

# Water Resources of Lower Colorado River- Salton Sea Area as of 1971, Summary Report

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 486-A





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*By* C. C. MCDONALD *and* O. J. LOELTZ

WATER RESOURCES OF LOWER COLORADO RIVER-SALTON SEA AREA

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## CONVERSION FACTORS

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[Factors for converting the English units used in this report to metric units are listed below]

Acres .....	$4.047 \times 10^{-3}$	Square kilometres (km <sup>2</sup> ).
Acre-feet (acre-ft) .....	$1.233 \times 10^{-3}$	Cubic hectometres (hm <sup>3</sup> ).
Acre-feet per year (acre-ft/yr) .....	$1.233 \times 10^3$	Cubic metres per year (m <sup>3</sup> /yr).
Cubic feet per second (ft <sup>3</sup> /s) .....	$2.832 \times 10^{-2}$	Cubic metres per second (m <sup>3</sup> /s).
Feet (ft) .....	$3.048 \times 10^{-1}$	Metres (m).
Feet per mile (ft/mi) .....	$1.894 \times 10^{-1}$	Metres per kilometre (m/km).
Gallons per day per foot [(gal/d)/ft] .....	12.42	Litres per day per metre [(l/d)/m].
Gallons per day per square foot [(gal/d)/ft <sup>2</sup> ] .....	40.75	Litres per day per square metre [(l/d)/m <sup>2</sup> ].
Gallons per minute (gal/min) .....	$6.308 \times 10^{-2}$	Litres per second (l/s).
Gallons per minute per foot [(gal/min)/ft] .....	$2.070 \times 10^{-1}$	Litres per second per metre [(l/s)/m].
Inches (in.) .....	$2.54 \times 10^{-2}$	Metres (m).
Miles (mi) .....	1.609	Kilometres (km).
Square feet (ft <sup>2</sup> ) .....	$9.290 \times 10^{-2}$	Square metres (m <sup>2</sup> ).

# WATER RESOURCES OF LOWER COLORADO RIVER—SALTON SEA AREA, SUMMARY REPORT AS OF 1971

By C. C. McDONALD and O. J. LOELTZ

## ABSTRACT

Distribution of the available supply of Colorado River water in an equitable manner to all parties dependent on that water will always pose problems. In recent years, a regional approach is being taken in seeking a solution to these problems.

Unless the ever-increasing demands on Colorado River water are curtailed, the demands will exceed the dependable supply before the end of the 20th century. The net supply of Colorado River water below Davis Dam for normal runoff conditions is estimated at 10.2 million acre-feet for 1975 and 8.4 million acre-feet for the year 2030. For dry conditions, the corresponding supplies are 8.2 million and 6.4 million acre-feet, respectively. The present basic allotment to Arizona, California, and Mexico is 8.7 million acre-feet per year, to which is added conveyance and storage losses averaging 900,000 acre-feet per year, making the total 9.6 million acre-feet of water per year. The supply probably will be adequate during periods of near-normal runoff until about 1980.

The river, either directly or indirectly, is the principal source of the ground-water supply. Large yields commonly are obtainable from wells that tap coarse Colorado River deposits. Evaporation from the river and from reservoirs consumes more than 1 million acre-feet of water per year. Riparian vegetation consumes more than 500,000 acre-feet of water per year. About 1.3 million acre-feet per year drains to the Salton Sea, where it evaporates. Normal annual evaporation from the sea is 69 inches.

Dissolved-solids concentration of the river water increases with distance downstream and with time. For 1951-55 the dissolved-solids concentration below Hoover Dam averaged 658 milligrams per litre, and at Imperial Dam, 706 milligrams per litre. For 1961-65 the concentration was 714 and 824 milligrams per litre, respectively.

The earth materials of the lower Colorado River-Salton Sea area comprise a basement complex of pre-Tertiary crystalline rocks, an overlying sequence of slightly to moderately deformed sedimentary and volcanic rocks of Tertiary age, and the virtually undeformed alluvial and windblown deposits of late Tertiary and Quaternary age, which were deposited after the Colorado River entered the area.

