Geologic and Hydrologic Features of Indian Wells Valley, California

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2007

Prepared in cooperation with the California Department of Water Resources

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By L. C. DUTCHER *and* W. R. MOYLE, JR.

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By L. C. DUTCHER and W. R. MOYLE, JR.

ABSTRACT

Ground-water pumpage in Indian Wells Valley, virtually a closed basin in the Mojave Desert of southern California, has gradually increased since 1945 and in 1966 has exceeded the average annual water yield (perennial supply). Plans are being developed by local agencies, in coordination with the U.S. Naval Weapons Center, China Lake, Calif., to manage the ground-water basin. In order to understand the ground-water system, a basin model will be developed to test the adequacy of existing data. This report summarizes the results of a study undertaken to develop the principal geologic and hydrologic parameters needed for a detailed quantitative study of the hydrology, including the future development of a ground-water basin model.

The ground-water basin contains a single body of ground water in alluvial deposits locally as much as 2,000 feet thick. The deposits consist mainly of sand and gravel but grade to silt and silty clay beneath the lower parts of the valley surface. Now this valley is occupied by playas, but during the Pleistocene it was occupied by perennial lakes.

On the floor of the valley, coalescing alluvial fans grade into moist playas where ground water discharges by evapotranspiration. The bordering uplands and mountains, including the Sierra Nevada on the west, consist of crystalline rocks. The basin-filling alluvial deposits have been cut by several major and numerous minor faults, which were determined by seismic exploration; several of these act as partial barriers to ground-water movement.

Coefficients of transmissivity range from almost zero at the basin margins to about 300,000 gallons per day per foot in the central part of the valley. Correspondingly, the storage coefficients in the area of unconfined ground water range from about 0.05 up to about 0.2. In the area of semiconfined to confined ground water, the estimated coefficient of storage is 1×10^{-3}.

Beneath most of the valley area there has been relatively little ground-water decline since 1920. During the period 1953–65, net decline ranged from a maximum of about 20 feet near Ridgecrest to about 8 feet near Inyokern.

Estimated usable ground water in storage in the upper 200 feet of saturated deposits underlying areas which total about 110 square miles is 2,200,000 acre-feet. If users plan eventual pumping of all the recoverable water in storage, some type of hydraulic barrier will probably be required along the east margin of the storage unit to prevent inflow of saline water from the playa areas.

The maximum developable yield of Indian Wells Valley ground-water basin, under existing conditions, is estimated to be 10,000 acre-feet. The total estimated ground-water discharge by evapotranspiration from Indian

Wells Valley in 1953 was 8,000 acre-feet; this amount represents a decline from an estimated discharge of 11,000 acre-feet in 1912. The maximum developable yield (10,000 acre-feet) is judged to be less than the estimated 1912 ground-water discharge, because it is assumed that a continuing evapotranspiration loss of not less than 1,000 acre-feet per year would be required to maintain a hydraulic gradient toward the playa areas where the water quality is poor. This loss would be necessary to prevent a reversal of the gradient and consequent deterioration of the water quality at established well fields by flow of water of poor quality from beneath the playas.

Ground-water pumpage in 1966 was about 12,400 acre-feet, 2,400 acre-feet greater than the estimated developable yield. Total ground-water discharge by pumping and evapotranspiration in 1966 however, was at least 20,000 acre-feet or about twice the perennial yield.

Ground water in the valley may be grouped by chemical quality into three general categories. The first category, the water of best quality, occurs in the alluvial deposits of shallow to medium thickness in the western and northwestern parts of the valley. The dissolved-solids content of the water there is generally less than 600 mg/l (milligrams per liter), the hardness 100–200 mg/l, chloride less than 100 mg/l, and boron and fluoride each less than 1 mg/l. Water of the second category occurs mainly in the deep zones in the central and south-central part of the basin, and, perhaps, in the deep deposits in the western part of the basin. The dissolved-solids content is also generally less than 600 mg/l, the percent sodium is about 65–99, boron commonly between 3 and 10 mg/l, and fluoride 1–4 mg/l. In water of the third category, sodium and chloride ions are dominant. This water occurs in the shallow deposits beneath the playa areas. The dissolved-solids content is more than 1,000 mg/l and chloride is more than 250 mg/l; locally the chloride ion content exceeds 3,000 mg/l.

INTRODUCTION

Indian Wells Valley is in the Mojave Desert east of the Sierra Nevada in southern California (fig. 1), about 125 miles north of Los Angeles. The valley is bounded on the east by the Argus Range, on the south by the El Paso Mountains, on the north by a low ridge and the Coso Range, and on the southeast by low bedrock hills. Most of the central part of the valley is less than 2,400 feet above mean sea level, and the largest and lowest playa, China Lake, is at an altitude of 2,152 feet.

The striking physiographic features of the valley are the steep fault scarp along the base of the Sierra Nevada and the broad alluvial fans that extend from the mouths of the Sierra Nevada canyons. The fans, which have coalesced to form alluvial plains several miles wide, slope with gradually decreasing steepness from the escarpment toward playas along the east side of the valley.

Indian Wells Valley has entirely internal surface drainage. Numerous small intermittent streams in the canyons of the Sierra Nevada convey runoff to the fans where, after crossing the Sierra Nevada fault zone, the seepage recharges the ground-water body. Recharge is also derived from the runoff of the Argus Range and from surface runoff and underflow from Rose Valley at Little Lake.

A narrow gorge southeast of China Lake (secs. 7 and 8, T. 26 S., R. 41 E.), now filled with windblown sand and part of the Salt Wells Valley drainage, once afforded the lowest exit for surface drainage from Indian Wells Valley. The divide on this gorge has a surface altitude of 2,190 feet. In secs. 30 and 31, T. 26 S., R. 41 E., a granite ridge at an altitude of about 2,400 feet marks the apparent site of rapids of another outlet through which discharge occurred in an earlier period when the level of a perennial lake was above 2,400 feet.

The area considered in detail in this report comprises the flat playas and alluvial slopes of Indian Wells Valley together with parts of the surrounding hills and mountains with their bordering alluvial fans. The larger part of the valley area lies within the U.S. Naval Weapons Center, China Lake, Calif.

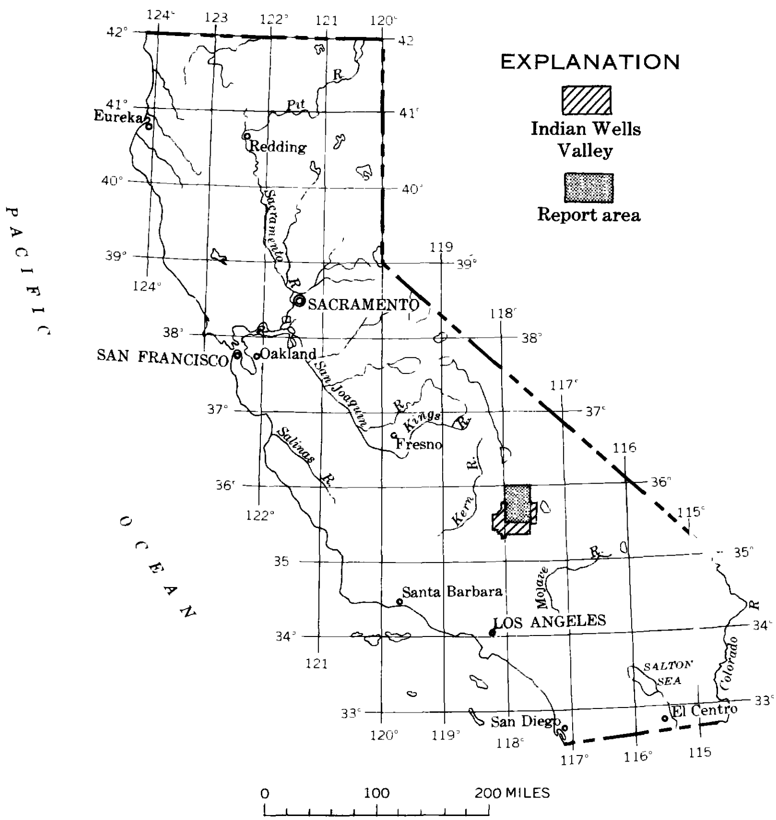


FIGURE 1.—Location of Indian Wells Valley and report area.

