Use of Ground-Water Reservoirs for Storage of Surface Water in the San Joaquin Valley California

By G. H. DAVIS, B. E. LOFGREN, *and* SEYMOUR MACK

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CONTENTS

ILLUSTRATIONS

[Plates are in separate volume]

TABLES

USE OF GROUND-WATER RESERVOIRS FOR STORAGE OF SURFACE WATER IN THE SAN JOAQUIN VALLEY, CALIFORNIA

By G. H. Davis, B. E. Lofgren, and Seymour Mack

ABSTRACT

The San Joaquin Valley includes roughly the southern two-thirds of the Central Valley of California, extending 250 miles from Stockton on the north to Grapevine at the foot of the Tehachapi Mountains. The valley floor ranges in width from 25 miles near Bakersfield to about 55 miles near Visalia; it has a surface area of about 10,000 square miles. More than one-quarter of all the ground water pumped for irrigation in the United States is used in this highly productive valley. Withdrawal of ground water from storage by heavy pumping not only provides a needed irrigation water supply, but it also lowers the ground-water level and makes storage space available in which to conserve excess water during periods of heavy runoff. A storage capacity estimated to be 93 million acre-feet to a depth of 200 feet is available in this ground-water reservoir. This is about nine times the combined capacity of the existing and proposed surface-water reservoirs in the San Joaquin Valley under the California Water Plan.

The landforms of the San Joaquin Valley include dissected uplands, low plains and fans, river flood plains and channels, and overflow lands and lake bottoms. Below the land surface, unconsolidated sediments derived from the surrounding mountain highlands extend downward for hundreds of feet. These unconsolidated deposits, consisting chiefly of alluvial deposits, but including some wide-spread lacustrine sediments, are the principal source of ground water in the valley.

Ground water occurs under confined and unconfined conditions in the San Joaquin Valley. In much of the western, central, and southeastern parts of the valley, three distinct ground-water reservoirs are present. In downward succession these are (1) A body of unconfined and semiconfined fresh water in alluvial deposits of Recent, Pleistocene, and possibly later Pliocene age, overlying the Corcoran clay member of the Tulare formation; (2) a body of fresh water confined beneath the Corcoran clay member, which occurs in alluvial and lacustrine deposits of late Pliocene age or older; and (3) a body of saline connate water contained in marine sediments of middle Pliocene or older age, which underlies the fresh-water body throughout the area. In much of the eastern part of the valley, especially in the areas of the major streams, the Corcoran clay member is not present and ground water occurs as one fresh-water body to considerable depth.

The ground-water body is replenished by infiltration of rainfall, by infiltration from streams, canals, and ditches, by underflow entering the valley from tributary stream canyons, and by infiltration of excess irrigation water. In much of the valley, however, the annual rainfall is so low that little penetrates deeply, and soil-moisture deficiency is perennial. Infiltration from stream chan-

nels and canals and from irrigated fields are the principal sources of ground-water recharge.

The ground-water storage capacity of the San Joaquin Valley has been estimated in an earlier report (Davis and others, 1959) as 93 million acre-feet. This is the quantity of water that would drain by gravity from the valley deposits if the regional water level were lowered from 10 to 200 feet below the land surface. Storage capacity was estimated for only the part of the valley considered to be potentially usable as a ground-water reservoir. In this study, a 200-foot depth was selected as a practical valleywide depth limit for unwatering under full utilization of the ground-water reservoir, even though in localized areas sections in excess of 350 feet in depth have already been dewatered.

Some of the factors that locally limit the utilization of the ground-water reservoir are inferior water quality, relatively impermeable surface soils, and relatively impermeable subsurface deposits. On the basis of a detailed analysis of a peg model, the subsurface geology of the San Joaquin Valley was subdivided into predominantly permeable and impermeable zones in the 10- to 50-, 50- to 100-, and 100- to 200-foot depth intervals. In general, the areas considered most favorable for cyclic ground-water storage average 45 percent of sand and gravel in the various depth zones, and the less favorable areas contain only 10 to 20 percent of sand and gravel.

The average depth of irrigation wells within the 16 ground-water storage units in the valley ranges from 200 feet in the San Joaquin River, Fresno interstream, and Kings River units to 1,500 feet in the Mendota-Huron unit. On the basis of about 15,000 pump-test records, made available by local power companies, the average water level, average specific capacity, and average plant performance for each township within each of these 16 storage-unit areas are computed. About 40,000 irrigation plants were in operation in the valley in 1955–56; however, on the average these were running only 25 percent of the time. The ground-water draft in most parts of the valley could be substantially increased by greater use of existing facilities.

Artificial recharge of the ground-water reservoir by deliberate spreading of excess surface water has been effective in the following five districts: the Chowchilla Water District, the Madera Irrigation District, the Kaweah Delta Water Conservation District, the Lower Tule River Irrigation District, and the North Kern Water Storage District. Most of the water is spread in stream channels, canals, and spreading ponds and is dependent principally on the availability of low-cost water. In the North Kern Water Storage District, as much as 63,500 acre-feet of surface water was recharged into the ground-water reservoir in 1 year, at infiltration rates for periods of 100 to 150 days of operation ranging from 0.24 to 1.71 acre-feet per acre per day from 7 ponds. The average infiltration rate at 6 of these ponds was less than 1 foot per day.

Infiltration studies made by various agencies along stream channels, canals, and irrigation ditches are summarized to show magnitude of, and range in, seepage rates per mile of channel or per unit area. Infiltration rates along these streams were found to vary considerably, depending on geologic conditions, the stage of discharge, and the nearness of the water table. In general, the measured rates of infiltration along unlined-channel reaches on the east side of the valley ranged from 2 to 4 cfs per mile.

Infiltration measurements made by the U.S. Geological Survey in some of the larger canals in the Bakersfield area showed that the loss ranged from 0.3 to 1.7 feet per day per unit area, depending in part on canal stage. In general, infiltration rates were observed to decrease away from the apex of the

Kern River fan in the Bakersfield area. Studies were made also in various specially constructed ditches and test plots on the west side in the Mendota-Huron area to determine the rate of infiltration and the influence of different soil types. Infiltration rates from the test ditches were generally higher than those from square test plots, probably because of the greater lateral flow away from the area of water spreading.

Recharge, discharge, and ground-water storage change for three selected areas, jointly occupying about one-fifth of the valley floor, were analyzed to arrive at approximate average rates of infiltration of water from the land surface to the ground-water body in years of maximum water supply and to appraise the magnitude of storage depletion in a year of deficient supply. These are areas where recharge is largely incidental to irrigation, but in each area some measures are taken to increase the recharge by release of water to stream channels, canals, or spreading basins. In the Madera Canal service area, recharge by infiltration from irrigated areas ranged from 283,000 to 671,000 acre-feet per year in the 3 years studied. The average infiltration rate over the entire area ranged from 1.6 acre-feet per acre in 1943, a year of deficient supply, to 3.9 acre-feet per acre in 1952, a year of excessive runoff.

Similar analysis of the Fresno-Consolidated area indicated that in 1952, a year of excessive supply, infiltration of water from the land surface to the water table averaged 3.4 feet for the irrigated area and 2.7 feet for the gross area. In the Kern River area, corresponding figures for 1952 were 4.3 feet for the irrigated area and 1.8 feet for the gross area.

The analysis of the recharge to the ground water reservoir in the Madera, Fresno-Consolidated, and the Kern River areas shows that very large volumes of water infiltrate to the ground-water reservoir in years of surplus supply even under the existing regimen, in which recharge is chiefly incidental. Undoubtedly, if an ample supply were available, much greater quantities of water could be diverted to recharge by increased releases to stream channels, canals, and spreading basins and by greater application of water to the land.

Similar application of water to other favorable areas in the valley probably would greatly increase the present rate of replenishment. Thus, substantially more extensive use of ground-water storage capacity in the San Joaquin Valley seems physically feasible, and on the basis of present knowledge of geologic and hydrologic conditions, a major part of the 93 million acre-feet of ground-water storage capacity seems usable in cyclic storage operations.

INTRODUCTION

More than one-quarter of all the ground water pumped for irrigation in the United States is used in the San Joaquin Valley of California. Widespread pumping began about 1900 and, especially since 1940, has increased at an accelerated rate. In response to this heavy withdrawal, ground-water levels in extensive areas of the valley have declined rapidly. The water-level decline will continue as long as ground-water pumpage exceeds the natural and artificial recharge to these ground-water reservoirs.

Unconsolidated alluvial deposits, which constitute the principal source of ground water in the San Joaquin Valley, make up the extensive ground-water reservoir that underlies the valley floor to depths of hundreds of feet. This ground-water reservoir, which has storage capacity estimated to be 93 million acre-feet to a depth of 200 feet, equal to roughly 9 times the capacity of the present and proposed surface-water reservoirs in the valley, necessarily will have a major part in future water developments. The storage capacity of this vast ground-water reservoir can be effectively utilized, however, only to the extent that it can be emptied during periods of heavy demand and refilled during periods of surplus supply. Evaluation of the potential usable capacity of the ground-water reservoir is a complex problem, affected by economic and legal as well as by physical controls. Basic questions with respect to physical conditions are (1) where and how can recharge be accomplished, (2) at what rate can the water be put underground, and (3) at what rate can the reservoir be dewatered during periods of deficient supply.

SCOPE OF INVESTIGATION AND PURPOSE OF REPORT

In August 1954, as a result of conferences between the U.S. Geological Survey and the California Division of Water Resources (now the Department of Water Resources), it was agreed that the Geological Survey as part of its cooperative program with the State would make a reconnaissance of the utilization of ground-water storage capacity in San Joaquin Valley with specific reference to recharge.

The objectives of the investigation were to (1) assemble or obtain either qualitative or quantitative data on areas of ground-water storage capacity in the San Joaquin Valley that can be used for cyclic recharge and draft; (2) interpret such data in relation to the geologic and hydrologic conditions, in order to derive as specific answers as practicable regarding usable volumes of ground-water storage capacity; and (3) present obtainable facts and conclusions concerning areas where the ground-water reservoir can be recharged at a practical rate, methods of recharge that seem best suited, and the estimated rate at which recharge water can be put underground.

Collection of data and field investigation began in the early part of 1955 and continued until August 1956. Analysis of data and preparation of this report continued intermittently into 1959. The work has been done with funds made available jointly by the Geological Survey and the State for cooperative investigations of ground-water basins in California.

The investigation was made under the general supervision of J. F. Poland, then district geologist in charge of ground-water investigations in California, and under the direct supervision of G. H. Davis. The fieldwork on water losses from canals and ditches and on inter-aquifer circulation was done by B. E. Lofgren and P. R. Wood, assisted by R. L. Ireland, R. L. Swan, W. A Cochran, Jr, and W. B. Bull, of the Ground Water Branch, and R. E. Whitman, of the Surface

Water Branch, of the Geological Survey. Data were analyzed and the report was prepared by G. H. Davis, B. E. Lofgren, and Seymour Mack.

LOCATION AND GENERAL FEATURES OF THE AREA

The San Joaquin Valley constitutes roughly the southern two-thirds of the Central Valley of California (fig. 1). It is enclosed on

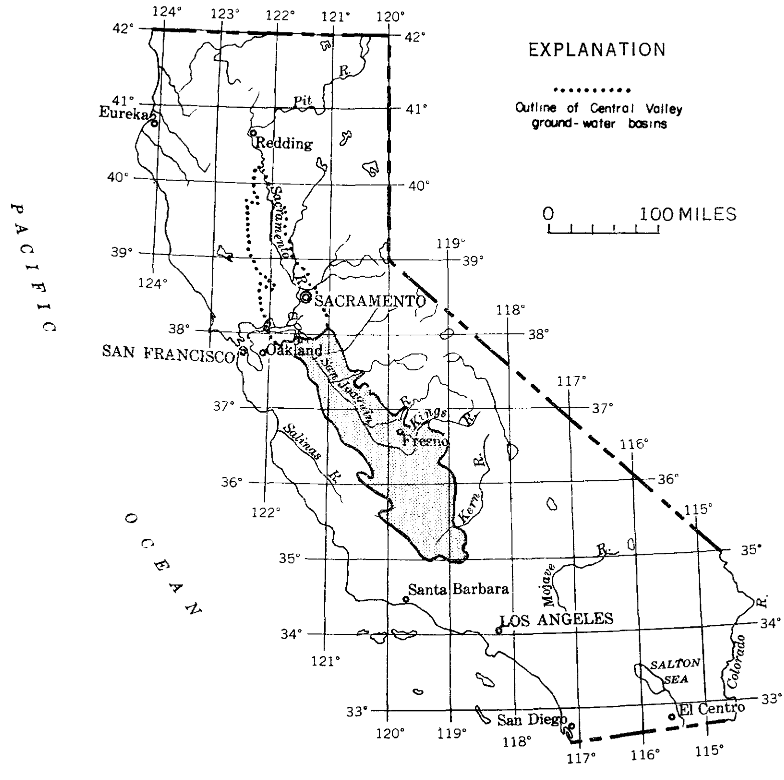

FIGURE 1.—Map of California showing area of this report

the east, west, and south by mountains, and on the north is continuous with the Sacramento Valley—the northern section of the Central Valley. To the east, the Sierra Nevada forms a continuous mountain wall, and to the west, the Coast Ranges are an unbroken barrier between the Central Valley and the Pacific Ocean, interrupted only at San Francisco Bay by the valley of the combined Sacramento and San Joaquin Rivers. The Tehachapi and San Emigdio Mountains form the southern boundary of the valley.

The San Joaquin Valley extends 250 miles from Stockton at the combined deltas of the Sacramento and San Joaquin Rivers to Grapevine at the foot of the Tehachapi Mountains (pl. 1). It ranges in width from 25 miles near Bakersfield to as much as 55 miles near Visalia and averages 35 miles in its entire length. The area of the valley floor is about 10,000 square miles, excluding the rolling foothills that skirt the mountains.

The valley floor slopes gently northward from an altitude of about 500 feet above sea level 21 miles south of Bakersfield to sea level in the Sacramento-San Joaquin Delta area. Alluvial fans along the sides of the valley rise to altitudes as high as 1,800 feet above sea level. The gentle northward slope of the valley is interrupted near the Kings River 15 miles west of Hanford by a low divide that has more than 25 feet of relief. This divide separates the San Joaquin Valley into two drainage basins; the northern one is tributary to the San Joaquin River, which discharges to the Pacific Ocean through San Francisco Bay; the southern one is a basin for the most part of interior drainage tributary to evaporation sumps in the trough of the valley, chiefly Tulare and Buena Vista Lake beds.

The southern part of the Sierra Nevada drains chiefly to the San Joaquin Valley through the San Joaquin River and its principal tributaries, the Stanislaus, Tuolumne, and Merced Rivers. It drains also through the Kings, Kaweah, Tule, and Kern Rivers, which discharge into Tulare and Buena Vista Lake beds. Part of the flood flow of the Kings River is tributary to the San Joaquin River by way of Fresno Slough, and at times during floods Tulare Lake has overtopped the low divide to the north and flowed into the San Joaquin River. Most of the drainage from the Coast Ranges is westward to the Pacific, and no large streams enter the San Joaquin Valley from the west.

The climate of the San Joaquin Valley is characterized by hot summers and mild winters. Midday temperatures in midsummer are high, occasionally 110°; extremes as high as 120° have been recorded. The diurnal temperature variation also is extreme; especially in summer when frequently it is 40° or more.

Annual precipitation decreases from north to south and from east to west across the valley. The average annual precipitation ranges from 3.99 inches at Buttonwillow in the southern part of the valley to 15.21 inches at Farmington in the northeastern part. On the west side, the range is from 3.99 inches at Buttonwillow to 9.55 inches at Tracy at the north end. On the east side, the range is from 6.22 inches at Bakersfield at the south end to 15.21 inches at Farmington. Precipitation figures are the mean for the 50 years 1897–1947 (California State Water Resources Board 1951, table 54).

Streamflow, which is the most important factor in the water supply of the San Joaquin Valley, depends almost wholly on the amount and distribution of precipitation in the Sierra Nevada. As moist air moves in from the Pacific Ocean and ascends the western slope of the Sierra Nevada, precipitation increases and reaches a maximum in the higher parts of the range. The mean annual precipitation exceeds 40 inches in much of the higher mountainous part of the Sierra Nevada tributary to the San Joaquin Valley and exceeds 60 inches in small isolated areas (California State Water Resources Board, 1951, pl. 3). During winter snowfall is heavy in the Sierra Nevada above the 3,000- to 4,000-foot-level; depths as great as 308 inches have been recorded at Donner Summit at the crest of the range in the Sacramento River drainage area (California State Water Resources Board, 1951, p. 308). The April 1 normal water content at that location, when the water content of the snowpack generally is at a maximum, is 44 inches. This snowpack acts as a natural storage reservoir of far greater capacity than manmade reservoirs in the area and retains most of the seasonal runoff until the late spring and early summer. For example, the average flow of the Kings River from March to June is 72 percent of its annual total (California State Water Resources Board, 1951, p. 346). The mean seasonal runoff to the San Joaquin Valley for the water years 1894–95 to 1946–47 is estimated by the California State Water Resources Board (1951, p. 407) to have been about 9.7 million acre-feet, of which 6.4 million acre-feet drained to the San Joaquin River and 3.3 million acre-feet to the Tulare Lake basin.

Precipitation and runoff in the Central Valley vary not only from winter to summer but from year to year. The runoff in a very dry year may be less than one-third of the average, and in very wet years the runoff may be greater than twice the average. Furthermore, there is a cyclic variation in precipitation and runoff characterized by periods of several years when the climate is wetter or dryer than normal. Hence, the dependable supply of surface water is limited by the quantity available in a series of dry years. The dependable natural supply, however, may be augmented by storing excess water during wet periods for use during dry periods. The need for such carryover storage may be met by constructing surface reservoirs or by utilizing ground-water reservoirs.

Depletion of ground-water storage by heavy pumping during periods of deficient runoff not only provides needed water supply, but also draws down the ground-water level and makes storage space available in which to conserve surplus water during periods of excess runoff. Such conservation is possible when the proper balance is maintained through an effective combination of pumping and replenishment. Full utilization of the water supply of the Central Valley will require utilization of both surface- and ground-water reservoirs in the most efficient combination.

ACKNOWLEDGMENTS

The writers are grateful for the cooperation and assistance received from other government agencies, Federal, State, and local, from private companies, and from individuals in the San Joaquin Valley. Water-level records, crop-survey information, and consumptive-use data were furnished by the California Department of Water Resources; U.S. Bureau of Reclamation; the Fresno, Consolidated, and Madera Irrigation Districts; the Buena Vista Water Storage District; and the Kern County Land Co. Engineers of the Pacific Gas & Electric Co. and the Southern California Edison Co. supplied information on pumpage and pump-test data. Special thanks are due to the Calflax Corp., Giffin Inc., and the Kern County Land Co. for cooperation and material assistance in canal and ditch-loss studies. Information on seepage rates from subsidence-test plots was made available by the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley.

WELL-NUMBERING SYSTEM

The well-numbering system used by the Geological Survey in California shows the locations of wells according to the rectangular system for the subdivision of public lands. For example, in the number 29/26–23R1, which was assigned to a well 8 miles west of Bakersfield, the part of the number preceding the slash indicates the township (T. 29 S.); the number following the slash is the range number (R. 26 E.); the digits following the hyphen is the section number (sec. 23); and the letter following the number indicates the 40-acre subdivision of the section as shown in figure 2 below.

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

FIGURE 2.—Well-numbering system.

Within each 40-acre tract, the wells are numbered serially, as indicated by the final digit of the well number. Thus, well 29/26–23R1 was the first well in the SE¼SE¼ sec. 23 to be listed. Other locations such as test plots, ditches, and weirs also have been designated within the proper 40-acre tract by this same system, but no number is used after the letter.

Most of the San Joaquin Valley is south and east of the Mount Diablo base line and meridian; the foregoing abbreviation, therefore, is sufficient for most well locations. The only exception applies to a small area in Kern County at the south end of the valley that is referred to the San Bernardino base line and meridian. To avoid confusion, wells in that area are distinguished by use of the letters *N* and *W* after the township and range numbers, respectively, as, for example, well 11N/20W–6N1 7 miles northwest of Wheeler Ridge.

COLLECTION OF DATA AND FIELD PROGRAM

Collection of data for the investigation began early in 1955. Major water-distribution agencies were canvassed for information relating to artificial-recharge experiments and operations, and crop-survey and consumptive-use data, as available, were collected for several water-service units proposed for detailed studies.

The field investigations were concerned chiefly with determining rates of infiltration in specific areas and rates of movement of water from aquifers of high head to those of low head through wells tapping both. As a part of the infiltration studies, field tests were carried out on several canals diverting from the Kern River during June and July 1955. During April to June 1956, deep-well current-meter measurements were made of circulation between water-bearing zones in 25 irrigation wells in western Fresno County. In June and July 1956, carefully controlled measurements of water losses by infiltration were made in two ditches constructed for that purpose in western Fresno County. Measurements of water losses were made in test plots operated by the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley from the summer of 1956 to the summer of 1958 chiefly for investigating land-surface subsidence.

GEOLOGIC SETTING

MAJOR LANDFORMS

The Central Valley of California is a great structural downwarp between two zones of uplift, the Sierra Nevada block on the east and the Coast Ranges on the west. These main topographic features are fairly old, the San Joaquin Valley having received the erosional debris from the flanking highlands almost continuously since late Mesozoic time.

The topography of the San Joaquin Valley may be divided into several geomorphic types as follows: (1) Dissected uplands, (2) low alluvial plains and fans, (3) river flood plains and channels, and (4) overflow lands and lake bottoms (pl. 1).

The dissected uplands along the margins of the valley are underlain by unconsolidated to semiconsolidated continental sediments of late

Tertiary and early Quarternary age that have been slightly to moderately tilted or folded. The topography varies from deeply dissected hill land, where the relief is as great as 500 feet, to gently rolling land, where the local relief is not more than 10 feet.

The low alluvial plains and fans, which border the dissected uplands along their valleyward margins, are generally flat and relatively featureless and are underlain by undeformed to slightly deformed alluvial deposits. These plains occupy most of the valley floor and comprise the most intensively developed agricultural and urban areas.

The river flood plains and channels lie along the San Joaquin and Kings Rivers in the trough of the valley and along the major streams of the east side that drain the Sierra Nevada. The flood plains are well defined where the rivers are incised below the levels of the low plains and fans and the dissected uplands. The underlying deposits are made up largely of coarse sandy materials laid down in the streambeds and finer silty materials spread over the flood plains at times of high water. Where the rivers are flanked by low-lying overflow lands, as in the trough of the valley, the flood plains might be considered as extending the full width of the overflow lands. Silty deposits similar to those laid down on the well-defined flood plains are generally confined to the natural levees that slope away from the rivers; therefore, this report restricts the term "flood-plain deposits" in the trough of the valley to these natural levees.

The overflow lands and lake bottoms include the historic beds of Tulare, Buena Vista, and Kern Lakes, now largely reclaimed for cultivation, and the topographically low lands in the trough of the valley between the low plains and the natural levees of the trunk streams. These low lands were poorly drained under natural conditions, when they were flooded periodically. Much of the overflow land is now protected from flooding by levees and artificial floodways, but thousands of acres, particularly in the southern part of the valley, are still subject to periodic flooding.

To the east of the San Joaquin Valley, the Sierra Nevada rises in a distance of about 60 miles to a crestline ranging from 9,000 to more than 14,000 feet in altitude. From the highest altitude at Mount Whitney (14,495 ft), the altitude of the crestline declines generally northward.

GENERAL GEOLOGY

The Sierra Nevada may be compared with a tilted plateau, uplifted along a series of faults along its east flank and depressed along its west flank, where it is overlain by the sedimentary deposits of the Central Valley. Because of this marked asymmetry of the Sierra Nevada, its crestline lies along the eastern border of the range. Near the south end, the general trend of the range is complicated by major faults near the valley border, which break the Sierra block, and along which differential movement has taken place.

The Coast Ranges, which border the valley on the west, comprise a series of longitudinal ranges and intervening valleys oriented parallel to the long axis of the San Joaquin Valley. The topography of the Coast Ranges is dominated by the geologic structure, which is characterized by parallel faults and folds oriented about N. 30°–40° W.

The south and southeast borders of the valley are formed by the foothills of the San Emigdio and Tehachapi Mountains, respectively. These ranges represent a transition between the geologic structures of the Sierra Nevada and the Coast Ranges. Here the granitic rocks of the Sierra and the fringe of Tertiary sediments curve southwestward to the San Andreas fault. The Tertiary sedimentary rocks are progressively more deformed toward the west as the linear folded structures of the Coast Ranges are approached.

The rocks forming the Sierra Nevada include metamorphosed shale, sandstone, limestone, and chert, intruded by great masses of granodiorite and related igneous rocks.

Recent age determinations by the potassium-argon method (Curtis and others, 1958, p. 10–13) indicate that the plutonic rocks of the Sierra Nevada were emplaced during two distinct periods of orogeny. The older rocks range in age from 133 to 143 million years and were emplaced in Late Jurassic time. The younger rocks range in age from 78 to 95 million years and were emplaced in Late Cretaceous time.

In the Coast Ranges, the Franciscan and Knoxville formations, in part equivalent to the metamorphic rocks of the Sierra Nevada, are exposed. Most of the Coast Ranges, however, are formed of younger sedimentary formations, strongly folded and faulted, and no extensive igneous mass contemporaneous with that of the Sierra Nevada is present.

The basement of structural floor of the Central Valley has been shown to be asymmetrical. It slopes gently westward to its greatest depth near the western margin of the valley. Within this trough lies a fairly complete section of strata of Cretaceous, Tertiary, and Quaternary ages, indicating almost continuous deposition throughout that time. The trough was at one time an arm of the sea, and dominantly marine sediments were deposited until about the middle of the Tertiary period; however, the proportion of nonmarine sediments has gradually increased from that time to the present.

The maximum thickness of sedimentary rocks is at the southern end of the valley where Tertiary and Quaternary sediments aggregate 28,000 feet just north of Wheeler Ridge (Dibblee and Oakeshott, 1953, p. 1502). Accumulation of sediment and consequent downwarping has been so rapid in this area that the postmiddle Pliocene continental deposits exceed 15,000 feet in thickness (de Laveaga, 1952, p. 102).

The Sierra Nevada block has been tilted westward since Late Cretaceous time, causing it to shed erosional debris westward into the Central Valley, and also giving a westward tilt to the sediments that lap upon the block. The older formations are more tilted than the younger ones because of the progressive or intermittent tilting, and no folding of consequence occurred during this movement. Compression was dominant in the area west of the trough and resulted in the complex folded and faulted structures of the Coast Range and such notable petroliferous anticlines as Kettleman Hills.

The extensive alluvial fans along the eastern margin of the valley contain high proportions of clean well-sorted gravel and sand deposited by the perennial streams flowing westward from the Sierra Nevada—the Stanislaus, Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern Rivers. These fans are very extensive because the streams that built them were continually shifting laterally from channels clogged with sediment. The materials in the fans are heterogeneous in that the channel deposits are interbedded with the somewhat finer grained and less well-sorted deposits which were spread beyond the channels during floods. The channel deposits become progressively finer grained away from the canyon mouths, and, ordinarily, the maximum grain size is that of coarse sand only a few miles from the mountain front, where the permeability of the fan deposits is high.

The interstream areas between the major alluvial fans along the east side of the valley are underlain by poorly sorted fine-grained fluvial sediments deposited by intermittent streams. Wells drilled in these areas commonly penetrate poorly sorted silt, fine sand, and clay, interbedded with a few lenses of coarse sand or gravel that represent buried channels of minor streams. The permeability of sediments in these zones is considerably lower than that of the principal fan materials.

The streams along the southern and western parts of the valley drain small areas on the leeward side of the Coast Ranges. The total runoff from these intermittent streams is small, although they are subject to sudden floods. Extensive fans have been built, but the sediments are poorly sorted and contain high proportions of fine sand, silt, and clay. In many areas the unsorted products of torrential-stream deposition, commonly identified in well logs as "clay and gravel," are common. The alluvial sediments of the western and southern parts of the valley, as a general rule, are of low permeability in comparison with the fluvial deposits of the east side.

Near the trough of the valley the fluvial deposits of both the east and west sides of the valley grade into, and interfinger with, extensive masses of fine-grained sediments deposited in lakes and swamps. These sediments consist of clay and silt and well-sorted sand deposited in lakes as deltas near the mouths of rivers. The area of lake and swamp deposition has shifted widely in the past in response to climatic and geologic changes, but it has been confined mostly to the central part of the valley. Lacustrine conditions presumably were most widespread during late Pliocene time, when the diatomaceous Corcoran clay member, 20 to 150 feet thick, was deposited over a 5,000 square-mile area, extending from the north end of the valley southward to Buttonwillow. The stream-channel deposits in the central part of the valley are well sorted, but generally they are fine grained because of the low stream gradient.

GROUND WATER

OCCURRENCE

The unconsolidated continental deposits are the principal source of ground water in the San Joaquin Valley. These deposits, consisting chiefly of alluvium but in some areas including widespread lacustrine sediments, are far more permeable than the consolidated rocks that make up the surrounding mountains. The consolidated rocks in general are barriers to ground-water movement. The ground-water basin is continuous northward to the ground-water basin of the Sacramento Valley.

Ground water occurs under unconfined (water-table) and confined (artesian) conditions. The water table, or surface of an unconfined water body, is the upper surface of the zone of saturation, where the hydrostatic pressure is equal to the atmospheric pressure. Confined water is contained in aquifers overlain by materials of sufficiently low permeability to hold water in the aquifer under pressure. Ideal examples of either type of occurrence are rare in nature, because even the least permeable confining beds permit slow, perhaps imperceptible, movement into or out of confined aquifers. Conversely, water bodies that appear to be unconfined may respond to stresses of short duration, such as barometric variations and earthquake shocks, in much the same manner as bodies of confined water.

Because of the heterogeneity of the alluvial deposits of the San Joaquin Valley, the degree of confinement differs widely. In much of the alluvial fill, movement of ground water is inhibited sufficiently to cause differences in head between aquifers during periods of heavy pumping; but, during periods of little draft, water levels recover to a level coincident with the water table. Under such conditions, ground water is said to be semiconfined, implying that, although the aquifers are subject to pressure effects over short periods, the artesian head adjusts to equilibrium with the water table over long periods of time.

Throughout much of the western, central, and southeastern parts of the San Joaquin Valley, three distinct bodies of ground water occur. In downward succession these are (1) A body of unconfined and semiconfined fresh water in alluvial deposits of Recent, Pleistocene, and possibly late Pliocene age, overlying the Corcoran clay member of the Tulare formation; (2) a body of fresh water, which is confined beneath the Corcoran clay member, and which occurs in alluvial and lacustrine deposits of late Pliocene age or older; and (3) a body of saline connate water contained in marine sediments of middle Pliocene or older age, which underlies the fresh-water body throughout the area.

Much of the eastern part of the valley, especially the areas of the alluvial fans of the major streams from the Stanislaus River south to the Kaweah River, is not underlain by the Corcoran clay member of the Tulare formation; consequently, only one unconfined to semiconfined fresh-water body occurs in these areas.

Confined aquifers occur in several areas of the San Joaquin Valley. The extent of confining beds is discussed in some detail in a previous report of the Geological Survey (Davis and others, 1959, p. 76–81). The most extensive confining unit in the valley is the Corcoran clay member, which underlies the central and western parts of the valley.

Ground water is confined effectively also in other areas beyond the known extent of the Corcoran clay member, notably in the area east of Delano, along the southeastern and southern margins of the valley, and beneath Buena Vista Lake bed. Davis and others (1959, p. 88) suggest that the confinement in the area east of Delano may be caused by fine-grained swamp deposits that probably represent an eastward extension of the Corcoran clay member. Confinement in aquifers along the southern rim of the valley may be caused by poorly sorted fluvial deposits of low permeability derived from the flanking mountains and by lacustrine strata deposited in an ancestral Buena Vista Lake.

SOURCE OF GROUND WATER

The ultimate source of the ground water in the San Joaquin Valley is precipitation in the valley and its tributary drainage basins. Replenishment to the ground-water body may be either by infiltration of rain, by infiltration from streams, canals, ditches, and ponds, by underflow through the permeable materials in the tributary stream canyons, and by infiltration of irrigation water applied in excess of plant requirements.

Infiltration of rain may be a significant source of recharge to the ground water when soil moisture is not deficient. In much of the valley, however, the annual rainfall is so low that soil-moisture deficiency is perennial, and infiltration of rain is not significant.

Infiltration from streams flowing across the valley is an important source of recharge to the ground-water body, and before large-scale irrigation it was the principal source. Measurements of flow at various points along the streams entering the valley commonly indicate channel losses of many thousands of acre-feet per year, most of which represents recharge to the ground-water body. The intermittent streams that enter the valley along its western and southern borders lose some of their flow by evapotranspiration; but most of the water infiltrates, except in times of exceptional flood when surface flow is established to the main drainage of the valley. None of the streams south of Los Banos Creek on the west side of the valley and south of the Kern River on the east side have well-defined channels reaching the main drainage of the valley, which indicates that little water leaves these areas as surface flow.

Infiltration losses from irrigation canals and ditches and infiltration by excess irrigation water applied to cultivated lands contribute heavily to the ground-water supply—doubtless a greater contribution than that from the stream channels. Where the soil and underlying material are of low permeability, as in the central part of the valley (pl. 3), the downward penetration of water is slow. Accordingly, infiltration from canals and ditches is small in such areas, and most of the irrigation water in excess of crop need runs off in drainage channels or collects in closed depressions. Where the soil and underlying material are relatively permeable, as on the low plains on both sides of the valley, infiltration from canals may take up a substantial portion of the total supply of irrigation water. To satisfy irrigation demands in such areas sufficient water must be diverted to offset canal losses and still leave enough water for farm delivery. The overall effect is that replenishment of ground water is much greater than where the soil is impermeable.

The confined aquifers are recharged principally by inflow of water from unconfined and semiconfined deposits beyond the featheredges of the confining beds; but presumably they are also recharged in part from slow downward penetration of water through the confining beds where the hydraulic gradient is favorable.

GROUND-WATER MOVEMENT

Ground water moves, in response to the hydraulic gradient, from areas of recharge to areas of discharge. Under natural conditions, the unconfined and semiconfined ground water in the San Joaquin Valley moved from recharge areas along the sides of the valley toward topographically low central areas, where it was discharged at the land surface or was consumed by plants.

Water-level contours, based on measurements made in 1905–07 (Mendenhall and others, 1916, pl. 1), show that the movement of ground water in the unconfined and semiconfined deposits at that time was generally in the direction of the slope of the land surface. Little information is available on the hydraulic gradient in the principal confined aquifer during early development, but it is presumed that the water moved slowly toward the center of the valley and then northward in the direction of the Sacramento-San Joaquin Delta. The artesian head in the confined aquifer was sufficient to raise the water level above the land surface in wells tapping that aquifer beneath much of the central part of the valley (Mendenhall and others, 1916, pl. 1). Some water, therefore, must have moved upward through the confining clay bed in the central area.

The diversion of surface water from the streams and the development of ground-water supplies for irrigation have lowered the water level, changed the hydraulic gradient, and in some places, the direction of movement of the ground water. Water-level contours in the spring of 1952 (Davis and others, 1959, pl. 15) show that ground water in the unconfined and semiconfined aquifers at that time was moving chiefly from areas irrigated by surface water to areas of discharge, chiefly areas of heavy irrigation pumpage, and to natural drains in areas of heavy application of surface water. Movement of the water in the confined deposits was toward areas of heavy pumpage of ground water, which now are the principal zones of discharge.

Fluctuations of water levels in wells indicate changes in the amount of ground water in storage, for they occur chiefly in response to changes in the rates of recharge or discharge of ground water. These fluctuations may be classified as seasonal and as long-term (persistent) changes. In areas where recharge is comparatively slow and where pumping has been heavy, water levels have declined consistently, and the amount of water in storage has decreased. In areas where the rate of recharge is high in proportion to the amount of water pumped, the water levels are drawn down during the pumping season but recover when pumping stops. The long-term trends in such areas are related to climatic variations and the resulting variations of the streamflow. Water-level trends in the unconfined and semiconfined aquifers commonly reflect long-term trends in runoff in the streams, which are the sources of recharge to the ground-water body. Accordingly, during periods of deficient runoff, water levels may decline fairly consistently for several years; conversely, during periods of excessive runoff, water levels may rise consistently for several years (Davis and others, 1959, pls. 17–23, figs. 2–4).

USE OF GROUND WATER

Ground water was the chief source of water for all uses in the San Joaquin Valley in 1957. Because of its ready availability and convenience, its use for irrigation has exceeded that of surface water. Because of its purity and convenience, it is also virtually the only source of municipal, industrial, domestic, and stock water.