The alluvial deposits constitute the upper principal part of the ground-water reservoir. Beds of coarse sand and gravel, deposited chiefly by the Colorado River, yield copious quantities of water to irrigation and other large wells. Ground water in the valleys is derived almost wholly from the Colorado River, except in the Yuma area where a significant part was derived from the Gila River.

Sulfate reduction appears to be a major process in the chemical alteration of river water to ground water that contains fewer dissolved solids than river water. Fresh water (less than 1,800 mg/l dissolved solids) extends to depth of more than 2,500 feet in the south-central and southwestern parts of the Yuma area. Beneath most areas in central Imperial Valley, ground water

contains sufficient dissolved solids to make it unsatisfactory as a domestic or an irrigation supply.

Westward movement of ground water to Mexico in 1960-63 was about 33,000 acre-feet per year; southward movement east of the river was about 35,000 acre-feet per year. A large part of the leakage from the All-American Canal in the 37-mile reach west of Pilot Knob, estimated at 150,000 acre-feet annually in 1961-63, moves southward across the international boundary to Mexicali Valley.

Pumpage from drainage wells, sumps, and drains adjacent to Yuma Mesa increased from about 70,000 acre-feet in 1960 to 146,000 acre-feet in 1969. This increased drainage added to the problem of satisfactorily disposing of 200,000 acre-feet per year of moderately saline (4,000-6,000 mg/l) pumped return flow from the Wellton-Mohawk area.

## INTRODUCTION

The annual flow of the lower Colorado River of about 9 million acre-feet is vital to the economic well-being of millions of people in Arizona, California, Nevada, and northern Mexico. The river furnishes four-fifths of the water that has changed much of southern California from a barren desert to one of the most productive agricultural areas and to the largest and fastest growing industrial and municipal area in the United States. More than half a million acres in Imperial and Coachella Valleys alone is irrigated with Colorado River water. Billions of kilowatt-hours a year of electricity is generated with Colorado River water. Millions of people in more than 100 cities in southern California receive Colorado River water through the Colorado River aqueduct, which heads at Parker Dam on the main stem of the river 250 miles to the east. The river also is virtually the sole source of water for the arid lands of western Arizona. Several hundred thousand acres in Arizona and California along the main stem of the river is irrigated with river water. The arid region of southern Nevada is dependent on the river for water that will be needed for further substantial development of that part of the State. Mexico, too, depends heavily on the Colorado River for a large irrigation development in the Mexicali Valley of Baja California and Sonora, Mexico.

In recognizing that the extensive uses of Colorado River water and the increasing demands for water might cause the total demands to exceed the available supply, the U.S. Geological Survey was prompted in 1960 to undertake a comprehensive study of the water resources of the lower Colorado River-Salton Sea area. The study, known as the lower Colorado River project, was similar to an earlier investigation made by the U.S. Geological Survey of the water resources of the upper Colorado River (Iorns and others, 1965). A summary of the lower Colorado River project and of the resulting findings is the subject of the present report.

The lower Colorado River Project includes most of the areas for which the lower Colorado River is the principal source of water supply. As defined by drainage boundaries, the project area consists of the Salton Sea drainage basin and the natural drainage basin of the Colorado River below Davis Dam, Ariz.-Nev., excluding the Bill Williams River basin above the gaging station near Alamo, Ariz., and the Gila River basin above the Wellton-Mohawk Irrigation and Drainage District. To facilitate the investigations and the reporting thereon, the project area was divided into subareas, the principal ones of which are designated the Needles area, the Parker-Blythe-Cibola area, the Yuma area, and the Imperial Valley area.

Limited studies of areas in Mexico were made in collaboration with the Mexican Government only insofar as necessary to delineate the hydrologic problems and the relations of the various components affecting the water resources near the international boundary. The relation of the project area to the entire Colorado River basin is shown in figure 1. The major features of the Colorado River system and the principal places of use of Colorado River water in the project area are shown in figures 2-4.