The old stage route from Mojave to Keeler runs along the western border of the valley past Indian Wells, the springs for which the valley was named. The Los Angeles Aqueduct, which carries water from Owens Valley, north of Indian Wells Valley, to Los Angeles, has been cut into the escarpment of the Sierra Nevada from Little Lake to Indian Wells. South of Indian Wells the aqueduct skirts the base of the Sierra Nevada.

The climate of Indian Wells Valley is arid. Average rainfall on the valley ranges from about 6 inches to less than 4 inches. Most of the precipitation on the valley floor occurs during the period October through March; during the remainder of the year, rain falls infrequently as summer thundershowers. Hot days and cool nights characterize the summers of Indian Wells Valley; warm days and cold nights are usual in the winter. Relatively high wind velocities are common in the valley, and the prevailing winds blow from the southwest, although strong northerly winds are also recorded occasionally.

PURPOSE AND SCOPE

This report was prepared by the U.S. Geological Survey, Water Resources Division, in cooperation with the California Department of Water Resources, as a part of the continuing studies of water resources of the arid areas of California. The work was done during 1968 under the general supervision of R. Stanley Lord, district chief in charge of water-resources investigations in California.

Much geologic and hydrologic data for Indian Wells Valley were collected in a program that extended over a period of many years prior to this study. The facts include well logs, water-level measurements in wells, chemical analyses of water, data from geophysical explorations, data from surface and subsurface geologic mapping, and estimates of water yield and ground water in storage. Despite this long history of data collection there remains a large area, nearly half of that part of the valley which is underlain by thick alluvial deposits, where wells have not been drilled and are lacking.

Long-range plans to assure an economical water supply for the future of Indian Wells Valley are being developed by the Naval Weapons Center, China Lake, Calif., and the Indian Wells Valley County Water District. In order to carry out these plans a knowledge of the hydrologic system is required. Hydrologic studies of Indian Wells Valley are being continued by the Geological Survey, in cooperation with the Naval Weapons Center and the Indian Wells Valley County Water District, in order to construct and use a ground-water basin model of Indian Wells Valley (R. M.

Bloyd, Jr., written commun., 1969). The data and interpretations presented in this report will serve as the substantial initial input to such a model.

The system concept is valid for studies of ground-water basin management; the advent of hydrologic simulation models affords opportunities to analyze hydrologic systems in ways not possible before. The hydrological end results of a systems study are: (1) Understanding how the system works in nature and (2) predicting the effects of various proposed water-management practices. Simulation, as applied to hydrologic systems, can be defined as the representation of the system with all its inherent characteristics and probable responses to water management. Such a representation implies the artificial creation of conditions for model operation which are analogous to those that are likely to be experienced in actuality. In general, there are five phases of ground-water basin management; the phases are interdependent as to timing and data collection, and each phase can be broken down into smaller work tasks. The five general phases are: (1) Definition of the physical nature of the basin; (2) development of a working hydrologic model; (3) analysis of management factors, including economic and social factors which relate to the management plan; (4) analysis of alternative management plans; and (5) implementation of plans.

This report has two principal purposes: (1) To provide the necessary initial input to fulfill only the first phase of the overall management tasks outlined above, and (2) to document the initially developed input data so it can be readily compared with the final data. The development of a useful hydrologic model will undoubtedly necessitate the modification of some of the hydrologic inferences presented in this report. The degree and nature of the needed modifications may prove useful to hydrologists working in similar ground-water basins.

The principal units of work to be accomplished during the definition phase preceding ground-water basin modeling are outlined below: (1) Select a grid network for modeling the basin related to the size of basin, density of data, and need for modeling detail; (2) define the distribution of aquifer coefficients of storage and transmissivity; (3) define geologic control such as basin boundaries, ground-water barriers, depth of basin, vertical separation of aquifers, and relation of aquifers; (4) determine historic pumping rate and quantity; (5) determine historic ground-water recharge; and (6) determine historic ground-water altitudes.

Therefore, the scope of the work included the qualitative description or quantitative assessment of the several features, characteristics, and variables listed above. Additionally, the chemical quality of the ground water and its relation to the geologic and hydrologic framework were described to provide the background needed by those responsible for developing the water supply.

Previous studies of the area necessarily resulted in conclusions and interpretations principally related to elements of the hydrologic budget. More data have become available since those studies were made; consequently, the estimates in this report diverge somewhat from those derived earlier. Data are still deficient for many parameters, and considerable subjective judgment was exercised in developing both the older estimates and those in this report.

For this report some of the estimates of the principal data components were made with few direct data whereas others could be made only by extrapolation if data were not available. Despite these complications, the resulting geologic and hydrologic parameters probably are a reasonably valid representation of actual conditions, even though there may be considerable error in detail.

Additional units of work will be needed during the basin-modeling phase: measurements of vertical permeability of the deposits in the area of natural ground-water discharge were not obtained, and transmissivities of the fault zones are not measurable. These values, however, can be estimated during the modeling process by computations, and the adjusted values can then be used without introducing significant modeling error in addition to errors introduced by using standard geologic and hydrologic data which inherently do not have high accuracy.

PREVIOUS WORK AND ACKNOWLEDGMENTS

Hydrologic work in Indian Wells Valley was started by the Geological Survey in 1912 by C. H. Lee (1913) who estimated the perennial yield. In 1920 D. G. Thompson (1929) included the valley in a general investigation of the Mojave Desert Region. During the period 1925–55, Kunkel and Chase (1969) studied the geology and hydrology of the valley, collected a large quantity of data, and estimated the recharge, discharge, perennial yield, and storage in two large ground-water units in the central and western parts of the valley. By 1962 Moyle (1963) had compiled a reconnaissance geologic map of the valley and a report tabulating the hydrologic data collected by all workers and agencies prior to that time.

Subsequent to the completion of the work by Kunkel and Chase in 1955, the Geological Survey has continuously maintained a data-collection program in the valley in collaboration with the Naval Weapons Center.

In addition to the work and reports by the Geological Survey cited above, other hydrologic investigations included those by Whistler (1923), J. P. Buwalda (written commun., 1944), Paul Bailey (written commun., 1946), and Wilcox, Hatcher, and Blair (1951).

Samsel (1950) mapped the southeastern part of the Cross Mountain quadrangle, and Dibblee (1952) mapped the Saltdale quadrangle; Moyle (1963) did much of the field geologic mapping used in this report.

A refraction seismic investigation of Indian Wells Valley was completed by Zbur (1963), who was assisted in the fieldwork by W. R. Moyle, Jr. Other geophysical studies, including gravity and magnetic surveys, were completed by the Naval Weapons Center.

Data and work from the previous studies and reports were freely used by the authors in the preparation of this report; without the contributions of the previous workers, this study would not have been possible.

WELL-NUMBERING SYSTEM

Wells are numbered according to their location in the rectangular system for subdivision of public land (fig. 2). That part of

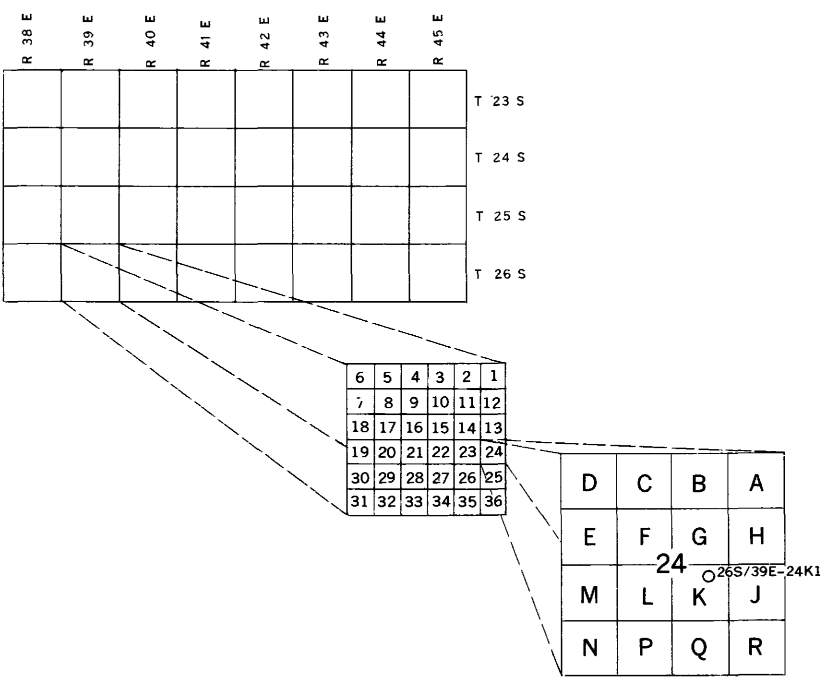


FIGURE 2.—Well-numbering system.

the number preceding the slash (as in 26S/39E–24K1) indicates the township (T. 26 S.); the number after the slash indicates the range (R. 39 E.); the number after the dash indicates the section (sec. 24); the letter after the section number indicates the 40-acre subdivision of the section according to the lettered diagram. The final digit is a serial number for wells in each 40-acre subdivision. The area lies entirely in the southeast quadrant of the Mount Diablo base line and meridian.