The census of 1950 (U.S. Census of Agriculture, 1952, p. 3–44) indicated that 24 percent of the irrigated land in the San Joaquin Valley was supplied by surface water, 51 percent was supplied by ground water, and 25 percent was supplied by a combination of the two. The California State Water Resources Board (1955, table 104) estimated that as of about 1951 3.145 million acres was irrigated in the San Joaquin Valley south of Stockton. To supply this irrigation demand, gross surface-water diversions in 1952 approximated 8.5 million acre-feet, and ground-water pumpage approximated 7.5 million acre-feet in 1952 (fig. 3). Demand for water for other uses is minor in comparison with that for irrigation; for example, water deliveries to urban and

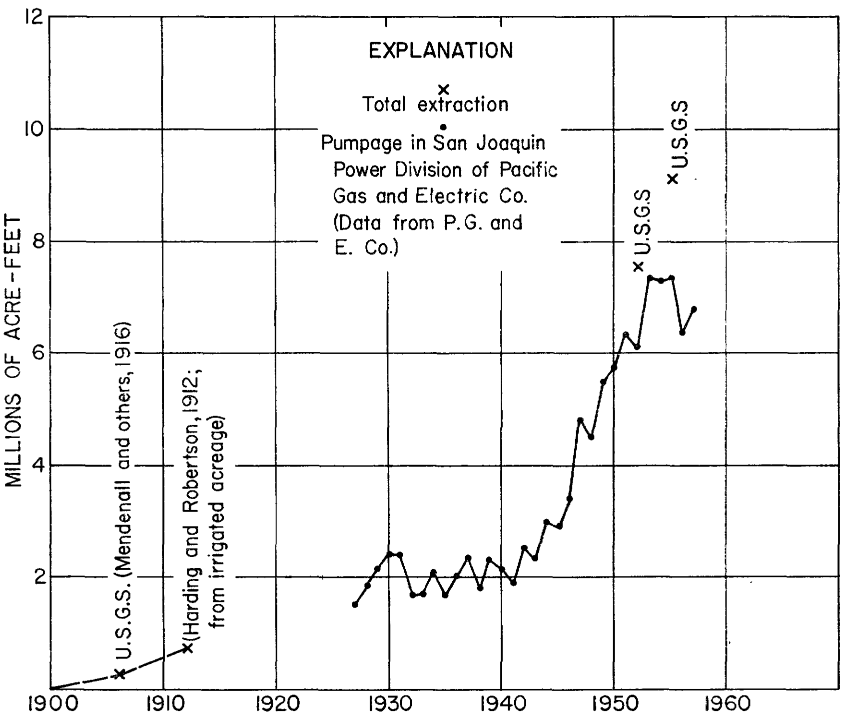

FIGURE 3.—Extraction of ground water for irrigation in the San Joaquin Valley, 1900–57.

suburban areas in the San Joaquin Valley as of about 1951 were estimated to be 135,000 acre-feet (California State Water Resources Board, 1955, tables 106, 114).

Continued increase of irrigated acreage in the San Joaquin Valley after 1951 caused an increase in ground-water pumpage to almost 9 million acre-feet by 1955–56 (table 2). The amount of ground-water pumped for irrigation for the period 1900–57, based on the best available data, is shown graphically in figure 3. Ground water was not utilized extensively for irrigation in the San Joaquin Valley until about 1900. By slow but steady growth, ground-water withdrawal had reached about 225,000 acre-feet per year by 1906 (Mendenhall and others, 1916, table 4). Harding and Robertson (1912, p. 192) reported that 171,760 acres was irrigated by ground water in the San Joaquin Valley in 1912. About 700,000 acre-feet of ground water, or about 4 feet of water per acre, was needed to irrigate this area.

For the period 1927–57, estimates of annual ground-water pumpage in the area served by the San Joaquin Power Division of the Pacific Gas & Electric Co., were used in compiling figure 3. The method used in arriving at the amounts shown is described on page 34. Figure 3 shows an overall increase in pumpage in the San Joaquin Power Division area from about 1.5 million acre-feet in 1927 to about 6.8 million acre-feet in 1957. Most of this increase took place between 1945 and 1953 during a period of high crop prices.

Estimates of total pumpage in the San Joaquin Valley were made by the Geological Survey for 1952 and 1955 by supplementing the estimates of the Pacific Gas & Electric Co. with other data, as described on page 34. The estimate shown for 1955, about 9 million acre-feet, represents more than a quarter of the withdrawal of ground water for irrigation in the United States for that year (MacKichan, 1957.)

GROUND-WATER STORAGE CAPACITY

Preceding sections of this report indicate that the rainfall on, and recharge to, the San Joaquin Valley differ greatly from year to year and also over longer periods. Water stored in the permeable deposits in the San Joaquin Valley helps to moderate the fluctuations in surface supply caused by seasonal and long-term variations in rainfall and recharge and provides a dependable source in periods of drought. Without this underground storage, the water economy of the area would be limited to the water supply available during the driest years.

Beneath much of the valley, water-bearing deposits contain fresh water at depths far greater than those now reached by wells. The ground-water storage capacity of economic importance, however, referred to here as "total storage capacity," is that generally within economic reach of present-day pumping equipment and use. The following section deals only with the uppermost 200 feet of materials below the land surface.

Thomasson and others (1960, p. 279), in the study of the Putah area in the southwestern part of the Sacramento Valley, used the following terms in describing ground-water storage capacity: (1) The total storage capacity; (2) the natural reservoir capacity, or the part of the total capacity required to level out cyclic variations in recharge from natural sources; (3) the artificial reservoir capacity, or the part that could be unwatered and replenished artificially to augment the natural supply; and (4) the remainder of the total capacity. This remainder, item (1) less items (2) and (3) would not increase the perennial safe supply of the area. The sum of items (2) and (3) is commonly referred to as the usable ground-water storage capacity of a ground-water reservoir.

The Geological Survey recently issued a report on ground-water conditions and storage capacity of the San Joaquin Valley (Davis and others, 1959), from which the following discussion (p. 19–22) is summarized.

The ground-water storage capacity estimated for the San Joaquin Valley is the volume of water that would drain by gravity from the materials underlying the several ground-water storage areas if the regional water level were lowered from 10 feet below the land surface to 200 feet below the land surface. It may be defined also as the volume of water required to resaturate the deposits after they are drained.

SELECTION OF DEPTH ZONES

Throughout most of the valley, storage of water within 10 feet of the land surface probably would not be practicable because of the danger of waterlogging. The 200-foot depth was selected as a practical valleywide depth limit for unwatering under full utilization of the ground-water reservoir for cyclic storage, although local unwatering to depths substantially greater than 200 feet may be economically feasable. Unwatering to depths as great as 350 feet already has occurred locally in the southeastern part of the valley, east of U.S. Highway 99 between Earlimart and Bakersfield, and near Wheeler Ridge. Thus, the upper limit of the storage zone is fixed by physical conditions, but the lower limit is arbitrary, and may need to be modified, as operating experience dictates. The storage capacity within the 10- to 200-foot depth range was estimated for 3 depth zones to allow flexibility in future studies of the operation of the ground-water reservoir. The 3 depth zones are 10 to 50, 50 to 100, and 100 to 200 feet below the land surface.

The storage capacity of the deposits in the San Joaquin Valley was derived by multiplying the volume of sediments in each of several storage unit by estimated specific yields. The specific yield of a rock is defined by Meinzer (1923, p. 28) as the ratio of the volume of water a saturated sample of rock material will yield by gravity to the volume of the sample. The procedure involved several basic steps as follows: (1) Construction of a three-dimensional peg model of the valley; (2) subdivision of the valley into subareas, the deposits beneath which comprise the ground-water storage units; (3) selection of the 10- to 50-, 50- to 100-, and 100- to 200-foot depth zones for analysis; (4) grouping of materials described in well logs according to ranges of permeability; (5) assignment of average specific-yield values to the several categories of material; and (6) computation of ground-water storage capacity.

AREAS FOR WHICH STORAGE CAPACITY WAS COMPUTED

Storage capacity was computed only for the part of the San Joaquin Valley potentially subject to operation as a ground-water reservoir. The bordering Sierra Nevada and Coast Ranges, which are underlain chiefly by non-water-bearing rocks, were excluded, as were most of the dissected uplands along the margin of the valley and the lake beds and overflow lands along the valley trough. The dissected uplands were excluded primarily because of the low permeability of the underlying materials and the deep dissection of the terrane. The lake beds and overflow lands were not considered because of the low permeability of the soils, excessive accumulation of harmful salts and alkali in the soils, and susceptibility of the areas of flooding. A few small areas near the valley margin were excluded because of insufficient well-log data. A total of approximately 1,367,000 acres within the valley thus was excluded from computations of storage capacity.

The remainder of the valley, comprising principally the low plains and fans, was divided into 16 ground-water storage units (pl. 2). Subdivision of the valley deposits into storage units was made by analysis of the subsurface geology represented on the peg model, specifically the geology of the deposits within 200 feet of the land surface. By this analysis it was possible to obtain a generalized separation of sediments deposited in the various fan and interfan areas. The 16 storage units include a total of approximately 4,724,000 acres.

As estimated by the method described above, ground-water storage capacity in the San Joaquin Valley totals 93,000,000 acre-feet in the uppermost 200 feet of sediments. This figure is broken down in table 1

TABLE 1.—*Estimated ground-water storage capacity of the San Joaquin Valley, by ground-water storage units*

[Davis and others (1959, table 8, p. 252)]

Ground-water storage unit	Area (acres)	Depth, in feet								Number of wells used			
		10–50		50–100		100–200		All zones					
		Specific yield (percent)	Storage capacity (acre-feet)	Specific yield (percent)	Storage capacity (acre-feet)	Specific yield (percent)	Storage capacity (acre-feet)	Specific yield (percent)	Storage capacity (acre-feet)	10–50	50–100	100–200	Total
Tuolumne River	571,000	12.8	2,930,000	12.0	3,420,000	8.5	4,840,000	10.3	11,190,000	694	545	277	652
Merced Interstream	99,000	8.1	320,000	7.5	370,000	4.8	480,000	6.2	1,170,000	61	56	38	61
Chowchilla River	129,000	7.5	390,000	6.9	450,000	6.2	800,000	6.6	1,640,000	60	62	45	65
San Joaquin River	462,000	10.5	1,940,000	11.6	2,680,000	12.6	5,860,000	11.9	10,480,000	392	393	216	411
Fresno Interstream	49,000	8.2	160,000	7.4	180,000	5.3	260,000	6.4	600,000	87	84	28	90
Kings River	576,000	14.1	3,250,000	12.2	3,520,000	12.4	7,160,000	12.7	13,930,000	553	467	191	573
Dinuba Interstream	96,000	6.8	260,000	8.3	400,000	5.8	560,000	6.7	1,220,000	139	124	74	151
Kaweah-Tule River	481,000	9.5	1,830,000	10.4	2,490,000	9.8	4,730,000	9.9	9,050,000	705	706	570	772
Lindsay Interstream	60,000	6.2	150,000	6.7	200,000	7.3	440,000	6.9	790,000	96	97	95	104
White-Poso	289,000	9.5	1,100,000	8.6	1,240,000	9.1	2,620,000	9.1	4,960,000	503	502	501	525
Kern River	446,000	12.7	2,260,000	13.2	2,940,000	12.5	5,590,000	12.7	10,790,000	510	514	437	528
Edison-Maricopa Front	238,000	12.0	1,140,000	14.0	1,670,000	13.3	3,160,000	13.2	5,970,000	230	238	254	256
Antelope Plain	[1] 285,000	[2] 7½	860,000	[2] 7½	1,070,000	[2] 7½	2,140,000	[2] 7½	4,070,000				
Mendota-Huron	639,000	8.3	2,130,000	8.8	2,820,000	9.0	5,990,000	9.0	10,940,000	46	116	171	171
Los Banos	103,000	10.9	450,000	11.3	580,000	11.6	1,200,000	11.4	2,230,000	52	57	48	60
Tracy-Patterson	201,000	11.9	960,000	10.7	1,080,000	10.0	2,000,000	10.6	4,040,000	193	192	179	204
Total for storage units	4,724,000	10.6	20,100,000	10.6	25,100,000	10.1	47,800,000	10.3	93,000,000	4,276	4,153	3,124	4,623
Excluded areas:													
Buena Vista Lake bed	[1] 37,000												
Tulare Lake bed and vicinity	[3] 969,000												
Dos Palos area	[1] 361,000												
Total excluded	[1] 1,367,000												
Grand total of storage and excluded areas	[4] 6,091,000												

[1] Area measured on 1:250,000 base map of San Joaquin Valley.
[2] Approximate figure (assumed); probable range 5–10 percent.
[3] Tulare Lake area, 683,000 acres; Fresno Slough area, 286,000 acres.
[4] 9,517 square miles.

into 20,100,000 acre-feet in the interval 10 to 50 feet, 25,100,000 acre-feet in the interval 50 to 100 feet, and 47,800,000 acre-feet in the interval from 100 to 200 feet below the land surface.

CYCLIC STORAGE IN GROUND-WATER RESERVOIRS

FLUCTUATIONS OF GROUND-WATER STORAGE

Changes in the quantity of water stored in the underground reservoir are indicated by fluctuations of water levels in wells. The significant water-level fluctuations fall into two broad classes—those that occur annually and reflect seasonal variations in runoff and those that occur over a period of several years and reflect variations in the total precipitation. The annual fluctuations are superimposed on the long-term fluctuations.

Fluctuations in ground-water storage in unconfined aquifers are analogous to changes in storage in surface reservoirs, because the water level in both rises as a result of inflow or recharge and declines as a result of outflow or discharge. Long-term increases of water in storage in surface reservoirs are classed as "carry-over storage." Rising ground-water levels indicate a similar carry-over storage in ground-water reservoirs.

Annual changes in the quantity of water in storage in the ground-water reservoir generally are related to differences in the rate and amount of replenishment to, and withdrawals from, the ground-water reservoir.

As described on page 7, the snowpack of the Sierra Nevada acts as a natural reservoir and retains most of the annual precipitation in the mountains until late spring and early summer. Accordingly, on the east side of the San Joaquin Valley, ground-water storage in areas tributary to unregulated streams reaches a maximum during the late spring and early summer period of heavy streamflow. In areas served by regulated streams, the period of maximum ground-water storage coincides with the periods of heaviest application of water for irrigation in midsummer.

Little snow falls in the barren Coast Ranges, although the distribution of precipitation is similar to that of the Sierra Nevada. The region has only a scanty vegetation and sparse soil cover; little of the precipitation, therefore, is retained for a substantial length of time, but most runs off shortly after the rain falls. Accordingly, the unconfined ground-water basins tributary to these mountains on the west side of the San Joaquin Valley generally reach their maximum storage level during the winter period of maximum precipitation and streamflow.

Ground-water storage is at a minimum when replenishment from streamflow is small and discharge from the reservoir is large. In most of the valley, this minimum-storage level is reached in early autumn before winter precipitation in the valley or mountains. In the southern part of the valley, however, where many winter crops are grown and winter withdrawals of ground water for irrigation are heavy, the minimum ground-water storage level occurs locally in early winter.

The long-term fluctuations in ground-water storage are related to cyclic variations in the annual precipitation on the drainage basins tributary to the San Joaquin Valley. In California, cyclic variations are common, in which the annual runoff is considerably above or below average in a succession of wet or dry years, respectively. Fluctuations of water levels in wells completed in confined aquifers represent changes in artesian pressure, which in areas distant from a source of recharge are related chiefly to elastic compression of the deposits in response to changing loads. In wells that tap semiconfined deposits, most short-term fluctuations over periods of as much as a few months may represent changes in pressure, whereas the long-term fluctuations over periods of a year or longer generally represent unwatering or refilling of the deposits. Changes in storage indicated by fluctuations in artesian pressure cannot be computed by the specific-yield method, but under certain conditions they can be analyzed mathematically from observations of the behavior of water levels in wells during pumping of a nearby well (Theis, 1935, p. 522).

NATURAL AND ARTIFICIAL RESERVOIR CAPACITY

The natural reservoir capacity of a ground-water basin is that part of the total storage capacity that is required to store the recharge from natural sources through cyclic variations of supply and demand. If the natural recharge were constant from year to year, this volume would be equivalent to the difference between recharge and withdrawals during a seasonal cycle. However, because the annual recharge is not constant, the natural reservoir capacity must include not only the volume dewatered during normal seasonal fluctuations but also for a volume which, if unwatered in a series of dry years, would be recharged naturally in a series of wet years.

The artificial reservoir capacity of a ground-water basin is that part of the total storage capacity that could be unwatered in a series of dry years and recharged artificially with imported water in a series of wet years. This volume plus the natural reservoir capacity equals the usable storage capacity, which is the volume of sediments that can be dewatered economically in a basin or ground-water storage unit.

Quantitative estimates of the usable ground-water storage capacity of the San Joaquin Valley would require costly and extensive testing in the field, which was beyond the scope of this investigation. However, factors tending to limit the utilization of the ground-water storage reservoirs are discussed below.

FACTORS LIMITING UTILIZATION OF GROUND-WATER RESERVOIRS

QUALITY OF WATER

Most of the ground water in the 10- to 200- foot depth interval in the San Joaquin Valley is of usable quality. Consequently, water quality probably would not limit the utilization of the ground-water reservoirs for carryover storage except in a few areas. The most extensive bodies of ground water of inferior quality are beneath the trough of the valley (pl. 2). Most of these bodies are in areas that already have been excluded from consideration as ground-water storage reservoirs because of the low permeability of the surface or subsurface deposits. Areas containing water of poor quality within the ground-water storage reservoirs are (1) an area of about 20 square miles west and south of Mendota, where the ground water of the upper water-bearing zone commonly contains more than 2,500 ppm (parts per million) and some contains as much as 5,000 ppm of dissolved solids and 1,000 ppm of chloride (Davis and Poland, 1957, p. 462); (2) an area of western Fresno County, near Panoche and Little Panoche Creeks, where the ground water of the upper water-bearing zone contains high concentrations of chloride and boron (Davis and Poland, 1957, p. 462); (3) an area along the eastern margin of the Antelope Plain unit, where wells yield sulfate chloride waters of 1,500 to 3,000 ppm dissolved solids (Wood and Davis, 1960, p. 60); (4) areas along the eastern border of the valley in the Lindsay interstream unit, where beds containing high sodium chloride waters locally are penetrated by wells within 300 feet of the land surface (U.S. Bur. Reclamation, 1948, pl. 14 and table 3); and (5) a poorly defined area in the western part of the Tuolumne River unit where wells drilled to depths greater than about 100 feet locally penetrate beds containing water high in sodium and chloride (Davis and others, 1959, pl. 5). Plate 2 shows the area underlain by water of poor quality within the various storage units.

IMPERMEABLE SOILS

The permeability of a soil relates to the ability of the soil to transmit fluids. The surface character of soil commonly is the controlling factor in infiltration of water, but the volume and nature of the pore spaces also are of importance. Baver (1948, p. 237) points out that most of the water that passes through the soil moves through the larger noncapillary pores. Soils whose pores are in the capillary size range, such as clay, are virtually impervious. Vertical cracks, rootholes, worm holes, and other openings greatly increase the infiltration of water through a soil; but extensive beds of clay, cemented zones, or other horizontal features reduce the infiltration rate. The adsorbed cations in soils and in water applied to soils also may affect their permeability, particularly those of a clayey type (Baver, 1948, p. 137).

The infiltration of water through a soil is governed by the least permeable member of the profile. Young soils that have little profile development are the most homogeneous and have the highest permeability. Old soils, conversely, show much profile development and commonly contain accumulations of clay or cemented zones of low permeability, which greatly restrict the infiltration of water. Clayey soils of any age are generally of low permeability because most of the intergranular pores are in the capillary size range.

A general subdivision of the soils of the San Joaquin Valley based on their relative permeability is shown on plate 3. The soils have been subdivided into four classes on the basis of published reports of soil surveys cited on plate 3. The classes are as follows: (1) Young alluvial-fan and basin-rim soils (permeable to moderately permeable), (2) old alluvial-fan soils (moderately to poorly permeable), (3) basin soils (poorly permeable to nearly impermeable), and (4) dissected upland and mountain soils. The boundaries shown are generalized from the large-scale maps of the soil reports, and no attempt was made to classify the soils in units smaller than the series. For example, the soils of the Panoche series (Retzer and others, 1946) were all included in the young alluvial-fan and basin-rim soils, including the full textural range from Panoche loamy fine sand to Panoche clay loam.

Impermeable soils affect the usability of a ground-water storage reservoir for cyclic storage operations by hindering the downward movement of water to the water table. In areas of impermeable soils, potential recharge from streams, irrigation ditches, and precipitation is largely lost to ground-water recharge by surface runoff and evapotranspiration. Water spreading for recharge is economically feasible only where large quantities of water can be placed underground in a relatively short time. In soils of low permeability, prohibitively large areas would be required for water spreading, and proportionately higher water losses by evapotranspiration would result.

Detailed study of the soils with particular reference to permeability is a necessary preliminary to any large-scale artificial-recharge project. The soils reports published by the U. S. Department of Agriculture and the Agricultural Experiment Station, University of California, are an excellent source of preliminary information, but infiltration rates should be measured in the field before major work is undertaken.

689-414—63——3

IMPERMEABLE SUBSURFACE DEPOSITS

Impermeable subsurface deposits restrict the utility of a ground-water reservoir. Although impermeable materials may be highly porous, they do not transmit water readily. Accordingly, little water is yielded by gravity drainage, and the storage capacity of such materials is correspondingly small. Moreover, where deposits of low permeability are widespread in the upper part of a ground-water reservoir, they restrict the movement of water to deeper, more permeable deposits. Thus, it is conceivable that a reservoir with a large ground-water storage capacity might prove virtually useless for artificial recharge if extensive layers of material of low permeability so restricted infiltration of water that artificial recharge by water spreading was not economically feasible.

Because permeability and specific yield are related in a general way, estimates of specific yield can serve as an indication of the overall permeability of the storage units. Specific-yield estimates given in this report (table 1) were compiled for an earlier report of the Geological Survey (Davis and others, 1959) and were based largely on field and laboratory work of other investigators in California (Eckis and Gross, 1934; Piper and others, 1939; and Kues and Twogood, 1954). Certain modifications were made to conform with conditions in the San Joaquin Valley. The specific yield of certain types of sediments in the San Joaquin Valley are shown in the following table.

Material	Specific yield (percent)
1. Gravel; sand and gravel; and related coarse gravelly deposits	25
2. Sand, medium- to coarse-grained, loose, well-sorted	25
3. Fine sand; tight sand; tight gravel; and related deposits	10
4. Silt; gravelly clay; sandy clay; sandstone; conglomerate; and related deposits	5
5. Clay and related very fine grained deposits	3

Deposits of low permeability in the San Joaquin Valley include the last 3 categories in the above table, ranging in specific yield from 3 to 10 percent and yielding little water to wells. Larger supplies are obtained from wells tapping sand and gravel beds in the major alluvial fans in the valley. In general, poorly permeable deposits underlie the lake beds, the interstream areas, and some of the minor stream areas. The lake beds comprise Buena Vista and Tulare Lake beds; the interstream areas, the Lindsay, Dinuba, Fresno and Merced interstream storage units; and the minor stream areas, the White-Poso, Kaweah-Tule, and Chowchilla River storage units (pls. 3–5).

FAVORABLE AREAS FOR UTILIZATION OF GROUND-WATER STORAGE CAPACITY

PEG-MODEL ANALYSIS

An analysis of the subsurface geology of the San Joaquin Valley was made by use of a peg model (Davis and others, 1959, p. 199–201) to differentiate predominantly permeable and impermeable zones in the 10- to 50-, 50- to 100-, and 100- to 200-foot depth intervals. Because the sediments within the three depth zones are composed of varying percentages of materials with a wide range of permeability, an arbitrary classification was made based on their utility for storage. Accordingly, areas containing less than about 40 percent of permeable materials within a specific depth zone were considered for this analysis to be less favorable prospects for ground-water storage operations. Conversely, areas having 40 percent or more of permeable materials within a specific depth zone were considered as being most favorable for utilization as ground-water storage reservoirs.

In general, the favorable areas have an average of about 45 percent of sand and gravel in the various zones, and the less favorable areas contain only 10 to 20 percent of sand and gravel. Plates 3, 4, and 5 show the areas in which the 10- to 50-, 50- to 100-, and 100- to 200-foot depth zones, respectively, are considered most favorable for operation of the ground-water reservoirs for storage.

Because of the general lack of information on the 100- to 200-foot depth zone in much of the valley, a third category, "undetermined utility," is shown on plate 5. Measurement of the lithologic units in about 35 percent of the wells represented on the peg model was considered sufficient for accurate subdivision of the deposits into these 3 categories.

FAVORABLE AREAS DELINEATED

Plates 3, 4, and 5 show large areas of high permeability and specific yield in all depth zones in the vicinity of the larger alluvial fans in the valley, namely those of the Kern River, the San Joaquin and Kings Rivers, and the Merced, Tuolumne, and Stanislaus Rivers.

The most southerly of the areas of high permeability is the Edison-Maricopa Front storage unit, where the areas of the three depth zones nearly coincide. The sediments in this unit were deposited largely, if not altogether, by intermittent streams on alluvial fans of relatively steep gradient. The relative amounts of sand and gravel are about equal in these deposits, in marked contrast to those of the major storage units on the east side of the valley, in which sand constitutes most of the coarse material.

Adjoining the Edison-Maricopa Front unit on the north is the Kern River storage unit, which occupies an area of 446,000 acres, or nearly 700 square miles. The permeable deposits of the alluvial fan of the

Kern River occupy about 75 percent of the Kern River storage unit and extend westward from Bakersfield about 25 miles. The area favorable for ground-water storage is about 20 miles north-south near the center of the storage unit, but from about 15 miles west of Bakersfield, the area narrows and swings northward near the western margin of the unit. Within this area, most of the permeable material is reported to be sand; gravel constitutes less than one-fifth of the coarse-grained deposits. The sands are mostly well sorted and consist mainly of crystalline-rock detritus from the Sierra Nevada, although the sands in the vicinity of Buttonwillow and Semitropic Ridges may be derived in part from the Coast Ranges. Most of the gravel in the storage unit is in the vicinity of Bakersfield, adjacent to and underlying the Kern River, where it represents the deposition by that stream near the head of its fan. The maps for all 3 depth zones (pls. 3–5) are remarkably similar and indicate little or no change in the pattern of alluviation for the overall interval from 10 to 200 feet below the land surface.

The White-Poso ground-water storage unit, which occupies an area of 289,000 acres just north of the Kern River unit, contains only small scattered areas of permeable sediments (pl. 3). The deposits within this unit were laid down by the White River, Poso Creek, Deer Creek, and several smaller streams. All these streams head in the lower western slopes of the Sierra Nevada where precipitation is meager. Consequently, their flow is relatively small, and their deposits generally are less sorted and finer grained than those of the major streams. Davis and others (1959, p. 231) suggest that the smaller average grain size may be partly due to the fact that much of the material has been reworked from the belt of semiconsolidated Tertiary and early Quaternary sediments that flank the unit on the east and thus has undergone two or more cycles of erosion and deposition.

To the north in the Kaweah-Tule storage unit, extensive areas of permeable deposits underlie the apexes of the Kaweah and Tule River fans and also the western part of the unit (pl. 3). The permeable deposits of the Kaweah River are particularly extensive in the 50- to 100-foot depth zone (pl. 4). The highly permeable section along the western margin of the unit is best shown in the 100- to 200-foot depth zone (pl. 5). Most of the gravel strata are in the northeastern part of the unit at the head of the fan of the Kaweah River and near Porterville in the southeastern part, at the head of the fan of the Tule River. In the Tule River area, the gravel strata are largely confined to the 10- to 50-foot zone. In the Kaweah River area, they extend somewhat deeper, but they are not abundant below the 50- to 100-foot zone. Gravel is rare elsewhere in the unit and generally is not found west of U.S. Highway 99.

The largest favorable area for ground-water storage in the San Joaquin Valley includes most of the adjoining Kings River and San Joaquin River storage units (pl. 3), which occupy an area of about 1,038,000 acres, or 1,620 square miles. It is estimated that the permeable deposits shown on plate 3 underlie 80 to 90 percent of that area. The sands are, for the most part, well sorted and their average specific yield may be higher than the assigned average value for sand of 25 percent. The areas of permeable deposits in the Kings River and San Joaquin River storage units are similar on the maps of both the 10- to 50-foot and 50- to 100-foot depth zones (pls. 3, 4). Much of the area of the 100- to 200-foot zone (pl. 5) is shown as being of undetermined permeability because of a general lack of information. Where information is available, however, the sediments generally are highly permeable, and it is inferred that the deposits of the deepest zone are similar to the two shallower zones in permeability and areal extent.

Adjoining the favorable area in the San Joaquin River and Kings River units on the northwest is a broad area of predominantly permeable deposits, which underlie parts of the Los Banos and Mendota-Huron storage units and the overflow lands of the San Joaquin River (pl. 3). The overflow lands have been excluded from consideration as ground-water reservoirs (p. 20) and therefore are not discussed here. In the area considered favorable for storage, which includes about 100 square miles in the southern two-thirds of the Los Banos storage unit and about 150 square miles in the northern part of the Mendota-Huron unit, permeable deposits are widespread in the 10- to 50-foot depth zone (pl. 3). Plate 4 shows that the highly permeable deposits have a similar distribution in the 50- to 100-foot zone as well. In the 100- to to 200-foot zone, however, permeable deposits are much less extensive and are prominent only in a narrow band along the east edge of the Los Banos unit (pl. 5).

The most northerly area in the valley considered favorable for ground-water storage consists of parts of the Tracy-Patterson and Tuolumne River storage units. The Tracy-Patterson unit includes a narrow belt of coalesced alluvial fans in the northwestern part of the valley between the San Joaquin River and the northeast border of the Coast Ranges. The larger alluvial fans are those of Corral Hollow, Del Puerto, and Orestimba Creeks. The Tuolumne River storage unit adjoins the Tracy-Patterson unit on the east and includes the alluvial plains of three major eastern tributaries of the San Joaquin River—from north to south, the Stanislaus, Tuolumne, and Merced Rivers. The Tuolumne unit has an area of 571,000 acres, or 892 square miles. Plate 3 shows that in the 10- to 50-foot zone permeable deposits underlie almost the entire area of the storage unit, except for a rectangular east-west-trending body of sediments of low permeability about 6 miles wide between the Stanislaus and Tuolumne Rivers. A similar belt occupies the 50- to 100-foot depth zone (pl. 4). In addition, a similar east-west-trending body of deposits of low permeability lies between the Tuolumne and Merced Rivers in the vicinity of Turlock. Little information is available concerning the nature of the deposits in the 100- to 200-foot depth zone in this storage unit, except that in areas where wells penetrate this depth interval, the deposits are predominantly of low permeability (pl. 5).

Geologic section A–A′ (pl. 6) shows the vertical extent of permeable and impermeable deposits to a depth of 200 feet below the land surface along a line extending the length of the east side of the valley. It crosses the principal alluvial fans of the east side and most of the favorable areas of the valley for ground-water storage. On the well logs, one pattern is used for the coarse permeable materials—gravel, sand and gravel, and sand; and another for the less permeable materials—fine sand, silt, and clayey materials. At the top of the section, horizontal strips representing the 3 depth zones illustrated on plates 3 to 5 relate those maps to the section.

The highly permeable areas of the east-side storage units are shown on plate 6 as well as the broad area between the Kern River fan and the Kings River fan, which is almost devoid of sandy materials in the 10- to 50-foot depth zone. The deeper zones are more permeable in this interfan area, especially near the south edge of the Kings River fan. The area between the coarse deposits of the San Joaquin River and those of the Tuolumne River similarly is deficient in the more permeable materials, especially in the 10- to 50-foot zone.

The most promising areas for artificial recharge in the San Joaquin Valley are indicated by the relative permeability of the soils and the areal extent of relatively permeable deposits in the 10- to 50-foot depth interval (pl. 3).

DEPLETION OF GROUND-WATER STORAGE

A prerequisite to utilization of a ground-water reservoir for storage is that it be susceptible to depletion at a practical rate. In surface reservoirs, the only limitation on the rate of depletion is the capacity of the outlet works. A ground-water reservoir, however, is depleted by pumping, seepage at the land surface, evaporation, transpiration, or subsurface outflow to adjoining areas. Seepage, evaporation, and transpiration occur chiefly when the reservoir is nearly full; these factors, therefore, are of minor importance in considering cyclic storage operations. The importance of subsurface outflow can be minimized if large ground-water storage units are selected for operation.

The chief method of depletion of the ground-water reservoir in cyclic storage operation must be by pumping from wells. Efficient operation of the ground-water reservoir during the depletion phase involves operational problems common to well fields presently used for water supply or drainage. Among these are achieving an economical balance between conflicting requirements, avoiding mutual interference between wells, and achieving uniform dewatering without drilling an excessive number of wells. Because the requirements for effective depletion are less stringent than those for replenishment, generally areas that can be replenished efficiently also can be depleted efficiently.

DISCHARGE UNDER NATURAL CONDITIONS

Under the natural conditions that prevailed in the San Joaquin Valley before the middle of the 19th century, the unconfined and semiconfined ground water moved from recharge areas along the sides of the valley toward the low central part of the valley, where it discharged at the land surface by either seepage or evapotranspiration. The great alkali areas of the southwestern and central parts of the valley indicate natural discharge of ground water by evaporation.

More than half a century after the first settlements were established, withdrawal of ground water was still small in volume. Mendenhall (Mendenhall and others, 1916, p. 30–31) reported between 500 and 600 flowing wells and a somewhat greater number of pumped wells in the San Joaquin Valley in 1905–06. He estimated the average annual yield of these wells to be about 225,000 acre-feet.

Water-level contours (Mendenhall and others, 1916, pl. 1) based on measurements made in 1905–07 show that ground water in the unconfined and semiconfined deposits then moved generally in the direction of the slope of the land surface toward areas of natural discharge in the lower part of the valley. Little information is available on the hydraulic gradient in the principal confined aquifer under initial conditions of development, but it is inferred that the water moved slowly toward the center of the valley and then northward toward areas of discharge in the Sacramento-San Joaquin Delta. The artesian head in the aquifer was sufficient to raise water above the land surface in wells tapping that aquifer beneath much of the central part of the valley (Mendenhall and others, 1916, pl. 1). Therefore, substantial quantities of water presumably moved slowly upward through the clay confining bed.

Although ground-water development was small at the time of Mendenhall's early work (1905–07), irrigation with surface water had been practiced for some time. Small diversions were made as early as the 1850's from the Kaweah River for irrigation of alfalfa and other crops near Visalia in Tulare County. The first diversion works on the Kings

River were built in the early 1870's to carry water for irrigation of fruit orchards and vineyards near Fresno. In 1875, the Calloway Canal began to deliver 500 cfs (cubic feet per second) from the Kern River to a large area north of that river. In 1909, Fortier and Cone (1909, p. 7) reported that probably more than 1 million acres were irrigated in the San Joaquin Valley, chiefly by surface water.

The application of large quantities of surface water for irrigation had modified the natural ground-water regimen substantially even before ground water was used extensively for irrigation. Fortier and Cone (1909, p. 8) reported that rises of ground-water levels in the Fresno area of 20 feet in 4 years were not uncommon after the importation of surface water for irrigation. In the Modesto and Turlock areas, they reported a rise of the water table of 15 to 20 feet in the first 3 years of irrigation with surface water (idem, p. 47).

The general effect of early irrigation with surface water was to raise the ground-water levels and thus to increase greatly the natural ground-water discharge.

The general rise of the water table also resulted in serious damage in many irrigated areas by waterlogging and accumulation of alkali in the soils. In some areas, extensive drainage works—deep ditches, drainage wells, or a combination of both—were built to control the rising water table. In many of these areas, however, the shallow water table ceased to be a problem as the use of ground water pumped from wells for supplemental irrigation increased. For example, in the vicinity of Fresno, where the water table stood within 10 feet of the land surface in 1909 (Fortier and Cone, 1909, p. 10), the depth to water was 30 feet or more in 1952 (pl. 7). This drainage problem was alleviated without construction of special works, but almost entirely by greater utilization of ground water for supplemental irrigation.

DEWATERING UNDER PRESENT IRRIGATION PRACTICE

The chief form of ground-water discharge in the San Joaquin Valley under present irrigation practice is by pumping from wells. In 1955–56, pumpage for irrigation was estimated to be about 9 million acre-feet. (See table 2 and fig. 3.)

In the northeastern part of the valley in the areas that are irrigated from the Stanislaus, Tuolumne, and Merced Rivers, and in the part of the west side of the valley served from the San Joaquin River, the water table is maintained at shallow depth, and ample opportunity exists for ground water to discharge to streams and artificial drains and by evapotranspiration. Considerable natural discharge also occurs in the natural sumps of Tulare, Buena Vista, and Kern Lake beds, where the ground water stands close to the land surface.

Most of the ground-water discharge at the land surface probably occurs in an area of about 3,300 square miles, shown on plate 7 as the area in which the depth to water is less than 10 feet below the land surface.

Elsewhere in the San Joaquin Valley, withdrawals of ground water generally equal or exceed the long-term replenishment, and the water levels are sufficiently deep to preclude substantial natural discharge. Where withdrawals have exceeded long-term replenishment, the ground-water levels have declined substantially, thus making space available for storage of ground water. Depths to water have not changed greatly in most of the valley from 1952 to 1957, although recovery of water levels of several feet has been reported in the service areas of the Madera Canal near Chowchilla and in southern Tulare County near Delano, where water levels have risen rapidly since water deliveries from the Friant-Kern Canal began in 1951 and ground-water pumpage declined.