### DEMANDS FOR WATER, ACCOMPANYING PROBLEMS, AND RESULTING LEGISLATION

Because most of the project area is arid to semiarid, attempts to divert river water for agriculture date back to the earliest settlement. However, the wide annual fluctuations of river stage, discharge, and silt load carried by the river caused most early attempts to divert water to be short-lived, and all diversion works were expensive to maintain and were only partly satisfactory.

California led the States of the lower basin in the early and expanding use of Colorado River water.

However, this early development of the river water and plans for further development did not go unnoticed by the other States of the Colorado River basin. Consequently, by agreement among the States, in what is known as the Colorado River Compact of 1922, the water of the Colorado River was apportioned between the upper basin States (Colorado, New Mexico, Utah, and Wyoming) and the lower basin States (Arizona, California, and Nevada) on the basis that each group was to have the exclusive beneficial consumptive use of 7.5 million acre-feet of water per year.

Six years later, in 1928, Congress adopted the Boulder Canyon Project Act authorizing construction of Hoover Dam and powerplant and of the All-American Canal to Imperial and Coachella Valleys. Demands for river water increased rapidly with the building of Hoover Dam and other main-stream dams which controlled the annual floods, thereby permitting orderly and reliable diversions.

The rapid development of uses of Colorado River water in the United States caused concern in Mexico about the continued availability of Colorado River water for irrigation in Mexico. About 1940 Mexico began negotiations with the United States leading to a recognition of Mexican rights to water from the Colorado River and the Rio Grande. As a result of these negotiations, the Rio Grande, Colorado, and Tijuana Treaty was signed in 1944 and ratified in 1945. Under terms of the treaty Mexico is guaranteed 1.5 million acre-feet of Colorado River water annually. The treaty guarantee is a first lien on the flow of the river and therefore limits the availability of water in the United States for meeting growing demands.

Although the Boulder Canyon Project Act of 1928 authorized a compact to divide the lower basin's share of the Colorado River water among Arizona, California and Nevada, the States were not able to agree as to their respective shares. Finally, in 1952 Arizona filed a suit in the Supreme Court of the United States (known familiarly as *Arizona v. California et al*) seeking to establish its right to river water. The Supreme Court, on March 9, 1964, decreed that of the first 7.5 million acre-feet per year available in the main stream for use in the three lower basin States, Arizona was to receive 2.8 million acre-feet; California, 4.4 million acre-feet; and Nevada, 300,000 acre-feet; and that any flow available for such use in excess of 7.5 million acre-feet was to be divided equally between Arizona and California, except that Nevada was entitled to 4 percent of the excess, which was to come from Arizona's share. The apportionment of flows in years when such flows would be less than 7.5 million acre-feet is to be determined by the Secretary of the Interior in