GROUND-WATER GEOLOGY

GEOHYDROLOGIC UNITS OF THE BASIN

The material shown as alluvium in the geologic sections and on the geologic map (pl. 1) includes all the material mapped by Moyle (1963) as landslide deposits, dune sand, sand and interdune playa deposits, younger fan deposits, younger alluvium, older alluvium, older fan deposits, old lacustrine deposits, old lakeshore deposits, and old dune sand. They are all of late Quaternary age.

In this report the stratigraphic units of Indian Wells Valley are divided into two main groups on the basis of capacity to contain and yield ground water (pl. 1). The first group, nonwater bearing, includes the basement-complex rocks of pre-Tertiary age, the volcanic rocks of Tertiary and Quaternary age, and the basalt, of Quaternary age. The second group, water bearing, includes the continental deposits of Tertiary and Quaternary(?) age, and the alluvium and playa deposits of Quaternary age.

The alluvium of Pleistocene and Holocene age is the principal water-bearing unit of Indian Wells Valley. It is unconsolidated, moderately to well-sorted gravel, sand, silt, and clay; it is moderately to poorly permeable and, where saturated and well sorted, yields water to wells at rates of more than 4,000 gpm (gallons per minute). The alluvium consists of lenticular beds of clastic material derived from the surrounding mountains and hills. Local units of alluvium are heterogeneous mixtures ranging in grain size from gravel to silt or clay. In general, however, much of the alluvium is fairly well-sorted coarse sand and gravel with a gradual decrease in grain size and a relatively higher proportion of bedded sand and silt toward the central part of the valley. In the eastern part of the valley, extensive silt and clay beds, presumably deposited in perennial lakes, partly confine ground water in the deep aquifers.

The thickness of the alluvium in the central part of the valley was determined during a geophysical study by Zbur (1963). Mainly on the basis of the refraction seismic data collected along more than 89 miles of refraction recordings (pl. 1) and of the data from a few relatively deep test holes, he determined the thickness of the alluvium to be nearly 2,000 feet in the deepest part of the basin.

The seismic data reveal four main layers of rocks and deposits, which, from deepest to shallowest, have average seismic velocities, in feet per second, as follows: 15,600–16,000; 9,600; 7,300–7,400; and 5,700–6,100. The highest velocity layer represents the basement complex, the velocity of the continental deposits is about 9,600 fps (feet per second), and the alluvium consists of two layers, the upper of which has a velocity considerably less than the lower. A refracting horizon between the deeper and shallower parts of the alluvium was found consistently throughout the valley during the seismic work and was a reliable marker. Although careful logging of the deep test wells failed to disclose a recognizable lithologic change at the refracting horizon separating the two units of the alluvium, the authors theorize that the average velocity differences are caused by compaction or consolidation of the deeper alluvium. A weathered zone could have developed on the surface of the valley floor during a pause in the depositional cycle. If such a depositional pause did in fact occur, a soil horizon or weathering zone which now acts as a widespread refractor might have developed. Carefully collected samples or cores from deep test wells would reveal the lithology of such a refractor.

The playa deposits of Holocene age consist mainly of silt and clay and are of low permeability. Water contained in these deposits usually has a moderate to very high concentration of dissolved solids. Because of their relatively small thickness, the playa deposits are not distinguished on the geologic sections; these deposits are underlain by the alluvium.

GROUND-WATER BARRIERS

The Indian Wells Valley area is an intensely faulted structural depression. Major faults border the Sierra Nevada along the west margin of the valley, and many faults of smaller displacement border the east margin of the valley. Geologic, geophysical, and hydrologic data within the valley indicate several major faults (pl. 1) along which the basement-complex rocks, the continental deposits, and the alluvium have been displaced. Several of the faults that cut the alluvium restrict the movement of ground water between the recharge areas on the west and the discharge, or playa, areas on the east (pls. 2, 3). Most of the major faults in the valley strike northwest; the faults subdivide the basin into a series of ground-water subunits. Many of the short faults along or near the east margin of the basin presumably strike northeast.

Although the faults in the valley area displace the alluvium and influence the movement of ground water, most are concealed beneath the shallowest alluvial deposits. For most places, data are not available to determine the depth below the surface where the zone of reduced permeability caused by movement along the fault becomes effective. In some places the barrier may be effective through all the alluvial deposits from the base up to the water table; in other places unfaulted alluvial deposits may extend across the concealed faults, and water in the shallow materials could flow across the barrier without interruption. The question of the effectiveness of the barriers in the shallow materials cannot be answered at this time; neither can the permeability of the barrier-producing materials nor the coefficient of transmissivity of the faulted zones be determined. These values, therefore, must be estimated by future workers before a calibrated ground-water basin model of the area can be developed.

COEFFICIENTS OF TRANSMISSIVITY AND STORAGE

Lines of equal coefficients of transmissivity [1] of the alluvium, exclusive of the continental deposits, (pl. 4) were compiled using data from aquifer tests (McClelland, 1964), drillers' logs of wells (Morris and Johnson, 1967), and selected specific capacity [2] tests using the formula:

$$T = C_s B,$$

where

T is the coefficient of transmissivity,

C_s is the tested specific capacity of the well, and

B is a factor which was estimated to be 2,000 for Indian Wells Valley.

The factor B was estimated by a method similar to that used by Bredehoeft and Farvolden (1964, fig. 9, p. 209). The errors involved are such that the transmissivities interpreted tend to be low. Well losses tend to lower the specific-capacity values; partial penetration of the aquifers by the wells also tends to lower the values, as does sedimentary anisotropy. On the basis of experience gained in other valleys having similar geologic conditions

[1] Coefficient of transmissivity: Expressed as the rate of flow of water, in gallons per day, at the prevailing water temperature through each vertical strip of the aquifer 1 foot wide, having a height equal to the saturated thickness of the aquifer and under a hydraulic gradient of 1 foot per foot.

[2] Specific capacity: The well discharge, in gallons per minute, divided by the drawdown, in feet.

and where verified ground-water basin models have been completed, the writers find that original transmissivity values estimated by the specific capacity-transmissivity relations according to Bredehoeft and Farvolden (1964), using a *B* factor of 1,200–1,500, have consistently proved about 40–60 percent low. Therefore, for water-table conditions a *B* factor value of 2,000 was used in estimating transmissivity in this report.

In some small areas, existing wells penetrate all or nearly all the alluvium, and thus the well tests and data were used directly to estimate the coefficient of transmissivity of virtually the entire thickness of the water-bearing material; the very small transmissivity of the continental deposits was not considered. In most of the area, however, pump tests and drillers' logs of wells that penetrate only the upper part of the water-bearing materials were used to estimate formation permeability.[3] In those areas a relation between permeability and aquifer thickness was developed, and then it was extrapolated downward to estimate the transmissivity of the full thickness of the aquifers.

The transmissivity of the saturated alluvium ranges from about 300,000 gallons per day per foot in the central part of the valley to almost zero at the basin margins (pl. 4).

The accuracy of the estimates, particularly in the large areas where available data are meager or lacking, cannot be verified until some type of ground-water basin model is developed whereby the data can be tested by simulation of ground-water flow.

Lines of equal coefficients of storage[4] (pl. 4) were compiled from drillers' logs of wells, using pumping tests, geologic data, and specific-yield[5] values developed for the various alluvial materials during studies elsewhere in California (Johnson, 1967).

Like the estimated coefficients of transmissivity, the accuracy of the estimated storage coefficients cannot be verified until some type of ground-water basin model is developed; when that is done all the geohydrologic parameters can be tested.

The coefficient of storage was estimated from the drillers' logs in the water-table system and from long-term aquifer tests in the artesian system; however, the coefficient of storage is difficult

[3] Permeability: A measure of the capacity of a material to transmit water. The coefficient of permeability is the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at the field water temperature.