PRODUCTIVITY OF IRRIGATION WELLS

Reliable information on the number, depths, and yields of irrigation wells and on the water-yielding properties of the deposits is necessary for proper planning of the operation of the ground-water storage reservoirs in the San Joaquin Valley. The information collected during this study falls into two general categories, changing or unchanging with time. Such data as depths of wells, average drawdown, average discharge, and average specific capacity relate chiefly to the water-bearing character of the aquifers and are relatively stable. Data on the number of wells, depth to water, average power consumption, and pumpage are influenced greatly by climatic and economic conditions and may change substantially from year to year.

Estimates of the average depth of irrigation wells within the 16 ground-water storage units in the valley are given in the table below. These estimates were based upon the peg model of the San Joaquin Valley described in an earlier report of the Geological Survey (Davis and others, 1959, p. 199), in which records of nearly 5,000 wells were used. Although the average depths presented are approximate only, they probably are well within the limit of error indicated by rounding.

Ground-water storage unit	*Average depth (feet)*
Tuolumne River	250
Merced interstream	300
Chowchilla River	300
San Joaquin River	200
Fresno interstream	200
Kings River	200
Dinuba interstream	250

Ground-water storage unit	*Average depth (feet)*
Kaweah-Tule River	300
Lindsay interstream	450
White-Poso	750
Kern River	450
Edison-Maricopa Front	900
Antelope Plain	[1] 1,100
Mendota-Huron	[2] 1,500
Los Banos	350
Tracy-Patterson	500

[1] Based on very few wells.
[2] Estimated from geologic sections.

Information on the number of wells, ground-water withdrawals, and related data on pumpage, obtained from electric-power-consumption records, is summarized by electric-power operating units in table 2. These operating units (fig. 4) comprise the nine districts of the San Joaquin Division of the Pacific Gas & Electric Co; part of the Stockton Division of the Pacific Gas & Electric Co. on the west side of the valley in Stanislaus and San Joaquin Counties; the Valley Division of the Southern California Edison Co.; and the combined areas of the South San Joaquin, Oakdale, Modesto and Turlock Irrigation Districts. The periods for which the data were compiled and the methods of compilation differ somewhat, but the items tabulated probably are comparable within the limits of the rounding of the figures given in table 2. The data for the San Joaquin Division of the Pacific Gas & Electric Co. were compiled by the company, and those for the Stockton Division were estimated by projection of a detailed study in 1949. The figures for the valley Division of the Southern California Edison Co. were computed by the authors from totals of power consumption furnished by that company, using averages of kilowatthours per acre-foot obtained from more than 5,000 pump-efficiency tests made by the company during 1950–54. The estimates of pumpage by the irrigation districts were taken from annual reports made by the districts to the California District Securities Commission. The pumpage in the San Joaquin Division of Pacific Gas & Electric Co., approximately four-fifths of the total, is for the agricultural year May 1, 1955, to April 30, 1956. All the other estimates are for the 1955 calendar year. The averages shown in columns 3, 5, 6, and 7 of table 2 were weighted by the number of wells in each unit, not by area. The average load factor (column 7) is the percentage of the time the wells operated; it is obtained by dividing the average annual hours of use by the number of hours in a year.

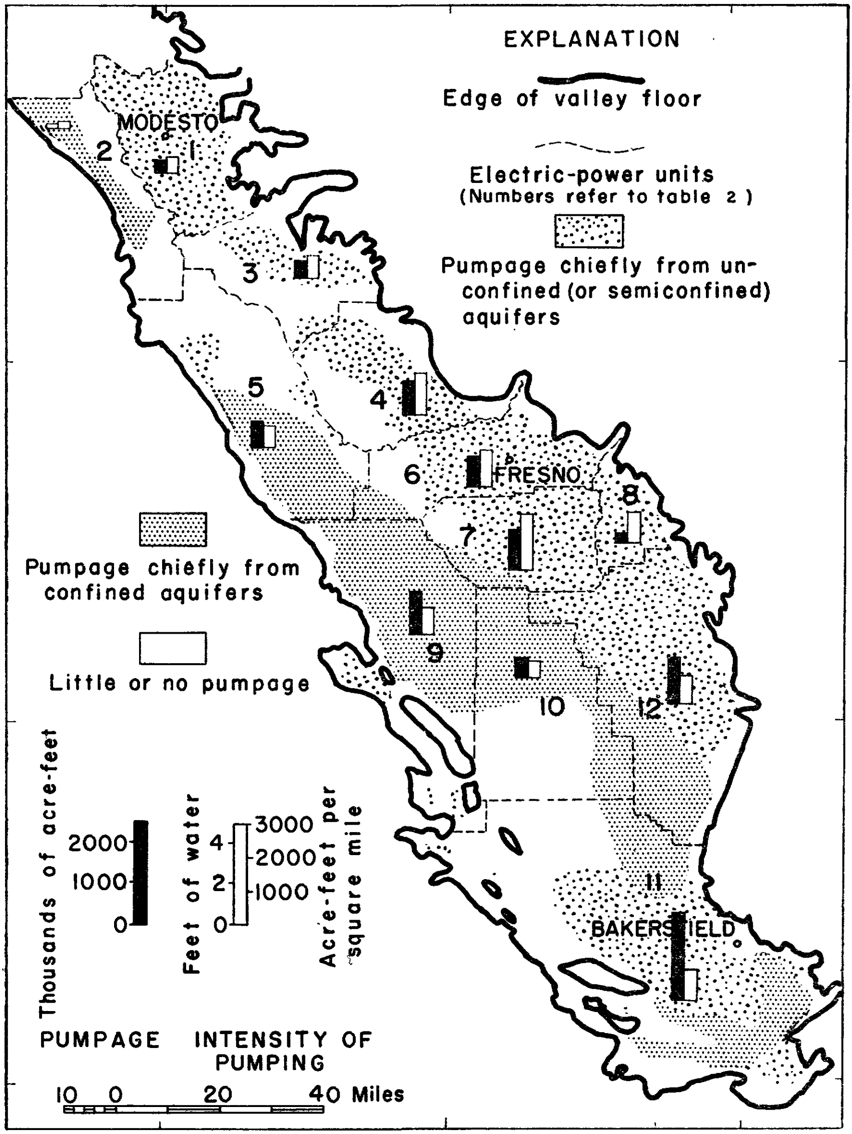

FIGURE 4.—Distribution of pumping draft in the San Joaquin Valley, 1955–56.

TABLE 2.—*Estimated ground-water pumpage for irrigation in the San Joaquin Valley, 1955–56*

Electric power unit	Number of plants (1)	Connected horse-power (2)	Average kilowatt-hour per acre-foot (3)	Acre-feet pumped [1] (4)	Average acre-feet per plant (5)	Average annual hours used (6)	Average load factor, percent (7)
IRRIGATION DISTRICT							
1. Combined unit:							
a. South San Joaquin	44	508		20,000	455		
b. Oakdale	64	1,591		28,000	438		
c. Modesto	95	2,313		110,000	1,118		
d. Turlock	175	3,608	91	160,000	889		
Total	378	8,020		318,000	841		
PACIFIC GAS & ELECTRIC CO.							
2. West part Stockton Division				[2] 100,000			
3. Merced District	1,600	31,306	121	423,000	265	1,861	21.2
4. Madera District	4,001	70,889	163	802,000	200	2,107	24.0
5. Los Banos District	1,564	92,131	476	667,000	426	3,926	44.7
6. Fresno District	6,874	79,299	122	745,000	108	1,309	14.9
7. Selma District	6,867	85,288	116	981,000	143	1,520	17.3
8. Dinuba District	3,856	37,272	172	237,000	62	1,708	19.4
9. Coalinga District	960	121,920	686	829,000	863	5,310	60.4
10. Corcoran District	2,315	49,745	273	485,000	210	3,029	34.5
11. Kern District	5,554	319,018	374	2,140,000	386	2,861	32.6
SOUTHERN CALIFORNIA EDISON CO.							
12. Valley Division	5,325	226,667	303	1,320,000	233	2,628	30.0
Total or weighted average	39,294	1,121,555	227	9,047,000	223	2,199	25

[1] Rounded. [2] Estimated.

Data on yield and capacity of irrigation wells compiled from pump-efficiency tests are presented as averages by township units in table 3. About 50,000 test records were made available for this study through the courtesy of the Pacific Gas & Electric Co. and the Southern California Edison Co. About 15,000 tests representing the most recent test on each well for the period 1950–54, were used in compiling the averages given in table 3.

The frequency and areal coverage of tests differ somewhat between operating units. In general, the most complete and up-to-date records are from areas where large pumps that consume large quantities of electric power are used. This is because of the savings that may be realized by keeping a close check on the efficiency of individual plants.

TABLE 3.—*Yield characteristics of irrigation wells in the San Joaquin Valley by townships*

[Data presented as averages. Pump test data from Pacific Gas & Electric Co. and Southern California Edison Co.]

Townships	Number of tests (discharge)	Static level (feet)	Pumping level (feet)	Drawdown (feet)	Discharge (gpm)	Specific capacity (gpm per foot)	Kilowatt-hour per acre-foot	Plant efficiency
Mount Diablo base line and meridian								
T. 1 S., R. 5 E	4	10	34	24	1,182	37	57	51
T. 1 S., R. 6 E	48	14	45	29	881	36	94	53
T. 1 S., R. 7 E	38	15	34	16	1,163	72	142	52
T. 1 S., R. 8 E	88	28	48	16	1,181	74	100	53
T. 1 S., R. 9 E	25	46	63	19	895	57	125	57
T. 1 S., R. 10 E	11	76	98	16	1,331	102	145	59
T. 1 S., R. 11 E	2	-------	111	-------	685	-------	184	60
T. 2 S., R. 4 E	1	141.8	200.8	-------	118	-------	778	-------
T. 2 S., R. 5 E	17	23	69	32	1,163	31	239	57
T. 2 S., R. 6 E	22	14	73	22	1,316	38	136	51
T. 2 S., R. 7 E	22	11	30	13	993	64	186	54
T. 2 S., R. 8 E	24	17	27	11	762	77	232	56
T. 2 S., R. 9 E	23	26	45	16	994	54	160	52
T. 2 S., R. 10 E	33	75	95	18	1,238	73	216	61
T. 2 S., R. 11 E	15	95	111	20	1,340	57	194	64
T. 2 S., R. 12 E	4	53	105	33	1,238	66	198	65
T. 3 S., R. 5 E	16	140	190	29	1,225	30	351	52
T. 3 S., R. 6 E	29	36	134	34	1,242	10	293	54
T. 3 S., R. 7 E	1	-------	-------	-------	805	-------	48.4	25
T. 3 S., R. 10 E	8	72	91	20	1,260	74	165	62
T. 3 S., R. 11 E	4	94	119	21	1,270	78	163	61
T. 3 S., R. 13 E	1	89.9	121.6	31.7	460	14.5	383	68
T. 4 S., R. 6 E	7	-------	206	-------	1,178	-------	384	51
T. 4 S., R. 7 E	7	35	57	16	1,731	72	141	58
T. 4 S., R. 13 E	1	14.6	-------	-------	1,251	-------	75.1	-------
T. 5 S., R. 7 E	18	128	160	43	1,354	14	329	60
T. 5 S., R. 8 E	3	67	95	28	576	18	560	66
T. 5 S., R. 12 E	1	-------	15.3	-------	1,573	-------	139.1	71.2
T. 5 S., R. 13 E	2	20.6	43	-------	1,448	51	217	53
T. 5 S., R. 14 E	1	9.0	12.1	3.1	61	19.7	332.1	28.1
T. 6 S., R. 7 E	2	-------	-------	-------	532	-------	678	-------
T. 6 S., R. 8 E	41	95	150	33	1,132	56	342	55
T. 6 S., R. 9 E	2	-------	59	-------	2,000	-------	50	60
T. 6 S., R. 11 E	30	31	42	15	1,077	83	95	52
T. 6 S., R. 12 E	10	34	51	17	1,086	69	110	53
T. 6 S., R. 13 E	6	39	58	20	831	39	122	51
T. 6 S., R. 14 E	1	-------	-------	-------	335	-------	274	52
T. 7 S., R. 8 E	22	47	83	13	1,318	151	203	55
T. 7 S., R. 9 E	19	21	55	18	819	37	278	64
T. 7 S., R. 10 E	2	-------	25	-------	1,764	-------	72	49
T. 7 S., R. 11 E	16	16	40	24	2,117	105	80	55
T. 7 S., R. 12 E	8	22	36	14	1,197	89	101	60
T. 7 S., R. 13 E	8	19	28	13	738	42	130	47
T. 7 S., R. 14 E	13	16	33	19	1,691	128	156	68
T. 7 S., R. 15 E	5	26	55	29	516	29	439	53
T. 8 S., R. 8 E	10	51	89	27	747	33	187	54
T. 8 S., R. 9 E	27	21	50	22	735	35	120	52
T. 8 S., R. 10 E	5	44	103	-------	1,424	-------	176	59
T. 8 S., R. 11 E	2	20	57	37	2,351	64	109	56
T. 8 S., R. 12 E	7	19	50	31	1,263	60	99	55
T. 8 S., R. 13 E	11	13	34	21	1,516	81	71	51
T. 8 S., R. 14 E	7	37	53	15	711	48	123	53
T. 8 S., R. 15 E	56	41	63	24	854	46	128	55
T. 8 S., R. 16 E	37	37	69	32	586	23	153	52
T. 9 S., R. 8 E	2	66	94	28	573	-------	175	55
T. 9 S., R. 9 E	25	28	57	31	964	53	133	54
T. 9 S., R. 10 E	19	30	54	27	1,414	59	103	59
T. 9 S., R. 11 E	12	13	52	39	1,968	55	100	54
T. 9 S., R. 12 E	18	30	68	37	1,605	49	118	57
T. 9 S., R. 13 E	31	56	72	16	737	58	136	56
T. 9 S., R. 14 E	99	67	80	14	682	60	158	54
T. 9 S., R. 15 E	85	58	75	17	815	58	144	55

TABLE 3.—*Yield characteristics of irrigation wells in the San Joaquin Valley by townships*—Continued

Townships	Number of tests (discharge)	Static level (feet)	Pumping level (feet)	Drawdown (feet)	Discharge (gpm)	Specific capacity (gpm per foot)	Kilowatt-hour per acre-foot	Plant efficiency
Mount Diablo base line and meridian—Continued								
T. 9 S., R. 16 E.	30	65	90	25	857	39	164	59
T. 9 S., R. 17 E.	14	50	67	23	478	26	158	44
T. 10 S., R. 9 E.	3	52	97	44	594	15	234	48
T. 10 S., R. 10 E.	43	36	61	21	1,186	73	116	56
T. 10 S., R. 11 E.	26	32	56	25	1,570	76	101	59
T. 10 S., R. 12 E.	21	18	48	31	1,685	60	97	57
T. 10 S., R. 13 E.	50	24	58	33	1,489	60	107	58
T. 10 S., R. 14 E.	122	53	68	16	987	72	129	57
T. 10 S., R. 15 E.	73	67	79	14	726	63	148	56
T. 10 S., R. 16 E.	92	81	98	18	509	42	197	53
T. 10 S., R. 17 E.	28	77	93	20	669	38	187	55
T. 10 S., R. 18 E.	7	39	57	22	702	41	184	55
T. 10 S., R. 19 E.	5	32	52	20	1,205	61	93	57
T. 11 S., R. 10 E.	43	113	139	26	993	45	162	56
T. 11 S., R. 11 E.	39	143	199	37	1,435	48	321	64
T. 11 S., R. 12 E.	11	33	56	29	1,354	53	134	55
T. 11 S., R. 13 E.	34	15	43	31	1,697	61	85	53
T. 11 S., R. 14 E.	20	34	61	26	1,428	75	116	55
T. 11 S., R. 15 E.	43	33	48	15	1,176	81	101	53
T. 11 S., R. 16 E.	142	68	85	17	647	53	167	54
T. 11 S., R. 17 E.	151	65	83	17	564	42	163	54
T. 11 S., R. 18 E.	71	65	81	16	439	38	196	51
T. 11 S., R. 19 E.	3	319	340	20	939	92	505	67
T. 11 S., R. 20 E.	1	--------	--------	--------	1,621	--------	68.7	--------
T. 11 S., R. 21 E.	1	47.5	54.2	6.7	60	9	384.9	31.7
T. 11 S., R. 22 E.	1	12.7	36	23.0	14	6	445.6	27.6
T. 12 S., R. 11 E.	40	240	305	30	1,317	54	537	61
T. 12 S., R. 12 E.	17	209	268	36	1,223	46	443	62
T. 12 S., R. 13 E.	8	152	211	52	826	22	517	50
T. 12 S., R. 14 E.	2	25	62	37	2,615	71	117	56
T. 12 S., R. 15 E.	22	37	56	18	1,813	104	99	62
T. 12 S., R. 16 E.	34	62	80	19	824	48	152	55
T. 12 S., R. 17 E.	110	68	81	13	622	53	169	54
T. 12 S., R. 18 E.	105	77	86	9	614	90	167	55
T. 12 S., R. 19 E.	47	67	79	12	733	77	170	58
T. 12 S., R. 20 E.	59	54	56	15	645	41	137	50
T. 12 S., R. 21 E.	74	50	67	16	436	37	142	50
T. 12 S., R. 22 E.	18	33	58	26	261	13	159	47
T. 12 S., R. 25 E.	1	--------	8.4	--------	214	--------	170.4	41.4
T. 13 S., R. 11 E.	2	--------	--------	--------	1,221	--------	894	--------
T. 13 S., R. 12 E.	36	360	436	42	1,355	44	690	65
T. 13 S., R. 13 E.	32	357	386	41	1,015	31	742	55
T. 13 S., R. 14 E.	16	211	201	40	1,665	41	372	59
T. 13 S., R. 15 E.	39	48	68	20	1,608	89	113	63
T. 13 S., R. 16 E.	36	36	58	21	1,210	64	104	58
T. 13 S., R. 17 E.	106	41	56	15	792	64	113	54
T. 13 S., R. 18 E.	85	45	55	9	608	65	113	52
T. 13 S., R. 19 E.	86	46	54	9	386	62	135	49
T. 13 S., R. 20 E.	118	43	52	9	551	76	162	53
T. 13 S., R. 21 E.	144	30	42	12	647	67	98	52
T. 13 S., R. 22 E.	78	30	44	16	437	47	122	46
T. 13 S., R. 23 E.	9	18	39	21	185	20	184	37
T. 13 S., R. 24 E.	2	--------	19	--------	34	--------	561	--------
T. 14 S., R. 12 E.	19	490	553	30	1,245	39	859	65
T. 14 S., R. 13 E.	34	477	514	25	1,262	45	858	65
T. 14 S., R. 14 E.	45	296	341	36	1,145	47	586	61
T. 14 S., R. 15 E.	8	142	203	29	1,347	48	375	60
T. 14 S., R. 16 E.	16	39	56	20	1,753	85	110	53
T. 14 S., R. 17 E.	79	42	55	14	805	65	105	56
T. 14 S., R. 18 E.	126	41	53	13	878	76	102	56
T. 14 S., R. 19 E.	95	31	40	10	850	94	86	47
T. 14 S., R. 20 E.	125	33	41	9	684	87	104	52
T. 14 S., R. 21 E.	132	30	38	9	570	74	93	50
T. 14 S., R. 22 E.	94	31	43	12	515	53	102	49
T. 14 S., R. 23 E.	30	44	57	16	565	39	144	46
T. 14 S., R. 24 E.	17	46	61	17	183	15	193	44
T. 15 S., R. 12 E.	5	--------	640	--------	1,148	--------	1,154	59
T. 15 S., R. 13 E.	35	--------	616	--------	1,308	--------	1,009	63

TABLE 3.—*Yield characteristics of irrigation wells in the San Joaquin Valley by townships*—Continued

Townships	Number of tests (discharge)	Static level (feet)	Pumping level (feet)	Drawdown (feet)	Discharge (gpm)	Specific capacity (gpm per foot)	Kilowatt-hour per acre-foot	Plant efficiency
Mount Diablo base line and meridian—Continued								
T. 15 S., R. 14 E	35	354	400	35	1,137	43	623	64
T. 15 S., R. 15 E	24	167	205	40	1,453	44	344	46
T. 15 S., R. 16 E	72	68	88	21	1,073	71	145	61
T. 15 S., R. 17 E	117	64	85	22	1,419	85	139	64
T. 15 S., R. 18 E	41	40	57	16	1,219	84	117	58
T. 15 S., R. 19 E	137	40	53	19	777	65	112	54
T. 15 S., R. 20 E	178	35	46	13	607	55	104	53
T. 15 S., R. 21 E	100	28	38	11	588	63	106	50
T. 15 S., R. 22 E	83	33	45	12	642	63	100	53
T. 15 S., R. 23 E	55	52	63	11	514	60	150	50
T. 15 S., R. 24 E	67	59	73	16	273	28	174	43
T. 15 S., R. 25 E	7	73	129	56	163	4	418	39
T. 16 S., R. 14 E	17	439	429	--------	1,265	57	807	64
T. 16 S., R. 15 E	33	360	408	--------	1,172	--------	708	62
T. 16 S., R. 16 E	14	187	225	36	1,606	57	403	62
T. 16 S., R. 17 E	40	107	137	30	1,406	58	--------	64
T. 16 S., R. 18 E	34	65	82	18	1,162	82	172	60
T. 16 S., R. 19 E	128	47	62	17	677	50	134	56
T. 16 S., R. 20 E	208	39	54	15	678	49	114	55
T. 16 S., R. 21 E	122	34	47	13	703	62	97	54
T. 16 S., R. 22 E	100	31	41	11	592	69	107	52
T. 16 S., R. 23 E	59	30	42	12	584	52	88	53
T. 16 S., R. 24 E	84	42	52	11	498	59	127	50
T. 16 S., R. 25 E	56	63	82	22	307	25	210	49
T. 16 S., R. 26 E	9	28	41	14	277	26	146	41
T. 17 S., R. 14 E	3	--------	705	--------	1,458	--------	1,151	65
T. 17 S., R. 15 E	59	387	602	--------	1,224	--------	1,060	62
T. 17 S., R. 16 E	37	350	390	32	1,163	42	669	62
T. 17 S., R. 17 E	28	242	280	34	1,151	39	460	63
T. 17 S., R. 18 E	43	109	138	23	1,188	60	239	62
T. 17 S., R. 19 E	60	51	73	25	867	42	150	57
T. 17 S., R. 20 E	36	33	51	20	708	45	103	52
T. 17 S., R. 21 E	28	31	45	16	823	54	89	55
T. 17 S., R. 22 E	47	23	36	15	811	59	80	43
T. 17 S., R. 23 E	32	23	34	11	902	83	74	53
T. 17 S., R. 24 E	41	21	31	15	1,107	80	77	52
T. 17 S., R. 25 E	137	70	--------	15	341	30	199	48
T. 17 S., R. 26 E	202	59	84	18	264	26	189	45
T. 17 S., R. 27 E	7	36	--------	48	84	8	266	45
T. 17 S., R. 28 E	3	13	--------	--------	278	--------	225	37
T. 18 S., R. 15 E	15	--------	714	--------	1,222	--------	1,232	64
T. 18 S., R. 16 E	33	428	550	--------	1,218	--------	953	62
T. 18 S., R. 17 E	40	340	432	27	1,097	53	780	59
T. 18 S., R. 18 E	29	314	309	30	993	39	573	58
T. 18 S., R. 19 E	13	88	137	30	968	41	260	55
T. 18 S., R. 20 E	15	33	57	24	439	31	135	42
T. 18 S., R. 21 E	29	40	52	16	550	42	113	53
T. 18 S., R. 22 E	15	37	58	17	796	49	108	54
T. 18 S., R. 23 E	34	65	--------	14	600	49	168	52
T. 18 S., R. 24 E	152	47	--------	12	632	59	129	50
T. 18 S., R. 25 E	210	41	--------	10	484	65	120	46
T. 18 S., R. 26 E	284	64	--------	13	317	41	185	46
T. 18 S., R. 27 E	144	57	--------	24	190	17	240	42
T. 18 S., R. 28 E	1	75	--------	4	259	65	181	47
T. 19 S., R. 16 E	18	--------	614	--------	982	--------	987	66
T. 19 S., R. 17 E	46	--------	507	--------	1,321	--------	920	59
T. 19 S., R. 18 E	30	366	411	42	1,504	48	722	60
T. 19 S., R. 19 E	7	146	251	30	923	28	443	59
T. 19 S., R. 20 E	10	66	108	32	698	28	203	56
T. 19 S., R. 21 E	14	61	97	28	426	18	157	49
T. 19 S., R. 22 E	22	52	94	23	761	40	150	17
T. 19 S., R. 23 E	122	79	--------	14	674	54	181	54
T. 19 S., R. 24 E	196	81	--------	13	608	60	191	53
T. 19 S., R. 25 E	216	47	--------	12	604	56	135	48
T. 19 S., R. 26 E	393	111	--------	14	313	33	282	48
T. 19 S., R. 27 E	5	98	--------	7	140	28	466	45
T. 20 S., R. 15 E	34	210	241	38	963	43	415	61
T. 20 S., R. 16 E	16	158	278	37	906	31	482	57
T. 20 S., R. 17 E	49	530	519	--------	1,330	--------	905	60

TABLE 3.—*Yield characteristics of irrigation wells in the San Joaquin Valley by townships*—Continued

Townships	Number of tests (discharge)	Static level (feet)	Pumping level (feet)	Drawdown (feet)	Discharge (gpm)	Specific capacity (gpm per foot)	Kilowatt-hour per acre-foot	Plant efficiency
Mount Diablo base line and meridian—Continued								
T. 20 S., R. 18 E	28	321	433	45	1,271	33	760	61
T. 20 S., R. 19 E	29	235	290	31	1,178	56	491	61
T. 20 S., R. 20 E	3	179	205	27	1,732	68	333	68
T. 20 S., R. 21 E	10	117	205	37	1,715	73	351	63
T. 20 S., R. 22 E	16	74	110	33	1,078	38	193	61
T. 20 S., R. 23 E	186	95	107	13	573	52	221	53
T. 20 S., R. 24 E	223	81	95	13	492	45	217	50
T. 20 S., R. 25 E	160	69	86	18	625	42	183	50
T. 20 S., R. 26 E	344	192	211	23	221	14	477	48
T. 20 S., R. 27 E	111	219	254	35	103	6	617	45
T. 21 S., R. 15 E	17	168	212	25	947	49	412	57
T. 21 S., R. 16 E	41	142	184	34	845	33	371	57
T. 21 S., R. 17 E	10	------	562	------	1,217	------	975	59
T. 21 S., R. 18 E	40	280	351	------	963	------	633	61
T. 21 S., R. 19 E	19	245	288	30	900	41	504	59
T. 21 S., R. 20 E	24	210	242	24	1,910	73	424	60
T. 21 S., R. 21 E	8	152	185	31	1,223	46	363	58
T. 21 S., R. 22 E	25	78	111	33	682	23	232	47
T. 21 S., R. 23 E	58	110	124	24	1,139	58	253	57
T. 21 S., R. 24 E	96	86	108	22	728	50	215	52
T. 21 S., R. 25 E	145	109	131	24	676	35	263	53
T. 21 S., R. 26 E	220	94	110	19	575	43	238	51
T. 21 S., R. 27 E	232	95	121	27	297	20	303	46
T. 21 S., R. 28 E	24	87	103	16	422	44	298	47
T. 22 S., R. 16 E	3	------	543	------	577	------	954	50
T. 22 S., R. 18 E	1	297.2	366.9	69.7	1,318	18.9	568.1	66.2
T. 22 S., R. 22 E	14	92	158	31	1,036	41	294	56
T. 22 S., R. 23 E	56	107	144	31	1,080	48	282	60
T. 22 S., R. 24 E	109	128	145	21	672	38	289	54
T. 22 S., R. 25 E	153	152	172	20	545	41	374	51
T. 22 S., R. 26 E	190	144	161	15	558	43	328	54
T. 22 S., R. 27 E	61	107	131	30	288	26	326	47
T. 22 S., R. 28 E	15	87	109	24	150	8	316	37
T. 23 S., R. 23 E	9	113	166	50	868	23	321	55
T. 23 S., R. 24 E	40	114	143	------	871	37	249	58
T. 23 S., R. 25 E	158	144	174	27	514	27	369	51
T. 23 S., R. 26 E	76	195	222	26	773	41	442.5	56
T. 23 S., R. 27 E	21	230	278	29	319	13	636	48
T. 23 S., R. 28 E	1	11	------	------	1,726	------	248.6	67.1
T. 24 S., R. 18 E	22	194	251	28	590	39	530	54
T. 24 S., R. 19 E	6	207	224	65	1,046	17	687	65
T. 24 S., R. 22 E	4	116	140	24	498	21	351	42
T. 24 S., R. 23 E	10	146	175	18	707	50	326	55
T. 24 S., R. 24 E	8	87	133	43	595	33	256	61
T. 24 S., R. 25 E	147	191	228	38	571	19	483	51
T. 24 S., R. 26 E	94	332	358	39	693	26	739	53
T. 24 S., R. 27 E	21	363	379	36	428	20	840	50
T. 25 S., R. 18 E	6	118	104	11	242	23	652	43
T. 25 S., R. 19 E	11	259	320	91	735	9	596	55
T. 25 S., R. 22 E	7	116	153	37	994	37	317	52
T. 25 S., R. 23 E	58	125	149	24	665	42	300	59
T. 25 S., R. 24 E	50	117	140	25	864	56	283	54
T. 25 S., R. 25 E	140	189	218	31	640	24	453	54
T. 25 S., R. 26 E	125	332	363	37	618	25	707	54
T. 25 S., R. 27 E	12	383	437	54	683	13	853	53
T. 26 S., R. 18 E	28	183	213	40	275	13	478	49
T. 26 S., R. 22 E	10	112	145	28	133	39	282	55
T. 26 S., R. 23 E	37	115	131	16	921	65	261	56
T. 26 S., R. 24 E	68	138	160	22	936	58	304	58
T. 26 S., R. 25 E	102	217	240	19	623	59	458	56
T. 26 S., R. 26 E	83	303	323	21	780	47	600	58
T. 26 S., R. 27 E	1	------	308.2	------	804	------	535.7	59.5
T. 27 S., R. 22 E	16	133	161	26	1,012	61	317	49
T. 27 S., R. 23 E	73	143	161	16	1,264	92	302	60
T. 27 S., R. 24 E	198	146	160	14	681	65	326	55
T. 27 S., R. 25 E	84	168	182	14	1,060	102	349	56
T. 27 S., R. 26 E	48	273	295	23	1,092	56	531	60

TABLE 3.—*Yield characteristics of irrigation wells in the San Joaquin Valley by townships*—Continued

Townships	Number of tests (discharge)	Static level (feet)	Pumping level (feet)	Drawdown (feet)	Discharge (gpm)	Specific capacity (gpm per foot)	Kilowatt-hour per acre-foot	Plant efficiency
Mount Diablo base line and meridian—Continued								
T. 28 S., R. 22 E	8	43	64	26	2,186	88	135	60
T. 28 S., R. 23 E	16	77	94	14	1,245	110	173	56
T. 28 S., R. 24 E	91	110	123	12	924	92	241	55
T. 28 S., R. 25 E	257	122	134	11	643	78	263	55
T. 28 S., R. 26 E	105	223	247	22	1,258	81	542	58
T. 28 S., R. 27 E	28	318	341	19	1,100	62	643	57
T. 28 S., R. 28 E	8	117	159	28	1,684	87	270	56
T. 29 S., R. 22 E	2	48	73	25	3,171	128	128	63
T. 29 S., R. 23 E	23	55	74	19	1,700	112	132	58
T. 29 S., R. 24 E	20	55	75	21	1,432	86	143	56
T. 29 S., R. 25 E	53	58	70	13	977	88	142	54
T. 29 S., R. 26 E	39	46	55	9	763	96	116	52
T. 29 S., R. 27 E	17	44	62	18	518	44	149	46
T. 29 S., R. 28 E	32	215	259	42	622	28	508	55
T. 29 S., R. 29 E	17	318	368	56	778	21	592	61
T. 30 S., R. 24 E	5	49	64	15	2,111	285	162	49
T. 30 S., R. 25 E	8	52	74	26	1,188	72	159	50
T. 30 S., R. 26 E	6	33	49	16	1,349	75	99	57
T. 30 S., R. 27 E	59	42	60	19	1,059	78	129	56
T. 30 S., R. 28 E	49	100	120	20	834	57	263	53
T. 30 S., R. 29 E	120	279	304	21	973	89	544	58
T. 30 S., R. 30 E	33	298	377	68	893	25	703	59
T. 31 S., R. 26 E	7	34	58	23	1,774	76	118	51
T. 31 S., R. 27 E	44	45	65	21	1,009	63	136	52
T. 31 S., R. 28 E	39	86	114	27	1,020	49	224	56
T. 31 S., R. 29 E	102	213	239	22	1,191	97	430	63
T. 31 S., R. 30 E	37	292	320	26	1,332	104	553	63
T. 32 S., R. 24 E	5	184	220	38	1,245	81	450	64
T. 32 S., R. 25 E	7	263	325	70	684	51	768	45
T. 32 S., R. 26 E	14	238	310	64	713	12	617	53
T. 32 S., R. 27 E	3	22	54	27	1,290	45	115	53
T. 32 S., R. 28 E	46	183	225	44	1,520	49	440	57
T. 32 S., R. 29 E	78	237	264	27	1,426	73	462	59
San Bernardino base line and meridian								
T. 12 N., R. 22 W	7	294	345	44	1,080	37	608	55
T. 12 N., R. 21 W	9	---	---	---	1,007	---	632	---
T. 12 N., R. 20 W	13	267	305	30	1,549	58	559	60
T. 12 N., R. 19 W	20	284	307	34	1,786	92	524	60
T. 12 N., R. 18 W	3	346	333	34	1,210	---	655	61
T. 11 N., R. 22 W	2	402	487	85	796	---	---	53
T. 11 N., R. 21 W	2	273	345	72	1,765	26	574	62
T. 11 N., R. 20 W	17	322	355	26	1,522	129	614	61
T. 11 N., R. 19 W	60	373	392	16	1,729	118	638	64
T. 11 N., R. 18 W	18	309	337	35	1,223	81	617	59

POSSIBILITIES OF GREATER UTILIZATION OF GROUND-WATER RESERVOIRS

Although many areas in the San Joaquin Valley were subject to overdraft of the local ground-water supply as of 1958, additional pumping from the ground-water reservoirs would be feasible in much of the valley.

The possibilities for increased pumping, in decreasing order of facility are: in irrigated areas now supplied wholly with ground water, in areas now supplied wholly or largely by surface water, and in areas not presently irrigated.

The first possibility could be implemented readily by pumping present wells a greater proportion of the time. As indicated on table 2, the nearly 40,000 irrigation plants in the San Joaquin Valley in 1955–56 were actually running only 25 percent of the time on the average. Except in a few areas of intensive use of wells, farmers generally irrigate chiefly during the daylight hours and only when crops require water.

Increasing the ground-water draft by greater use of present facilities would introduce many engineering-economic problems, however. Increasing pumping over long periods would require large increases in electric-power supplies, additional facilities for drilling and deepening wells and servicing pumps, and additional works to convey water pumped in excess of local demand.

Full use of present wells would cause rapid decline of water levels in most of the valley, thus reducing the yields of wells and requiring deepening of many wells and lowering of pumps to maintain production. Table 2 suggests that ground water could be pumped at an initial rate of 25 to 30 million acre-feet per year with present pumping plants, allowing 25 percent of the time for shutdown for maintenance and repairs. Pumping of this magnitude could result in dewatering the 10- to 200-foot storage zone within a few years. (See table 1.)

In irrigated areas now served wholly or largely by surface water, additional utilization of the ground-water reservoirs would require large expenditures for electric-power facilities, new wells, and works for conveying surplus water out of the areas in periods of excess supply. The justification for such large expenditures must be based on the value of the conservation aspect of the operation, any flood-control benefits that might accrue as a result of diversions from streams at peak flow, the elimination of drainage problems caused by high water tables, and the salvage value of water now wasted through evapotranspiration due to high water tables.

The development of ground-water supplies in areas not presently irrigated is a less important but significant possibility. Much of the lower part of the valley is unsuitable for cultivation owing to the excessive surface accumulation of mineral salts or alkali, as well as to the high density and low permeability of the soils. These soils support a sparse natural pasture that is little used at present. On the eastern side of the valley trough, these poor soils border areas of better soils that are cultivated intensively. Permeable water-bearing deposits commonly extend beneath large areas of alkali soils and serve to transmit water from the cultivated areas to the alkaline areas, where it is lost by evapotranspiration. Thus, operation of the cultivated areas as ground-water storage reservoirs also would result in utilizing storage beneath the areas of alkali soil, even though no water be applied at the land surface in the alkaline areas. Utilization of the ground-water reservoirs in this manner would include installation of wells and conveyance works for exporting water from nonirrigable lands. Depletion of the water in storage should be limited to the recharge that could take place by subsurface inflow of ground-water along the perimeters of the areas because the generally low permeability of the overlying soils probably would limit recharge in large quantities from the land surface.