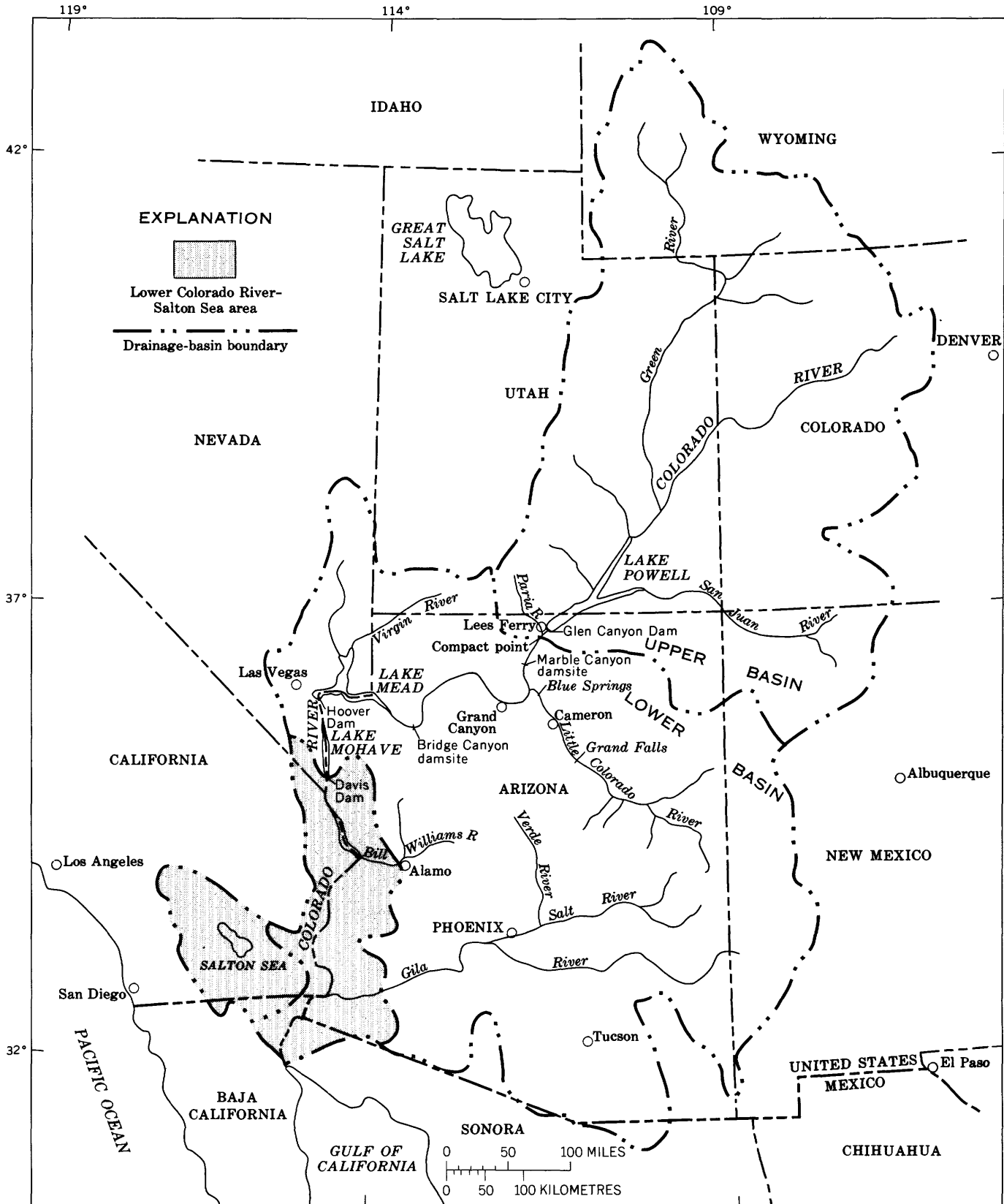


FIGURE 1.—Index map of the Colorado River and Salton Sea drainage basins, showing the project area.