[4] Coefficient of storage: The volume of water an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface.

[5] Specific yield: As used in this report, specific yield is the ratio of the volume of water which, on the average and after a long period, would drain by gravity from a given volume of the originally saturated material.

to determine accurately because generalizations are frequently used in compiling drillers' logs. In the water-table system, the coefficient of storage ranges from 0.05 to 0.30. If the pumping is small, any error in estimating the value of the coefficient of storage will not be significant in terms of comparing actual with predicted water levels in wells; however, if the ground water extractions are large, the value of the coefficient of storage is significant. In the artesian (confined) system, the coefficient of storage can range from 1×10^{-5} to 1×10^{-3}. Confinement begins near the center of the valley and continues to the playa area. Local confinement may occur throughout the valley because of stringers of impervious materials.

No attempt was made to estimate the coefficients of transmissivity of the fault zones; the estimates shown on plate 4 do not account for the reduced transmissivity of the faults, even in those areas where the faults coincide with the lines showing equal transmissivity. In those places, the estimated transmissivity are meant to apply only to the alluvial materials near the fault zones. For modeling purposes, the fault-zone transmissivity can be computed by assigning a thickness to the fault zone, determining the apparent hydraulic gradient from the assumed thickness and hydraulic head on either side, and then computing transmissivity by assuming that the flow on either side and through the fault zone is constant.

In the eastern part of the area where ground-water is confined beneath clay or silt lenses, the coefficients of transmissivity and storage shown on plate 4 apply only to the deposits that contain the main water body of Kunkel and Chase (1969). The coefficients of transmissivity and storage are unknown for the deposits that contain the shallow water body of Kunkel and Chase (1969). In the western part of the area, where the coefficients of storage (pl. 4) are greater than 0.01, the coefficients of transmissivity and storage represent all the alluvial deposits beneath the water table in 1968.

CONCEPTUAL MODEL OF THE GROUND-WATER FLOW SYSTEM

The writers' concept of the physical ground-water flow system in Indian Wells Valley is presented in simplified form in figure 3. Figure 3*A* shows the flow system through a single ground-water body contained in alluvial deposits which everywhere are considerably more permeable in the horizontal direction than in the vertical.

Also shown are greatly magnified natural differences in vertical and horizontal permeability caused by the presence of fine-grained silt and clay interbedded with much more permeable sand. Such clay and silt lenses and beds are common in the central and eastern parts of Indian Wells Valley; therefore, throughout the single water-body system, head differences will be measurable even in closely spaced wells of different depths wherever the ground-water flow has a considerable vertical component. This system occurs in areas of natural recharge by infiltration of water from the surface or in areas where water is discharged by evapotranspiration from the earth's surface into the atmosphere. Such a system, as described above and sketched in simplified form in figure 3*A*, seems most nearly to represent the true ground-water flow system of Indian Wells Valley. If it is the true system, separate or distinct water bodies do not exist. Instead, the body of ground water is contained in heterogeneous alluvial deposits; the water body is locally unconfined or is only semiconfined, and the vertical heterogeneity is most marked in the eastern part of the valley near the playas.

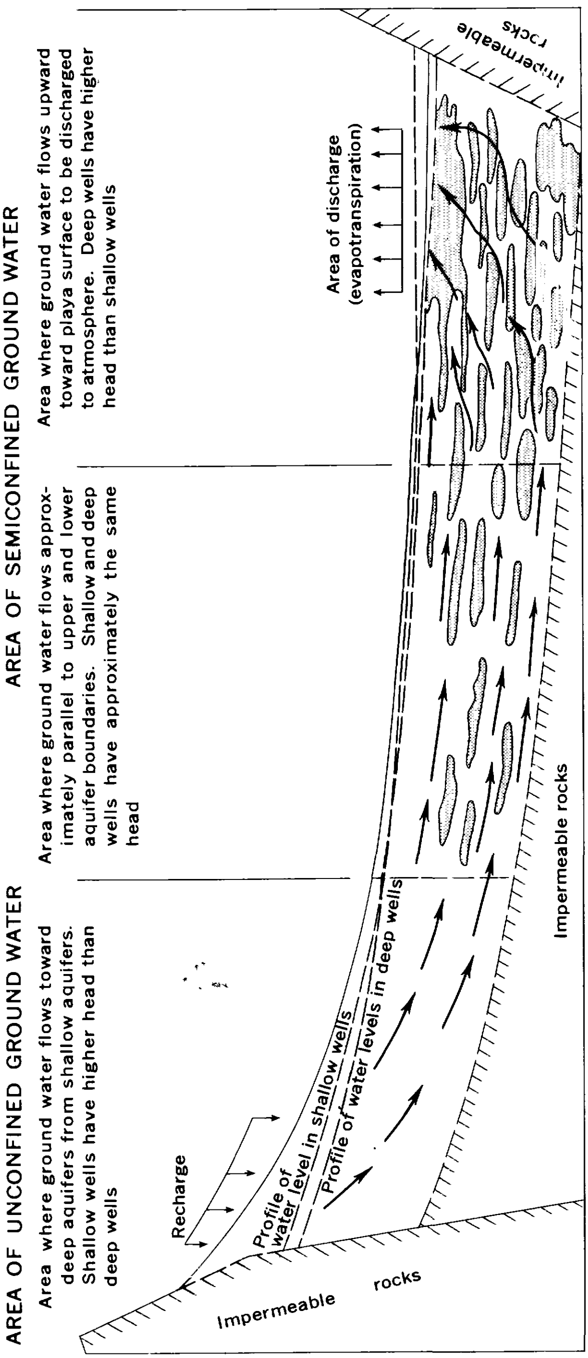
Because no single potentiometric surface can be illustrated where water levels in all wells are depth-dependent, such a simple conceptual model of the ground-water flow system introduces complications in: (1) The presentation of hydrologic data on maps and (2) the quantitative calculations or simulations inherent to three-dimensional ground-water basin modeling. Solutions for the needed three-dimensional flow equations have not yet (1972) been found; therefore, in order to present the hydrologic data on maps or to proceed with the planned ground-water basin modeling, simplified but workable generalizations of the flow system must be made.

A diagram of the most suitable generalization of the actual flow system in Indian Wells Valley is presented in simplified form in figure 3*B*. Here the small head differentials between deep and shallow wells in the recharge (western) part of the area are ignored and two water bodies, separated by distinct clay beds, are assumed to exist in the discharge (eastern) part of the area. Presumably a model of the ground-water basin will be constructed by using the same or a similar generalization. The hydrologic data presented on maps in this report reflect this simplified generalization.

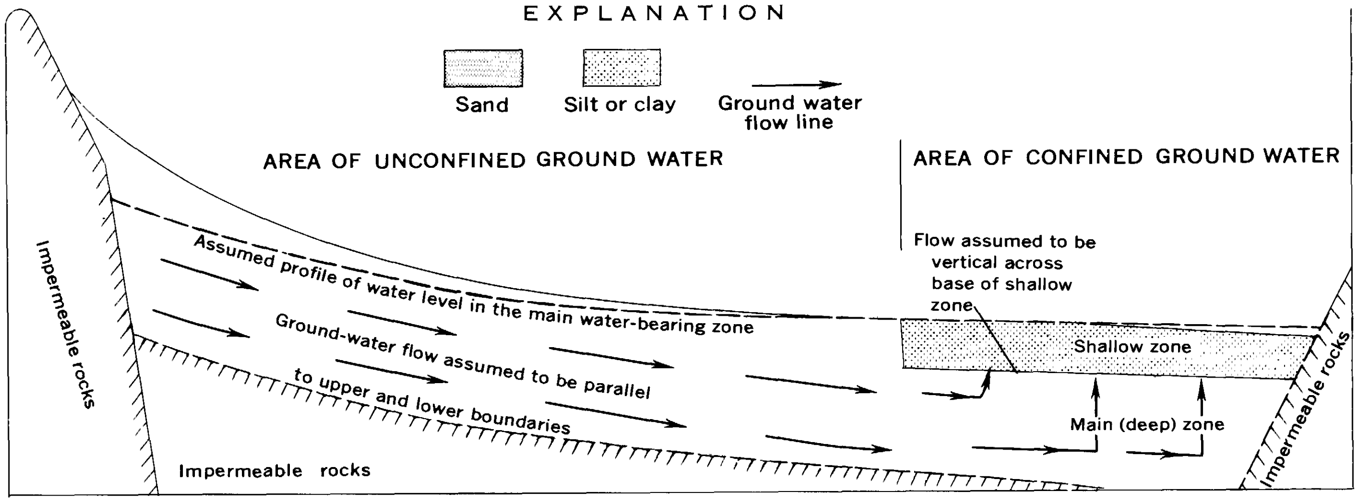
GROUND-WATER HYDROLOGY

OCCURRENCE AND MOVEMENT OF GROUND WATER

All the ground water in Indian Wells Valley is derived from precipitation. No evidence exists of any underground source or