Ground-water reservoirs beneath areas having soil of poor quality have been utilized for many years by the James Irrigation District in the area southwest of Fresno. Two canals, supplied by wells spaced at intervals of about ¼ to ½ mile, extend 7 miles northeast and 7 miles north of the district into an area of nonirrigable land. By pumping 20 to 30 thousand acre-feet annually from these wells the James Irrigation District has been able to meet irrigation demands that otherwise would have been far in excess of the supply of surface water available to the district from the Kings River.

In summary, it should be emphasized that any of the foregoing measures should be considered only in connection with utilization of ground-water storage as part of a coordinated operation of both surface- and ground-water storage in the most efficient combination. Such an operation of surface- and ground-water storage in the Central Valley is contemplated in the California Water Plan (California Dept. Water Resources, 1957, p. 209), and specific areas have been treated in some detail in that publication.

REPLENISHMENT OF GROUND-WATER STORAGE

Under natural conditions, the ground-water reservoirs of the San Joaquin Valley were replenished by infiltration from the streams that traversed the valley and by infiltration of rain on the valley floor. On most of the valley floor, however, the average annual precipitation is less than 12 inches (California State Water Resources Board, 1951, pl. 3), which, for practical purposes, is considered to be the minimum average annual precipitation at which infiltration is appreciable (Blaney, 1933, p. 89). Thus, infiltration from streams was the chief source of replenishment to the ground-water body before irrigation began.

The natural regimen first was disturbed when stream waters were diverted for irrigation. The early canals and ditches were unlined structures which lost water freely to permeable soils, especially as water was often applied extravagantly by the early irrigators. The net effect of these diversions was to increase replenishment to the ground-water reservoirs to such an extent that, in many areas of the valley, the reservoirs became filled to capacity and waterlogging resulted (Fortier and Cone, 1909). In places where stream water was unavailable or insufficient for irrigation, ground-water supplies were developed to satisfy the demand. These withdrawals tended to balance the excess replenishment from surface water in many areas, and in others overdraft resulted and ground-water levels declined. As ground-water storage thus became available, many plans were formulated which envisioned diverting water from the natural streams during high flow and spreading it in basins or natural channels to permit infiltration to the ground-water reservoir. This artificial recharge, or the practice of increasing by artificial means the amount of water that enters a ground-water reservoir (Todd, 1959, p. 1), has been carried on extensively in the San Joaquin Valley, and it is discussed on pages 45–50 of this report.

Whether the replenishment is natural or artificial, the chief limitation to the amount of water replenished is the ability of the soils and subsurface deposits to transmit large volumes of water rapidly from the land surface to the ground-water reservoir. The principal method of replenishing unconfined reservoirs is to maintain a depth of water on the surface long enough to accomplish the desired infiltration. Replenishment to confined aquifers cannot be accomplished by this method, however, owing to the presence of the impervious confining layer. To replenish confined aquifers rapidly, water must be introduced laterally, that is, from unconfined ground-water bodies beyond the limit of the confining beds, or through wells or shafts that penetrate the confining bed.

RECHARGE UNDER PRESENT IRRIGATION PRACTICE

Recharge to the ground-water reservoirs may be classed as natural recharge, that which would occur without any alteration of the natural regimen, and artificial recharge, that which results from the work of man. The natural recharge in the San Joaquin Valley consists chiefly of infiltration from the natural channels of the streams. Artificial recharge may be considered as incidental, occurring as a consequence of ordinary irrigation practice, and deliberate, resulting from specific efforts to place water in storage in the underground reservoirs.

Although much effort has been devoted to deliberate recharge projects in the San Joaquin Valley, incidental recharge undoubtedly greatly exceeds the deliberate recharge. The gross surface diversion for irrigation was about 8.5 million acre-feet, and ground-water pumpage was about 7.5 million acre-feet per year as of 1952. The surface diversions vary greatly from year to year according to the natural supply, and the ground-water pumpage had increased to 9 million acre-feet by 1955–56. However, by comparing the total irrigation supply for 1952 (about 16 million acre-feet) with the reported irrigated acreage for 1951 (about 3.145 million acres), it seems that the available supply was about 5 feet of water for each acre of irrigated land. The California State Water Resources Board (1955, table 115) estimated that consumptive use of applied water by crops in the San Joaquin Valley south of Stockton was about 6.160 million acre-feet as of 1951, or about 2 feet of water. Thus, it appears that almost 10 million acre-feet of the total irrigation supply, or about 3 feet of water, was not used by the crops but was lost through infiltration, evaporation, transpiration by noncrop vegetation, and as surface and subsurface outflow from the valley.

Data are not adequate to provide an accurate estimate of the proportion of the total water supply that finds its way to the ground-water reservoir by infiltration, but it would be surprising, indeed, if it were less than one-quarter of the total supply, or about 4 million acre-feet in 1952. By comparison, the deliberate recharge in the valley seldom exceeds a few hundred thousand acre-feet per year even in years of excessive runoff. In 1955–56, the deliberate artificial recharge in the San Joaquin Valley totaled only 287,000 acre-feet.[1]

Despite the large annual replenishment to the ground-water reservoirs, severe local overdraft has caused great declines of water levels in much of the San Joaquin Valley, and in many areas great volumes of dewatered sediments are available for ground-water storage as needed (pl. 7).

ARTIFICIAL RECHARGE IN THE SAN JOAQUIN VALLEY

Artificial recharge may be accomplished by direct or indirect methods. Direct methods are (1) water spreading, which includes diverting water into shallow basins, ditches, or furrows, prolonging the time in which water is in contact with a naturally influent channel, and applying excess water for irrigation; (2) recharge through pits and other excavations of moderate depth; and (3) recharge through relatively deep wells and shafts. The indirect method is that of inducing the movement of water from lakes and streams into the underground formations by pumping water from wells, collectors, or galleries near the surface-water sources.

Successful water-spreading operations have been carried out for many years in several areas in southern California on soils composed primarily of coarse sand, gravel, and cobbles. Because infiltration rates in such deposits generally are high, the operating problems have

[1] California Dept. of Water Resources, unpublished data.

been concerned mainly with the building and maintaining of dikes, revetments, and ditches (Mitchelson, 1949). These areas in southern California are particularly suited for water spreading, because the soils are highly permeable and are of little value for agriculture. Water-spreading operations in the San Joaquin Valley, however, must be carried on for the most part on finer, less permeable soils.

The chief form of deliberate artificial recharge in the San Joaquin Valley is water spreading in stream channels and canals, although some projects utilize a combination of channels and spreading basins, and one large project uses spreading basins almost exclusively. Minor quantities of water used for cooling are recirculated to the ground-water reservoir through wells in the Fresno area and elsewhere, but no large-scale projects use wells for artificial recharge.

Agencies carrying out deliberate artificial recharge include the Chowchilla Water District, the Madera Irrigation District, the Kaweah Delta Water Conservation District, the Lower Tule River Irrigation District, and the North Kern Water Storage District. The Chowchilla Water District and Madera Irrigation District rely on infiltration from natural channels and ditches to put the water underground. The Kaweah Delta Water Conservation District and the Lower Tule River Irrigation District use natural channels, canals, and ditches to spread natural flow and water purchased from the Friant-Kern Canal. The North Kern Water Storage District relies mainly on spreading basins for recharge, although substantial infiltration takes place from the canals that supply these basins.

The construction of Friant Dam on the San Joaquin River and of its northern and southern distribution conduits, the Madera Canal and Friant-Kern Canal, made it possible to conserve much of the flow of the San Joaquin River that formerly had wasted to the sea. Water stored at Friant Dam is sold by the Bureau of Reclamation in 2 price classes: Class 1 water, the firm or minimum supply, sold for $3.50 per acre-foot; Class 2, the nonfirm supply, sold for $1.50 per acre-foot. Flood-flow waters on at least one occasion have been delivered at no cost to water users. Most of the water users served by the canals use Class 1 water as a base supply to be supplemented by purchases of Class 2 water as available and by pumping from private wells. Because of its high cost, little Class 1 water is spread for ground-water replenishment; Class 2 water is delivered to irrigators or spread for replenishment, depending upon the demand for water at the time it becomes available. Several agencies, notably the Chowchilla Water District, the Madera Irrigation District, the Lower Tule River Irrigation District, and the Kaweah Delta Water Conservation

District, have purchased large amounts of Class 2 water specifically for water spreading, chiefly in ditches and natural stream channels. No detailed record of the disposal of this surplus water is available, however, and it is impossible to determine unit rates of infiltration from the existing information.

PROJECTS UTILIZING SPREADING BASINS

Because of the low cost, stream channels and canals are used extensively in artificial recharge. Spreading basins are commonly used, however, to augment the infiltration from the existing transmission systems. The chief benefit of spreading basins is that they permit temporary storage and thus make it possible to conserve large flows that may exceed the infiltration capacity of the channels and canals in a given area.

In their report "Artificial recharge in California," Banks and others (1954, table 1) summarized the active projects in the southern San Joaquin Valley as of 1954. They reported 12 spreading basins operated by the Kaweah Delta Water Conservation District in conjunction with spreading in the channels of the Kaweah and St. John's Rivers, and Cross, Mill, Packwood, Cameron, and Deep Creeks. Also reported were three spreading basins of the Lower Tule River Irrigation District, used in conjunction with the natural channels of the Tule River to spread natural flows and large quantities of water supplied from the Friant-Kern Canal.

One of the largest and best recorded water-spreading projects in the San Joaquin Valley is that of the North Kern Water Storage District. Beginning with the formation of the district in 1936, a concerted effort has been made to place as much surplus water from the Kern River in underground storage as feasible. Substantial infiltration losses occur from the canals of the district (Trowbridge, 1950), but large volumes of water have been spread, as indicated in the following table compiled from unpublished records of the North Kern Water Storage District.

Infiltration from spreading basins in the North Kern Water Storage District

Year	Infiltration (acre-feet)	Year	Infiltration (acre-feet)
1938	20, 345	1946	23, 504
1939	7, 754	1947	9, 604
1940	33, 960	1948	4, 266
1941	32, 929	1949	0
1942	3, 352	1950	3, 932
1943	0	1951	5, 924
1944	19, 347	1952	51, 624
1945	39, 314	1953	63, 449

Detailed records for 1938 indicate that the average infiltration rates for periods of 100 to 150 days of operation ranged from 0.24 to 1.71 acre-feet per acre per day from 7 ponds. The maximum rate was noted at the smallest pond (3.3 acres) and presumably shows the effect of lateral spreading to a greater extent than at the other 6 ponds, which ranged in area from 16.1 to 53.8 acres. The average infiltration was less than 1 foot per day at the larger ponds. During the 3 to 5 months that the ponds were flooded, an average of 86 acre-feet per acre of water was placed underground.

PROJECTS UTILIZING STREAM CHANNELS AND CANALS

Although spreading of surplus water for ground-water storage in natural stream channels and canals offers many obvious advantages, few of the major streams of the San Joaquin Valley lend themselves readily to this sort of management because of their topographic positions and the economics of water distribution. All the major streams north of the Kaweah River (pl. 1) enter the valley at altitudes far below the average altitude of the valley floor and flow westward across the valley in trenches incised in the dissected uplands, low plains, and fans (p. 9). To deliver large quantities of water from these streams to the lands where spreading can be carried out effectively, major detention and conveyance works are required.

The Kaweah, Tule, and Kern Rivers, however, enter the valley at about the average altitude of the valley floor, and distributaries or former channels spread out across young alluvial fans. Natural channels, therefore, are readily available for disposal of surplus water. As a result, most of the water spreading in the past has been from these streams, especially from the Kaweah River, which splits into a maze of distributaries near where it enters the valley east of Visalia.

In a sense, any irrigation system in the valley that distributes water through natural channels or unlined canals could be considered to be an artificial recharge project. Deliberate artificial recharge projects however, are limited to those of the Kaweah Delta Water Conservation District, the Lower Tule River Irrigation District, the North Kern Water Storage District, and possibly the Chowchilla Water District and the Madera Irrigation District. The latter two districts utilize the natural flows of the Chowchilla and Fresno Rivers, respectively, augmented by water purchased from the Friant-Kern Canal of the U.S. Bureau of Reclamation for recharge. When water is available from either source in excess of irrigation demand, it is shunted into the channels of Ash and Berenda Sloughs in the Chowchilla District and Dry Creek, the Fresno River, and Cottonwood Creek in the Madera District where infiltration from the streams replenishes the ground-water reservoir.

RECHARGE THROUGH WELLS

Little experimental work has been done in the San Joaquin Valley on recharge through wells, although this method has been practiced for many years by industries that use ground water for cooling in Fresno. Since 1928, the Yosemite Ice Plant reportedly has pumped about 500 gpm (gallons per minute) of cooling water from one well and returned it to the ground-water reservoir through 2 nearby recharge wells. Similarly, the Loughead Refrigeration Plant for many years has returned as much as 425 gpm of circulated ground water through a 12-inch well 150 feet deep. The Fresno Ice Arena also has returned cooling water at a rate of about 350 gpm through a recharge well. Available data on recharge through injection wells in Fresno, as reported by the California Division of Water Resources (1952), are tabulated below:

Owner of well	Depth (feet)	Annual recharge (acre-feet)
Loughead Refrigeration Plant	150	59
Fresno Ice Arena	160	200
Veterans Administration Hospital	390	1, 100
Fresno County School Administration Building	144	230
Van Sickle Freezing Co	100	300
Peters and Garabedian	135	150

RECHARGE EXPERIMENTS IN NORTHERN KERN COUNTY

The North Kern Water Storage District began experimenting with water-spreading methods in 1936 and with test ponds in 1941 in the area north of Bakersfield. Early tests showed that in this area the infiltration rate decreased below the limit of practicality when water was held on the surface of undisturbed soil continuously for extended periods. An informal organization of interested public and private agencies was formed later to study methods of increasing infiltration rates and to carry out a joint investigation of water spreading in the San Joaquin Valley. In 1948, the Soil Conservation Service, U.S. Department of Agriculture, established a laboratory in Bakersfield for the study of soil physics, soil microbiology, and hydrology, with special reference to problems of artificial recharge. This laboratory has investigated infiltration rates in various types of soil, using numerous water and soil treatments to increase infiltration. Summaries of these research activities and results obtained to date are presented in various reports released by the cooperating agencies, particularly by Bliss and others (1950) and by Campbell (1955).

The experimental work by the Soil Conservation Service in Kern County led Bliss (1950, p. 4) to conclude that the decline in rates of infiltration of water from ponds under continued submergence was due chiefly to microbial activity in the soil. Figure 5 shows typical infil-

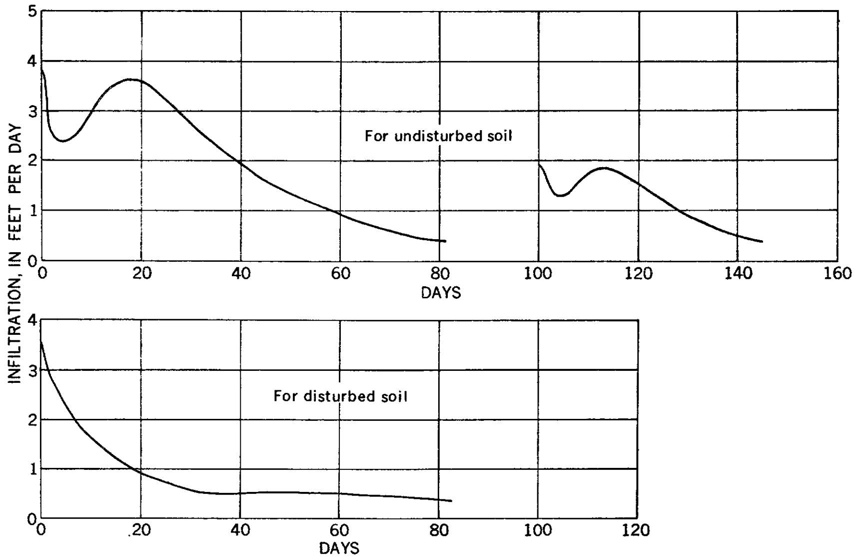

FIGURE 5.—Typical curves of infiltration rates from ponds in the Minter Field area (Bliss and others, 1950, figs. 1*A*, *B*.)

tration rates observed in pond experiments on disturbed and undisturbed soils in the Kern County area. The general S-shaped curve also was noted in ditch experiments by the Geological Survey in western Fresno County (fig. 13). In the typical S-shaped curve, the initial rapid decline is attributed to dispersion and swelling of soil particles on wetting (Bliss and others, 1950, p. 16). The slow increase from the first low is attributed to solution of air by the percolating water, thus opening more pores for the passage of water. The final slow decrease in infiltration is due chiefiy to biologic activity in the soil, which slowly seals the pores.

Vegetative treatments, including the growth of Bermuda grass and Paragrass, have greatly increased infiltration rates under some conditions. Relatively large increases in infiltration rates were observed after addition of organic material, especially cotton-gin waste, to the soil. Under such treatment, ponds have taken 14 to 16 feet of water per day compared to normal rates of 3 to 4 feet per day (Bliss and others, 1950, p. 5).

INFILTRATION RATES SUMMARIZED FROM OTHER INVESTIGATIONS

Although most irrigation systems in the San Joaquin Valley serve as incidental artificial recharge projects and several agencies operate deliberate recharge projects as described earlier, surprisingly little quantitative data have been published on the amount of water put in storage and unit rates of infiltration. For the convenience of the reader the results of several quantitative tests are summarized below.

On August 31, 1954, a total of 23 flow measurements were made on Ash and Berenda Sloughs in the Chowchilla Water District to determine rates of infiltration loss from the channels of these two streams (Howard Stoddard, Consulting Engineer, written communication, 1954). Under conditions of steady flow, a total loss in excess of 119.0 cfs, or 53 percent of the original streamflow, was detected in a 16-mile reach of Ash Slough, indicating an average loss of 7.43 cfs per mile of stream channel. Of this total, 71 percent, or 83.6 cfs, occurred in a 3½ mile reach between U.S. Highway 99 and the head of Bethel Canal, indicating an average loss of 23.9 cfs per mile in that reach. Only 28 cfs was lost in the upper 8 miles of the Ash Slough section, an average rate of 3.5 cfs per mile. Similar measurements on Berenda Slough indicated a total loss of 41 cfs in 13 miles of stream channel, or an average loss of 3.2 cfs per mile.

In an attempt to determine representative rates of infiltration in natural stream channels in the area served by the Madera Canal, a series of streamflow measurements were made by the U.S. Bureau of Reclamation on several streams entering the valley from the mountains to the east. A summary of the measured infiltration rates, as reported by the Bureau of Reclamation (1955), is listed below.

Cottonwood Creek (including Hildreth Creek).—During a 3-day period in January 1945 flow of 11 cfs at Borden decreased to no flow at La Vina 11.6 miles downstream, which indicated a minimum infiltration rate of 0.96 cfs per mile. A similar series of measurements in February 1945, during a 5-day period of uniform flow of 90 cfs at Borden, indicated a loss of 57.5 cfs from the 23-mile reach of channel from Borden downstream and an average infiltration rate of 2.5 cfs per mile of channel.

Fresno River.—Infiltration rates ranged from 2.4 cfs per mile at low flow to more than 7 cfs per mile at higher flows.

Dry Creek.—In November 1951, with 81 acre-feet per month (about 1.35 cfs) flowing past the Madera Canal crossing, no flow reached Dixieland, 17 miles downstream. The reported average infiltration rate of 0.08 cfs per mile for this distance obviously is a minimum.

In February 1951, a loss of 256 acre-feet per month in this same 17-mile rear (the flow diminished from 341 acre-feet per month at the Madera Canal to 85 acre-feet per month at Dixieland) indicated an average infiltration of 0.25 cfs per mile.

Berenda Slough.—With roughly 47 cfs flowing past the Santa Fe railway bridge during a 10-day test in January 1940, no flow reached the Johnson Road crossing 15.3 miles downstream. This indicates a minimum loss of 3.1 cfs per mile. At flows sufficient to cause flow at Johnson Road, infiltration rates are only slightly greater.

During a test made in January 1942, with 321 cfs passing the Santa Fe railway bridge, only 262 cfs was measured passing Johnson Road, which indicated a total loss of 59 cfs and an average rate of 3.8 cfs per mile.

Ash Slough.—In February 1945, flow of 54 cfs past the Santa Fe railway bridge decreased to no flow at Tyler Road, 17.6 miles downstream, which indicated a minimum loss of 3.1 cfs per mile.

In February 1942, flow of 106 cfs at the Santa Fe railway bridge resulted in flow of 45 cfs at Tyler Road, which indicated a loss of 61 cfs in this same reach at an average rate of 3.5 cfs per mile.

Chowchilla River.—With 16 cfs passing the Santa Fe railway bridge in January 1946, no flow passed a measuring point 12.5 miles downstream which indicated a minimum loss of 1.3 cfs per mile.

In February 1946, flow of 38 cfs at the same bridge decreased to 12 cfs at the measuring point 12.5 miles downstream, which indicated a loss of 2.1 cfs per mile of channel.

In an effort to determine infiltration from the Outside Canal, a series of streamflow measurements were made by the U.S. Bureau of Reclamation during the 1941 irrigation season (D. S. Stoner, written communication, Oct. 7, 1941). A relatively straight reach near the head of the canal that had few service diversions and a small fluctuation in discharge was selected for study. Three gaging stations, which segregated the canal into an upper reach 28,467 feet long and a lower reach 25,773 feet long, were selected. In the reach studied, the canal averaged 80 feet in width and normally had about 5 feet of water in it. Discharge measurements were made from June 17 to July 20, 1941, and from August 12 to August 23, 1941. Mean daily stream discharges were calculated for the upper and the lower reaches. The mean daily flow past the upper station ranged from 384 to 468 cfs during the period of test. Throughout the period of tests, the effect of infiltration from the canal on the water table was observed by means of auger holes near the canal. Although infiltration was sufficient to maintain a ground-water mound along the course of the canal, the losses as calculated from the discharge measurements were less than the limits of accuracy of the measuring equipment. It was concluded from the tests that the Outside Canal in the reach tested was losing water at an undetermined rate, but less than 1 percent of the discharge, or less than 4 cfs in the 10-mile reach studied.

Similar measurements reported by Rowher and Stout (1948) in canals of the Turlock Irrigation District, near Turlock, the Merced Irrigation District, near Merced; the Fresno Irrigation District, near Fresno; and the Alta Irrigation District, near Orange Cove, showed unit infiltration rates of as much as 3.38 feet per day on a sandy soil near Turlock and 3.81 feet per day in the Alta Irrigation District. Measurements reported by Rowher and Stout for unlined canals in the San Joaquin Valley are summarized in table 4.

TABLE 4.—*Summary of seepage measurements made in 1922 and 1923 in the San Joaquin Valley by Rowher and Stout*

Canal system	Canal	Section	Number of tests	Average discharge (cfs)	Unit infiltration from wetted area (feet per day)
Turlock Irrigation District.	Highline	Head to East Ave. bridge	2	136.60	0.239
Do	Lateral 17B	Head to sec. 17–20	4	17.43	2.61
Do	do	do	(1)	17.14	2.56
Do	do	Head to sec. 22	2	17.54	1.58
Do	do	Sec. 22 to sec. 17–20	2	15.36	3.38
Merced Irrigation District.	Yosemite-Le-Grande.	Flume 1 to tunnel	8	54.89	.335
Do	do	Farm bridge to tunnel	4	97.74	.551
Do	do	do	(1)	95.25	.39
Do	do	Flume 1 to flume 2	2	26.13	.559
Do	do	do	4	56.56	.465
Do	do	Flume 2 to tunnel	4	51.64	[2] .139
Do	Burchell Lateral	Burchell to Santa Fe RR	1	13.39	.076
Fresno Irrigation District.	Houghton	Grant Ave. to Westlawn Ave.	3	71.89	[2] 0.394
Do	do	do	(1)	64.7	.150
Do	Briggs ditch	Head to Jensen Ave	4	34.24	1.194
Do	do	do	(1)	34.24	1.19
Do	do	Head to Golden Dawn Ave	2	34.17	3.33
Do	do	Golden Dawn Ave. to Jensen Ave.	2	30.41	.204
Alta Irrigation District.	Main	Head to second lining	4	115.32	1.65
Do	do	do	1	620.78	3.81
Do	do	do	(1)	706.4	[2] .77
Do	do	Head to first lining	2	111.24	2.07
Do	do	First lining to second lining	2	105.31	1.63
Do	do	First lining to above Campbell ditch.	2	105.50	1.08
Do	do	Head to below Campbell ditch.	3	107.60	1.38
Do	do	First lining to below Campbell ditch.	3	101.15	0.09
Do	do	Below Campbell ditch to second lining.	2	99.01	3.04
Do	do	Above to below Campbell ditch.	2	96.37	2.23
Do	East branch	Orosi lateral to Sand Creek	6	53.34	[2] .782

[1] Continuous record.
[2] Gain.

Rowher and Stout (1948, p. 96) concluded from these and other measurements that the permeability of the material forming the lining of a canal, whether natural soil, a deposit of silt, or an artificial lining, is the dominant factor controlling the rate of infiltration under most circumstances. They noted also that in areas where the water table was close to the land surface, infiltration commonly was greatly reduced or gains in flow occurred. The soils in which the canals were excavated and the size of the canals had no consistent relation to the unit rates of infiltration.

From 1943 through 1947, the Kaweah Delta Water Conservation District conducted a water-spreading program on idle lands in the service area of the Kaweah River. Several large basins were inundated, some as large as 150 acres. Sustained infiltration rates through these soils averaged 0.5 foot per day (U.S. Bur. Reclamation, 1949).

Calculations of infiltration from large streams based on comparison of discharge at different gaging stations seldom are reliable because the channel losses commonly are less than the probable error of the measurements. The calculations are further complicated by error introduced by changes in channel and bank storage as the stage fluctuates. The problem of infiltration from the Mokelumne River was analyzed in considerable detail by the Geological Survey for the period 1926–33 and is reported on by Pritchett and others (1934). They concluded that estimates of momentary rates or of daily quantities lost or gained seem wholly unjustified (*1934* idem, p. 179), but that over a long period of careful measurements the errors tend to compensate and that yearly estimates presented are correct in relative magnitude. Their calculations indicate monthly infiltration rates from the Mokelumne River as great as 8 acre-feet per acre, although the loss in most months ranged from 2 to 4 acre-feet per acre. These estimates cannot be compared with similar estimates for unsaturated materials, however, because the water table was just beneath the stream, and losses were limited by the rate at which water could move laterally away from the streambed. The ground-water conditions in the vicinity of the Mokelumne River are similar in many respects to those in the vicinity of the other large perennial streams of the Central Valley. Thus, the losses from the Mokelumne could be considered as a rough index of the losses that might occur from any of the major streams in the valley under comparable conditions.

INFILTRATION RATES OBSERVED IN THIS INVESTIGATION

The rate of infiltration of water through alluvial deposits under field conditions is primarily a function of the properties of the wetted surface soil, modified to some extent by the depth and duration of submergence. Increasing the depth of submergence tends to increase slightly the rate of infiltration, whereas continued submergence tends to decrease the rate. Experiments have shown that the turbidity of the infiltrating water also is a major factor affecting the rate of infiltration. Lowdermilk (1929, p. 606–628) demonstrated that clear water will penetrate soil at a rate as much as 10 times as fast as agitated turbid water containing less than 1 percent of solids by volume.

One of the objectives of this investigation was to compute unit rates at which ground-water bodies are recharged under different field conditions. Although the investigation was limited in the extent of field research that could be undertaken, the following four experimental programs were conducted: (1) A series of measurements of infiltration from canals were made in the Bakersfield area; (2) a series of measurements of infiltration from two specially constructed test ditches were made near Huron in western Fresno County; (3) rates of infiltration were determined on three ¼-acre test plots in conjunction with land subsidence studies being made in Western Fresno County and, (4) measurements were made of movement of ground water between aquifers in 16 idle irrigation wells in western Fresno County. Only a few soil types found in San Joaquin Valley were tested, and only a few representative field conditions were studied. The results of the tests were consistent, however, and probably are of the right order of magnitude for infiltration rates under typical field conditions in the valley.

To compute infiltration rates two approaches have been used in this investigation: (1) by computing the infiltration rate from the difference in measured discharge at the ends of the reach and (2) by measuring directly the rate of descent of the water surface in a ponded area. For most streams of large flow and small loss, the inaccuracies inherent in measuring the flow are of greater magnitude than the loss from the stream. The measurement of ponded-water loss eliminates the effect of inaccurate flow measurements. In the ponded area, the rate of infiltration is determined by observing the rate of fall of the water surface under no-flow conditions and is obtained directly in terms of feet per day, or acre-feet per acre per day. The inflow-outflow approach was used in the studies of canal loss made in the Bakersfield area; the ponded-water approach was used in experiments made of infiltration rates in ditches and ponds in western Fresno County.

The authors recognize that the infiltration rate of water under ponded conditions may not be the same as that for flowing water on the same type of soil. However, little information is available on the comparative rates of infiltration under flowing and ponded conditions that can be applied to the soils of the San Joaquin Valley. Moving water tends to scour the bottom of the channel, thus preventing the clogging of the pores of the soil with silt. Conversely, turbid water tends to blanket the soil surface with a veneer of fine material of low permeability. Infiltration rates generally diminish rapidly with the application of silty water. Algal growth, changes in water viscosity, differences in water quality, differences in soils, and the position of the water table—all must be considered in a detailed analysis of the rates of infiltration under either ponded or flowing conditions. The effects of these various factors are beyond the scope of this investigation, and the information reported in the following sections should be considered only as indicative of conditions that might be met in the San Joaquin Valley.

INFILTRATION FROM CANALS IN THE BAKERSFIELD AREA

To determine representative rates of infiltration from the principal canals in the Bakersfield area, a series of inflow-outflow measurements were made in selected reaches of operating canals during May and June of 1955. The canals studied are owned by subsidiaries of the Kern County Land Co., as are most of the canals south of the Kern River. The locations of canals, points where measurements were made, and the general permeability of the soils of the Kern River service area are shown on plate 8. Much of the irrigation water for this area is diverted from the Kern River and distributed through a system of primary and secondary canals, which are operated almost continuously throughout the irrigation season.

Long reaches of canal having uniform cross sections and fairly consistent soil permeability, devoid of numerous diversions, and rapid changes in flow were selected for measurement.

The canal flow was measured above and below each reach with current meters according to the standard procedures of the Surface Water Branch of the Geological Survey (Corbett and others, 1943). The loss within the canal reach then was computed as the difference between these two measurements. The rate of loss is expressed in terms of cubic feet per second per mile of canal length and acre-feet per acre of wetted area in tables 5 to 10. Measurements were made after the flow in the canal had remained constant for several hours, and a continuous water-stage recorder near the headgate of each canal was checked before and during each set of measurements, to insure that no changes in flow had occurred. No attempt was made to determine evapotranspiration losses during this investigation because these losses would have been much less than the limits of accuracy of the measurements of flow.

To compute infiltration in terms of cubic feet per second per mile, and also acre-feet per acre per day, the generalized dimensions of each selected reach of canal was measured. Wetted perimeters were measured at short intervals along each reach with a weighted line submerged laterally from water line to water line. From these measurements, the average wetted perimeter was determined, which, when multiplied by the length of the selected reach, gave an approximation of the wetted area through which water could infiltrate. Most of the canals were broad and relatively shallow, and varied considerably in width. Tules and other water plants lined the canal banks and bottom in many places, which added to the difficulty of determining accurately the effective dimensions of the canal.

The results of the measurements of infiltration from selected canals in the Bakersfield area are summarized below.

Measurements of infiltration from the Levee Canal, headgate to Stine Canal.—Discharge measurements were made in the 3-mile section of the Levee Canal between its headgate at the Kern Island Canal and the head of the Stine Canal on 6 days in May and June 1955. Because of fluctuations in discharge of the canal, however, data from only three of these sets of measurements were sufficiently consistent to give reliable rates of infiltration from the canal. Three stations (pl. 8) were selected for measurement of flow as follows: (A–1) at the Kern County Land Co. measuring structure (29/28-18K), about 600 feet downstream from the canal headgate; (A–2) at a point about 100 feet above the Calloway weir (29/27–13Q); and (A–3) at the Kern County Land Co. measuring structure 30/27-26Q2), about 200 feet upstream from the headgate of the Stine Canal. Measuring sites A–1 and A–2 are 1.16 miles apart. The intervening sandy canal banks are lined with a dense growth of water grasses. In this reach, the wetted perimeter of the canal ranged from 26 to 52 feet and averaged 42 feet.

In the reach from site A–2 to site A–3, 1.85 miles in length, the wetted perimeter of the canal ranged from 42 to 80 feet and averaged 58 feet. Throughout this reach, the sandy canal banks are sparsely lined with water grasses and locally with numerous willow trees. A small quantity of water that leaked into the canal at the Calloway weir below station A–2 was of no significance and was not measured. A small diversion into the Castro ditch just upstream from site A–3 was measured and included in the discharge reported for site A–3.

The measurements of infiltration from the Levee Canal are summarized in table 5 and illustrated in figure 6. As shown in figure 6, the loss in the 3-mile reach between sites A–1 and A–3 ranged from 7.8 cfs at the lowest flow measured to 12.9 cfs at the highest flow. Thus, the minimum and maximum loss per mile in the measured range was 2.6 cfs per mile and 4.3 cfs per mile, respectively, in the reach between A–1 and A–3. The upper reach of the canal, site A–1 to A–2, which flanks the Kern River, lost water at a substantially greater rate than did the lower reach, A–2 to A–3. Moreover, the increase in loss per mile as flow increased was greater in the upper reach than in the lower (fig. 6).

The soils that underlie the Levee Canal in the reach between the headgate and the Stine Canal have been mapped as Cajon fine sandy loam (Cole and others, 1945). The surface layer of this soil, ranging

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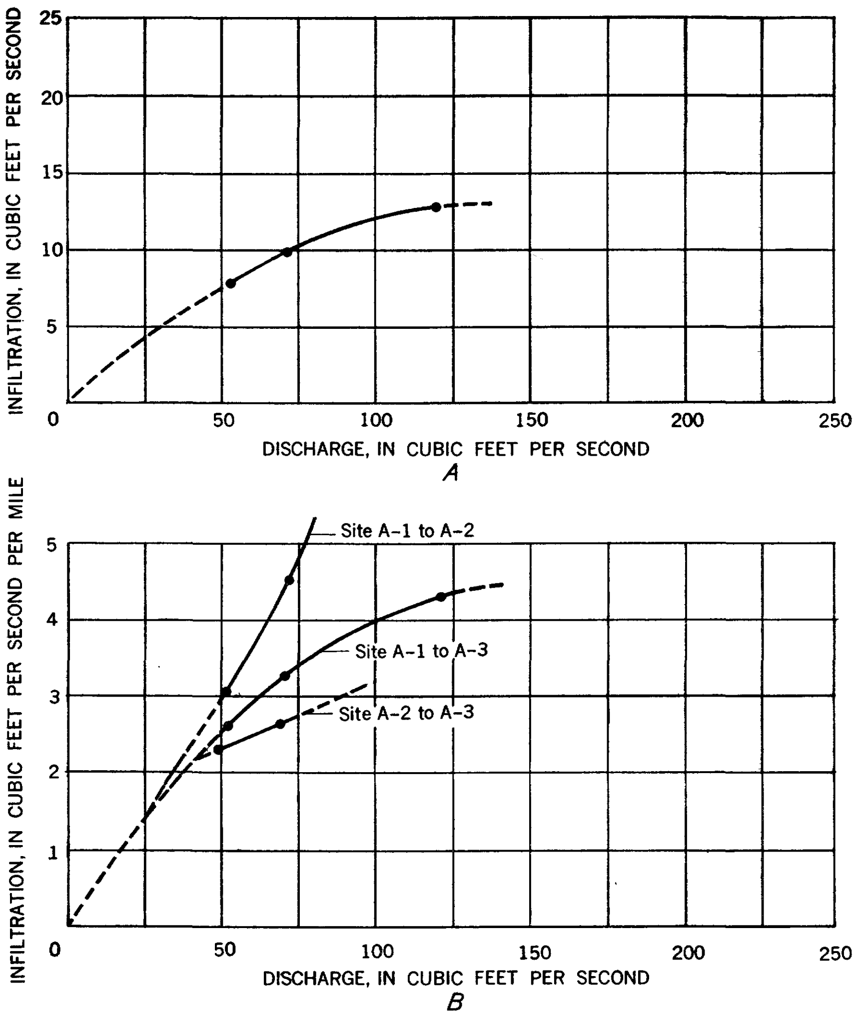

FIGURE 6.—*A*, Infiltration from the Levee Canal, head gate to Stine Canal, site A-1 to A-3. *B*, Infiltration per unit of length from the Levee Canal.

in thickness from 7 to 24 inches, is highly micaceous and consists of stratified, calcareous, granitic materials of medium- to coarse-grained texture. As indicated on plate 8, the soil is highly to moderately permeable.