WATER RESOURCES OF LOWER COLORADO RIVER—SALTON SEA AREA

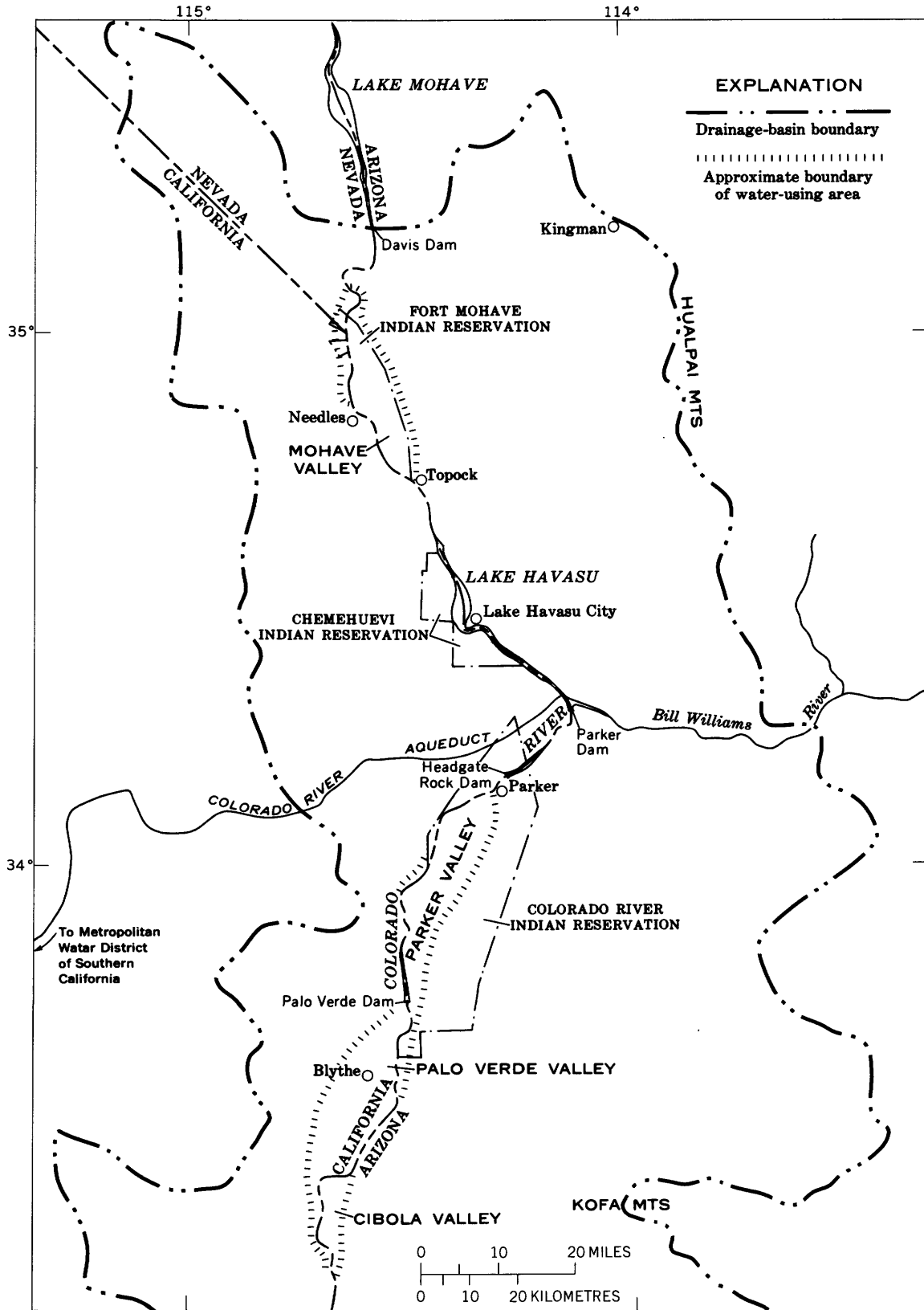


FIGURE 2.—Principal features of the Colorado River system and areas of water use between Davis Dam and the south end of Cibola Valley.