A. FLOW THROUGH DEPOSITS CONTAINING GROUND WATER THAT IS EITHER UNCONFINED OR SEMICONFINED



B. A METHOD OF SIMPLIFYING THE FLOW SYSTEM FOR SIMULATION, TREATING AS IF TWO GROUND-WATER BODIES WERE PRESENT

FIGURE 3.—Diagrammatic sections of two conceptual ground-water flow systems.

movement of water from outside the drainage area. More than 580 wells (Moyle, 1963) have been drilled in the area; most of these have been drilled into the alluvium of the central valley area. Although most of the wells have penetrated the main water body several hundred feet, many shallow wells in the northeastern part of the valley have penetrated fine-grained deposits only a few feet below the water table near the surface. These fine-grained deposits overlie extensive clay beds and lenses in the alluvium; the underlying clay beds confine the ground water in aquifers at greater depth. Data on the full extent of the shallow water body, which may be needed to solve the basin-modeling problems, are lacking because of the paucity of wells in large parts of the area. If such a body is assumed to extend throughout the same area where the estimated storage coefficient is 1×10^{-3} (pl. 4), simulation of the actual flow system will be possible.

Data on vertical permeability of the silt and clay beds in the alluvium between the shallow and deep parts of the alluvial deposits are not available; therefore, estimates of the coefficients of storage and transmissivity for the materials containing the shallow water body have not been made.

The long-term average ground-water recharge to the basin and the perennial yield are estimated from long-term discharge by evapotranspiration in the lowest parts of the valley. These estimates are presented in a following section of the report.

Ground water moves from the areas of recharge along the west margin of the basin, across the several ground-water subunits of the basin separated by faults, to the areas of ground-water discharge by evapotranspiration on or near the playas. According to the earliest available measurements which were affected little by pumping, small water-level displacements occurred at each barrier as the water moved toward the playas where it was discharged into the atmosphere. The water-level contour map for 1920–21 (pl. 2) indicates the general pattern of ground-water flow and shows three shallow depressions caused by pumping had developed in the water table even at that early stage of development. One shallow pumping depression, presumably only about 2 feet deep, was near Leliter north of Inyokern; another depression centered near what is now the town of China Lake; and a third very shallow depression, less than 2 feet deep, existed about midway between the other two depressions and between the two faults northeast of Inyokern.

Nearly all natural discharge was from the playa areas by evapotranspiration, and except near pumped wells, the ground-water pattern of movement under natural conditions was about as represented on the watel-level contour map for 1920–21 (pl. 2).

The 1953 measurements by Kunkel and Chase (1969) afforded the most complete records for use in depicting the subsurface flow patterns for the entire basin (pl. 2). The general pattern shown for that year was used as a guide in constructing the contour maps for earlier and later periods. Presumably, little change in the ground-water flow pattern occurred between 1920 and 1953; the two shallow pumping depressions near Leliter and northeast of Inyokern had nearly disappeared, probably because wells at the old ranches were no longer being used. The pumping depression near the town of China Lake, however, had grown deeper and shifted to the south where new industrial and public-supply wells were being pumped. Hydrographs shown on plate 5 indicate the areas where water levels were declining and the magnitude of the declines.

The contour map for 1953, although somewhat generalized as explained earlier, clearly shows the closed contours near the China Lake playa. There the ground water, discharged by evapotranspiration from the shallowest deposits, was replenished by flow through the confining clays and silts from the principal water bearing deposits below. Plate 2 also shows that, near the sewage-disposal plant of the Naval Weapons Center north of China Lake, the water level rose a few feet between 1921 and 1953. This water-level rise presumably was confined to the shallowest deposits and probably did not affect the head in the deeper water-bearing zones.

A water-level contour map for 1965 (pl. 3) indicates that increasing pumping caused a water-level decline in some areas. Conversely, since about 1953, recharge of treated sewage placed in ponds north of the weapons center headquarters, used to irrigate the golf course, caused a water-level rise in a limited area. Also, the 1965 map shows that large pumping depressions were developing around the pumped wells near Inyokern, near Ridgecrest, and about 4 miles west of China Lake.

Some ground-water flow was being diverted into those three pumping depressions, but the contours near the playas were little changed from those of 1953 and presumably from those since 1921 or earlier.

WATER-LEVEL CHANGES, 1953–65

Lines of equal net change in water-level in Indian Wells Valley between spring 1953 and spring 1965 are shown on plate 3. Two sets of lines are shown: One set shows net change in water level in the main water body and the second set shows net change in water level in the shallow water-bearing zone.

The water-level changes in the main water body during the period 1953–65 were negative. There was a measured net decline ranging from a maximum of more than 20 feet northwest of Ridgecrest to a minimum of about 8 feet near Inyokern and about 7 feet south of Satellite Lake playa (sec. 35, T. 26 S., R. 40 E.). In most of the marginal areas, however, the changes were negligible where known, and in the area of natural ground-water discharge near China Lake playa, the changes in the main water body were less than 1 foot or undetectable.

Most of the water-level changes in the shallow water body during the period 1953–65 were positive; the net recovery was due to recharging sewage and irrigating the golf course. The maximum water-level rise, about 6 feet, was near Richmond School in the weapons center, north of the headquarters area.

Hydrographs of water-level fluctuations in wells (pl. 5) show the rising levels in the shallow water body where recharge is occurring, the declining levels around the pumping holes, and the relatively unchanging conditions in most of the area where pumping is limited.

GROUND-WATER STORAGE CAPACITY

Ground-water storage capacity is defined as the reservoir space contained in a given volume of deposits. To be usable, the ground water in storage must be able to drain by gravity during periods of pumping or other discharge; that is, the deposits must be capable of being dewatered. Because the discharge from ground water during the period 1920–68 was supplied almost entirely from storage and because pumpage now (1972) exceeds the perennial yield, the ground-water storage capacity of Indian Wells Valley is an important factor in regard to the future supply. Thus, ground water in storage may be considered as a reserve to be utilized in conjunction with perennial yield.

STORAGE UNITS AND DEPTH ZONES

The ground-water storage capacity was computed for three principal contiguous areas in Indian Wells Valley. The selection of the storage units was based on the good water-yielding character of the deposits, the good quality of water, the economic pumping level (average depth to water about 180 feet), and the presence of ground water available for utilization. The extent of the three units, which cover about 110 square miles, is shown on plate 4.

Storage unit 1 has an area of about 21,800 acres. It is shown on plate 4 as the area where the estimated coefficient of storage ranges from 0.05 to 0.1. The average specific yield used in making the storage estimates was 10 percent.

Storage unit 2 has an area of about 19,500 acres. It is shown on plate 4 as the area where the estimated coefficient of storage ranges from 0.1 to 0.15. The average specific yield used in making the storage estimates was 15 percent.

Storage unit 3 occupies the west-central part of the valley and has an area of about 29,500 acres. Its estimated coefficient of storage shown on plate 4 ranges from 0.15 to 0.2 The average specific yield used in making the storage estimates was 20 percent.

In the valley-bordering area where the coefficient of storage shown on plate 4 is estimated to be less than 0.05, the storage was not computed because the deposits are thin and relatively impermeable. Also, storage was not computed for the east-central part of the area where the ground water is confined beneath clay beds or lenses and the water quality, though imperfectly known, is likely to be poor.

The problem of estimating the maximum distance that ground water can be lifted to the surface and still be considered usable involves the following economic considerations: (1) The cost of obtaining water from alternative sources, (2) the use of the water for domestic, agricultural, or other purposes, and (3) the question of whether or not the withdrawal of water will induce inflow of chemically inferior water from other parts of the basin.

Ground-water storage capacity in the three storage units has been estimated for the upper 200 feet of saturated deposits; the storage units extend downward 200 feet from the 1921 water level. A water level decline of 200 feet from the 1921 level probably would not be so great as to cause economical pumping lifts to be exceeded.