Measurements of infiltration from the Stine Canal.—Measurements of discharge were made in the Stine Canal at two sites (pl. 8) as follows: (B-1) at the Kern County Land Co. measuring station (29/27-26Q1), about 300 feet below the headgate near the junction with the Levee Canal, and (B-2) at (30/27-2L), a bridge near the center of sec. 2, T. 30 S., R. 27 E. The canal distance between these 2 meas-

TABLE 5.—*Infiltration from the Levee Canal, headgate to the Stine Canal*

Site	Date (1955)	Time (PDT)	Discharge (cfs)	Seepage loss (cfs)	Percent of initial discharge	Infiltration per unit length of canal (cfs per mile)	Infiltration per unit area (feet per day)
A-1	May 25	11:05 a.m.	70.2				
A-2	do	11:50 a.m.	65.1	5.1	7.3	4.4	1.6
A-3	do	1:55 p.m.	60.3	4.8	7.4	2.6	.7
Loss				9.9	14.1	3.3	1.0
A-1	June 3	8:40 a.m.	51.5				
A-2	do	10:00 a.m.	48.0	3.5	6.8	3.0	1.2
A-3	do	12:30 p.m.	43.7	4.3	9.0	2.3	.6
Loss				7.8	15.1	2.6	.8
A-1	June 15	7:00 a.m.	119.2				
A-3	do	2:50 p.m.	106.3				
Loss				12.9	10.8	4.3	1.4
Average rates of infiltration:							
Upper reach, A-1 to A-2						3.7	1.4
Lower reach, A-2 to A-3						2.4	.7
Sites A-1 to A-3						3.4	1.1

uring sites is 2.06 miles. In this reach, the sandy banks of the canal are lined with water grasses, and in a few places hydrophytes cover the canal bottom. The discharge of the canal fluctuated somewhat during the measurements, owing to the entry of varying amounts of waste water just above the canal headgate near site B-1.

The measurements of infiltration from the Stine Canal are summarized in table 6 and illustrated in figure 7. The seepage loss in this reach ranged from 1.7 cfs, when the flow at the headgate was 9.4 cfs, to 6.7 cfs, when discharge at the headgate was 65.7 cfs. The loss per mile of canal ranged from 0.9 cfs to 3.3 cfs.

In the 2-mile section, the wetted perimeter of the canal varied considerably, owing to channeling and erosion of the canal banks and bottom. For these reasons, measurements of the average wetted

TABLE 6.—*Infiltration from the Stine Canal*

Site	Date (1955)	Time (PDT)	Discharge (cfs)	Seepage loss (cfs)	Percent of initial discharge	Infiltration per unit length of canal (cfs per mile)	Infiltration per unit area (feet per day)
B-1	June 2	9:10 a.m.	9.4				
B-2	do	10:25 a.m.	7.7				
Loss				1.7	18.1	0.8	
B-1	May 24	10:45 a.m.	27.4				
B-2	do	11:45 a.m.	24.1				
Loss				3.3	12.0	1.6	
B-1	June 21	9:35 a.m.	65.7				
B-2	do	11:00 a.m.	59.0				
Loss				6.7	10.2	3.3	1.7

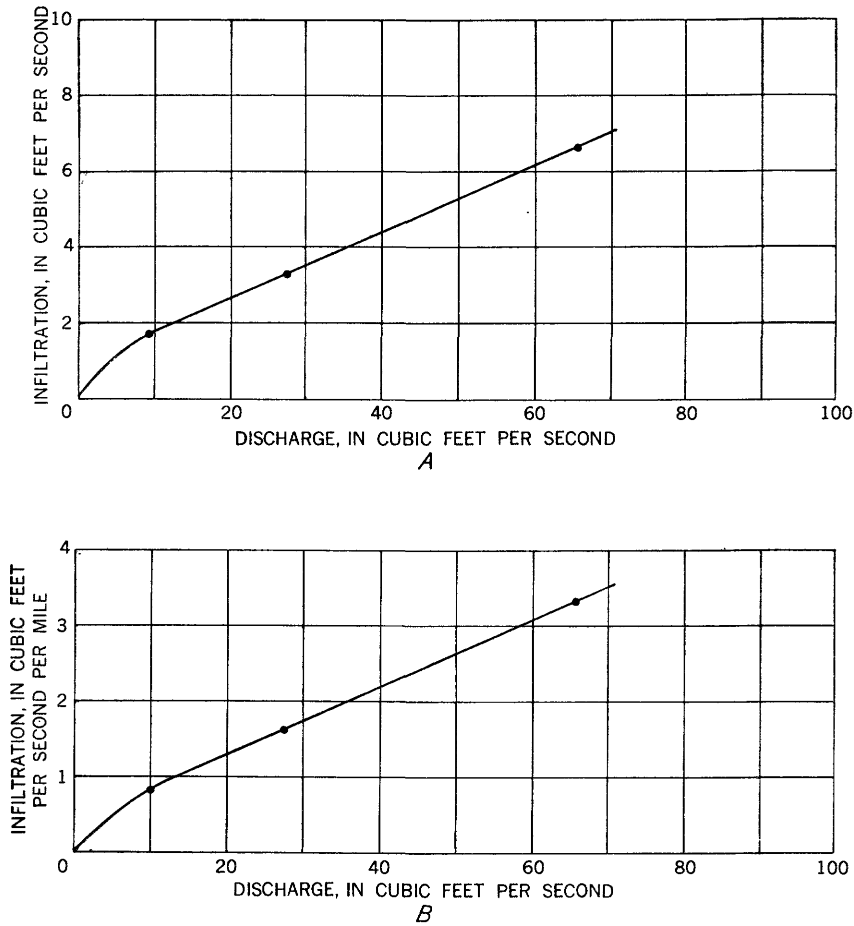

FIGURE 7.—*A*, Infiltration from the Stine Canal. *B*, Infiltration per unit of length from the Stine Canal.

perimeter were made only at the highest stage. Measurement of the wetted perimeter of the canal made only at highest stage (65.7 cfs), indicated that the average wetted perimeter was 32 feet.

Soils in the measured reach of the Stine Canal have been mapped as Cajon fine sandy loam and Cajon fine sand by Cole and others (1945). Both soils are young alluvial deposits that consist of granitic detritus. They are relatively permeable and well drained, and they show no profile development, for the subsoils differ little from the surface soils.

Measurements of infiltration from the Buena Vista Canal, headgate to Pacheco Road.—Discharge measurements were made in the Buena Vista Canal at 3 points in the 4.5-mile reach from its headgate in the NE¼SE¼, sec. 33, T. 29 S., R. 27 E., to Pacheco Road near the S¼ cor. sec. 18, T. 30 S., R. 27 E. (pl. 8). The following three stations were selected for measurements of discharge: (C–1) at the Kern County Land Co. measuring structure (29/27–33J) near the headgate of the canal; (C–2) at a point about 60 feet below weir 41–55 (30/27–9L) in the NE¼SW¼ sec. 9, T. 30 S., R. 27 E.; and (C–3) at a point about 100 feet below weir 89–40 near Pacheco Road (30/27–19C). In the 2.1-mile reach from site C–1 to C–2, the wetted perimeter of the canal ranged from 21 to 17 feet. An average wetted perimeter of 19 feet has been used in the computations of infiltration per unit of area (table 7). In the reach from site C–2 to C–3, a canal distance of 2.4 miles, the wetted perimeter of the canal ranged from 27 to 23 feet; and an average of 25 feet has been used in calculations of infiltration (table 7). Throughout the reach between sites C–1 and C–3, the banks of the canal are lined with water grasses and a few patches of tules.

One minor accretion and several small leaks at diversion gates were considered too small to be of consequence, and no corrections were made for them. Several discharge measurements were discarded because significant but unmeasured quantities of water had been diverted from the canal during the measurement period.

Table 7 summarizes the measurements of discharge in the section of the Buena Vista Canal between the headgate and Pacheco Road. Losses ranged from 0.52 cfs per mile to 0.86 cfs per mile; the average was 0.68 cfs per mile. In terms of infiltration per unit area, this represents 0.51 foot per day in the measured reach.

The soils traversed by the Buena Vista Canal north of Pacheco Road have been mapped by Cole and others (1945) as Cajon fine sandy loam and Cajon fine sand. Both soil types are developed on young alluvial deposits, consisting chiefly of granitic rock particles.

TABLE 7.—*Infiltration from the Buena Vista Canal, headgate to Pacheco Road*

Site	Date (1955)	Time (PDT)	Discharge (cfs)	Seepage loss (cfs)	Percent of initial discharge	Infiltration per unit length of canal (cfs per mile)	Infiltration per unit area (feet per day)
C-1	May 26	9:16 a.m.	29.4				
				1.1	3.7	0.52	0.45
C-2	do	11:35 a.m.	28.3				
				1.9	6.7	.79	.52
C-3	do	2:50 p.m.	26.4				
Loss				3.0	10.2	.67	.50
C-1	June 2	1:20 p.m.	29.0				
C-2	do	2:50 p.m.	27.2				
Loss				1.8	6.2	.86	.70
C-1	June 15	9:15 a.m.	41.3				
C-3	do	10:40 a.m.	38.2				
Loss				3.1	7.5	.69	.52
Average rates of infiltration:							
Upper reach, C-1 to C-2						0.69	0.6
Lower reach, C-2 to C-3						.79	.5
Sites C-1 to C-3						.68	.5

Good drainage, a lack of profile development, and relatively high permeability are characteristic of the soils of the Cajon series.

Measurements of infiltration from the Buena Vista Canal, south of the Taft Highway.—To provide data on infiltration on typical soils of the lower edges of alluvial fans, the Buena Vista Canal was measured at the following three sites south of the Taft highway, which coincides with the south line of T. 30 S. (pl. 8) : (D–1) at a point about 100 feet south of the Taft highway (31/26–2), (D–2) near Stine slough at a point about 160 feet below weir 24 (31/26–16E) in the SW¼NW¼ sec. 16, T. 31 S., R. 26 E., and (D–3) near the E¼ cor. sec. 19, T. 31 S., R. 26 E. The distance between measuring sites D–1 and D–2 is 3.2 miles, and between sites D–2 and D–3 it is 2.0 miles. The wetted perimeter of the canal in the upper reach, D–1 to D–2, averages 26 feet at high stage and 20 feet at low stage. A value of 23 feet was used in the computations in table 8. In the southern reach, the wetted perimeter ranged from 23 to 17 feet, and probably averaged about 20 feet at the time of the measurements of flow. In the reach measured, the bottom and banks of the canal were well sodded with water grasses and other hydrophytes, but no tules were present. In this reach, the canal traverses a generally uncultivated area that has a sparse cover of mesquite.

The measurements of infiltration from the Buena Vista Canal south of the Taft highway are summarized in table 8. On the basis of the few comparative measurements shown, it seems that the upper reach, D–1 to D–2, loses water at a slightly greater rate than the lower reach, D–2 to D–3.

In the reach of the Buena Vista Canal selected for measurement in this study, the underlying soils are described by Cole and others (1945) as Cajon sand and Cajon fine sandy loam. In almost the entire reach between sites D–1 and D–2, the canal is in Cajon sand; in the reach between D–2 and D–3 it is entirely in Cajon fine sandy loam. Between D–1 and D–2 the Cajon sand occurs as a long narrow tongue that presumably marks the site of a former stream channel. Both soils types are well-drained relatively permeable young alluvium that shows no profile development. The sites for measurements of flow were selected to determine whether there were significant differences in seepage between Cajon sand and Cajon fine sandy loam. Table 8 suggests that, at least at the stage measured, the difference in loss per unit area was small.

Measurements of infiltration from the East Side Canal.—Three sets of measurements of discharge were made in the East Side Canal in an area where it traversed older soils that have heavy-textured subsoils. Measurements were made at the following sites (pl. 8) : (E–1) at the

TABLE 8.—*Infiltration from the Buena Vista Canal south of the Taft Highway*

Site	Date (1955)	Time (PDT)	Discharge (cfs)	Seepage loss (cfs)	Percent of initial discharge	Infiltration per unit length of canal (cfs per mile)	Infiltration per unit area (feet per day)
D-1	June 10	10:45 a.m.	17.2				
				1.7	9.9	0.53	0.38
D-2	do	9:50 a.m.	15.5				
				.7	4.5	.35	.29
D-3	do	8:45 a.m.	14.8				
Loss				2.4	14.0	.46	.35
D-1	June 16	12:45 p.m.	24.8				
D-3	do	1:50 p.m.	22.7				
Loss				2.1	8.5	.40	.33
Sites D-1 to D-3						0.43	0.3

Kern County Land Co. measuring structure, about 200 feet below the headgate of the canal in the SE¼SE¼ sec. 18, T. 29 S., R. 28 E., and (E-2) at a point 0.36 mile southeast along the canal from Fairfax Road in the SW¼SW¼ sec. 36, T. 29 S., R. 28 E. The distance between these 2 measuring points is 5.77 miles, and the wetted perimeter of the intervening reach averages 39 feet. The banks and much of the bottom of the measured reach of canal were covered with a dense growth of grass, and tules were common in the upper section. Because of the flat gradient and heavy growth of water grass, which retard the movement of water, this is not a favorable canal in which to make accurate infiltration measurements.

The measurements of infiltration from the East Side Canal are summarized in table 9 and illustrated in figure 8. The infiltration ranged from 2.34 cfs per mile, or 1.0 feet per day in loss per unit area, when the flow at the upper site was 57.8 cfs, to 3.86 cfs per mile, or 1.6 feet per day, when the flow at the upper site was 67.7 cfs.

The measured reach of the East Side Canal is chiefly in the Adelanto loamy sand, a soil described by Cole and others (1945, p. 60) as having a rather strongly developed profile and restricted internal drainage. It is characterized by tough clay loam, containing segregated lime in the subsoil within about 3 feet of the land surface. From this description, it was expected that the infiltration from the East Side Canal would be generally lower than those of the canals on the more permeable young soils of Kern River alluvial fan. Instead, the measurements summarized in table 9 indicate that the infiltration per unit area from the East Side Canal was among the highest of the entire series of measurements. Evidently, the poorly permeable subsoils of the Adelanto soils do not limit the infiltration from the canal to any great extent.

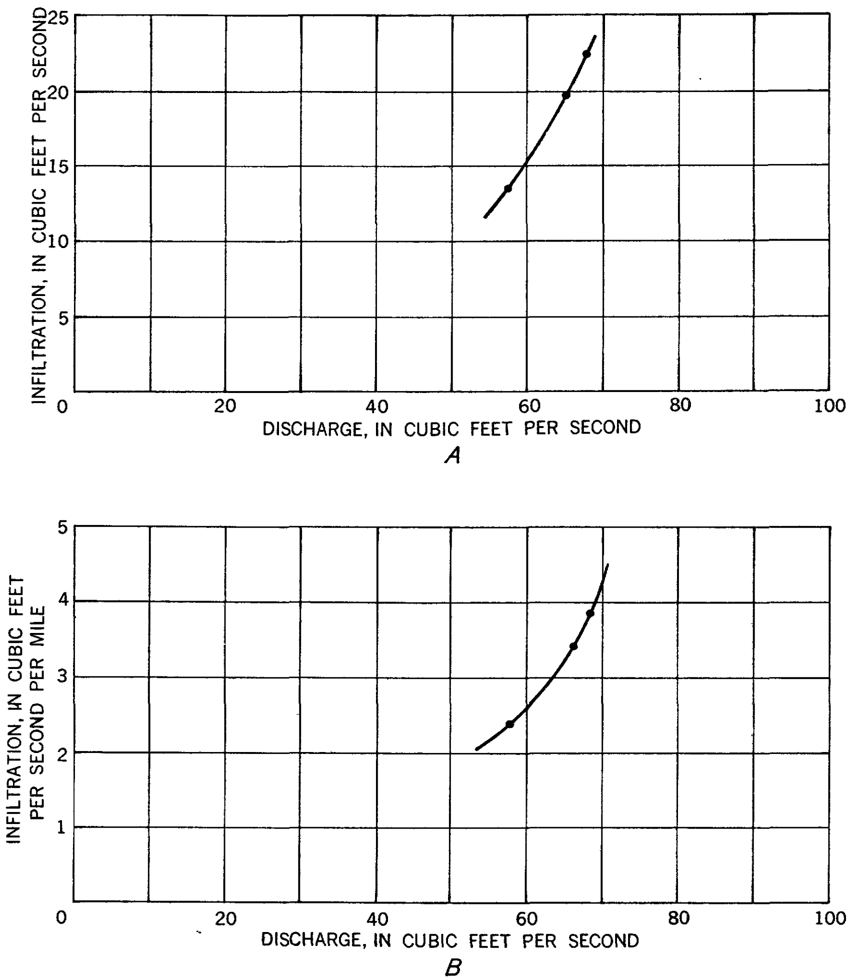

FIGURE 8.—*A*, Infiltration from the East Side Canal. *B*, Infiltration per unit of length from the East Side Canal.

TABLE 9.—*Infiltration from the East Side Canal*

Site	Date (1955)	Time (PDT)	Discharge (cfs)	Seepage loss (cfs)	Percent of initial discharge	Infiltration per unit length of canal (cfs per mile)	Infiltration per unit area (feet per day)
E-1	May 24	4:05 p.m.	57.8				
E-2	do	5:52 p.m.	44.3				
Loss				13.5	23.3	2.34	1.0
E-1	June 6	9:27 a.m.	67.7				
E-2	do	11:05 a.m.	45.4				
Loss				22.3	33.0	3.86	1.6
E-1	June 18	9:25 a.m.	65.2				
E-2	do	9:25 a.m.	[1] 45.6				
Loss				19.6	30.1	3.40	1.4
Average rates of infiltration: E-1 to E-2						3.20	1.3

[1] Adjusted for measured diversion of 0.4 cfs in reach gaged.

Measurements of infiltration from the Alejandro Canal.—Discharge measurements were made in the Alejandro Canal at the following two sites (pl. 8): (F–1) 75 feet downstream from a footbridge across the canal in the NW¼NE¼ sec. 26, T. 30 S., R. 25 E., and at (F–2) about 100 feet downstream from the Union Road bridge in the NE¼NE¼ sec. 13, T. 31 S., R. 25 E. (31/25–13A). These 2 sites are 4.50 miles apart, and the average wetted perimeter of the intervening reach was 30 feet. The canal banks are very irregular and locally are lined with water grasses and tules and scattered growths of willows and cottonwood.

The measursements of infiltration from the Alejandro Canal are summarized in table 10. At about the same stage on 2 nonconsecutive days, the losses were about equal, averaging 1.03 feet per mile and 0.6 foot per day in depth of water per unit area.

Soils traversed by the Alejandro Canal in the measured reach have been mapped by Cole and others (1945) as Cajon fine sandy loam, Cajon fine sandy loam—shallow phase, Chino loam and Cajon sand. The surface soils of these types are high in soluble salts, and in many areas salt crusts are visible on the surface. Both the Cajon and Chino soils have developed on young alluvial deposits laid down by the Kern River. The Cajon soils show no profile development; they generally have good internal drainage and are highly to moderately permeable. (See pl. 8.) In contrast, the Chino soils show moderate profile development and have a compact subsoil that tends to restrict infiltration of water.

TABLE 10.—*Infiltration from the Alejandro Canal*

Site	Date (1955)	Time (PDT)	Discharge (cfs)	Seepage loss (cfs)	Percent of initial discharge	Infiltration per unit length of canal (cfs per mile)	Infiltration per unit area (feet per day)
F-1	June 20	2:30 p.m.	29.8				
F-2	do	4:15 p.m.	25.2				
Loss				4.6	15.4	1.02	0.56
F-1	June 22	8:45 a.m.	29.5				
F-2	do	10:00 a.m.	24.8				
Loss				4.7	15.9	1.04	.57
Average of 2 measurements						1.03	0.6

CONCLUSIONS BASED ON MEASUREMENTS OF INFILTRATION FROM CANALS IN THE BAKERSFIELD AREA

Calculations of infiltration based on measurements of discharge in canals in the Bakersfield area showed that in most of the canals the loss was less than 20 percent of the flow at the upstream measuring site and thus was near the percent of error inherent in the measurement procedure. However, the results presented in tables 5 to 10 were consistent and therefore probably are representative of the actual loss.

Comparison of the rates of infiltration from the several canals that were measured show little correlation with soil types as mapped by Cole and others (1945). Some of the highest infiltration rates, in fact, were found in the East Side Canal (table 9) in a reach which traverses mostly old soil described as having restricted internal drainage (p. 63). Conversely, some of the lowest infiltration rates were observed in the Buena Vista Canal (table 7) in a reach where it traverses the relatively permeable soils of the Cajon series (p. 61). Thus, it would seem from this lack of correlation that the standard soil surveys should be used with caution in estimating potential rates of water loss from canals. This is not entirely surprising, however, considering that most of the canals studied cut deep through the surface soils into the underlying alluvial deposits.

Figure 9 summarizes the rates of infiltration determined during

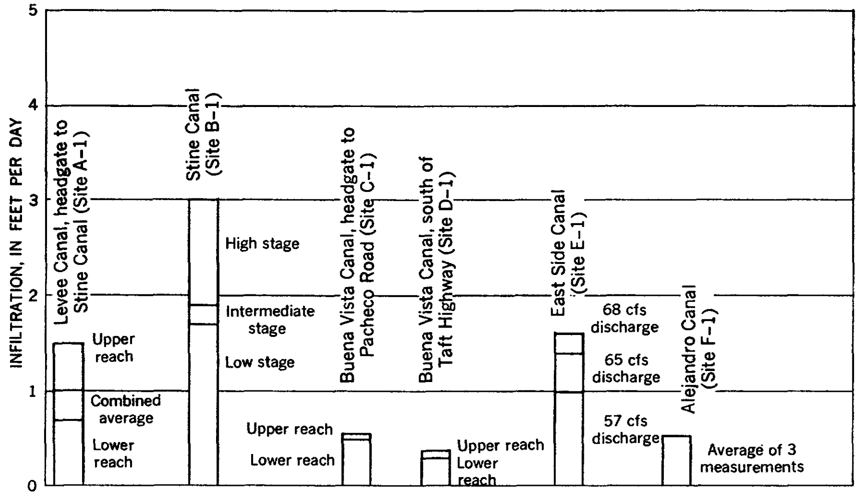

FIGURE 9.—Summary of canal-loss studies in the Bakersfield area.

studies in the Bakersfield area. A rather rough correlation does appear between distance from the apex of the alluvial fan of the Kern River to the measured reaches and the rates of infiltration. In general, the infiltration per unit area decreased with increased distance from the apex of the fan near Bakersfield. The apparent relation of infiltration to distance from the apex of the fan may be related to a general decrease in average grain size and permeability away from the source of the deposits. It also may be related to the fact that the depth to ground water beneath the fan is shallowest in its outer reaches (pl. 7), perhaps resulting in a buildup of the ground-water mound beneath the canal.

The rate of infiltration also showed a relation to the stage in the canal (fig. 9). In each set of measurements that spanned more than one stage, the greatest loss per unit area occurred at the higher stage, although the loss in percent of initial flow generally was greater at lower stages. Evidently the greater wetted area available for infiltration and greater head at high stages account for the greater loss.

INFILTRATION FROM DITCHES NEAR HURON

To evaluate the magnitude of infiltration from irrigation ditches in typical soils on the western slope of the San Joaquin Valley, measurements of water loss were made over a period of 5 to 6 weeks in the summer of 1955 in 2 specially constructed ditches near Huron in western Fresno County. Efforts to make similar measurements in an unused irrigation ditch failed, owing to the numerous gopher holes that caused uncontrollable and unmeasurable leaks.

The general method of study was to maintain sufficient flow into the test ditch to keep the water level as near a constant stage as possible. The infiltration from the ditch was determined each day by shutting off the supply of water and measuring the drop in head on several staff gauges. As a check, the rate of inflow needed to maintain a constant stage was compared with the infiltration rate.

Both tests indicated a high initial rate of infiltration until the soil became thoroughly wet. The infiltration rate stabilized, then continued to decline slowly throughout the period of the test. The plotted daily values of infiltration from the Calflax ditch (fig. 13) suggest an S-curve similar to those observed in water-spreading tests in Kern County (p. 50), in which the early low value is attributed to the swelling of clay particles, followed by an increase in infiltration as the result of the elimination of entrapped air from the soil pores. The slowly declining rate of infiltration noted in both ditch tests is similar to that observed in the pond tests (p. 50) and presumably is due to the same cause, namely, the clogging of the soil pores by bacterial activity or perhaps the accumulation of silt in the ditches.

Plots of the daily infiltration rates (figs. 11, 13) show considerable scatter. Some of the erratic plots appear to occur when the water level in the ditch was above or below the average level maintained, and on particularly windy days. Furthermore, a crude cyclic pattern can be seen in figure 11, for which the authors offer no explanation.

The fact that the rate of infiltration on the permeable Panoche loam was higher than that on the poorly permeable Oxalis silty clay was not surprising, although at no time did the ratio of the infiltration rate of the Giffen ditch to that of the Calflax ditch exceed 1.63, and by the end of the test, the ratio of the rates had declined to 1.27. This fact suggests that the clogging effect noted earlier was more effective in the more permeable Panoche loam than in the Oxalis silty clay.

Giffen ditch.—To determine typical losses from ditches in the more permeable soils of a typical alluvial fan on the west slope of the San Joaquin Valley, a fallow field was selected for testing in sec. 19, T. 20 S., R 17 E., about 5 miles southwest of Huron and about 1,000 feet southeast of Los Gatos Creek (pl. 9). The soil has been mapped by Harradine and others (1952) as Panoche loam, which they describe as forming on young alluvial fans. It has little profile development and is moderately permeable throughout. The soil was relatively sandy in the immediate vicinity of the test ditch.

A ditch, 1,527 feet long and roughly 2 feet deep, was cut as close to the land-surface contour as practicable so that water could be kept ponded at about the same depth throughout the length of the ditch. A map and cross sections of the test ditch are shown in figure 10 and the general location is shown on plate 9. Giffen, Inc., the owners of

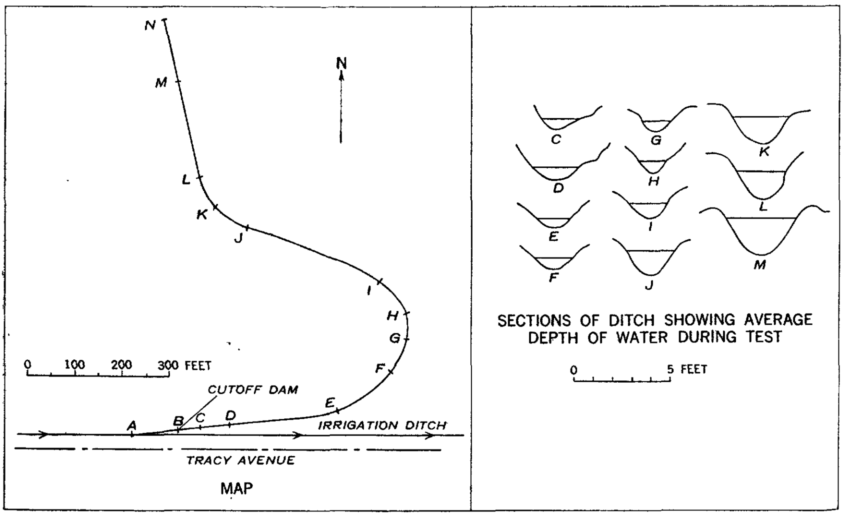

FIGURE 10.—Map and sections of the Giffen ditch.

the property, allowed the use of the land, built the ditch, and supplied the water for the test. The surface soil was dry and had received no water since the previous winter's rains, about 5 months earlier. Barley had been grown under irrigation the previous winter.

Water was supplied continuously to the test ditch by siphoning from an irrigation ditch over an earth cut-off dam shown at *B* in figure 10. The flow was regulated to maintain a constant head in the test ditch by varying from 5 to 8 the number of 1-inch-diameter syphon tubes in use. The inflow to the test ditch was gaged by recording the time and number of tubes in use and the difference in head between the supply ditch and the test ditch. These data were converted to flow by use of standard tables. Throughout the 45-day test, the head in the test ditch seldom fluctuated more than 0.1 foot in a 24-hour period, except during the periods when the water supply was shut off to make seepage measurements.

Water was first admitted to the test ditch on June 20, 1955. Once the ditch was filled, the water supply was regulated to maintain a constant depth of 1 to 2 feet of water (fig. 10). The infiltration rate was determined by shutting off the water supply for a predetermined time each day and measuring the decline in water level at staff gages located at three points *C*, *J*, and *M* (fig. 10). These measurements, recorded in feet of water per hour, were converted to feet per day. The results are listed in table 11 and shown graphically in figure 11. The measurements of decline in depth were compared with the measured inflow as a check of the accuracy of the system.

In the early part of the test, about 70 gpm was required to maintain the water in the ditch at a constant level, but only about 50 gpm was required by the end of the 45-day test. As shown in figure 11 and table 11, infiltration rates diminished from a maximum of 3.8 feet

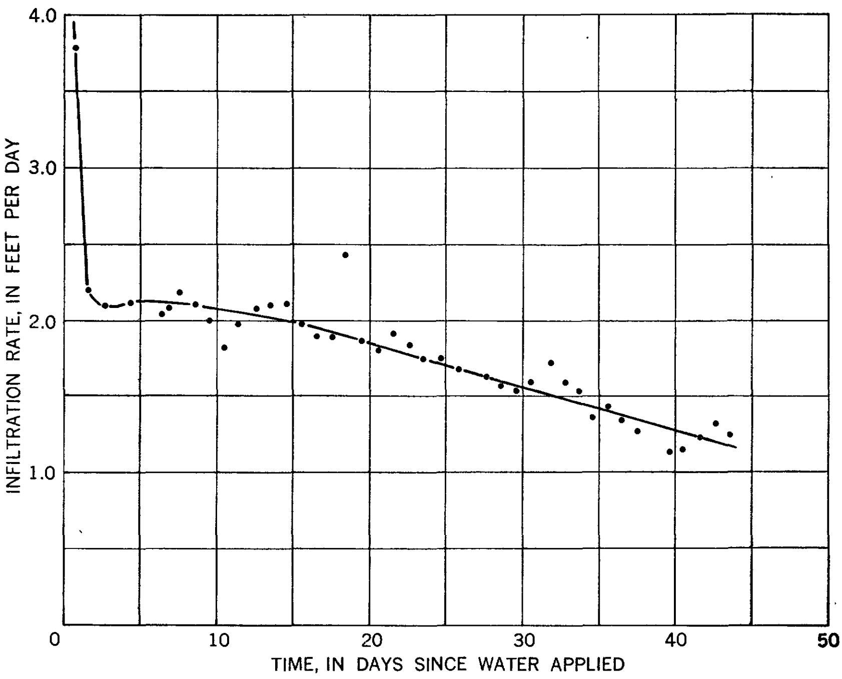

FIGURE 11.—Infiltration rate at the Giffen ditch.

per day on the first day of the test to a low of 1.24 feet per day after 45 days of operation. The graph also shows a cyclic fluctuation in the rate of infiltration of 0.2 to 0.3 foot per day with a period of about 10 days, which is superimposed on the generally downward-trending curve. Several of the erratic points shown in figure 11 correspond with especially windy days or days when water in the ditch was deeper or shallower than usual; however, no explanation of the apparent cyclic fluctuations is offered.

TABLE 11.—*Infiltration from the Giffen ditch*

[Ditch full, beginning of test, June 20, 10:00 a.m.]

Date	Time	Rate of infiltration (feet per day)				Remarks
		Gage			Average	
		C	J	M		
June 20	10:00 a.m.	----------	----------	----------	----------	
20	12:23 p.m.	5.45	3.4	2.56	3.8	
21	4:04 p.m.	2.17	2.22	2.23	2.2	
22	11:04 a.m.	2.08	2.29	1.96	2.1	
26	10:19 a.m.	2.15	2.02	2.02	2.06	
26	2:54 p.m.	2.23	2.02	2.06	2.10	
27	11:00 a.m.	2.40	2.17	2.17	2.2	
27	4:20 p.m.	1.68	2.16	2.40	2.1	
28	11:20 a.m.	2.02	2.12	2.02	2.1	
29	1:10 p.m.	1.98	2.04	1.95	2.00	
30	12:45 p.m.	1.92	1.80	1.77	1.83	
July 1	12:15 p.m.	1.92	2.04	2.04	2.00	
2	12:00 p.m.	----------	2.16	2.04	2.1	
3	11:20 a.m.	2.24	1.96	2.12	2.11	
4	4:00 p.m.	2.16	2.01	2.16	2.11	
5	11:10 a.m.	----------	1.92	2.07	2.0	
6	11:30 a.m.	1.92	1.92	1.92	1.9	
7	2:20 p.m.	1.92	1.92	1.92	1.9	
8	1:51 p.m.	2.52	2.40	2.40	2.45	Windy.
9	10:42 a.m.	1.92	1.92	1.92	1.9	
10	12:35 p.m.	1.74	1.88	1.88	1.8	
11	2:05 p.m.	1.92	1.93	1.93	1.92	
12	12:48 p.m.	1.92	1.85	1.74	1.84	
13	12:04 p.m.	1.80	1.71	1.71	1.75	
14	11:50 a.m.	1.68	1.71	1.83	1.74	
15	11:34 a.m.	1.68	1.69	1.71	1.69	
17	2:30 p.m.	1.56	1.68	1.68	1.64	
18	2:02 p.m.	1.56	1.68	1.56	1.60	
19	3:53 p.m.	1.32	1.56	1.80	1.56	
20	1:48 p.m.	1.56	1.68	1.56	1.60	
21	12:40 p.m.	1.76	1.60	1.76	1.71	Water too high.
22	10:32 a.m.	1.56	1.56	1.68	1.60	High water.
23	1:04 p.m.	1.44	1.56	1.56	1.52	
24	12:52 p.m.	1.32	1.44	1.32	1.36	Low water.
26	12:38 p.m.	1.44	1.39	1.44	1.42	
27	10:38 p.m.	1.44	1.32	1.32	1.36	Late evening.
28	12:00 a.m.	1.32	1.32	1.20	1.28	Midnight.
29	10:45 a.m.	1.08	1.20	1.08	1.12	Low water.
30	10:28 a.m.	1.08	1.20	1.20	1.16	
31	1:50 p.m.	1.20	1.32	1.20	1.24	
Aug. 1	2:05 p.m.	1.32	1.32	1.32	1.32	High water.
2	1:55 p.m.	1.20	1.32	1.20	1.24	

Calflax ditch.—To determine loss from irrigation ditches in the less permeable soils of the margins of the alluvial fans on the west slope of the San Joaquin Valley, a fallow field was selected for testing in the SE¼NE¼, sec. 35, T. 18 S., R. 17 E., 8 miles north of Huron (pl. 9). The soil was mapped by Harradine and others (1952) as Oxalis silty clay, which they described as a basin-rim soil. It forms on fine-textured alluvium, has a heavy texture, and normally contains some alkali concentration. Both the surface soil and subsoil are described as having low permeability.

A ditch 1,220 feet long was dug. Because it was not practicable to lay the ditch out along the land-surface contour, the ditch was dug oblique to the slope. Therefore, a greater depth of water was required at the low end to keep the upper end submerged. Accordingly, both the width of the water surface and the depth of water in the ditch increased eastward. A map and cross sections of the test ditch are shown in figure 12 and the general location of the site on plate 9. The

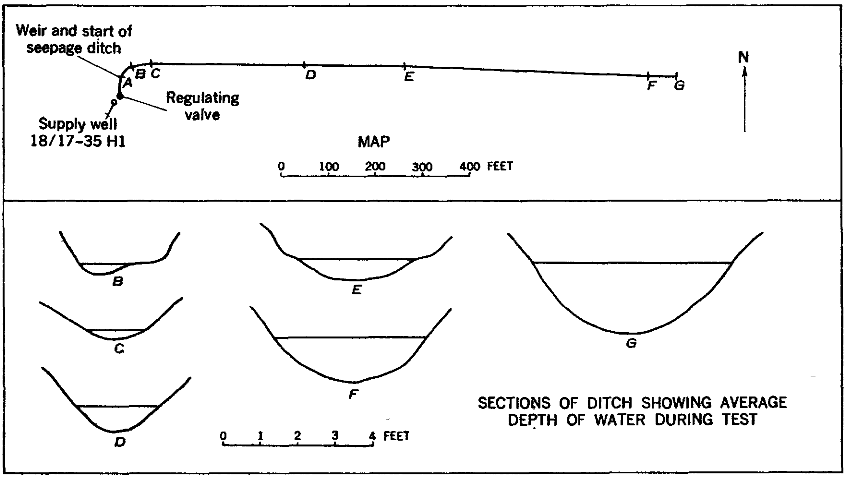

FIGURE 12.—Map and sections of the Calflax ditch.

owners of the property, the Calflax Corp., kindly furnished the land for the test, built the ditch, and supplied the necessary water. The surface soil was dry and had received no water since the winter rains 5 months earlier.

Water was supplied continuously to the test ditch over a 90°-V-notched weir at point *A* (fig. 12). The flow was regulated by means of a valve to maintain a constant flow over the weir and a uniform water level in the ditch. Daily readings were made of the flow over the weir to determine the quantity of water entering the ditch.