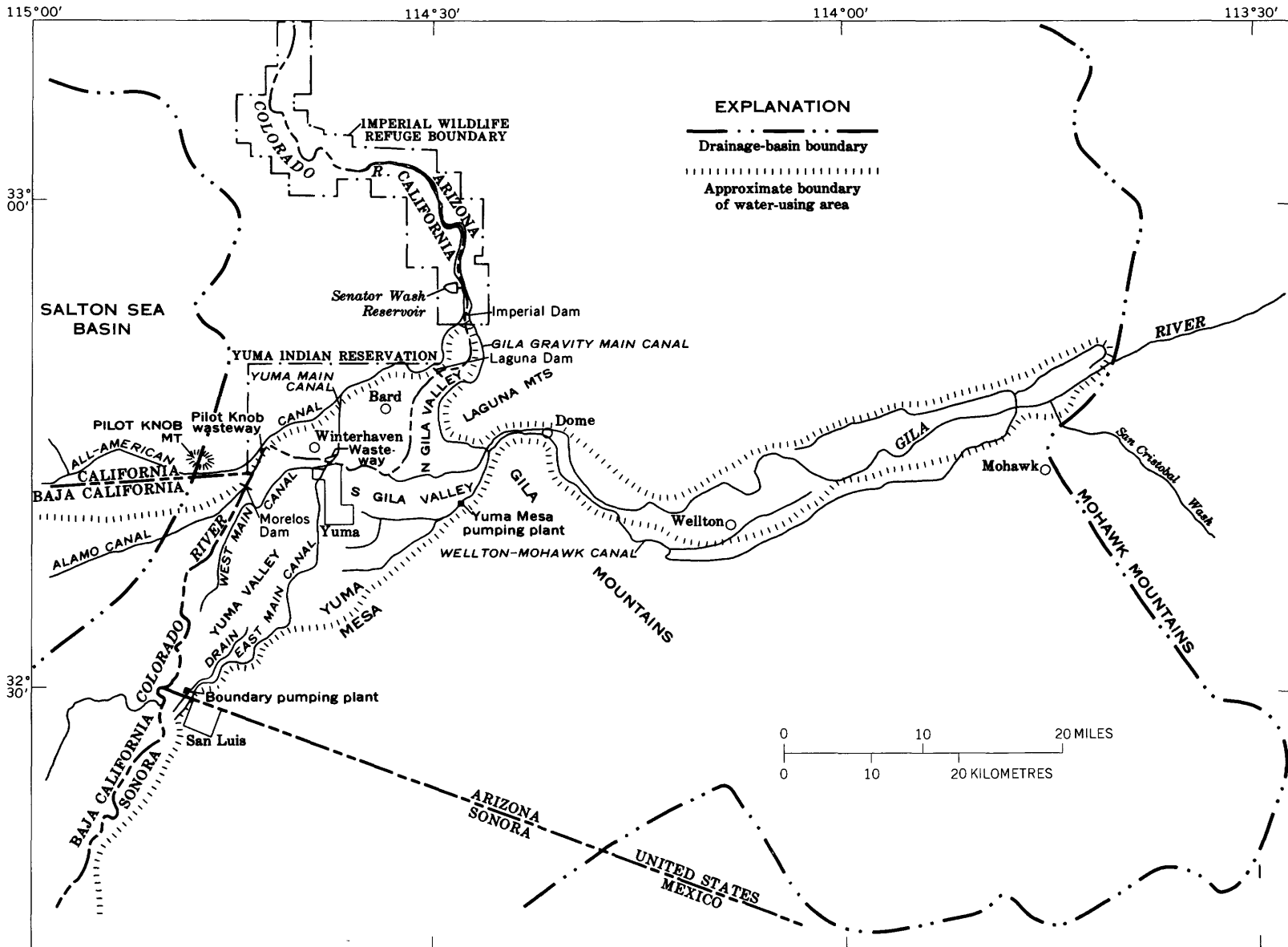


FIGURE 3.—Principal features of the Colorado River system and areas of water use below Cibola Valley.

accordance with broad outlines set forth in the Decree and in the Colorado River Basin Project Act (Public Law 90-537, September 30, 1968). (See p. A33 for major features of the act).

Of principal concern to California and Arizona is the apparent inadequacy of the Colorado River to meet their growing demands for water. On the basis of the projects completed and those authorized there is little doubt among the lower basin States that the water

supply of the lower Colorado River system is overcommitted.