Estimating whether or not withdrawal of water for use to a depth of 200 feet below the 1921 water level will induce inflow of chemically inferior water from the playa area or elsewhere is much more complicated. Several effects are imperfectly known: The possible barrier effect of faults between the ground-water storage units and the playa area, and the extent of water containing objectionable constituents or high concentrations of dissolved solids beneath the playas or at depths not yet reached by wells beneath the storage units. Because of the uncertainties regarding the chemical quality of water which might eventually be pumped from the storage units, water-basin managers desiring to deplete fully the recoverable ground water in storage in the three storage units should be aware that a need to protect against the intrusion of water of inferior chemical quality, either from the playa areas or from deep deposits, might occur at some pumping stage in the future.

All the water stored within the full 200-foot depth beneath the 1921 water table has been included in the estimates, however, because it is assumed that dewatering the 200-foot interval would induce inflow of good-quality water from the areas southwest, west, and northwest of China Lake. It was assumed also that, if necessary, some type of hydraulic barrier, either a line of injection wells or pumped wells, could be put into use along the east margin of the ground-water storage units to prevent intrusion of chemically inferior water from the playa areas. If such a barrier proved necessary, the economics of pumping ground water would be changed because of the expense of installing, operating, and maintaining it.

ESTIMATED USABLE GROUND-WATER STORAGE CAPACITY

The estimated ground-water storage capacity of storage units 1, 2, and 3 (pl. 4), was computed as the product of the area, in acres, the saturated thickness of 200 feet, and the average specific-yield value for the depth zone in each unit. The estimates so derived are shown in table 1. This table shows that the estimated total

TABLE 1.—*Estimated ground-water storage capacity in the upper 200 feet of saturated deposits*

Storage unit	Total area (acres)	Total volume (acre-ft)	Average specific yield (percent)	Total storage capacity [1] (acre-ft)
1 ------	21,800	4,360,000	10	440,000
2 ------	19,500	3,900,000	15	580,000
3 ------	29,500	5,900,000	20	1,180,000
Total -	70,800	14,160,000	[2] 15.5	2,200,000

[1] Rounded to nearest 10,000 acre-feet.
[2] Weighted average.

ground-water storage capacity is approximately 2,200,000 acre-feet for the three storage units.

Utilization of all this storage would, however, be impossible with the existing distribution of pumping plants. For any contemplated future expansion, additional wells, judiciously spaced within the storage units, would be necessary.

GROUND-WATER PERENNIAL YIELD

Prior to the advent of man in Indian Wells Valley, ground-water discharge occurred almost entirely by evapotranspiration and in very small part by ground-water underflow or outflow to Salt Wells Valley. Since the development of large-capacity wells, discharge by pumping has increased steadily and in 1966 was greater than the natural discharge.

EVAPOTRANSPIRATION

Evapotranspiration, which is the combined processes of evaporation from moist soil and transpiration from plants, occurs in the eastern part of Indian Wells Valley, near China Lake (pl. 6).

Detailed field mapping of the principal ground-water discharge units and of depths to water in 1953, shown on plate 6, was completed by Kunkel and Chase (1969). The map data as well as the computations of evapotranspiration by Kunkel and Chase (1969, figs. 12 and 13 and tables 7–9) were used in estimating perennial yield of the Indian Wells Valley ground-water basin.

The rate of evaporation from soil varies, among other factors, with the depth to the water table. Significant evaporation virtually ceases when the water table is below a depth of 9 feet; actually, evaporation continues at a very low rate in some small areas where levels are at much greater depth. Field observations in Indian Wells Valley indicate that in very tight clay, evaporation may lower the water level in wells to as much as 10 feet below the land surface.

The dominant phreatophytes are pickleweed (*Allenrolfea occidentalis*) and saltgrass (*Distichlis spicata*), and where these grow, the rate of transpiration of ground water varies both with density of plant growth and depth to ground water. These species generally do not draw water from a depth greater than 8 feet (Meinzer, 1927).

Water levels in wells in the area of evapotranspiration fluctuate annually. Generally the highest water level occurs about March 15–30, and the level gradually recedes until about September 15–30 after which it begins to rise. During the period 1912–66, intermittent records from wells in the area of evapotranspiration indicate that the yearly range in water-level fluctuations was from 0.2 foot to more than 3.2 feet and averaged less than 1 foot.

Lee (1913) classified the moist lands in and around China Lake into six types; to each type he assigned annual rates of evaporation for the purpose of determining total evapotranspiration from ground water in the discharging area. The rates of Lee are reliable for those types which have data, but his estimated rate of evapotranspiration of 31,600 acre-feet per year is no longer considered valid because he worked when only poor maps and no aerial photographs were available and when little work had been done on rates of evapotranspiration.

More recent work in other areas by Smith and Skarn (1927), Lee (1942), Young and Blaney (1942), Blaney (1952) indicated that the rates of evaporation assigned in 1913 to the various units of discharge were probably too high; therefore, Kunkel and Chase (1969) revised the values for evapotranspiration. Rates for bare soil or for soil with a very sparse growth of pickleweed or saltgrass (10-percent density or less) were determined largely from work by Smith and Skarn (1927).

The consumptive use (evapotranspiration) for areas covered by saltgrass or pickleweed was calculated by Kunkel and Chase (1969) from the formula developed by Blaney and Criddle (1949) and Blaney (1951). The formula follows:

$$U = \Sigma kf = KF,$$

where

U is the consumptive use of vegetation for any period,

k is the monthly empirical consumptive-use coefficient for the type of vegetation in a particular locality,

f is a monthly consumptive-use factor obtained by multiplying the mean monthly temperature by the monthly percentage of daytime hours of the year,

K is an empirical consumptive-use coefficient for the growing period, and

F is the sum of the monthly consumptive-use factors for the growing period.

Consumptive-use coefficients (k) for a dense (100 percent) saltgrass growth for various depths to ground water in Indian Wells Valley are shown in the table below. These values also have been applied to pickleweed.

Depth to water (ft)	*Coefficient* [1] *k*	*Depth to water (ft)*	*Coefficient* [1] *k*
1	0.8	5	0.3
2	.6	6	.2
3	.4	7	.2

[1] Values suggested by H. F. Blaney, Senior Irrigation Engineer, Division of Irrigation and Water Conservation, Soil Conservation Service Research, U.S. Dept. of Agriculture.

The graph prepared by Kunkel and Chase (1969, fig. 12) showing rates of evaporation and evapotranspiration assigned to areas of fine-grained bare soil, of 100-percent saltgrass cover, and of 25-percent saltgrass or pickleweed cover for various depths to ground water is shown on plate 6. The table on plate 6, also from Kunkel and Chase (1969 p. 69), shows the estimated total evapotranspiration from moist lands in and around China Lake in 1912 and 1953.

Measurements of water levels in 1953 indicated that since the time Lee (1913) calculated the evapotranspiration, there was a net decline of the water table. The estimated total discharge by evapotranspiration was 8,000 acre-feet in 1953 compared with the estimated discharge of 11,000 acre-feet in 1912. The apparent decrease of about 3,000 acre-feet is presumably due to the increase in ground-water pumpage since 1912. Ground water that was earlier lost by natural processes is now lost by pumping and so has caused a net decline of water levels beneath the moist areas.

PUMPAGE

All agriculture in Indian Wells Valley requires irrigation. Prior to 1944 irrigation was the main use of ground water; since 1944 the ground water has been mainly used by the Naval Weapons Center or for public supply.

Other large users of ground water have been the town of Trona, the Stauffer Chemical Co. (formerly Westend Chemical Co.), and the American Potash and Chemical Co.; these users export water to Trona, Westend, and Searles, which are outside the watershed and study area. In addition, relatively small quantities. of ground water are used to supply the needs of scattered small ranches.

In 1912 eight wells were equipped with "modern power pumps" which delivered water for irrigation (Lee, 1913); the best of the wells tested had yields of less than 540 gpm. By 1919 many acres of land had been filed on at the U.S. Land Office, and considerable prospecting for ground water had been done; however, little actual development of ground water had taken place. According to Thompson (1929), the irrigated acreage did not exceed 800 acres in 1919. On the basis of these reports, ground-water pumpage prior to 1919 probably did not exceed 2,000 to 4,000 acre-feet per year and possibly was considerably less.