Water was first admitted to the ditch on June 26, 1955, and the test was concluded 37 days later on August 2, 1955. After the ditch was filled, the supply was regulated to maintain a depth of water that ranged from 0.25 foot at the upper end to 2.0 feet at the lower end. Infiltration was measured by shutting off the supply for a short period each day and observing the decline in water level on staff gages at points *C*, *E*, and *F* (fig. 12). As at the Giffen ditch, the measurements were recorded in feet of water per hour and then converted into feet per day. The results are listed in table 12 and shown graphically in figure 13. The infiltration rate stabilized at about 1 foot per day

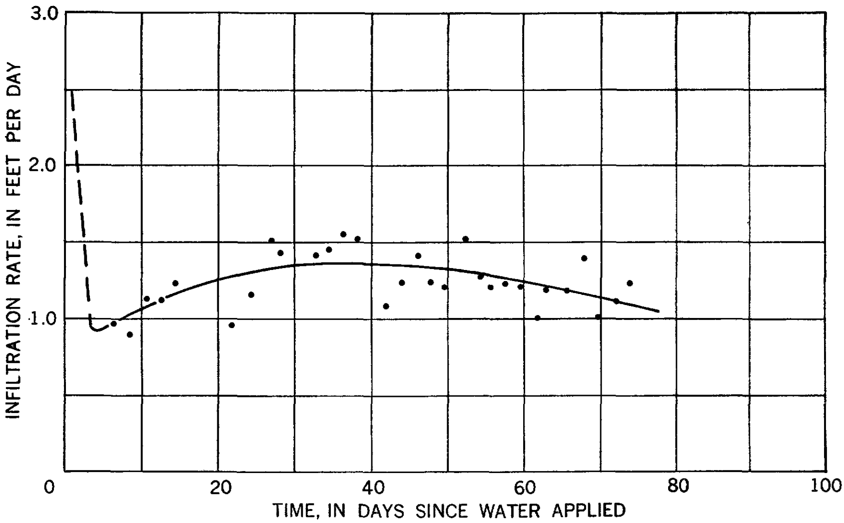

FIGURE 13.—Infiltration rate at the Calflax ditch.

TABLE 12.—*Infiltration from the Calflax ditch*

[Beginning of test, June 26, 12:00 p.m.]

Date	Time	Rate of infiltration (feet per day)				Remarks
		Gage			Average	
		C	E	F		
June 26	12:00 p.m.	----------	----------	----------	----------	
29	5:34 p.m.	0.96	0.96	0.96	0.96	
30	5:34 p.m.	.84	.84	.96	.88	
July 1	4:04 p.m.	1.08	1.20	1.08	1.12	
2	3:04 p.m.	1.08	1.08	1.20	1.12	
3	2:44 p.m.	1.08	1.32	1.32	1.24	Water high in ditch.
4	1:04 p.m.	1.76	1.76	1.76	1.76	Water high. Some leakage.
7	10:24 a.m.	----------	.96	.96	.96	Water low.
8	10:34 a.m.	1.08	1.20	1.20	1.16	
9	3:30 p.m.	1.68	1.44	1.44	1.52	Rate high. Water low before test.
10	3:20 p.m.	1.44	1.44	1.44	1.44	
11	10:50 a.m.	1.20	1.32	1.32	1.28	Rate low.
12	4:45 p.m.	1.28	1.50	1.50	1.42	
13	5:50 p.m.	1.69	1.19	1.52	1.47	
14	2:04 p.m.	1.76	1.43	1.47	1.55	
15	2:19 p.m.	1.56	1.58	1.46	1.53	
16	4:17 p.m.	----------	----------	----------	----------	
17	11:21 p.m.	1.08	1.08	1.08	1.08	
18	10:56 p.m.	1.20	1.20	1.32	1.24	
19	12:20 p.m.	1.44	1.60	1.28	1.44	
20	10:46 a.m.	1.20	1.32	1.32	1.25	
21	10:15 a.m.	1.20	1.20	1.20	1.20	
22	2:14 p.m.	1.69	1.44	1.44	1.52	
23	10:11 a.m.	1.20	1.32	1.32	1.28	
24	10:20 a.m.	1.20	1.20	1.20	1.20	
25	9:50 a.m.	1.20	1.32	1.20	1.24	
26	9:36 a.m.	1.20	1.20	1.20	1.20	
27	7:00 a.m.	.98	1.08	.96	1.00	
27	11:00 p.m.	1.20	1.20	1.20	1.20	
29	7:20 a.m.	1.20	1.20	1.20	1.20	
30	7:40 a.m.	1.32	1.44	1.44	1.40	Slight leakage.
31	10:15 a.m.	.96	.96	1.12	1.01	Water low in ditch.
Aug. 1	11:07 a.m.	1.08	1.08	1.20	1.12	
2	11:07 a.m.	1.32	1.20	1.20	1.24	

by the third day of the test, increased slowly to 1.5 feet per day by the 15th day, and declined to about 1 foot per day after 37 days of operation.

INFILTRATION FROM SUBSIDENCE TEST PLOTS IN WESTERN FRESNO COUNTY

In conjunction with studies of land subsidence, three experimental plots were constructed on the west side of the San Joaquin Valley (pl. 9) on soils that are known to subside after the initial application of water for irrigation. These plots were near the foothills of the Coast Ranges in western Fresno County, south and west of the town of Mendota. In this area, severe slumpage and soil cracking commonly occur along ditches or wherever water accumulates in ponds. Undulating, irregular relief develops on formerly level fields when irrigation is attempted.

In an attempt to determine the nature and magnitude of the soil compaction and the depth zones in which the settlement occurs, three test plots were constructed to measure the rate of infiltration of ponded water and to determine accurately the rate and magnitude of subsidence that resulted therefrom. At each site, a square test plot roughly 100 feet on a side was constructed by leveling the area and pushing up a levee 4 feet high. Bench marks were placed on the surface and a several depths below the surface of the test plot so that periodic observations of subsidence could be made during the water-spreading operation. A typical example of the arrangements of the test plots is shown in figure 14. Water was supplied to each of the plots through a pipeline and was maintained at a depth of 1 foot or more when water was available. The rate of infiltration was measured daily at each plot by observing the decline in water level to when the water supply was turned off. A more complete description of the subsidence test plots and preliminary results obtained therefrom is given in a progress report of the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley (1958).

Test plot B.—Test plot B is 14 miles south and 3 miles west of Mendota in the NE¼NE¼ sec. 16, T. 16 S., R. 14 E. (pl. 9) on the alluvial fan of Arroyo Ciervo. The plot is on virgin, or undisturbed, soils that undergo extensive near-surface subsidence when wetted. These soils, which have developed on young alluvial fans and flood plains, have been mapped as Panoche silty clay loam (Harradine and others, 1952). They show little profile development and are relatively permeable, for the subsurface deposits have moderate to high permeability to depths of more than 300 feet.

Water was first applied to test plot B on October 3, 1956, and subsidence was observed almost immediately in the surface bench marks

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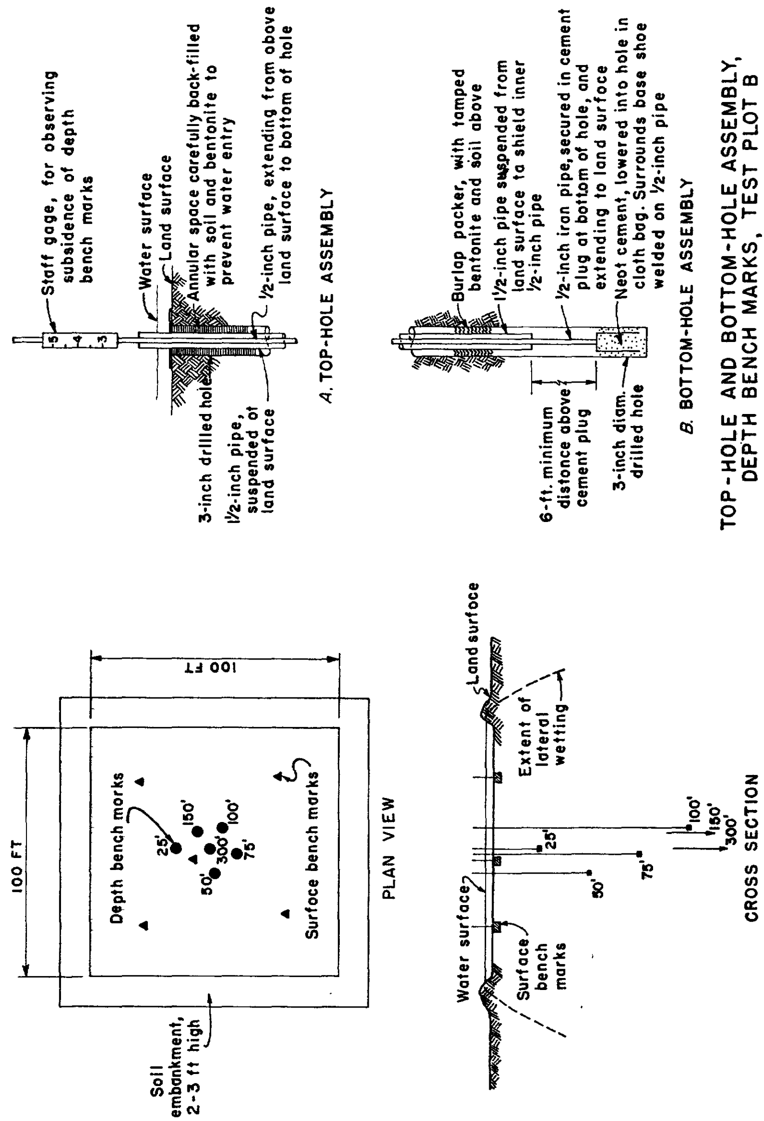

FIGURE 14.—Plan and section of test plot B, 16/14-16A

(fig. 15). The rate of infiltration from the plot decreased from an early rate of more than 1 foot per day to a sustained rate of 0.4 foot per day after 20 days of operation. After 5 days of drying in late December 1956, the infiltration rate dropped rapidly to 0.25 foot per day, where it remained throughout the period of test, except for subsequent interruptions in the water supply when the plot dried out. As of January 30, 1958, a total of about 129 feet, or 29.6 acre-feet, of water had infiltrated from the roughly quarter-acre test plot during the first 16 months of operation.

The upper graph of figure 15 indicates that each time the test plot was permitted to dry out, the subsequent rates of water penetration were no higher and sometimes were considerably lower than before the drying. Thus, after 6 days of drying in late December 1956, the rate dropped from 0.4 foot per day to a new low rate of 0.3 foot per day, a decrease of 25 percent. In an attempt to increase the infiltration rate from the test plot, the floor of the test plot was treated with krilium in mid-June 1957, while the plot was dry. No noticeable increase in

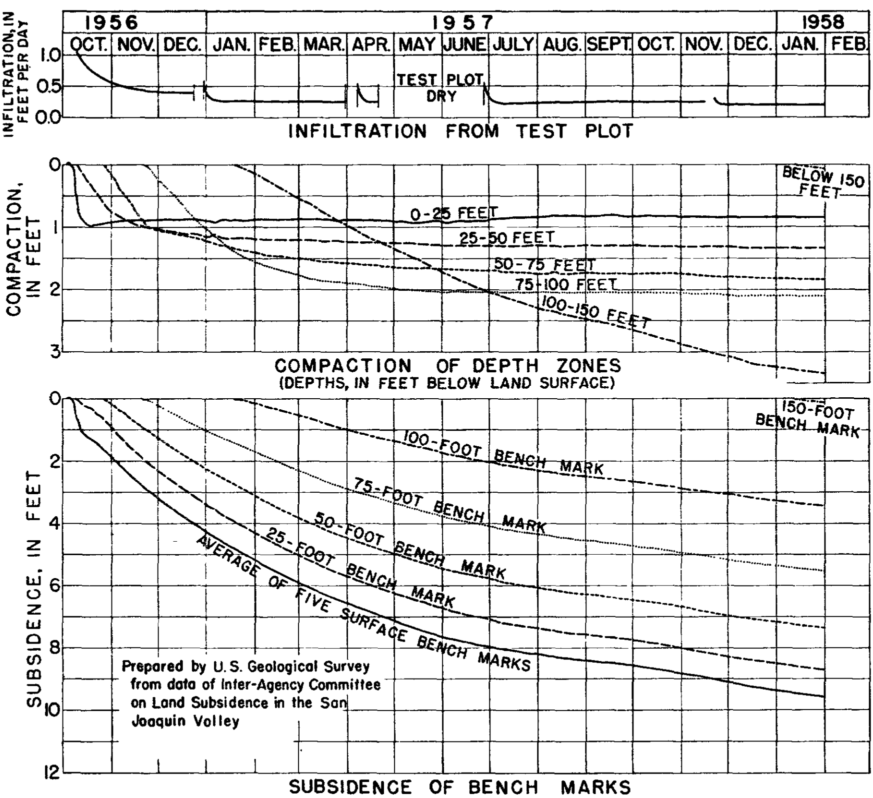

FIGURE 15.—Infiltration, compaction, and subsidence at test plot B.

infiltration rate resulted from this treatment; instead, 2 weeks after the treatment, the infiltration rate was notably less than it had been before treatment.

The six curves in the lower graph of figure 15 show the subsidence that occurred at each of the bench marks. The time interval between the start of movement of successive depth bench marks is a measure of the time required for water to penetrate each depth zone. The compaction in each of the depth zones is shown in the center graph. By the end of January 1958, the average subsidence at the surface was 9.53 feet, and the subsidence that was then being recorded was taking place in the sediments below the 150-foot depth.

The rate of advance of the wetted front by depth is indicated by a semilogarithmic plot of depth versus time of initial movement in figure 16. Although this plot actually indicates the movement of the subsidence front, compaction of the sediments begins when the sediments are first wetted; thus, this curve also approximates the position of the wetted front. As shown, there is a straight-line relationship below the 50-foot depth, suggesting that the lateral spread of water is uniform throughout the depth zone from 50 to 150 feet. From the beginning of plot operation to the time the wetted front reached the 50-foot depth, the rate of infiltration from the test plot was decreasing at a rapid rate. This apparently accounts for much of the deflection of the straight-line relationship in the early period of record. Extrapolation of the curve of figure 16 suggests that about 6 years would be required for the wetted front to reach the 200-foot depth.

Test plot C.—Test plot C is 16 miles due south of Mendota, just west of State Highway 33 in the NE¼NE¼, sec. 25, T. 16 S., R. 14 E. (pl. 9). This site is 3 miles east and 2 miles south of test plot B on the alluvial fan of Arroyo Hondo, roughly 3 miles northeast of the foothills of the Coast Ranges. The test plot is on virgin soils that undergo compaction when wetted. The soils have been mapped by Harradine and others (1952) as Panoche loam, which develops on young alluvial fans and flood plains. The soils show little profile development and are relatively permeable. The subsurface deposits are similar to the surface soils and are relatively permeable to depths of 300 feet or more. Five surface bench marks and six bench marks at depths of 25, 50, 75, 100, 150, and 300 feet were installed to indicate the magnitude of the subsidence and the rate of advance of the waterfront during the water-spreading operation.

Water was first introduced into the test plot in December 1956 and was supplied intermittently until February 1957. As shown in the upper graph of figure 17, the rate of infiltration ranged from 1.5 feet per day at the beginning of the study to a stable rate of 0.7 foot per

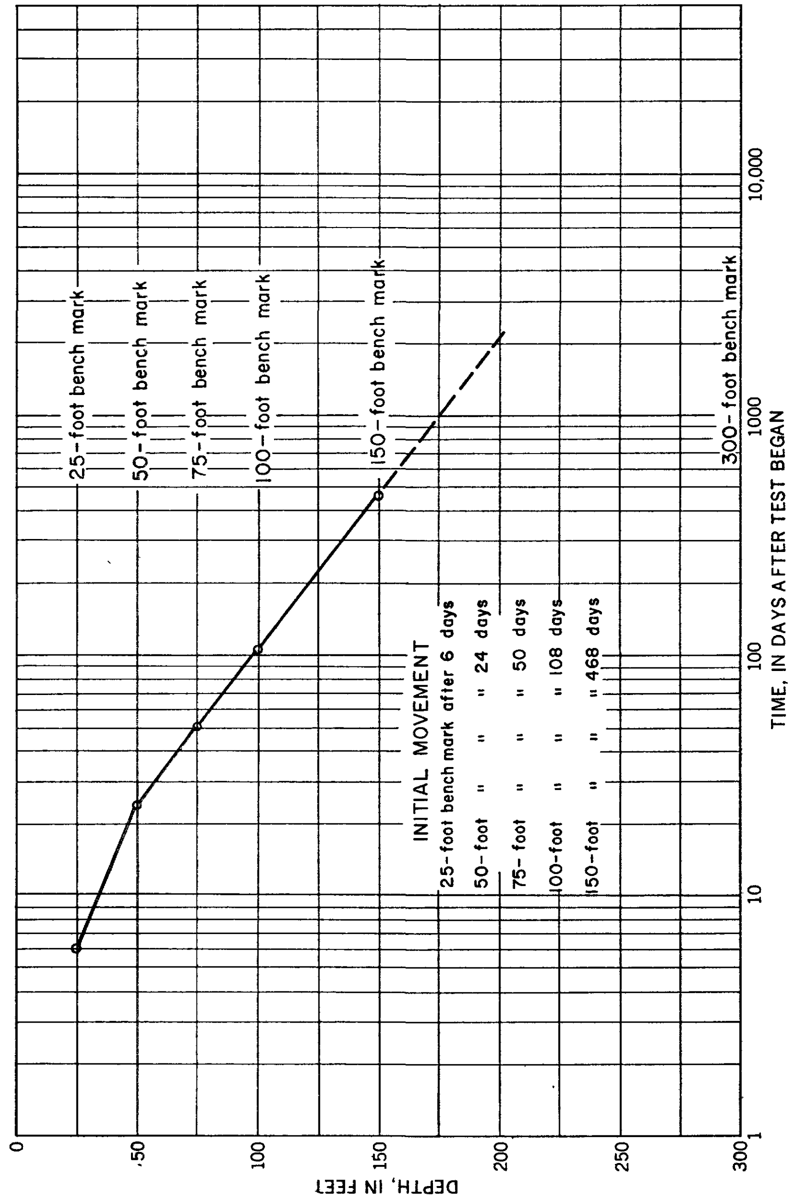

FIGURE 16.—Time of initial movement of depth bench marks at test plot B.

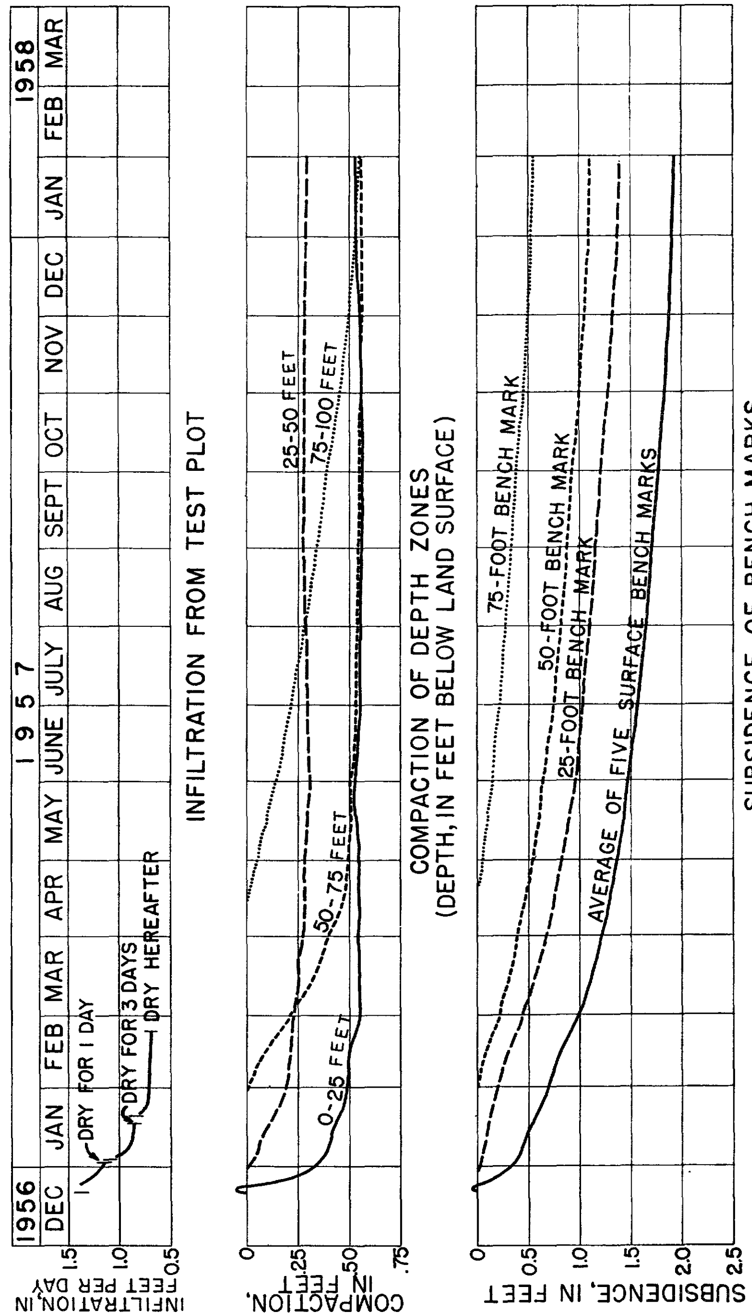

FIGURE 17.—Infiltration, compaction, and subsidence at test plot C.

day after 64 days of operation. This is substantially greater than the rate of infiltration measured in the Panoche silty clay loam at test plot B. During the 64 days of operation a cumulative depth of 53 feet of water was applied to plot C. Even though the plot had been dry for more than 11 months on January 30, 1958, the land was still subsiding, which indicated that water was still percolating downward through the subsurface deposits.

The four curves of the lower graph of figure 17 show the observed subsidence of the bench marks. The curves of the center graph show the compaction in the sediments in the several depth zones.

Test plot D.—Test plot D is 17 miles due west of Mendota in the SE¼NE¼ sec. 31, T. 13 S., R. 12 E. (pl. 9). As were plots B and C, this site is on virgin soil in an area that would undergo extensive subsidence with the initial application of water. The soil at plot D was mapped by Harradine and others (1952) as Panoche loam, the same type of soil as at plot C.

Plot D was constructed in the early summer of 1956, and water was first applied in August of that year. This site was discontinued after 2 months because of the high cost of supplying water. As shown in the upper graph of figure 18, the infiltration decreased from an early rate of more than 0.9 foot per day to less than 0.4 foot per day after 2 months of operation. The rate of infiltration was still declining rapidly when the water supply to the test plot was discontinued. During the 2 months of operation, about 7.5 acre-feet, or a cumulative depth of about 33 feet of water, was applied to the plot.

The curves of the lower graph of figure 18 show the rate and magnitude of subsidence of the bench marks at plot D. The amount of compaction in the several depth zones is shown in the curves of the center graph. As at test plot C, land subsidence and downward movement of applied water was continuing as of January 30, 1958, although the plot had been dry for more than 15 months.

Conclusions drawn from measurements at test ditches and plots.—Computations of infiltration rates show that the pattern of infiltration was similar, although of different magnitude at the three subsidence test plots. Infiltration in feet per day for the three plots as well as the Giffen and Calflax test ditches is illustrated for comparison in figure 19. The curves from the test plots showed similar trends, which resembled the typical curve for disturbed soils from spreading ponds in Kern County (fig. 5). The highest and lowest rates, those of plots C and D, were both recorded on Panoche loam; the intermediate rate, that for plot B, was on Panoche silty clay loam. From this it would seem that there was little difference in infiltration capacity within the Panoche soil series.

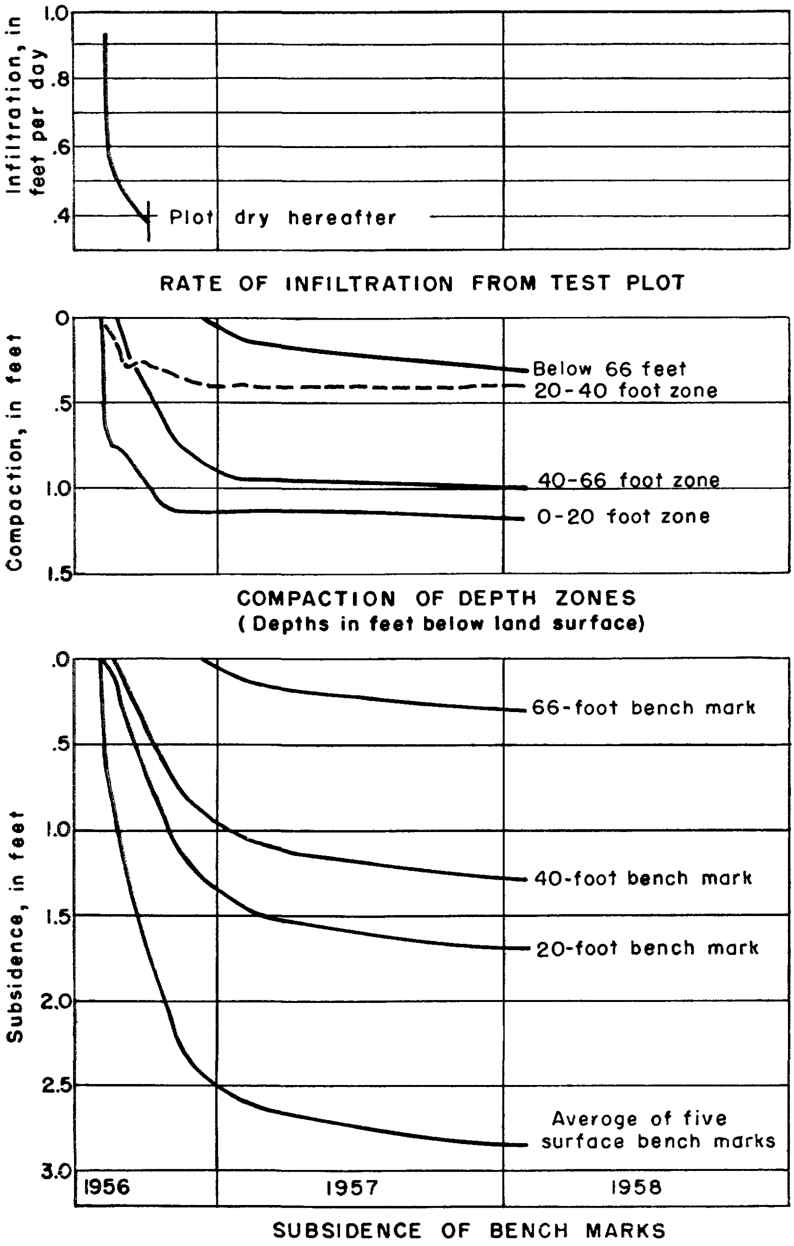

FIGURE 18.—Infiltration, compaction, and subsidence at test plot D.

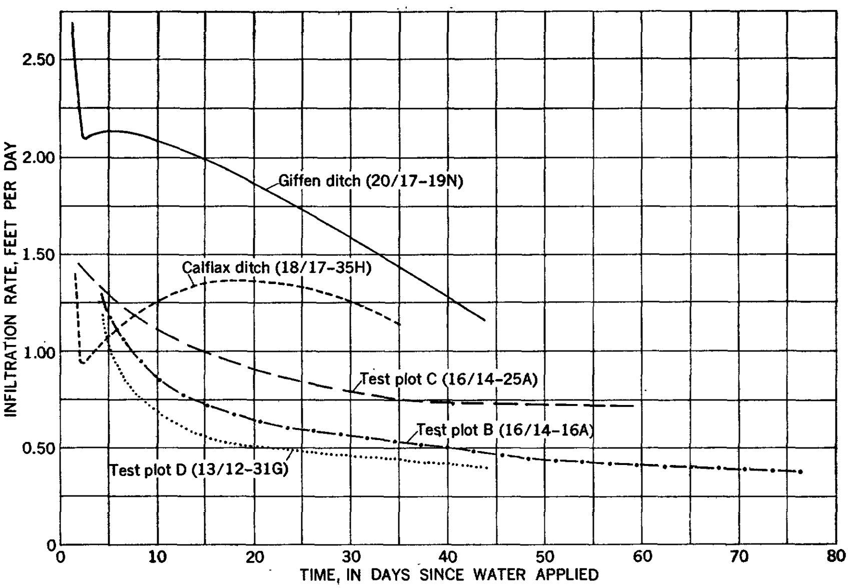

FIGURE 19.—Rates of infiltration at test plots and ditches in western Fresno County.

Unlike the infiltration curves of the test ditches (fig. 19), which showed a flattening or rise in infiltration rate after a sharp initial decline, the curves from the test plots showed a steady decline for about 20 days, after which the infiltration rate declined gradually through the period shown. The generally higher rates from the two ditches evidently are related to the greater lateral flow from the ditches compared to that from the square test plots.

INTERAQUIFER CIRCULATION OF GROUND WATER

As described on page 14, the fresh-water-bearing deposits in much of the San Joaquin Valley are separated into two distinct water-bearing zones by a laterally extensive lacustrine bed, the Corcoran clay member of the Tulare formation, which confines the water of the lower water-bearing zone under pressure. As of 1905–07, the head in the confined aquifers of the lower zone stood near or above the land surface in much of the axial part of the valley (Mendenhall and others, 1916, pl. 1) and presumably stood near or above the water table throughout the remaining extent of the Corcoran clay member (Davis and others, 1959, pl. 14). Heavy pumping in excess of replenishment has reduced greatly the head in the lower zone, so that the piezometric surface of the confined system as of 1952 was as much as 300 feet deeper than the water table (Davis and others, 1959, pl. 15).

The greatest decline of the piezometric surface has been in western Fresno and Kings Counties, where virtually the entire irrigation supply for roughly half a million acres is pumped from wells. Of the 1¼ million acre-feet of ground water pumped in western Fresno and Kings Counties in 1952–53, Davis and Poland (1957, pl. 432) estimated that on the order of 75 to 80 percent is from the confined aquifers of the lower water-bearing zone.

The area of heaviest ground-water pumpage and greatest decline of artesian head extends southeastward from about the Fresno-Merced County line to the dry bed of Tulare Lake and from the axial trough of the valley westward to the foothills of the Coast Range. The difference in head between the piezometric surface of the lower zone and the water table in this area in 1952 is shown on plate 10. Because the lower water-bearing zone is of great economic importance in the west side of the valley, the rate at which it can be recharged is of great value in planning for future operation of the reservoir. Davis and Poland (1957, p. 446) estimated that as of 1951 roughly 200,000 acre-feet of water entered the west side yearly from areas to the east and northeast; however, they did not present any quantitative estimates of circulation of water from the upper zone to the lower zone. The difference in head across the Corcoran clay member suggests that, if that unit were sufficiently permeable, substantial quantities of water might pass through it. Furthermore, the clay has been punctured by several thousand wells, many of which may transmit substantial amounts of water downward from the upper to the lower zone.

To evaluate the magnitude of the possible interaquifer movement of ground water, current-meter traverses were made in 16 wells (table 13) to determine the order of magnitude of flow down well casings. The results of these tests are presented below. Because of conflicting data on the permeability of the Corcoran clay member, estimates of the quantity of water moving directly through this confining bed are not included.

CURRENT-METER MEASUREMENTS IN WELLS

The sound of falling water in idle irrigation wells in the heavily pumped areas of the west side of the San Joaquin Valley has long been recognized as evidence that ground water has been circulating downward through the casings of active and abandoned wells from the upper water-bearing zone to the lower zone. Until recently, however, no measurements have been made of the rate of downward circulation.

During the summer of 1956, an Au deep-well current meter (Fiedler and Nye, 1933, p. 233) was used to measure the velocity of interaquifer flow in 16 idle irrigation wells in the area of greatest difference of head. The wells tested are shown on plate 10, and the results are listed in table 13. Measurements were made to depths as great as 1,400 feet, and downward flows of as much as 1.1 cfs were recorded. In most of the wells tested, water entered through breaks in the casing above the Corcoran clay member, moved downward, and left the casing through perforations in the lower water-bearing zone (fig. 20).

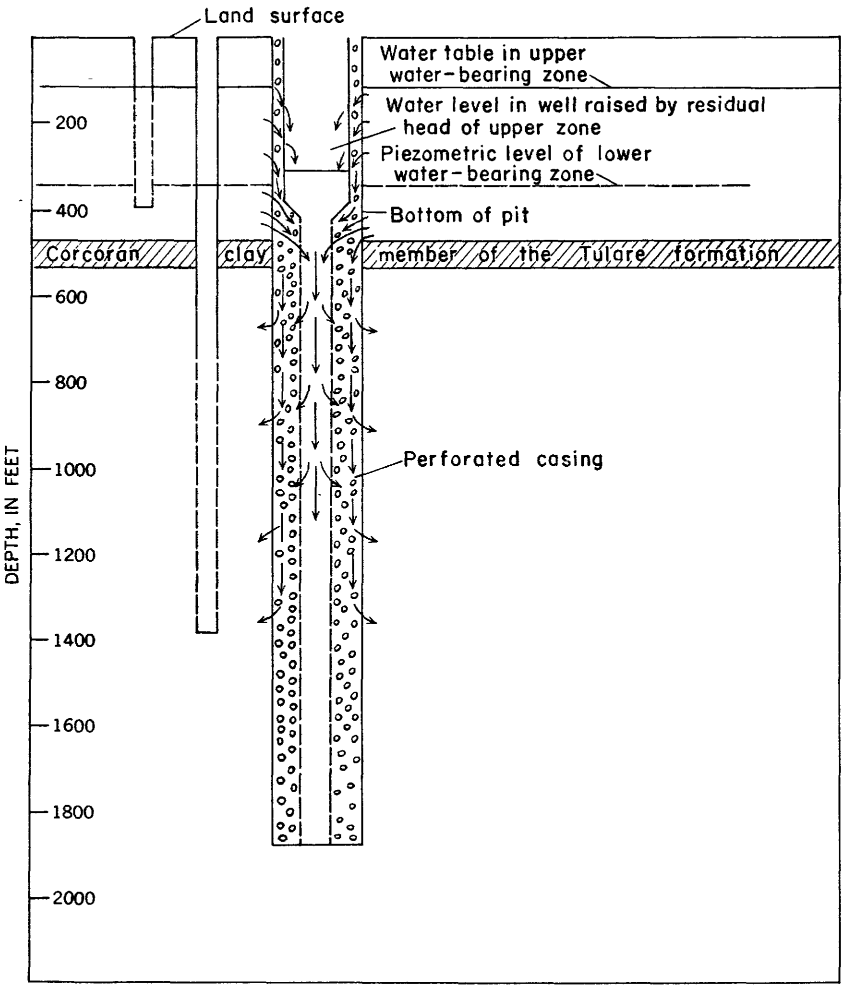

FIGURE 20.—Diagrammatic sketch of typical well showing general path of water circulation from upper to lower zone when pump is not operating.

No estimate was made of the rate of ground-water circulation through the gravel envelope around each well casing.

The Au deep-well current meter used in this investigation consists of a helical impeller mounted in a tubular shield, which is lowered on a cable to the desired depth in a well (Fiedler and Nye, 1933, pl.

42 and p. 233). A two-wire electric circuit connects the submerged meter in the well to a set of earphones at the land surface. Audible clicks on the earphones, which indicate revolutions of the impeller, are timed and, in turn, are converted to the velocity of the moving water in the casing by means of calibration curves.

In normal operation, a series of velocity readings are taken with the meter at rest at several depths in a well. By taking meter readings sufficiently close together, the precise point of water entry to, and departure from, the well can be determined. The direction of flow can be determined by comparing the apparent velocity recorded when the meter is in motion.

The downward velocity of ground-water circulation in the wells measured ranged from a trace to 2.0 feet per second, or, as summarized in table 13, from a trace to 1.1 cubic feet per second. In all the older wells tested, downward circulation of ground water was detected, but in six newly constructed wells no ground-water movement was measured.

TABLE 13.—*Results of flow measurements made in wells with the deep-well current meter*

Depth (feet)	Flow (cfs)	Depth (feet)	Flow (cfs)
14/12-12N1 [Employee's Enterprises 3. Welded steel casing, gravel packed, perforated 558 to 1,709 ft, 16-in diameter to 558 ft, 12¾-in to 858 ft, 10¾-in to 1,518 ft, and 9⅝-in to 1,709 ft. Velocity measured May 9, 1956. Depth to water, 524.5 ft below top of casing]			
550	0	900	0.12
600	.20	1,000	.19
650	.23	1,100	.16
700	.13	1,200	.16
800	.16	1,300	.11
14/12-25Q1 [Employee's Enterprises 21. Welded steel casing, gravel packed, perforated 666 to 1,773 ft. Velocity measured May 8, 1956. Depth to water, 576.8 ft below top of casing]			
No flow between 600 and 1,100 ft.			
14/13-17E1 [Employee's Enterprises 32. Welded steel casing, gravel packed, 18-in diameter to 753 ft, 12¾-in to 1,353 ft, 10¾-in to 1,380 ft. Velocity measured May 8, 1956. Depth to water, 510.5 ft below top of casing]			
600	0	800	0.15
700	Trace	900	.19
734	.12	1,000	.19
750	.13	1,100	Trace
760	.12		

TABLE 13.—*Results of flow measurements made in wells with the deep-well current meter*—Continued

Depth (feet)	Flow (cfs)	Depth (feet)	Flow (cfs)

14/13-29Q1

[Employee's Enterprises 15. Welded steel casing, gravel packed, perforated 621 to 1,803 ft, 16-in diameter to 621 ft, 12¾-in to 926 ft, 10¾-in to 1,555 ft, and 9¾-in to 1,803 ft. Velocity measured May 9, 1956. Depth to water 539.9 ft below top of casing]

539–800	0	1,000	0.14
900	.12	1,050 [1]	.18

[1] Obstruction at 1,050 ft prevented deeper readings.