In addition to the problem of an inadequate supply, there are also problems of conflicts of interest concerning utilization of the available supply. Demands for water include not only municipal, irrigation, and electrical-power-generation demands, but also, in recent years, a mushrooming recreational demand. Conflicts of interest among these diverse

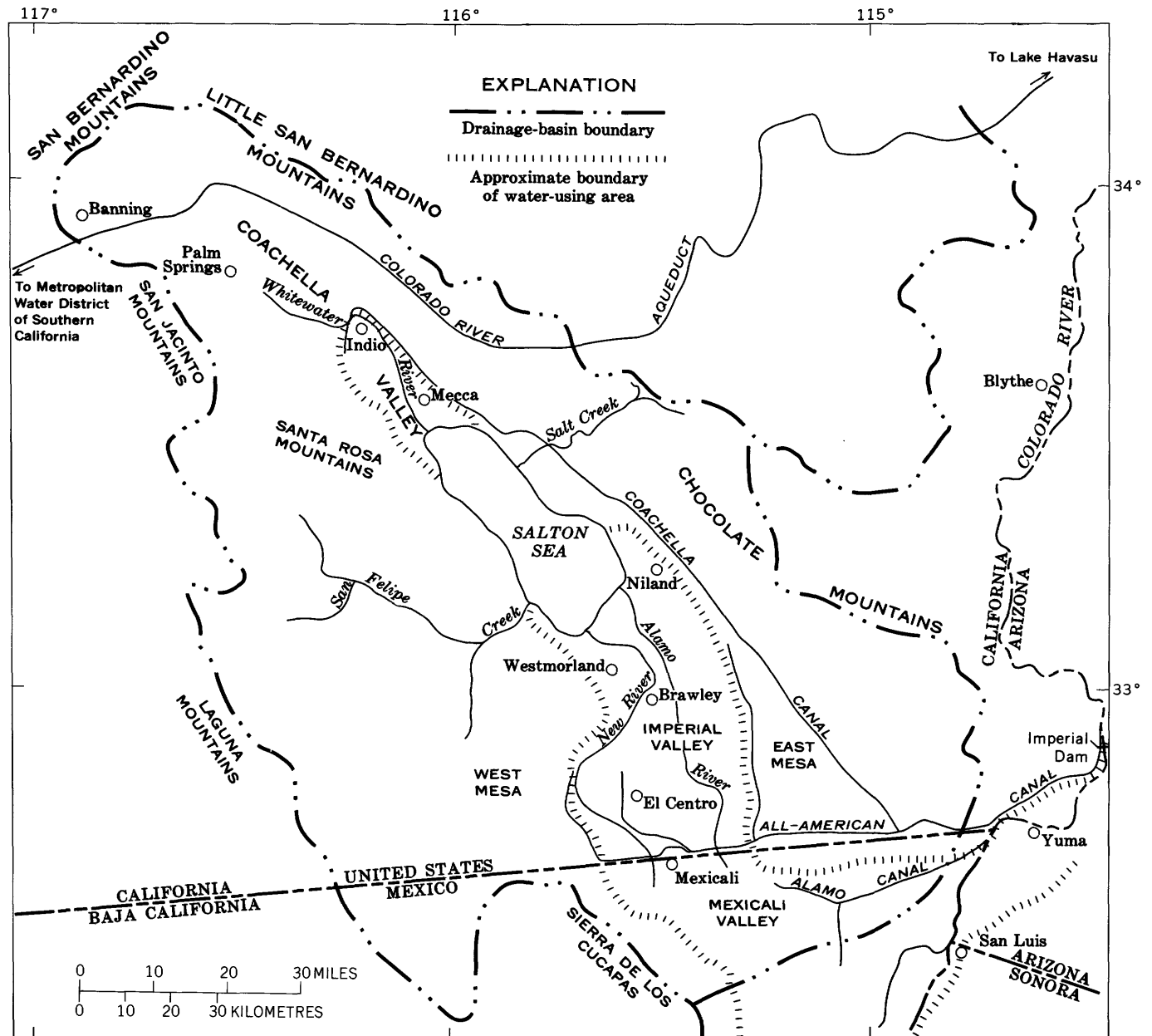


FIGURE 4.—Principal features of the Colorado River distribution system and areas of water use in the Salton Sea basin.

demands are almost inevitable. River management, a responsibility of the U.S. Bureau of Reclamation, therefore becomes increasingly difficult.