For the period 1920–42 data are not available on which to base an estimate of the ground-water pumpage. Bailey (1946) inspected many of the ranches in Indian Wells Valley in 1921, and at that time only one, the Bowman property, seemed to be commercially productive. Reports of longtime residents support this observation. Paul Bailey (written commun., 1946) estimated 1943 pumpage for irrigation in Indian Wells Valley as 1,590 acre-feet, and between 1919 and 1943 the ground-water pumpage for irrigation probably did not exceed 2,000 acre-feet per year.

In 1944 ground-water pumpage for irrigation was greatly reduced when the Navy acquired a large part of Indian Wells Valley; much of the land purchased had been used for ranching. Pumpage for irrigation in 1946 was estimated at 900 acre-feet, and, since then, agricultural development has shifted to land outside the weapons center. From 1951 through 1969 average annual pumpage for irrigation has increased only slightly.

Estimates of pumpage for all uses in the period 1942–69 are shown in table 2. These data were compiled from available metered

TABLE 2.—*Estimated pumpage, in acre-feet, for calendar years 1942–69*

Year	Pumpage	Year	Pumpage	Year	Pumpage	Year	Pumpage
1942 -----	2,300	1949 -----	5,600	1956 -----	9,400	1963 -----	11,000
1943 -----	2,800	1950 -----	6,000	1957 -----	9,400	1964 -----	11,600
1944 -----	3,200	1951 -----	6,500	1958 -----	9,400	1965 -----	11,600
1945 -----	3,600	1952 -----	7,200	1959 -----	10,000	1966 -----	12,400
1946 -----	4,200	1953 -----	8,200	1960 -----	10,600	1967 -----	12,300
1947 -----	4,600	1954 -----	8,400	1961 -----	10,300	1968 -----	13,000
1948 -----	5,000	1955 -----	9,000	1962 -----	11,000	1969 -----	13,500

records. Every well and pumping plant in Indian Wells Valley was inspected by Kunkel and Chase (1969) in 1953, and for unmetered wells annual pumpage was estimated on the basis of the use of the water.

Pumpage for the Inyokern Water District and the Ridgecrest Water Co. was compiled from records of metered accounts, estimated unmetered accounts, and estimated line loss. Additional pumpage was computed by totaling the estimated pumpage of 10 small water companies and cooperatives around Ridgecrest. Those estimates were based on reports of owners and users, and on an estimate of the number of persons served, using 200 gallons per day per person.

Pumpage for the American Potash and Chemical Co. was compiled wholly from metered records furnished by Village Service, a subsidiary of the company. Pumpage for the Stauffer Chemical Co. was compiled from metered records and estimates by the company.

Pumpage for irrigation is based on an estimate of consumptive use of the crops grown in the valley, and therefore is more nearly an estimate of the net draft rather than gross pumpage. Wilcox, Hatcher, and Blair (1951) indicated that the only irrigation in Indian Wells Valley in 1946 was on the Lynn (later Henderson) and Smith (later Hedrick) ranches which irrigated a reported total of 341 acres as follows: 217 acres of alfalfa, 100 acres of wheat, and 24 acres of barley. Irrigated acreage of crops from 1951 through 1953 was 315 acres in 1951, 365 acres in 1952, and 560 acres in 1953. All the crops were alfalfa except in 1953 when 40 acres was planted to both oats and alfalfa and 70 acres to potatoes. On the basis of work of the U.S. Bureau of Reclamation (1952) in the Victorville and Barstow areas along the Mojave River, the consumptive use of water by these crops in Indian Wells Valley, estimated to be the same as in the Mojave River valley, is 3½ acre-feet per acre for alfalfa and 1½ acre-feet per acre for potatoes, wheat, oats, and barley.

Pumpage for domestic and stock use is the total estimated pumpage of 34 small-capacity wells. These totals include small quantities for yard and garden irrigation.

USABLE GROUND-WATER YIELD

An estimate of perennial yield for a ground-water basin is usually developed from the basic concept that, under natural conditions prior to pumping, the recharge equals the natural discharge. Hence, perennial yield is equal to the recharge or the natural discharge, minus any unrecoverable natural ground-water discharge, plus any salvable induced recharge. For all practical purposes, in Indian Wells Valley there is no salvable induced recharge; therefore, the amount of natural discharge pumped each year should not deplete the ground-water storage to the depth that would induce the inflow of chemically inferior water. The method used to estimate the perennial yield in Indian Wells Valley is:

Perennial yield = Recoverable evaporation and plant transpiration (evapotranspiration) plus any recoverable ground water that may discharge by underflow out of Indian Wells Valley (estimated to be less than 50 acre-feet per year).

To intercept all recharge into the valley would require reducing the natural water loss to zero. There is an evapotranspiration loss in and near China Lake and east of Ridgecrest because the water managers maintain a slight hydraulic gradient toward the areas of poor-quality water. Furthermore, under normal pumping practices, controlling the gradient, and hence, the natural discharge, is difficult. Accordingly, natural water loss by evapotranspiration and ground-water outflow probably could not be reduced to less than 1,000 acre-feet per year.

Thus, the developable yield of the basin is equal to the long-term average annual natural discharge (perennial yield), prior to any pumping, of about 11,000 acre-feet (Kunkel and Chase, 1969) minus the loss of at least 1,000 acre-feet, annually tolerated in order to prevent quality deterioration of the remaining supply, or:

Developable yield = 11,000 (perennial yield) − 1,000 = 10,000 acre-feet.

Ground-water pumpage in 1966 was about 12,400 acre-feet (table 2) or about 2,400 acre-feet greater than the estimated developable yield, and total discharge was at least 20,000 acre-feet, or about 10,000 acre-feet more than the estimated developable yield. Total discharge in excess of the developable yield is increasing and will probably continue to increase because pumping is not able to intercept a large part of the ground water that continues to be discharged by natural processes on the playas. This fact is supported by the small estimated reduction in natural discharge, possibly only 3,000 acre-feet per year, during the period 1912–53. In fact, water-level-contour maps indicate that water levels in the shallow deposits near China Lake are now rising owing to recharged sewage effluent and that evapotranspiration from the playas may now (1972) be increasing rather than decreasing.

The fact that in 1966 the total discharge exceeded the estimated developable yield by more than 10,000 acre-feet clearly indicates that pumping ground water at the present rate cannot be continued indefinitely. Eventually pumpage must be reduced or water must be imported into the valley. On the other hand, the estimated coefficients of storage in much of the valley are large; the total quantity of ground water in storage is enormous. The estimated usable ground water in storage is 2,200,000 acre-feet, and if wells are properly spaced for withdrawing the water without causing the water quality to be impaired by inflow of poor water to pumped areas, the present pumping rates could be continued for many years. By a conservative estimate, at the 1966 pumping rate, the usable ground water in storage in the upper 200 feet of saturated deposits would constitute a supply great enough to last at least 180 years.

CHEMICAL QUALITY OF GROUND WATER

Representative chemical analyses of ground water pumped from wells in the valley are shown by diagrams of the chemical quality of water (pl. 5). These diagrams show the general quality of the water, areal differences in water quality, and areas where water quality is similar. Guidelines for good domestic and irrigation water, described in the following sections, are empirical and in a sense arbitrary; therefore, they are best used to compare water and should not be considered standards.

In general the dominant cations and anions in ground water in Indian Wells Valley are either sodium and bicarbonate or sodium and chloride. Ground water in the valley may be grouped into three general categories which are summarized in the following table.

Category	*Sodium plus potassium range (percent of total cations)*	*Total dissolved solids (mg/l)*	*Total hardness (mg/l)*	*Chloride (mg/l)*	*Boron (mg/l)*	*Fluoride (mg/l)*
I	35–60	>600	100–200	<100	<1.0	<1.0
II	65–99	<600—<1,000	30–100	>100	3–>10	<1.0–>4.0
III	65–99	>1,000	>100	>250–>3,000	3–10	1.0–>4.0

The chemical quality of water of the first category is the best available in Indian Wells Valley. Water of the first category occurs in the deposits of medium depth in the western part of the basin and throughout most of the area north of Inyokern. It is highly variable in ratios among the principal ions.

In water of the second category, sodium and bicarbonate ions are dominant. In general, the dissolved solids approximate or are less than the concentrations of the water of the first category. Water of the second category occurs mainly in deeper zones near the weapons center main gate and extends westward within the limits of the ground-water subunit underlying Ridgecrest as far as the western extension of the two bordering faults. Water in the deep parts of the main body in the vicinity of China Lake and in the area east of Ridgecrest may be in the second category because it contains fewer dissolved solids than water from shallower wells which contain water from the third category.