14/14-14G2

[Fedora Farms. Welded steel casing, gravel packed, 16-in diameter. Velocity measured June 13, 1956. Depth to water 241 ft below top of casing]

No flow between 300 and 900 ft.

15/13-8N1

[Employee's Enterprises M-6. Welded steel casing, gravel packed, perforated 639 to 1,798 ft, 16-in diameter to 600 ft, 12¾-in to 900 ft, 10¾-in to 1,798 ft. Velocity measured May 23, 1956. Depth to water 595 ft below top of casing]

650	0	750	0.44
675	.49	800	.47
707	.44	1,000 [1]	.47

[1] Obstruction at 1,000 ft prevented deeper readings.

15/14-33M

[Murrietta Farms. New well, just developed. Velocity measured June 5, 1956. Depth to water 447.5 ft below top of casing]

No flow between 450 and 1,200 ft.

16/15-26N3

[Vista del Llano 33. Welded steel casing, gravel packed, 16-in diameter to 550 ft, 12¾-in to 1,160 ft, and 10¾-in to 1,650 ft. Velocity measured May 22, 1956. Depth to water 405 ft below top of casing]

700	Trace	1,000	0.26
800	Trace	1,100	Trace
910	0.19		

17/15-27K1

[M. Griffen 3. Welded steel casing, gravel packed, perforated 912 to 2,130 ft, 16-in diameter to 767 ft, 12¾-in to 1,059 ft, 10¾-in to 1,111 ft. Velocity measured June 13, 1956. Depth to water 537 ft below top of casing]

537–925	0	1,100	0.48
975	.18	1,200	.48
1,025	.48	1,300	.48

TABLE 13.—*Results of flow measurements made in wells with the deep-well current meter*—Continued

17/16-4E1

[Vista del Llano 6. Welded steel casing, gravel packed, perforated 416 to 1,580 ft, 16-in diameter to 416 ft, 10¾-in to 1,260 ft, 9½-in to 1,580 ft. Velocity measured June 5, 1956. Depth to water 326 ft below top of casing]

Depth (feet)	Flow (cfs)	Depth (feet)	Flow (cfs)
475	0	525	.46
485	.54	549	1.09
500	.36	600 [1]	.96

[1] Obstruction at 610 ft prevented deeper readings.

17/16-5N1

[Vista del Llano 12. Welded steel casing, gravel packed, perforated 417 to 1,821 ft, 16-in diameter to 417 ft, 12-in to 742 ft, and 10-in to 1,821 ft. Velocity measured May 22, 1956. Depth to water 291 ft below top of casing]

No flow 300 to 715 ft. Obstruction at 715 ft at prevented deeper readings.

17/16-7R1

[Vista del Llano 7. Welded steel casing, gravel packed, 16-in diameter to 757 ft, 12¾-in to 1,278 ft, and 10¾-in to 1,860 ft. Velocity measured May 23, 1956. Depth to water, 405 ft below top of casing

No flow 405 to 1,200 ft.

17/16-8L1

[Vista del Llano 8. Welded steel casing, gravel packed, perforated 553 to 1,800 ft, 16-in diameter to 550 ft, 12¾-in to 1,150 ft, 10¾-in to 1,800 ft. Velocity measured May 23, 1956. Depth to water 376 ft below top of casing]

Depth (feet)	Flow (cfs)	Depth (feet)	Flow (cfs)
550	0	900	0.27
650	.54	1,000	.20
700	.14	1,100	.16
800	.13	1,200	Trace

19/17-19D1

[Giffen 48. Welded steel casing, gravel packed, perforated 721 to 2,063 ft, 16-in diameter to 721 ft, 12¾-in to 1,000 ft, and 10¾-in to 2,063 ft. Velocity measured June 13, 1956. Depth to water 458 ft below the land surface]

Depth (feet)	Flow (cfs)	Depth (feet)	Flow (cfs)
700	0	900	0.12
800	.12	1,000	Trace

19/17-19P1

[Giffen 47. Welded steel casing, gravel packed, perforated 665 to 2,030 ft, 16-in diameter to 665 ft, 12¾-in to about 1,000 ft, 10¾-in to 2,030 ft. Velocity measured April 25, 1956. Depth to water, 334 ft below top of casing]

Depth (feet)	Flow (cfs)	Depth (feet)	Flow (cfs)
400	0	900	0.16
450	.51	1,100	.16
700	.21		

TABLE 13.—*Results of flow measurements made in wells with the deep-well current meter*—Continued

Depth (feet)	Flow (cfs)	Depth (feet)	Flow (cfs)
	19/18-33N2		
[Boston Ranch 68. Welded steel casing, gravel packed, perforated 632 to 2,025 ft, 16-in diameter to 632 ft, 12¾-in to 1,352 ft, and 10¾-in to 2,025 ft. Velocity measured May 10, 1956. Depth to water 396.6 ft below the land surface]			
575	0	950	0.38
600	Trace	1,050	.43
625	.42	1,150	.39
650	.47	1,240	.38
750	.40	1,350	.37
850	.38		

There were about 1,000 irrigation wells in 1956 tapping the lower water-bearing zone in the area of heavy ground-water pumping on the west side of the valley, western Fresno and Kings Counties (p. 81). These wells in recent years have been in operation about 60 percent of the time. If the rates measured in idle wells (table 13) can also be considered as representative of the active irrigation wells, the downward flow through active irrigation wells during the 40 percent of the time they are shut off would be on the order of 75,000 acre-feet per year.

In addition to the 1,000 active irrigation wells in the area there are probably as many as 2,000 abandoned wells that originally tapped the lower water-bearing zone. Most of these wells were abandoned because the casings collapsed, and water no longer could be pumped at economical rates. Many of the casings still can be found, but many have been cut off below the land surface and covered. Water in these abandoned wells generally stands at a level intermediate between the piezometric surface of the lower zone and the water table, indicating that the wells still transmit some water between the zones. However, if the rates of flow were comparable to those in active wells, the water levels in the abandoned wells would be close to the piezometric surface of the lower zone. If the rate of flow in abandoned wells was as much as one-tenth that of the active wells, which seems reasonable, the flow down the abandoned wells would be on the order of 40,000 acre-feet per year, thus raising the total interaquifer movement of water through wells to the order of 100,000 acre-feet per year.

MOVEMENT THROUGH THE CORCORAN CLAY MEMBER OF THE TULARE FORMATION

Downward movement of water through the Corcoran clay member—the principal confining bed for the lower water-bearing zone—can be computed by Darcy's law, if the area in which flow occurs, the hydraulic gradient, and the permeability of the material through which the water flows are known.

The head differential between the upper semiconfined zone and the lower confined water-bearing zone for the central part of the valley between Los Banos and Kettleman City in 1952 is shown on plate 10. The average thickness of the Corcoran clay member is about 60 feet. Its permeability can be determined by laboratory tests of cored samples. Some laboratory tests have been made, but the results are conflicting.

Determinations of the permeability of samples of the Corcoran clay member with falling-head permeameters have been made by the U.S. Bureau of Reclamation laboratory at Sacramento and the hydrologic laboratory of the Geological Survey at Denver, Colo. Results of these tests are listed in table 14. In addition, the permeability of 16 samples of the Corcoran clay member have been calculated from one-dimensional consolidation tests made by the Earth Laboratory of the Bureau of Reclamation, Denver, Colo. Average results of these tests also are listed in table 14. The average permeability from the 6 falling-head permeater tests is 0.0027 gpd per sq ft (gallons per day per square foot), whereas the average permeability calculated from the one-dimensional consolidation tests is 0.000031 gpd per sq ft. The reason for this wide discrepancy in the average test results by the two methods is not known, but, in view of this, the authors have not attempted to estimate the quantity of water moving through the Corcoran clay into the lower water-bearing zone.

TABLE 14.—*Summary of permeability-test data for Corcoran clay member of the Tulare formation*

Type of test and agency	Location	Sample depth (ft)	Permeability (gpd per sq ft)	Sample description
Falling-head permeameter:				
U.S. Bureau of Reclamation, Region 2 Laboratory.	15-14-15A	642.1	0.0002	Clay.
	15-16-12B	573.0	.004	Silty clay.
	do	585.5	.002	Clayey silt.
U.S. Geological Survey, Denver Hydrologic Laboratory.	14/13-11D1	631.0	.005	
	do	652.0	.004	
	do	682.5	.0008	
Average of 6 samples			0.0027	
One-dimensional consolidation tests:				
U.S. Bureau of Reclamation, Denver Earth Laboratory:				
Average of 7 samples [1]	Various	257-699	0.000039	
Average of 9 samples [2]	do	257-699	.000024	
Average of 16 samples			0.000031	

[1] Load range, 200-400 psi.
[2] Load range, 400-800 psi.

ANALYSIS OF RECHARGE AND DISCHARGE IN SELECTED AREAS

To evalute rates of infiltration and the magnitude of incidental recharge, three typical intensively irrigated areas in the San Joaquin Valley were selected for detailed studies of recharge and changes in ground-water storage. Two independent methods were used as a check on the accuracy of the estimates. Studies were made for a year of excess supply to evaluate maximum rates of recharge and infiltration and for a year of deficient supply to evaluate rates of dewatering in the past.

Two methods were used to estimate changes in storage and recharge. The first, a direct approach, involved computing from water-level measurements the volume of sediments dewatered or saturated and determining the change in storage by applying to this volume an estimated specific yield. The other method, an indirect approach, required an inventory of all the elements of recharge to, and discharge from, the ground-water reservoir; the difference was taken as change in storage.

The chief consideration in selecting the study areas was that basic data should be available in sufficient detail to permit reasonably accurate estimates of change in ground-water storage and the elements of recharge and discharge. Estimates of specific yield of the subsurface deposits, which were available in published form, and sufficient measurements of depths to water in wells to define the fluctuations of the water table were deemed essential for the specific-yield method. Requirements for the inventory method were data on ground-water pumpage, surface-water supply, crop acreages, estimates of consumptive use, precipitation records, and information on the hydraulic gradient and transmissibility of the subsurface deposits to provide a basis for estimates of ground-water outflow and inflow.

A careful review of hydrologic information available for the San Joaquin Valley indicated that the data required were most adequate for the Madera Canal service area, the Fresno-Consolidated area, and the Kern River area. Results from the three areas are generally comparable, although minor differences in methods were required.

MADERA CANAL SERVICE AREA

The Madera Canal service area comprises the Madera Irrigation District and the Chowchilla Water District. It includes most of the east slope of the San Joaquin Valley between the Chowchilla River and the San Joaquin River in Madera County and contains about 300 square miles, or 195,000 acres. The principal geographic and hydrologic features of the area are shown on plate 11. Before 1949 the entire area was included in the Madera Irrigation District, but in that year the northern part of the Madera District was incorporated as the Chowchilla Water District. As shown on plate 2, the Madera Canal service area includes parts of two ground-water storage units—the San Joaquin River unit on the south and the Chowchilla River unit on the north.

Water for irrigation is obtained chiefly from wells, although large deliveries of water from the Madera Canal in recent years have alleviated a serious overdraft of the ground-water supply. The natural runoff of the Fresno and Chowchilla Rivers and lesser streams that drain the lower slopes of the Sierra Nevada are a smaller but, nevertheless, significant contribution to the total water supply. Precipitation, although generally too low to permit infiltration, is effective in meeting the water needs of irrigated crops and, therefore, is considered as an element of recharge. Deliveries of imported water from the Madera Canal in the years of the estimates (table 15) were made to the natural channels that traverse the Madera service area, and, accordingly, no effort has been made to segregate canal supply from the natural supply. Instead, the canal deliveries have been treated the same as the natural runoff in this report. Detailed records of diversion from the stream channels to the district ditches are not available; hence, it was not possible to compute infiltration by the method used in the Fresno-Consolidated and Kern River area studies (pp. 98–116). However, detailed records of surface inflow to and outflow from the area are available for the major streams, the Fresno River, and Ash and Berenda Sloughs (table 17), and it was possible to estimate the flow of the ungaged minor streams with a fair degree of accuracy by a correlation procedure. The difference between surface inflow and outflow thus obtained was computed as a contribution to the total supply (table 15).

Water-level contours (Davis and others, 1959, pl. 15) indicate that ground-water inflow is a significant element in the water supply of the Madera Canal service area. Owing to heavy overdraft of the local ground-water supply, a water-table depression has persisted in the area for many years. Accordingly, ground-water inflow to the area exceeded outflow from the area in all the years for which detailed studies were made. Estimates of the quantity of ground-water inflow and outflow are given in table 20.

The natural runoff of the streams of the Madera Canal service area is relatively small. Moreover, because the streams originate in the lower western slopes of the Sierra Nevada, the precipitation in the drainage areas occurs chiefly as rain instead of snow, and the water runs off quickly. Inasmuch as the runoff is concentrated chiefly in the winter and early spring, it has never served as a summer water supply to even small parts of the area. Before the completion of the Madera Canal in 1944 by the Bureau of Reclamation, ground water was the firm irrigation supply to the area, and surface water was distributed as supplemental water when available. During the years of the detailed studies (1943, 1945, and 1952), deliveries were made to the natural channels, and water was diverted to ditches at points downstream. Little effort was made to keep seepage losses down because it was recognized that infiltration of water lost from stream channels and ditches would recharge the ground-water reservoir. Accordingly, the figures for infiltration listed on table 21, especially for 1952, may seem very high in comparison with other irrigated areas. This incidental recharge is an effective method of conserving the available supply under the economic conditions that prevailed at the time.

Ground-water pumpage in the Madera Canal service area, as computed from records of the Pacific Gas & Electric Co., increased from 307,000 acre-feet in 1940 to 635,000 acre-feet in 1952 to 754,000 acre-feet in 1955. In most years since 1940, between two-thirds and three-quarters of the irrigation water used in the Madera Canal service area has been pumped from wells. Much of this pumpage is not used consumptively, but it returns to the ground-water reservoir by infiltration. Nevertheless, ground-water pumpage has exceeded the annual recharge to the ground-water reservoir for many years, and even in years of excessive runoff, such as 1952 (table 17), the net increase in storage was relatively small.

Net changes in ground-water storage have been estimated for three periods: for 1943 to show the regimen before importation of water through the Madera Canal, for 1945 to show conditions under the canal supply in a year of deficient runoff, and for 1952 to show conditions under the canal supply in a year of surplus runoff.

In comparing results obtained by the two methods described previously, some error is introduced due to differences in the periods represented by different classes of data. In the specific-yield computations, changes in storage were computed for the calendar year by using December water-level measurements. Likewise, data on precipitation used in the inventory computations were reported by calendar years. However, streamflow records are reported for a water year from October 1 to September 30, and pumpage as reported by the Pacific Gas & Electric Co. is for May 1 to April 30. Despite the differences in periods for which the data are reported, the authors believe that the error thus introduced is minor.

ESTIMATES OF CHANGE IN STORAGE BY THE SPECIFIC-YIELD METHOD

By the specific-yield method, the computations of the volumes of material drained and rewatered were based on planimeter measurements made on annual water-level change maps (not shown). The change in ground-water storage was computed by applying to the change in saturated volume an estimated specific-yield for the water-bearing depth zone in which the changes occurred. A review of water-level records for wells in the Madera Canal service area reveals that most of the changes in storage occurred in the zones between 20 and 100 feet below the land surface. For 1943, the specific-yield method indicated a depletion of ground-water storage of 62,000 acre-feet. Increases of ground-water storage of 18,700 and 59,499 acre-feet were indicated for 1945 and 1952, respectively (table 16).

ESTIMATES OF CHANGE IN STORAGE BY THE INVENTORY METHOD

The inventory method for computing change in storage consists of computing the recharge from all sources and deducting the discharge. The general approach used was to (1) compute the total water supply to the area, (2) deduct the estimated consumptive use by crops, (3) add the computed net ground-water inflow (inflow minus outflow) to obtain total recharge, and (4) deduct from the total recharge, the discharge (in this area only pumpage) to obtain the change in storage. The total supply to the area was computed as the sum of net surface-water supply and ground-water pumpage. Consumptive use of applied water was obtained as the product of unit consumptive use and crop acreage irrigated. The net ground-water inflow to the area was estimated from the hydraulic gradient, as shown on water-level contour maps, by means of the Darcy equation (p. 105). The estimates of recharge and discharge for the years 1943, 1945, and 1952 are summarized in table 15 and discussed on pages 93 to 98.

TABLE 15.—*Inventory of recharge and discharge, in acre feet, for the Madera Canal service area, 1943, 1945, and 1952*

	1943	1945	1952
Recharge elements:			
Net surface supply	112,000	221,000	360,000
Pumpage	389,000	438,000	635,000
Total supply	501,000	659,000	995,000
Less consumptive use	217,000	247,000	324,000
Deep penetration	283,000	412,000	671,000
Net ground-water inflow (inflow minus outflow)	36,000	26,000	38,000
Total recharge	319,000	438,000	709,000
Discharge element: Pumpage	389,000	438,000	635,000
Change in storage (recharge minus discharge)	−70,000	None	+74,000

COMPARISON OF ESTIMATES

Comparison of the estimates of change in ground-water storage by the specific-yield and inventory methods for the 3 years 1943, 1945, and 1952 (table 16) indicates close agreement of results.

The mean deviation, or difference between the mean and the higher and lower values, ranged from 9,350 acre-feet in 1945 to 4,000 in 1943. A more valid comparison of the data is the ratio of mean deviation to total recharge expressed as a percentage, which ranged from 2.1 in 1945 to 1.0 in 1952.

TABLE 16.—*Comparison of changes in ground-water storage in the Madera Canal service area computed by the specific-yield and inventory methods, 1943, 1945, and 1952*

	1943	1945	1952
Specific-yield method acre-feet	−62, 000	+18, 700	+59, 400
Inventory method do	−70, 000	None	+74, 000
Mean of two methods do	−66, 000	+9, 350	+66, 700
Mean deviation of the two methods do	4, 000	9, 350	7, 300
$\frac{\text{Mean deviation}}{\text{Total recharge (inventory method)}}$ percent	1. 3	2. 1	1. 0

The years selected for study spanned years of deficient and surplus water supply. Moreover, the ground-water pumpage increased by almost two-thirds between 1943 and 1952. The close agreement of results obtained by independent approaches under widely differing conditions of supply indicates that the methods of estimating change in ground-water storage were consistent, if not nearly correct, for the Madera Canal service area as a whole. It does not necessarily follow, however, that the estimates of individual elements of the computations were valid, although the close agreement of overall results does justify considerable confidence in the basic data and methods used to arrive at the individual elements of the computations.

COMPUTATIONS USED IN THE INVENTORY METHOD OF ESTIMATING CHANGE IN STORAGE

An explanation of methods use in estimating the elements of recharge and discharge in the inventory is given below, and detailed figures that were used are presented in tables 17 to 21. Information on surface inflow and outflow, on which the estimates of net surface supply were based, was obtained chiefly from the U.S. Bureau of Reclamation (1955); although, as indicated in table 17, some of the figures for flow were based on estimates by the authors. Estimates of pumpage for irrigation were modified from unpublished data in the files of the Fresno office of the Pacific Gas & Electric Co. Unit consumptive-use values were taken from the Bulletin 2 of the California State Water Resources Board (1955), and crop acreages were from unpublished records of the Madera Irrigation District and the Chowchilla Water District.

RECHARGE ELEMENTS

Total supply.—Because only incomplete records of stream diversions in the Madera Canal service area are available, it was impossible to separate stream and canal losses from irrigation losses in the inventory. However, reasonably accurate records were available of streamflow into, canal deliveries to, and surface outflow from the area.

Combined streamflow and water deliveries from the Madera Canal represent 20 to 30 percent of the total water applied to the land surface in the study area. This flow enters the area from the east in the natural channels of eight principal streams and from a series of diversions from the Madera Canal at the crossings of these streams. Much of this water is used for irrigation or seeps to the ground-water reservoir from the stream channels and ditches. As much as 50 percent of the surface water that enters the area in a given year, however, passes directly through, and is measured as outflow at, the western boundary of the area. Only that part of the streamflow that is retained in the area, that is, the inflow minus the outflow, can be considered effective in satisfying irrigation demands and in recharging the ground-water reservoir.

Records of annual flow of the eight principal streams that enter the Madera Canal service area for 1943, 1945, and 1952, as obtained from records of the Bureau of Reclamation, are shown in table 17. Also tabulated are the canal diversions to the area and the net surface-water supply retained in the area. Because records for several of the streams listed were not complete, a multiple correlation procedure was used in computing discharge values from the recorded discharge of nearby streams, as indicated in the footnotes of table 17.

The net surface supply together with the ground-water pumpage makes up the total water supply shown in table 15.

Consumptive use.—Consumptive use of water by irrigated crops cannot be measured directly, but must be approximated from assumed average rates of consumption of water for each crop. Average unit values of consumptive use adopted for this study were those published by the California State Water Resources Board (1955, table 113). These estimates represent the seasonal consumption of water by crops under average conditions of water supply and climate in the Madera area. The irrigated acreage by crops was obtained for each of the 3 years studied from crop surveys of the U.S. Bureau of Reclamation. Table 18 shows the unit consumptive use by crops, and table 19 shows acreages irrigated and consumptive use of applied water. In the

TABLE 17.—*Surface inflow and outflow in acre-feet, in the Madera Canal service area, 1943, 1945, and 1952*

[Flows of Fresno River and Madera Canal measured; others estimated from correlation curves]

	1943			1945			1952		
	Inflow	Outflow	Net	Inflow	Outflow	Net	Inflow	Outflow	Net
Ash Slough Berenda Slough	104,000	49,000	55,000	80,000	43,000	37,000	208,000	90,000	118,000
Berenda Creek Dry Creek Cottonwood Creek Hildreth Creek	8,000	67,000	57,000	8,000	71,000	49,000	10,000	101,000	91,000
Fresno River	116,000			112,000			182,000		
Madera Canal	----------	----------	----------	135,000	0	135,000	151,000	----------	151,000
Total	228,000	116,000	112,000	335,000	114,000	221,000	551,000	191,000	360,000

inventory, only consumptive use by irrigated crops has been considered. Consumptive use in nonirrigated areas probably approximates the annual precipitation and, therefore, would not enter the recharge-discharge equation. The effective precipitation (table 18) was computed from the daily precipitation records of the U.S. Weather Bureau station at Madera by a method suggested by Blaney (1928, p. 154). In this method, 0.5 inch is deducted from the total precipitation for each storm, to account for evaporation. The remainder is considered effective for plant use.

TABLE 18.—*Unit consumptive-use values (feet) used in the inventory of recharge and discharge, Madera Canal service area, 1943, 1945, and 1952*

[Effective precipitation at Madera, in feet: 1943, 0.5; 1945, 0.4; 1952, 0.5. Estimated by deducting 0.5 in. for evaporation from total precipitation for each storm, as reported for Madera, Calif., by the U.S. Weather Bureau]

Crop	Unit consumptive use[1] (including precipitation)	Unit consumptive use (less effective precipitation)		
		1943	1945	1952
Alfalfa	3.7	3.2	3.3	3.2
Irrigated pasture	3.7	3.2	3.3	3.2
Deciduous orchard	2.8	2.3	2.4	2.3
Vineyard	2.9	2.4	2.5	2.4
Cotton	2.5	2.0	2.1	2.0
Truck garden	1.8	1.3	1.4	1.3
Grain	1.0	.5	.6	.5
Milo	1.3	.8	.9	.8
Miscellaneous field crops	2.0	1.5	1.6	1.5

[1] Data from Bull. 2, California State Water Resources Board (1955, table 113).

TABLE 19.—*Estimated consumptive use of applied water by irrigated crops in the Madera Canal service area, 1943, 1945, and 1952*

Crop	1943			1945			1952		
	Unit consumptive use (feet)	Area irrigated (acres)	Consumptive use (acre-feet)	Unit consumptive use (feet)	Area irrigated (acres)	Consumptive use (acre-feet)	Unit consumptive use (feet)	Area irrigated (acres)	Consumptive use (acre-feet)
Alfalfa	3.2	22,800	73,000	3.3	24,800	81,800	3.2	23,300	74,600
Irrigated pasture	3.2	10,200	32,600	3.3	11,800	38,900	3.2	20,000	64,000
Deciduous orchard	2.3	3,000	6,900	2.4	4,200	10,000	} 2.4	21,600	51,800
Vineyard	2.4	19,800	47,500	2.5	21,300	53,200			
Cotton	2.0	21,700	43,400	2.1	23,800	50,000	2.0	62,700	125,400
Truck garden	1.3	1,500	2,000	1.4	1,500	2,100	1.3	1,700	2,200
Grain	.5	3,200	1,600	.6	(1)		.5	2,300	1,200
Milo	.8	2,200	1,800	.9	(1)		.8	500	400
Miscellaneous field crops	1.5	5,200	7,800	1.6	6,800	10,900	1.5	2,900	4,400
Total or weighted average	2.4	89,600	216,600	2.5	94,200	246,900	2.4	135,000	324,000

[1] None reported.

Infiltration was computed by deducting the consumptive use, which had been adjusted for effective precipitation, from the total water supply. Unlike the inventories for the Fresno-Consolidated, and Kern River areas, no deduction of 5 percent was made for evaporation from open-water surfaces and transpiration by noncrop vegetation because such irrecoverable losses had been mostly accounted for earlier in computing the net surface supply to the area.

Net ground-water inflow.—The difference between ground-water inflow and outflow is termed "net ground-water inflow." Computations of the rate of movement of ground water into and out of the Madera Canal service area were based on water-level contour maps of the area prepared for December 1943, 1945, and 1952 (not shown). On each map, the perimeter of the study area was subdivided into small subunits, and the rate of flow across each subunit was computed by Darcy's equation. The hydraulic gradient and the direction of movement of ground water were determined from the contours. The transmissibility of the subsurface deposits was estimated from specific capacity by a method described by Theis and others (1954, fig. 2). The values for specific capacity were obtained from pump tests made by the Pacific Gas & Electric Co. (table 3).

The computed quantities of ground-water inflow, ground-water outflow, and net ground-water inflow for each of the 3 years studied are listed in table 20.

TABLE 20.—*Ground-water inflow and outflow, in acre-feet, in the Madera Canal service area 1943, 1945, and 1952*

Year	Inflow	Outflow	Net inflow
1943	38, 000	2, 000	36, 000
1945	31, 000	5, 000	26, 000
1952	44, 000	6, 000	38, 000

As indicated in table 15, the ground-water inflow makes up only a small part of the recharge to the area. It differs but slightly from year to year and, therefore, is proportionately smaller during years of excessive streamflow runoff.

DISCHARGE ELEMENTS

Ground-water pumpage.—Pumpage, the principal form of discharge in the Madera Canal service area, was computed from records of the Pacific Gas & Electric Co. In these computations, the annual pumpage reported for the Madera operating district, which includes virtually all the San Joaquin Valley part of Madera County, was reduced in proportion to the number of plants in the area under study. The general method employed by the Pacific Gas & Electric Co. to compute pumpage is as follows: (1) For each township within the operating district, an average figure for kilowatthours per acre-foot is calculated from pump-efficiency tests, (2) this figure is multiplied by the number of pumps in each township, (3) the products thus obtained are totaled and divided by the number of pumps in the district, giving a weighted value of kilowatthours per acre-foot for the district, (4) the total kilowatthours consumed during the year is divided by the weighted average of kilowatthours per acre-foot to obtain the total pumpage in acre-feet.

RATES OF INFILTRATION

Unit rates of infiltration of water are presented in table 21 as an aid in evaluating the importance of incidental recharge in the total water supply of the Madera Canal service area.

The increase in infiltration over the years reflects not only greater net surface-water supply in the later years, but also a steady growth of ground-water pumpage during the period. The greatly increased water supply (table 15), which almost doubled between 1943 and 1952, was reflected by a large increase in the area irrigated.

TABLE 21.—*Estimated recharge by infiltration in the Madera Canal service area 1943, 1945, and 1952*

Year	Infiltration (acre-feet)	Area irrigated (acres)	Unit rate of infiltration (acre-feet per acre)	Gross area (acres)	Average infiltration in gross area (acre-feet per acre)
1943	283, 000	89, 600	3. 2	173, 000	1. 6
1945	412, 000	94, 200	4. 4	172, 400	2. 4
1952	671, 000	135, 000	5. 0	172, 400	3. 9

FRESNO-CONSOLIDATED AREA

The combined area of the Fresno and Consolidated Irrigation Districts referred to herein as the Fresno-Consolidated area includes about 425,000 acres, or about 660 square miles. The area includes parts of three ground-water storage units, as outlined on plate 2. From north to south, these comprise the southernmost part of the San Joaquin unit, extending from the San Joaquin River to its boundary with the Kings River and Fresno Interstream units; most of the Fresno Interstream unit; and most of the northern half of the Kings River unit.

The Fresno-Consolidated area receives a large supply of irrigation water from the Kings River (pl. 11). Losses from canals and ditches, infiltration of water applied in excess of plant needs, and infiltration from the channel of the Kings River make up the principal sources of recharge to ground water. Recharge sources of lesser importance are underflow of ground water from the neighboring uplands to the east and artificial recharge through flooding of natural ponds and pits with surface water diverted from the Kings River in excess of the immediate demand for irrigation. Infiltration from streams other than the Kings River has been ignored in the estimates of recharge because nearly all the small streams that enter the area from the east are channeled into the irrigation distribution systems and thus become part of the irrigation supply. During years of above-normal stream runoff, an ample supply of Kings River water is available to most of the land in the unit, and the ground-water reservoir is heavily recharged. During years of deficient runoff, however, the water allocated to the Fresno and Consolidated Irrigation Districts is proportionately less, and the water users must supplement their meager canal supply by large withdrawals from ground-water storage.

Diversions are sufficient to meet irrigation demand until about July 1 in most years, after which an increasing volume of ground water is pumped to supplement the declining surface supply from the Kings River. As a result of this irrigation pattern, ground-water levels commonly rise in the spring and early summer, reflecting increases in recharge to the ground-water reservoir caused by liberal application of canal water. The water levels decline in late summer as ground water is withdrawn from storage to supplement the decreasing surface supply (Davis and others, 1959, pl. 18).

In addition to discharge by pumping for irrigation, ground water is discharged by underflow along the western and northern boundaries of the Fresno-Consolidated area, transpiration by noncrop vegetation, and pumping for municipal and domestic water supplies.

Net changes in ground-water storage have been estimated for two periods: for 1948, to show the net decrease in storage during a depletion period; and for 1952, to show the net increase in storage during a replenishment period. For each period, the two independent methods described previously have been used as a check on the overall accuracy of the estimates. Ideally a comparison of net changes in storage determined by separate methods should span identical periods; however, the error involved in comparison of different periods is probably of minor significance (p. 91).

ESTIMATES OF CHANGE IN STORAGE BY THE SPECIFIC-YIELD METHOD

In the estimates based on specific yield, changes in saturated volume were computed in different ways for the Fresno District and the Consolidated District. The Consolidated Irrigation District makes periodic water-level measurements in a network of observation wells that are spaced uniformly throughout the district. Thus, area-weighted changes in saturated volume were obtained by simply averaging the changes indicated in the individual wells. In the Fresno Irrigation District, the observation wells were not spaced uniformly. Therefore, to compute changes in saturated volume, lines of equal change of saturated volume were drawn on a map (not shown), and the areas between the lines were measured with a planimeter. The measurements of these areas were multiplied by the value representing the average change in the areas, and the products were added to give the change in saturated volume. The computations of change in saturated thickness were based on January water-level measurements made in the years 1948, 1949, 1952, and 1953.

Changes in ground-water storage were computed by applying to the change in saturated volume an estimated specific yield for the depth zone, chiefly the 10- to 50-foot zone, within which the fluctuations occurred. Actually, four values of specific yield were used. The following specific yields, based on estimates by Davis and others (1959, table 6), were derived by averaging specific yields given for the individual townships within the storage units.

	Specific yield (percent)
Fresno Interstream storage unit	8. 2
San Joaquin storage unit	12. 3
Kings River storage unit:	
a. Part in the Fresno Irrigation District	14. 6
b. Part in the Consolidated Irrigation District	14. 9

For 1948, the net change in ground-water storage computed by this method was a decrease of 227,500 acre-feet. For 1952, the net change in storage was an increase of 167,900 acre-feet.

ESTIMATES OF CHANGE IN STORAGE BY THE INVENTORY METHOD

In the inventory method, data on crop acreages and effective precipitation were computed on a calendar-year basis. However, data on irrigation diversions were based on the water year (October 1 to September 30), and pumpage figures supplied by the Pacific Gas & Electric Co. are compiled for an agricultural year from April 1 to March 31.

The general approach used in the inventory of discharge and recharge elements was to consider the Fresno and Consolidated Irrigation Districts separately and for each district to compute the total water supply as the sum of canal diversions and irrigation pumpage. It has not been possible in this study to differentiate the amount of water contributed to the ground-water reservoir by excess irrigation and by losses from canals. Hence, total supply includes both these sources of replenishment. Consumptive use of applied water was obtained as the product of the acreage irrigated and unit consumptive-use values. This consumptive use was then subtracted from the total supply, giving total system loss (nonconsumptive use). Irrecoverable losses in the form of evaporation from open water surfaces and transpiration by noncrop vegetation were estimated to be 5 per cent of the difference between supply and total consumptive use. The total nonconsumptive use less the 5 percent difference between supply and total consumptive use was assumed to represent ground-water replenishment in the form of infiltration. Recharge by loss from the Kings River and minor streams was added to estimates of infiltration to obtain total recharge. The discharge elements of the ground-water equation comprises net ground-water outflow, irrigation pumpage, and consumptive use of ground water on urban and suburban lands within the area. Finally, the change in the ground-water storage was obtained as the difference between recharge and discharge. The estimates of recharge and discharge elements for the years 1948 and 1952 are summarized in tables 22 and 23.

TABLE 22.—*Inventory of recharge and discharge, in acre-feet, in the Fresno-Consolidated area, 1948 and 1952*

		1948		*1952*
Recharge:				
1. Stream seepage:				
Kings River		16,200		3,600
Minor streams		5,000		13,700
2. System losses:				
a. Fresno Irrigation District	298,300		670,800	
b. Consolidated Irrigation District	165,000		536,100	
Total	463,300		1,206,900	
Less 5 percent waste	23,200		60,300	
Infiltration		440,100		1,146,600
Total recharge		461,300		1,163,900
Discharge:				
1. Net ground-water outflow		24,000		35,000
2. Irrigation pumpage		909,700		966,500
3. Consumptive use of ground water in urban and suburban areas		31,000		34,800
Total discharge		964,700		1,037,000
Change in storage (recharge minus discharge)		−503,400		+126,900

COMPARISON OF ESTIMATES

Comparison of the estimates of change in ground-water storage computed by the specific-yield method and the inventory method (table 23) show reasonably close agreement for 1952 but rather poor agreement for 1948.

The comparison of the results for 1952 indicates about the same order of accuracy as shown in studies of the Madera Canal service area (table 16) and the Kern River area (p. 111). The results for 1948, however, indicate a serious disagreement between the methods used. Several of the elements involved in the computation were too small to include a discrepancy on the order of 250,000 acre-feet (table 23). In the inventory, only the ground-water pumpage was sufficiently large to allow an error of that magnitude. However, the pumpage, a quantity not subject to sharp change, estimated in the Fresno-Consolidated area and adjoining districts in 1948 was consistent with other years. Furthermore, it was computed by standard methods that have been used successfully by the Pacific Gas & Electric Co. for many years to estimate pumpage in the San Joaquin Valley.

It seems more likely that the discrepancy lies in the estimate by the specific-yield method, particularly in the estimate of volume of materials dewatered. Data upon which the map showing water-level changes for 1948 was based were barely adequate in the Fresno Irrigation District.

TABLE 23.—*Comparison of changes in ground-water storage in the Fresno-Consolidated area computed by the specific-yield and inventory methods, 1948 and 1952*

	Change in storage	
	1948	1952
Specific-yield method ....acre-feet..	−227, 500	+167, 900
Inventory method ....do....	−503, 400	+126, 900
Mean of both methods ....do....	−365, 400	+147, 400
Mean deviation of the two methods ....do....	138, 000	20, 500
Mean deviation / Total recharge (inventory method) ....percent..	29. 9	1. 8

COMPUTATIONS USED IN INVENTORY METHOD OF ESTIMATING CHANGE IN STORAGE

In the following paragraphs, a breakdown and explanation of the elements shown in table 22 is presented, both by year and by irrigation districts insofar as possible. The data used in the computations have been derived from several sources. Losses from the Kings River were obtained from the annual reports of the Kings River Water Master. Losses from Dry Creek and other minor streams in the area were estimated from the annual reports of the Fresno Irrigation District. Irrigation-diversion data were obtained from published and unpublished records of the California Department of Water Resources, and pumpage was obtained from unpublished records of the Pacific Gas & Electric Co. at Fresno. Unit consumptive-use values for the various crops in the Fresno area were obtained from Bulletin 2 of the California State Water Resources Board (1955, table 113), and crop acreages were obtained from the report of the Fresno Irrigation District and from the aforementioned records of the Department of Water Resources.

