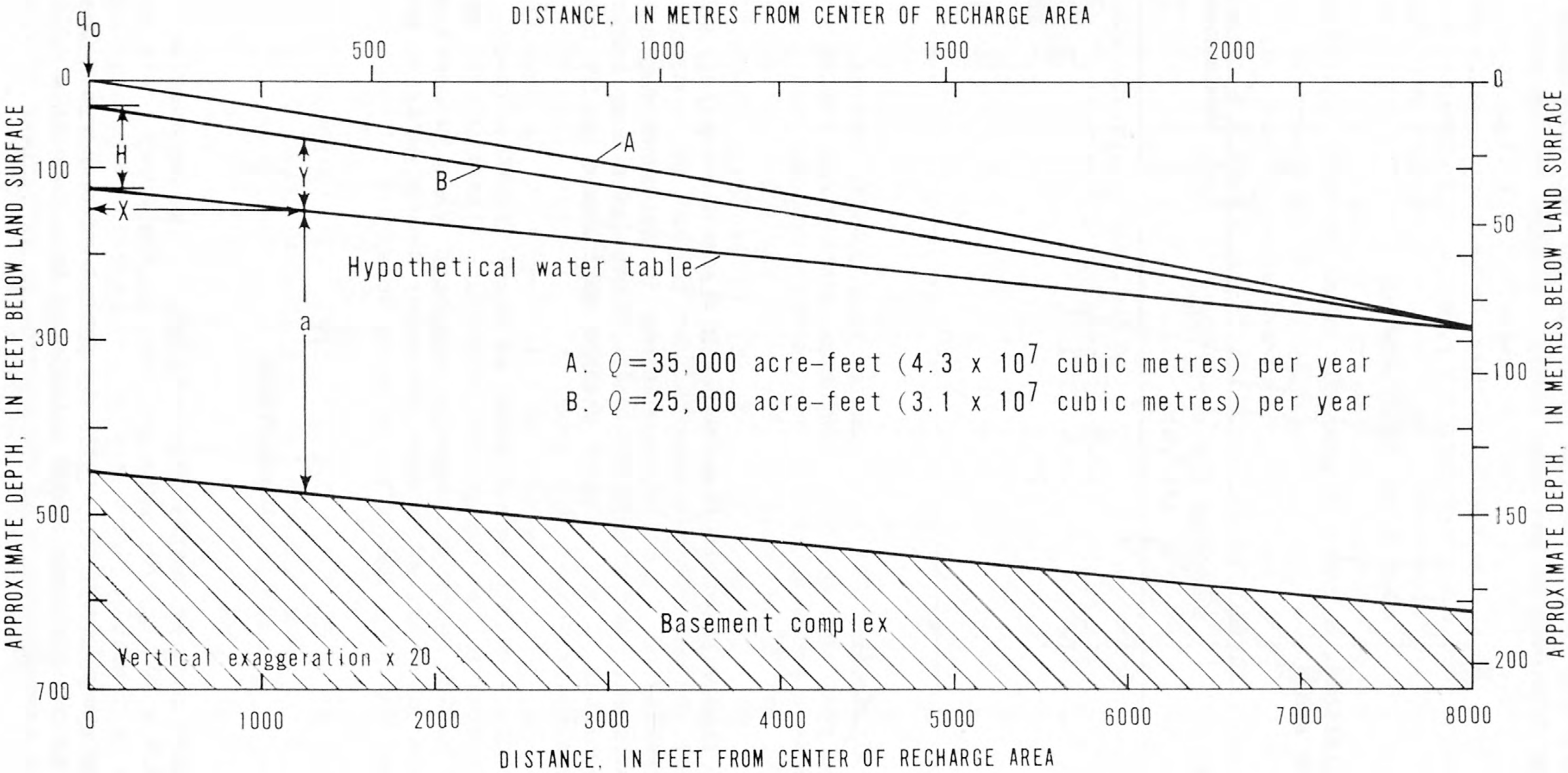


FIGURE 8.--Theoretical recharge mound (western basins).

recharged water away from the spreading grounds, and that there is sufficient storage capacity in the aquifer in most of the spreading-ground area. The results of test drilling indicate that the subsurface material at the spreading grounds is permeable enough to allow the recharged water to percolate to the water table. Some sandy clay, silt, and cemented sand and gravel layers were found that may locally retard the downward percolation of the recharged water. However none of these low-permeability layers is extensive enough to impede recharge in the spreading grounds.

The recharged water should move generally through the very permeable channel deposits along the Santa Ana River toward areas of pumpage. As water percolates through the river-channel deposits, seepage into the adjacent alluvium should provide recharge to heavily pumped aquifers in the Mentone and Redlands area.

Continued observation of the wells in the monitoring program will provide more information concerning barrier effects and general movement of the recharged water in the upper Santa Ana River area.

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