Because of the low calcium and magnesium content, the water of the second category is generally moderately soft and for this reason is desirable for domestic use. However, water from some wells has a fluoride concentration between 2.5 and 4.0 mg/l (milligrams per liter); that concentration range is above the recommended limit of the U.S. Public Health Service (1962). If used for human consumption, it should be blended with other water of lower fluoride concentration.

The boron concentration of the water of the second category commonly ranges from 3 to 10 mg/l or more and thus is generally unsuitable for irrigation of all but the most boron-tolerant crops. This concentration range is not known to be critical for domestic use, but in part accounts for the poor yield of orchards in earlier agricultural developments in Indian Wells Valley.

Water of the second category is generally similar to that of the first category, but it had probably undergone cation exchange—a natural process in which calcium and magnesium cations in the eastward-migrating ground water are exchanged for sodium and potassium cations contained in the water-bearing beds.

Sodium and chloride ions are dominant in water of the third category. The concentration of the chloride ion is generally above 250 mg/l and may be greater than 3,000 mg/l. In general, this water has a much higher concentration of dissolved solids than water of the first and second categories. Water of the third category generally occurs in the vicinity of China Lake playa and in the southeastern parts of the basin south and east of Ridgecrest. The dissolved-solids content of this water is generally above the desired limits for either irrigation or domestic uses. Locally, the water of the third category may be used for domestic consumption, but only if no other supply is available.

Several miles east and southeast of Ridgecrest, ground water probably is not contaminated by water from China Lake, but the quality reflects the presence of residual saline water of a former lake or lakes in that area. Although the water in the vicinity of China Lake and east of Ridgecrest is of the third category, it is in poor hydraulic continuity with the main water body to the west; the water-level-contour maps indicate that the movement of ground water has been from the area east of Ridgecrest toward China Lake. A thick clay zone in the alluvial deposits east of the main gate at the weapons center may form an effective barrier to such movement. Many local residents think that the high-chloride water east and southeast of Ridgecrest is related to inflow of saline water from China Lake. The heavy pumping in and near Ridgecrest may cause a deterioration of water quality by drawing in naturally occurring high-chloride water from the area to the east and southeast.

Although the general conclusions regarding the existence of the three general water types and their vertical and lateral extent seem tenable, meager chemical data now available indicate that water samples obtained from wells that tap thick aquifers may represent blends of two or more fairly distinct water types in the aquifers.

A deterioration in the chemical quality of the water pumped from well 26S/39E–19K1 was indicated by an increase in the dissolved solids from 632 mg/l in 1960 to 1,250 mg/l in 196?. In 1964, however, dissolved solids decreased to 707 mg/l. The well was tested in January 1965 to determine the source of the ground water containing the high dissolved-solids content. This well penetrates three permeable zones; opposite each zone the well casing is perforated. Inflatable packers were installed during the test so that the water samples could be selectively collected from the different perforated intervals during each of the five pumping events. Water samples were collected at the end of each pumping event; chemical analysis of these samples (table 3) indicated that the water from

TABLE 3.—*Chemical analyses of water from several depth zones in well 26S/39E-19K1*

[Constituents given in milligrams per liter]

Constituents	Date of collection				
	January 12, 1965				June 21, 1965
Depth packers set (ft)	[1] 590–625	[2] 540–803	[3] 625	[4] 540	[5] 570
Duration of pumping (hr)	3	2	9	----	----
Calcium (Ca)	155	189	128	112	78
Sodium (Na)	160	188	134	114	69
Bicarbonate (HCO_3)	15	34	49	78	76
Sulfate (SO_4)	150	175	120	98	51
Chloride (Cl)	444	540	360	300	172
Dissolved solids, residue on evaporation at 180°C	1,170	1,660	1,400	1,090	798
Hardness as $CaCO_3$	428	520	364	316	236
Specific conductance (micromhos at 25°C)	1,670	2,370	1,870	1,560	1,000
pH	7.1	7.0	----	7.6	8.2

[1] Water from middle perforated interval only.
[2] Water from middle and lower perforated intervals only.
[3] Water from upper and middle perforated intervals only.
[4] Water from upper perforated interval only.
[5] Well sealed below 570 feet.

the upper perforated interval was lower in dissolved solids than the water from either the middle or lower perforated intervals.

After January 1965, the well was permanently sealed 570 feet below land surface; the water sample taken in June 1965 had a dissolved-solids content of 798 mg/l. The chemical-quality diagram of sample 1 from this well (pl. 5) represents water pumped from the middle and lower perforated intervals; the diagram of sample 2 represents water pumped after the seal was installed.

Fluctuations in the dissolved solids from 1960 through 1964 were probably due to the variation in the percentage of water taken from the lower and middle perforated zones present in the sample.

REFERENCES CITED

Blaney, H. F., 1951, Consumptive use of water: Proc. Am. Soc. Civil Engineers, v. 77, separate 91, 19 p.

——— 1952, Determining evapotranspiration by phreatophytes from climatological data: Am. Geophys. Union Trans., v. 33, p. 61–65.

Blaney, H. F., and Criddle, W. D., 1949, Consumptive use of water in the irrigated areas of Upper Colorado River Basin: Div. Irrig. and Water Conserv., Soil Conserv. Service, U.S. Dept. Agriculture, Logan, Utah, 49 p.

Bredehoeft, J. D., and Farvolden, R. N., 1964, Disposition of aquifers in intermontane basins of northern Nevada: Internat. Assoc. Sci. Hydrology Pub. 64, p. 197–212.

Dibblee, T. W., Jr., 1952, Geology of the Saltdale quadrangle, California: California Div. Mines Bull. 160, 43 p.

Hulin, C. D., 1925, Geology and ore deposits of the Randsburg quadrangle, California: California Mining Bur. Bull. 95, 152 p.

Johnson, A. I., 1967, Specific yield—Compilation of specific yields for various materials: U.S. Geol. Survey Water-Supply Paper 1662–D, p. D1–D74.

Kunkel, Fred, and Chase, G. H., 1969, Geology and ground water in Indian Wells Valley, California: U.S. Geol. Survey open-file report, 84 p.

Lee, C. H., 1913, Ground-water resources of Indian Wells Valley, California: California State Conserv. Comm. report, p. 403–429.

——— 1942, Transpiration and total evaporation, *in* Physics of the earth, v. 9, Hydrology: New York, Dover Publication, Inc., p. 259–330.

McClelland, E. J., 1964, Aquifer-test computation for the Mojave Desert region, California: U.S. Geol. Survey open-file report, 47 p.

Meinzer, O. E., 1927, Plants as indicators of ground water: U.S. Geol. Survey Water-Supply Paper 577, 95 p.

Morris, D. A., and Johnson, A. I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey, 1948–60: U.S. Geol. Survey Water-Supply Paper 1839–D, 42 p.

Moyle, W. R., Jr., 1963, Data on water wells in Indian Wells Valley area, Inyo, Kern, and San Bernardino Counties, California: California Dept. Water Resources Bull. 91–9, 243 p.

Samsel, H. S., 1950, Geology of the southeast quarter of the Cross Mountain quadrangle, Kern County, California: California Univ., Los Angeles, unpub. M.S. thesis, 47 p.

Smith, Alfred, and Skarn, C. F., 1927, Maximum height of capillary rise starting with soil at capillary saturation: California Agr. Exp. Sta. Hilgardia, v. 2, p. 399–409.

Thompson, D. G., 1929, The Mohave Desert region, California: U.S. Geol. Survey Water-Supply Paper 578, 759 p.

U.S. Bureau of Reclamation, 1952, Report on Victor Project, California: Rept. of regional director, region 3, 42 p.

U.S. Public Health Service, 1962, Drinking-water standards, U.S. Public Health Services Pub. 956, 61 p.

Whistler, J. T., 1923, Report on Indian Wells Valley and Fremont Valley, California: California Div. Water Rights report, 83 p.

Wilcox, L. V., Hatcher, J. T., and Blair, G. Y., 1951, Quality of water in Indian Wells Valley, California: U.S. Dept. Agriculture, Salinity Lab. research report, 54, 98 p.

Young, A. A., and Blaney, H. F., 1942, Use of water by native vegetation: California Div. Water Resources Bull. 50, 160 p.

Zbur, R. T., 1963, A geophysical investigation of Indian Wells Valley, California: U.S. Naval Ordnance Test Sta., China Lake, Calif., Naval Ordnance Test Sta. Tech. Pub. 2795, 98 p.

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