RECHARGE ELEMENTS

Stream infiltration.—Losses from the Kings River have been determined from flows gaged at Piedra, east of the Fresno-Consolidated area, and at Lemoore Weir. These losses have been adjusted downward from the published figures because the Lemoore Weir lies several miles downstream from the edge of the Fresno-Consolidated area. The Piedra gaging station is several miles east of the limits of the study area, but between the area boundary and the gaging station, the Kings River flows through a rock channel and infiltration is at a minimum. Because the Kings River forms much of the south and east boundary of the area (pl. 11), total infiltration has been further diminished by 50 percent so as to exclude seepage that moves southward out of the area. Estimated infiltration losses from the Kings River and from minor streams are given in table 22.

System losses.—System losses (tables 22, 28) as used herein represent the difference between total water supply and consumptive use of water applied for irrigation. The total supply, shown in table 24, comprises two elements, canal diversions and pumpage.

TABLE 24.—*Canal diversions and pumpage, in acre-feet, in the Fresno-Consolidated area, 1948 and 1952*

	1948	1952
Fresno Irrigation District:		
Canal diversions	307, 400	543, 162
Pumpage	538, 500	555, 675
Total supply	845, 900	1, 098, 837
Consolidated Irrigation District:		
Canal diversions	169, 900	417, 300
Pumpage	371, 249	410, 780
Total supply	541, 149	828, 080

The estimated consumptive use of water applied for irrigation (tables 26, 27) was obtained as the product of unit consumptive-use values for the several crops and the acreages of each. Unit consumptive-use values (table 25), including effective precipitation, are given in Bulletin 2 (California State Water Resources Board, 1955, table 113). Effective precipitation, defined here as the cumulative total of precipitation exceeding 0.5 inch in each storm, was 0.2 foot at Fresno in 1948 and 0.8 foot in 1952.

TABLE 25.—*Unit consumptive-use values (feet) used in the inventory of recharge and discharge, Fresno-Consolidated area, 1948 and 1952*

[Effective precipitation at Fresno, in feet: 1948, 0.2; 1952, 0.8. Estimated by deducting 0.5 in. evaporation from total precipitation for each storm as reported from Fresno, Calif., by the U.S. Weather Bureau]

Crop	Unit consumptive use [1] (including precipitation)	Unit consumptive use (less effective precipitation)	
		1948	1952
Alfalfa	3.5	3.3	2.7
Irrigated pasture	3.5	3.3	2.7
Deciduous orchard	2.8	2.6	2.0
Citrus	2.8	2.6	2.0
Vineyard	2.9	2.7	2.1
Cotton	2.7	2.5	1.9
Truck garden	1.5	1.3	.7
Miscellaneous field crops	2.0	1.8	1.2

[1] Data from Bull. 2, California State Water Resources Board (1955, table 113).

TABLE 26.—*Estimated consumptive use of applied water by irrigated crops in the Fresno Irrigation District, 1948 and 1952*

[Adjusted to allow for effective precipitation]

Crop	Unit consumptive use (feet)		Area irrigated (acres)		Consumptive use (acre-feet)	
	1948	1952	1948	1952	1948	1952
Alfalfa	3.3	2.7	22,035	23,776	72,716	64,195
Pasture	3.3	2.7	20,500	17,490	67,650	47,223
Deciduous	2.6	2.0	26,185	23,068	68,081	46,136
Citrus	2.6	2.0	1,780	1,354	4,628	2,708
Vineyard	2.7	2.1	80,600	65,024	217,620	136,550
Cotton	2.5	1.9	42,875	67,320	107,188	127,908
Truck garden	1.3	.7	2,840	2,703	3,692	1,892
Miscellaneous field crops	1.8	1.2	3,345	1,171	6,021	1,405
Total or weighted average	2.7	2.1	200,160	201,906	547,596	428,017

TABLE 27.—*Estimated consumptive use of applied water by irrigated crops in the Consolidated Irrigation District, 1948 and 1952*

[Adjusted to allow for effective precipitation]

Crop	Unit consumptive use (feet)		Area irrigated (acres)		Consumptive use (acre-feet)	
	1948	1952	1948	1952 [1]	1948	1952
Alfalfa	3.3	2.7	5,635	5,635	18,596	15,214
Pasture	3.3	2.7	3,765	3,765	12,424	10,166
Deciduous	2.6	2.0	6,723	6,723	17,480	13,446
Citrus	2.6	2.0	2,752	2,752	7,155	5,504
Vineyard	2.7	2.1	95,964	95,964	259,103	201,524
Cotton	2.5	1.9	18,255	18,255	45,638	34,684
Truck garden	1.3	.7	188	188	244	132
Miscellaneous field crops	1.8	1.2	1,090	1,090	1,962	1,308
Not identified	[2] 2.3	[2] 1.7	5,905	5,905	13,582	10,038
Total or weighted average	2.7	2.1	140,277	140,277	376,184	292,016

[1] Area and crop patterns assumed the same as 1948, last previous reliable crop survey.
[2] For not identified crops, unit consumptive use was estimated as the average of the highest and lowest unit consumptive-use values.

TABLE 28.—*System losses in the Fresno-Consolidated area, 1948 and 1952*

	1948	1952
Fresno Irrigation District:		
Total water supply	845, 900	1, 098, 837
Less consumptive use of applied water	547, 596	428, 017
System loss	298, 304	670, 820
Consolidated Irrigation District:		
Total water supply	541, 149	828, 080
Less consumptive use of applied water	376, 184	292, 016
System loss	164, 965	536, 064

DISCHARGE ELEMENTS

Net ground-water outflow.—The net ground-water outflow from the Fresno-Consolidated area was computed as the difference between ground-water outflow and inflow computed for several segments of the perimeter. The following equation was used in the computations:

$$Q = TIL$$

in which Q is the quantity of water flowing across the perimeter of the area, T is the transmissibility of the deposits, I is the hydraulic gradient, and L is the length of the perimeter.

The coefficient of transmissibility was estimated from average values of specific capacity, multiplied by an empirical factor of 1,700, which Thomasson and others (1960, p. 222) found to be representative of the relationship between specific capacity and transmissibility in the southern Sacramento Valley. The ground-water gradient (I) and the lateral distance (L) were measured from water-level contour maps compiled by the California Division of Water Resources for the autumns of 1948 and 1952.

The results of computations are given in acre-feet as follows:

	1948	*1952*
Outflow from the area	46, 688	49, 898
Inflow to the area	−23, 096	−14, 220
Net ground water outflow	23, 592	35, 678

Irrigation pumpage.—Estimates of pumpage were made from unpublished data of the Pacific Gas & Electric Co. for the Fresno-Consolidated area. Compensation was made for districts that are only partly within the Fresno-Consolidated area. The pumpage estimate for the Fresno operating district (fig. 4, table 2) was reduced by the amount of pumpage in the James and Tranquillity Irrigation Districts. The pumpage estimate for the Selma operating district was reduced by

40 percent to conform with the number of wells in the Selma district that were within the boundaries of the Fresno-Consolidated area. The general method used by the Pacific Gas & Electric Co. to estimate pumpage is described on page 97.

Consumptive use of ground water in urban and suburban areas.—According to a crop survey in 1948, there were approximately 9,355 acres of water-using nonagricultural land in the Fresno-Consolidated area outside the city of Fresno. This area, composed mostly of homesites in suburban areas, had increased to approximately 11,845 acres by 1952. It is estimated by the authors that about 2 acre-feet per acre is pumped for domestic use and lawn irrigation in suburban areas, of which about 75 percent is consumed. For 1948 and 1952 the net consumptive use of ground water in the city of Fresno was estimated to be 17,000 acre-feet.[2]

	1948	*1952*
Suburban areas	14, 030	17, 770
City of Fresno	17, 000	17, 000
Total	31, 030	34, 770

RATES OF INFILTRATION

Unit rates of infiltration of applied water presented in table 29 have been computed for the Fresno-Consolidated area for 1952. The storage change estimated for 1952 by the specific-yield method (p. 100) agreed closely with that estimated by the inventory method. Accordingly, the figures for 1952 have been used to calculate unit percolation rates. Estimates of change in storage by the inventory and specific-yield methods in 1948 were too widely divergent to use in computations of unit rates of infiltration.

TABLE 29.—*Estimated recharge by infiltration of applied water in the Fresno-Consolidated area, 1952*

Unit	System losses	Infiltration (system losses less 5 percent waste)	Area irrigated (acres)	Unit rate of infiltration (acre-feet per acre)	Gross area (acres)	Average infiltration in gross area (acre-feet per acre)
	Acre-feet					
Fresno Irrigation District	670, 800	637, 300	201, 900	3.2	266, 000	2.4
Consolidated Irrigation District	536, 100	509, 300	140, 300	3.6	158, 000	3.2
Total or weighted average	1, 206, 900	1, 146, 600	342, 200	3.4	424, 000	2.7

KERN RIVER AREA

The Kern River area contains about 580,000 acres, or about 900 square miles (pl. 1). It encompasses roughly all the Kern River

[2] California Div. Water Resources, unpublished records.

storage unit in addition to most of the southern half of the White-Poso storage unit and includes all areas served by canals diverting from the Kern River and the intervening ground-water-service areas, as shown on plate 11.

The Kern River is the major source of surface water for the area and, for all practical purposes, can be considered the source of recharge to the ground-water reservoir. Poso Creek contributes some water by infiltration through its channel, but the amount is small compared to the supply from the Kern River. Replenishment occurs chiefly by losses from canals, by infiltration of irrigation water applied in excess of plant requirements, by infiltration from the channel of the Kern River, and by planned spreading of water for recharge. Water-level contours (Davis and others, 1959, pl. 15) indicate that recharge occurs also by subsurface inflow of ground water from the neighboring lands to the south and southeast of the unit, but presumably the quantity is small because of the generally low transmissibility of the sediments in those areas. Elsewhere along the borders of the area, the water-table gradient in 1952 was away from the Kern River area, showing that ground water was flowing out of the area in this part of its perimeter. Computations of net ground-water outflow, described on page 114 indicate that the excess of outflow over inflow in those years for which recharge and discharge were computed is as follows: in 1938, by 77,000 acre-feet; in 1942, by 78,000 acre-feet; and in 1952, by 42,000 acre-feet.

Most of the arable land in the Kern River area receives at least a partial water supply from canals that divert water from the river. Owing to extreme variations in the annual flow of the Kern River, however, this supply varies greatly from year to year. During years of very high runoff, the water supply generally is ample for the needs of all water users. Some water escapes from the area as surface outflow from Jerry Slough and Goose Lake bed northward to Tulare Lake bed. During years of deficient flow, however, few water users receive a full supply.

High runoff of the Kern River occurs in part in the winter, when rainfall on the lower reaches of the drainage basin causes high flows. Most of the runoff, however, is in the late spring and early summer, when melting snow in the high parts of the Sierra Nevada supplies most of the runoff. Thus, during periods of high flow in the river, recharge opportunities are at a peak—channel losses in the river are greatest, the canals and ditches operate at maximum capacity and infiltration from them is at a peak, and heavy application of water for irrigation results in greatly increased infiltration. Conversely, when the flow of the river is low, the recharge opportunities are at a minimum, and water users must rely largely upon ground water to supplement the surface supply. In the past, the natural variations in streamflow have resulted in reliance on ground-water storage as a form of regulation of the water supply. The operation of the reservoir was haphazard and unplanned, however, and resulted in heavy depletion of ground water in some parts of the area while other parts literally were wasting water. Exchange of water rights and storage of water at Isabella Reservoir (completed in 1954), together with substantial use of ground-water storage by the North Kern Water Storage District (Trowbridge, 1950) will tend to smooth out much of the irregularities in the water supply to the Kern River area.

Net changes in ground-water storage have been estimated for 3 years: for 1938 and 1952, to show the increase in ground-water storage during years of above-average runoff, and for 1942, to show the decrease in storage during a year of below-average runoff. For each period, the specific-yield method and inventory method described previously have been used as a check on the overall accuracy of the estimates. In comparing storage changes derived by use of the two methods, some error necessarily results because the periods for which certain types of data were available are not identical. This error, however, probably does not affect seriously the overall accuracy of the estimate. In the computations based on specific yield, changes in saturated volume were computed on a near calendar-year basis from lines of equal change of water levels based on December measurements in 1937 and 1938, 1941 and 1942, and 1951 and 1952. Similarly, estimates of consumptive use based on crop-survey data and effective precipitation were computed by calendar years. Information on stream diversions, however, was reported for the water year (October 1–September 30), and data on pumpage for irrigation, furnished by the Pacific Gas & Electric Co., were compiled for an agricultural year from April 1 to March 31.

ESTIMATES OF CHANGE IN STORAGE BY THE SPECIFIC-YIELD METHOD

Estimates of the volume of sediments dewatered and replenished in the periods cited above, were based on planimeter measurements of the water-level change maps (not shown). Change in ground-water storage was then computed by applying to the change in saturated volume an estimated specific-yield value for the depth zone within which the fluctuations occurred. Records of water levels in wells in the Kern River storage unit indicate that most of the changes involved in the estimates of change in storage occurred in the zone between 10 and 50 feet below the land surface. The weighted average specific yield for this depth zone is 12.7 percent (table 1). Most of the water-level changes in the White-Poso storage unit occurred in the zones between 50 and 200 feet below the land surface. The weighted average specific yield computed for this interval was 9 percent (Davis and others, 1959, table 6).

As indicated by the table below computations by the specific-yield method indicated increases in storage for 1938 and 1952 of 136,700 and 141,800 acre-feet, respectively, and for 1942 a decrease of 96,600 acre-feet.

The inventory approach to arriving at a value for change in ground-water storage consists of estimating the quantity of recharge from each source, differentiating between surface-water and ground-water sources, and estimating amounts of discharge.

Changes in ground-water storage in the Kern River area as computed by the specific-yield method

Unit	Acre-feet
1938	
Kern River	+72,013
White-Poso	+64,718
	+136,700
1942	
Kern River	−50,157
White-Poso	−46,425
	−96,600
1952	
Kern River	+112,734
White-Poso	+29,042
	+141,800

ESTIMATES OF CHANGE IN STORAGE BY THE INVENTORY METHOD

The general approach used in the inventory of recharge and discharge was similar to that used in determining storage changes in the Fresno-Consolidated area. The Kern River area was subdivided into convenient geographic units serviced by the several canal systems that divert water from the Kern River. The boundaries of the units follow closely those defined in a report on the North Kern Water Storage District by Trowbridge (1950, p. 58) and are shown on figure 32. The units are as follows:

1. North Kern Water Storage District.
2. South Side unit.
3. East Side unit.
4. West side unit; unit comprising the Pioneer and Beardsley-Rosedale units as defined by Trowbridge (1950) the Buena Vista Water Storage District and the lands between the Buena Vista Water Storage District and the Shafter-Wasco Irrigation District.
5. Shafter-Wasco Irrigation District.

In the inventory, total water supply was computed as the sum of surface-water diversions and pumpage for irrigation. Consumptive use of applied water was determined as the product of irrigated acreage and unit consumptive-use values. This consumptive use then was subtracted from the total water supply to obtain the nonconsumptive use or total system loss. Irrecoverable losses in the form of evaporation from open water surfaces and transpiration by noncrop vegetation were estimated arbitrarily to be 5 percent of the difference between supply and total consumptive use. The total nonconsumptive use, less the 5 percent difference between supply and total consumptive use, was assumed to represent ground-water return in the form of infiltration. For the Shafter-Wasco Irrigation District, which was supplied only with ground water, the estimate of infiltration was arrived at by deducting 15 percent of the total pumpage, following the State Water Resources Board's estimate of mean irrigation efficiency for the Kern area (1955, table 118). Recharge by seepage from Poso Creek and the Kern River were added to the estimates of infiltration to obtain total recharge. Discharge elements of the inventory include ground-water outflow and irrigation pumpage. The change in storage is the difference between recharge and discharge. The estimates of recharge and discharge elements for the years 1938, 1942 and 1952 are summarized in table 30.

TABLE 30.—*Inventory of recharge and discharge, in acre feet, for the Kern River area for 1938, 1942, and 1952*

	1938	1942	1952
Recharge elements:			
1. Seepage from streams:			
a. Poso Creek	27,000	11,500	52,000
b. Kern River above second point	52,000	48,800	75,500
c. Kern River below second point	23,200	44,000	32,000
Total seepage loss from streams	102,200	104,300	159,500
2. System losses:			
a. North Kern Water Storage District	116,700	24,500	102,500
b. South Side unit	76,000	30,300	486,900
c. East Side unit	7,900	3,400	12,900
d. West Side unit	177,100	73,200	464,600
e. Shafter-Wasco Irrigation District	13,600	15,400	25,800
Total system loss	391,300	146,800	1,092,800
Less 5 percent waste	19,600	7,300	54,600
Infiltration	371,700	139,500	1,038,200
Total recharge (infiltration plus stream seepage)	473,900	243,800	1,197,700
Discharge elements:			
1. Ground-water outflow	77,300	77,900	41,900
2. Irrigation pumpage	245,900	265,000	1,022,200
Total discharge	323,200	342,900	1,064,100
Change in storage (recharge minus discharge)	+150,700	−88,100	+133,600

COMPARISON OF ESTIMATES

Comparison of the estimates of change in ground-water storage by the specific-yield and inventory methods for the 3 years studied, shown in table 31 indicates close agreement of results.

The years selected for study spanned the widest range of conditions, including two periods of excessive streamflow and one of deficient flow. Moreover, the 2 years of excessive flow, 1938 and 1952, represented vastly different conditions because ground-water pumpage had increased more than fourfold in the interval. The close agreement under differing conditions indicates that the methods of estimating were at least consistent, if not precise, for the Kern River area as a whole. However, this conclusion does not necessarily apply to the geographic subdivisions used in the estimates.

TABLE 31.—*Comparison of changes in ground-water storage in the Kern River service area computed by the specific-yield and inventory method*

	1938	1942	1952
Specific-yield method acre-feet	+136, 700	−96, 600	+141, 800
Inventory method do	+150, 700	−99, 100	+133, 600
Mean of two methods do	+143, 700	−97, 850	+137 700
Mean deviation of the two methods do	7, 000	1, 250	4, 100
$\frac{\text{Mean deviation}}{\text{Total recharge (inventory method)}}$ percent	1. 5	0. 5	0. 3

COMPUTATIONS USED IN INVENTORY METHOD OF ESTIMATING CHANGE IN STORAGE

An explanation of the recharge and discharge elements used in the inventory and tables showing the figures used are presented below. Estimates of seepage from the Kern River and from Poso Creek were obtained from a report of the North Kern Water Storage District (Trowbridge, 1950) and from unpublished records in the files of the Kern County Land Co., the California Department of Water Resources, and the Buena Vista Water Storage District. Records of irrigation diversions were obtained from the North Kern Water Storage report (Trowbridge, 1950), from unpublished records in the files of the Kern County Land Co., and also from publications of the California Division of Water Resources (1951), and California Department of Water Resources (1958). Estimates of pumpage for irrigation were obtained from unpublished records of the Pacific Gas & Electric Co. in Fresno. Unit consumptive-use values for the various crops in the area were from Bulletin 2 of the California State Water Resources Board (1955), and crop acreages were obtained from unpublished records in the files of the Kern County Land Co. and published and unpublished records of the California Department of Water Resources.

RECHARGE ELEMENTS

Stream seepage.—According to tables presented by Trowbridge (1950, p. 56–57), in only about 25 percent of the 29 seasons from

1919–20 to 1947–48 did any flow of Poso Creek pass beyond the western boundary of the Kern River area. Trowbridge estimated that of the mean seasonal runoff of 18,500 feet for the period 1919–20 to 1947–48 an average of 13,700 acre-feet, or 74 percent of the flow was absorbed. This same ratio of absorption was used in this inventory for all years. Losses from Poso Creek shown in table 30 are estimated from the annual flow at the Mon Bluff gaging station of the Kern County Land Co., sec. 3, T. 28 S., R. 28 E.

Seepage reported from the Kern River is based upon discharge measurements at two stations along the stream, together with a knowledge of diversions in the area. Under the terms of the Miller-Haggin Agreement of 1888, which resulted from Lux vs. Haggin, a suit between the riparian owners and the upstream appropriators on the Kern River, virtually all the flow of the Kern River was divided, and two permanent stations were established for the measurement of discharge of the river. The so-called First Point of Measurement is in sec. 2, T. 29 S., R. 28 E., at a point on the river channel above the uppermost diversions of all appropriative irrigation rights party to the agreement. Except for one or two very small upstream diversions to riparian river-bottom land, the entire runoff of Kern River has been measured regularly at this station, commonly referred to as "First Point." The so-called Second Point of Measurement, selected as a permanent station for streamflow measurement, is about 20 miles downstream from "First Point." (See pl. 11*C*.) In table 30, stream seepage between First Point and Second Point is shown as "Kern River above Second Point." The estimates of seepage from the Kern River above Second Point were obtained from Trowbridge (1950, table XII) for 1938 and 1942 and from unpublished records of the Kern County Land Co. for 1952. The estimates for the reach below Second Point were obtained from unpublished records of the Buena Vista Water Storage District.

System losses.—System losses, so designated because they include all losses of water incidental to the delivery and application of irrigation water, are defined as the difference between the total water supply and consumptive use of applied water (table 32). The total supply consists of surface diversions and ground-water pumpage, as shown by table 33. Water reaching Second Point is diverted exclusively for use by the Buena Vista Water Storage District. The so-called First Point water rights, which include most of the flow of the Kern River not allocated to the Buena Vista Water Storage District, are allotted to the North Kern Water Storage District, the South Side unit, the East Side unit and the West Side unit.

TABLE 32.—*System losses in the Kern River service area, in acre-feet, 1938, 1942, and 1952*

	1938	1942	1952
1. North Kern Water Storage District:			
Total water supply	172, 900	94, 700	228, 200
Less consumptive use	56, 200	70, 200	125, 700
System loss	116, 700	24, 500	102, 500
2. South Side unit:			
Total water supply	274, 000	250, 800	682, 000
Less consumptive use	198, 000	220, 500	195, 100
System loss	76, 000	30, 300	486, 900
3. East Side unit:			
Total water supply	41, 000	46, 000	62, 500
Less consumptive use	33, 100	42, 600	49, 600
System loss	7, 900	3, 400	12, 900
4. West Side unit:			
Total water supply	326, 500	265, 200	671, 100
Less consumptive use	149, 400	192, 000	206, 500
System loss	177, 100	73, 200	464, 600
5. Shafter-Wasco Irrigation District:			
Total water supply	90, 600	102, 400	172, 000
Less consumptive use	77, 000	87, 000	146, 200
System loss	13, 600	15, 400	25, 800

TABLE 33.—*Water supply to the Kern River area, in acre-feet, 1938, 1942, and 1952*

Water supply and year	North Kern Water Storage District	South Side unit	East Side unit	West Side unit	Shafter-Wasco Irrigation District
1938					
Canal diversions	160, 000	216, 400	18, 316	264, 400	
Pumpage:					
Electric (85 percent)	11, 000	49, 000	19, 300	52, 800	77, 000
Engine (15 percent)	1, 900	8, 600	3, 400	9, 300	13, 590
Total supply	172, 900	274, 000	41, 016	326, 500	90, 590
1942					
Canal diversions	81, 600	182, 600	21, 440	208, 400	
Pumpage:					
Electric (85 percent)	11, 100	58, 000	20, 900	48, 300	87, 000
Engine (15 percent)	1, 960	10, 200	3, 690	8, 500	15, 350
Total supply	94, 660	250, 800	46, 030	265, 200	102, 350
1952					
Canal diversions	197, 600	248, 000	16, 900	331, 100	
Pumpage:					
Electric (85 percent)	26, 000	369, 000	38, 800	289, 000	146, 200
Engine (15 percent)	4, 600	65, 000	6, 800	51, 000	25, 800
Total supply	228, 200	682, 000	62, 500	671, 100	172, 000

The estimate of 5 percent deducted from the system loss in arriving at a figure for infiltration allows for evaporation from open-water surfaces and transpiration by noncrop vegetation. Although it is an arbitrary figure, the writers believe that it is of the right order of magnitude.

689-414—63——9

Unit consumptive-use values, shown in table 34, were taken from estimates by the California State Water Resources Board (1955, table 113) on the Kern River area. A correction was applied to these unit values to account for effective precipitation. The effective precipitation, that part of the total precipitation available for plant use, was computed by the method described by Blaney (1928, p. 154), in which 0.5 inch is deducted from the total precipitation of each storm to account for evaporation. The precipitation data was from the record of the U.S. Weather Bureau station at Bakersfield, Calif. The estimated consumptive use of applied water is summarized in table 35.

TABLE 34.—*Unit consumptive-use values (feet) used in the inventory of recharge and discharge in the Kern River area, 1938, 1942, and 1952*

[Effective precipitation at Bakersfield, in feet: *1938*, 0.3; *1942*, 0.0; *1952*, 0.2. Estimated by deducting 0.5 in. for evaporation from total precipitation for each storm as reported for Bakersfield, Calif., by the U.S. Weather Bureau]

	Unit consumptive use[1] (including precipitation)	Unit consumptive use (less effective precipitation)		
		1938	1942	1952
Alfalfa	3. 6	3. 3	3. 6	3. 4
Irrigated pasture	3. 6	3. 3	3. 6	3. 4
Deciduous orchard	2. 8	2. 5	2. 8	2. 6
Citrus	2. 8	2. 5	2. 8	2. 6
Vineyard	3. 0	2. 7	3. 0	2. 8
Cotton	2. 8	2. 5	2. 8	2. 6
Truck garden	1. 5	1. 2	1. 5	1. 3
Hay and grain	1. 3	1. 0	1. 3	1. 1
Miscellaneous field crops	2. 0	1. 7	2. 0	1. 8

[1] Data from Bull. 2, California State Water Resources Board (1955, table 113).

TABLE 35.—*Estimated consumptive use of applied water by irrigated crops in the Kern River area in 1938, 1942, and 1952*

Unit and year	Area irrigated[1] (acres)	Estimated weighted average[2] consumptive use (feet)	Total consumptive use (acre-feet)
1938			
North Kern Water Storage District	21, 600	2. 6	56, 200
South Side unit	68, 260	2. 9	198, 000
East Side unit	12, 100	2. 7	33, 100
West Side unit	65, 000	2. 3	149, 400
Shafter-Wasco Irrigation District			[3] 77, 000
1942			
North Kern Water Storage District	27, 000	[4] 2. 6	70, 200
South side unit	68, 900	[5] 3. 2	220, 500
East Side unit	14, 700	[6] 2. 9	42, 600
West Side unit	68, 733	[7] 2. 8	192, 100
Shafter-Wasco Irrigation District			[8] 87, 000

See footnotes at end of table.

TABLE 35.—*Estimated consumptive use of applied water by irrigated crops in the Kern River area in 1938, 1942, and 1952*—Continued

Unit and year	Area irrigated [1] (acres)	Estimated weighted average [2] consumptive use (feet)	Total consumptive use (acre-feet)
1952			
North Kern Water Storage District	50, 251	[9] 2. 5	125, 628
South Side unit	67, 259	[10] 2. 9	195, 051
East Side unit	18, 360	[11] 2. 7	49, 572
West Side unit	71, 222	[12] 2. 9	206, 548
Shafter-Wasco Irrigation District			[13] 146, 200

[1] From Trowbridge (1950) and California Division of Water Resources (1943 and 1951).
[2] Consumptive-use values from table 34 applied to unpublished crop-survey data in files of California Department of Water Resources.
[3] Based on irrigation efficiency of 85 percent applied to total supply of 90,590 acre-feet.
[4] No crop survey made in 1942; therefore crop pattern of 1944 was used to compute weighted average.
[5] No crop survey made in 1942; therefore crop pattern of 1938 was used to compute weighted average.
[6] No crop survey made in 1942; therefore crop pattern of 1946 was used to compute weighted average.
[7] No crop surveys made in Beardsley-Rosedale and Pioneer units in 1942; therefore crop pattern of 1938 was used to compute weighted average in those areas. Buena Vista Water Storage District was as reported by California Div. Water Resources Bull. 21-N (1943).
[8] Based on irrigation efficiency of 85 percent applied to total supply of 102,000 acre-ft.
[9] No crop survey made in 1952; therefore crop pattern of 1948 was used to compute weighted average.
[10] No crop survey made in 1952; therefore crop pattern of 1947 was used to compute weighted average.
[11] No crop survey made in 1952; therefore crop pattern of 1947 was used to compute weighted average.
[12] No crop surveys made in Beardsley-Rosedale and Pioneer units in 1952; therefore unpublished data of the Buena Vista Water Storage District and crop pattern of 1947 were used to compute weighted average in those areas.
[13] Based on irrigation efficiency of 85 percent applied to total supply of 172,000 acre-ft.

DISCHARGE ELEMENTS

Net ground-water outflow.—The net ground-water outflow from the Kern River area was computed as the difference between outflow and inflow, as computed for segments of the perimeter of the area. The following equation was used in the computation:

$$Q=TIL$$

in which Q is the quantity of water flowing across the perimeter of the area; T is the transmissibility of the deposits; I is the hydraulic gradient; and L, the length of the perimeter.

The coefficient of transmissibility was estimated from average values of specific capacity (table 3), multiplied by an empirical factor of 1,700, which Thomasson and others (1960, p. 222) found was representative of the relationship between specific capacity of wells and transmissibility in the southern Sacramento Valley. The hydraulic gradient, I, and the lateral distance, L, were measured for several segments of the perimeter of the Kern River area in which substantial ground-water movement was indicated on water-level contour maps for fall 1938, 1942, and 1952 compiled by the California Division of Water Resources.

The results of computations are given in acre-feet as follows:

	1938	*1942*	*1952*
Outflow from the area	86, 471	77, 906	91, 572
Inflow to the area	−9, 167	None	−49, 689
Net ground-water outflow (rounded)	77, 000	78, 000	42, 000

Irrigation pumpage.—Estimates of pumpage were modified slightly from unpublished data of the Pacific Gas & Electric Co. to agree with the boundaries of units in the inventory. The general method used by the company in these pumpage computations was as follows: (1) For each township within a unit, an average figure for kilowatt-hours per acre-foot is determined from pump-efficiency tests, (2) this figure is multipled by the number of pumps in the township, (3) the products thus obtained are totaled and divided by the numbers of pumps in the unit, giving a weighted average kilowatthour per acre-foot figure for the unit, (4) the total kilowatthours consumed in the unit is divided by the weighted average kilowatthour per acre-foot figure to obtain the total pumpage in acre-feet.

RATES OF INFILTRATION

Table 36 shows infiltration rates in the Kern River area for the 1938, 1942, and 1952 irrigation seasons. Recharge as system losses

TABLE 36.—*Estimated recharge by infiltration in the Kern River area, 1938, 1942, and 1952*

Unit and year	System losses Acre-feet	Infiltration (system losses less 5 percent waste)	Area irrigated (acres)	Infiltration in area irrigated (acre-feet per acre)	Gross area (acres)	Average infiltration in gross area (acre-feet per acre)
1938						
North Kern Water Storage District	116, 700	110, 900	21, 600	5. 1	61, 850	1. 8
South Side unit	76, 000	72, 200	68, 260	1. 1	100, 150	. 7
East Side unit	7, 900	7, 300	12, 100	. 7	18, 000	. 4
West Side unit	177, 100	168, 200	65, 000	2. 6	358, 000	. 5
Shafter-Wasco Irrigation District	13, 600	12, 900	30, 380	. 4	42, 000	. 3
Total or weighted average	391, 300	371, 500	197, 340	1. 9	580, 000	. 6
1942						
North Kern Water Storage District	24, 500	23, 300	27, 000	. 9	61, 850	. 4
South Side unit	30, 300	28, 800	68, 900	. 4	100, 150	. 3
East Side unit	3, 400	3, 200	14, 700	. 2	18, 000	. 2
West Side unit	73, 200	69, 500	68, 730	1. 0	358, 000	. 2
Shafter-Wasco Irrigation District	15, 400	14, 600	29, 000	. 5	42, 000	. 3
Total or weighted average	146, 800	139, 400	208, 330	. 7	580, 000	. 2
1952						
North Kern Water Storage District	102, 500	97, 400	50, 250	1. 9	61, 850	1. 6
South Side unit	486, 900	462, 600	67, 260	6. 9	100, 150	4. 6
East Side unit	12, 900	12, 300	18, 360	. 7	18, 000	. 7
West Side unit	464, 600	441, 400	71, 220	6. 2	358, 000	1. 2
Shafter-Wasco Irrigation District	25, 800	24, 500	33, 400	. 7	42, 000	. 6
Total or weighted average	1, 090, 800	1, 038, 200	240, 490	4. 3	580, 000	1. 8

occurs not only through application of water in excess of crop needs, but also by seepage from canals. However, it has not been possible in this study to differentiate the proportions contributed by each source; hence, table 36 gives rates of infiltration that may exceed the amount of water applied as irrigation. The figures are useful, however, in assessing the total amount of infiltration in relation to irrigated and to gross acreage.

The unit values for seasonal infiltration by units range from a fraction of an acre-foot per acre to several acre-feet per acre. This wide range in values is indicative of the wide range in physical and economic conditions that govern the use of water in the Kern River area. Furthermore, the great differences in unit rates in several areas in 1938 and 1952 reflect major changes in the routing and distribution of water from the Kern River as described by Trowbridge (1950); however, a discussion of these features is beyond the scope of this report.

CONCLUSIONS

In general, it can be stated on the basis of hydrologic and geologic conditions that most of the ground-water storage capacity of the San Joaquin Valley as estimated on table 1 is usable. Locally, water of poor quality at shallow depth might actually prevent utilization of the areas indicated on plate 2 for ground-water storage, but even these areas might be made usable by flushing if the need was great enough. Soils and subsurface deposits of low permeability undoubtedly would affect the economic feasibility of utilization of the ground-water reservoirs, but in none of the 16 storage units of table 1 are such deposits so extensive as to prevent utilization of any of the units for storage.

Dewatering of the ground-water reservoirs at an average rate on the order of 20 feet a year during a 10-year period of deficient supply appears to be feasible. In fact, the pumping capacity of existing facilities probably could accomplish this amount of dewatering in most of the storage units (p. 42).

Replenishment of ground-water storage during a period of surplus water supply would involve greater economic and physical problems than the dewatering. The chief physical problems are the areas where recharge can be accomplished most effectively, the methods best suited to place the water underground, and the rates at which water can be placed in storage.

The most favorable areas for recharge, those where both surface and subsurface deposits are relatively permeable, have been delineated on plates 3, 4, and 5.

The methods of recharge considered practical include excess application of water for irrigation, seepage from stream channels and canals, spreading of water in artificial ponds, and injection of water through wells.

The analyses of changes in ground-water storage in the Madera Canal service area, the Fresno-Consolidated area, and the Kern River area show that very large volumes of water infiltrate to the ground-water reservoir in years of surplus supply even under the existing regimen in which recharge is chiefly incidental. Therefore, it is reasonable to assume that a similar combination of recharge by excess irrigation water combined with seepage from stream channels and canals would be equally effective in other parts of the valley in replenishing depleted ground-water reservoirs. Much recharge could be accomplished by the relatively simple expedient of providing excess supplies of water to water-distribution agencies. Incidental recharge thus could be augmented by planned spreading on cultivated land or in specially constructed ponds. For such an operation to proceed smoothly, temporary detention reservoirs would be required to retain heavy flows until the water could be distributed effectively.

The rates at which water can be placed in storage are critical in determining the economic feasibility of a ground-water storage operation. Runoff commonly occurs too quickly or at the wrong season to fit into an irrigation schedule. Therefore, if the water is to be conserved, it is necessary to provide temporary surface storage or to place it underground as quickly as it becomes available. A conjunctive operation of surface- and ground-water storage should provide the answer to most of the problems. Thus, heavy flows could be stored temporarily and the water released as quickly as it could be absorbed in the service areas. Stream channels and canals probably could serve as the major spreading areas in most of the valley, but spreading basins would be needed in sufficient capacity to handle any flows that could not be disposed of in the stream channels and canals.

Quantitative data cited in this report indicate that incidental recharge in typical areas irrigated by surface water is on the order of 3 to 5 feet of water per season in years of excess supply. It should be possible to achieve substantially greater rates by deliberate efforts. Measurements made in canals and ditches indicated infiltration of ½ to 3 feet per day in typical alluvial soils of the valley under normal operation conditions. Measurements under ponded conditions indicated initial infiltration rates of 2 to 4 feet per day on typical alluvial soils, but the rate diminished rapidly to a stable rate of less than a half a foot per day in most tests. The foregoing figures are not intended to be firm estimates, but presented merely to give the order of magnitude of infiltration under differing methods of water spreading.

Although injection of water through wells has proved successful in recharging with air-conditioning water, it is unlikely that wells could be utilized economically to dispose of surface flow in large quantities because of the high cost of desilting the water to prevent clogging of recharge wells. As shown by measurements of flow in wells (p. 81), they can be highly effective as an instrument of recharge in transmitting water through impermeable confining beds to depleted artesian aquifers.

To summarize: (1) Extensive use of ground-water storage in the San Joaquin Valley seems feasible relative to geologic and hydrologic conditions, and (2) present utilization of ground-water storage that has come about without deliberate planning indicates that it is economically feasible in many areas. However, more basic information is needed on the subject of rates of infiltration, geologic controls, and ground-water movement before firm estimates can be made of the usable ground-water storage capacity of the San Joaquin Valley.

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INDEX

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