In addition to problems of water quantity are the problems of water quality. Of particular concern to the irrigation communities is the salinity of the water. In the lower Colorado River, salinity has already reached sufficient concentration that a substantial part of the irrigation water must be used to wash excess concentrations of salt from the root zones of crops. As more water is used consumptively in the upper basin

States, the concentration of salts in the remaining water available to the lower reaches will increase. The rate at which the chemical quality will deteriorate and the effect of such deterioration on the economy of the lower basin States is of great concern to them.

Deteriorating water quality also has created international concern. A problem of this nature arose in 1962 when about 300 ft<sup>3</sup>/s of saline ground water pumped from drainage wells was discharged into the Gila River near its confluence with the Colorado River. The Mexican Government and water users in

the United States downstream from the points where the water entered the Colorado River protested the action. As a result of negotiations with Mexico, the United States agreed to construct a bypass conveyance channel that would permit any part or all of the saline drainage water to be discharged into the Colorado River below Morelos Dam, the point of diversion for most of the water delivered to Mexico. This arrangement was recognized as only a temporary solution to the problem. The Minute under which the operation was conducted was to be in effect for a period of 5 years following the date of completion and placing in operation of the conveyance channel, which occurred on November 16, 1965. In November 1970 and 1971 the Minute was extended for an additional year while both parties continued working for a permanent and effective solution.

### PURPOSE AND SCOPE

The general purpose of the lower Colorado River project study was to determine the quantity and extent of the various components of the total water resources of the lower basin and the relations among the various components in order to provide a better basis for the efficient and satisfactory management of the available water.

The study consisted of an evaluation of the quantity and quality of surface- and ground-water resources and their interrelations, the quantities available from the several sources, and a determination of the present disposition of those resources. Geologic and hydrologic phases of the study included determinations of: The location, extent, and hydraulic characteristics of aquifers; the sources, rates, and areas of recharge; the rates and areas of discharge; the relation of ground-water to surface-water supplies; and the magnitude and direction of ground-water movement within the principal ground-water reservoirs.

Measures were taken to obtain a better definition of the distribution and use of surface water, principally by improving stream-measuring facilities, but also by the addition or relocation of gaging stations on streams, canals, and drains. Water use by several species of vegetation for which few or no data were available from previous studies was determined experimentally by measuring rates of use by these species when grown in tanks whose tops were set flush with the land surface in a natural environment.

The rate of evaporation from free water surfaces, notably from the Salton Sea, the regimen of the Salton Sea, and the effects of future water use in the Salton Sea basin were studied.

Chemical quality studies included ground-water and surface-water supplies, and a regional appraisal of the character of the total water resources. Salt-balance determinations' being made by irrigation districts when the investigation began, were supplemented, and some were made for other areas where needed.

### PROJECT HISTORY

The lower Colorado River project was started July 1, 1960, with its headquarters in Yuma, Ariz. During the first year ground-water studies in the Yuma, Imperial and Coachella Valleys, and Parker-Blythe-Cibola areas were begun. Also begun were the studies pertaining to the surface-water supply of the project area and the studies for determining evaporation from the Salton Sea, consumptive use rates by phreatophytes, and chemical quality of both surface- and ground-water supplies.

Progress reports on these studies were presented at public meetings held in December 1961, March 1963, and May 1964 at Yuma, Ariz.

In 1962 fieldwork pertaining to the study of evaporation from the Salton Sea was completed, and ground-water studies in the Coachella Valley were suspended pending the completion of a report on the water supply of that area by the California Department of Water Resources.

By mid-1964 the first of two electric analog models of the Yuma area was being built in the Phoenix hydrologic laboratory of the U.S. Geological Survey. Also, gravity, aerial magnetometer, Earth resistivity, and seismic surveys were being used to supplement the test drilling and other geologic investigations.

In 1966—because of newly acquired evidence regarding the hydrologic significance of the Algodones fault—additional investigations in the Yuma area were undertaken. The additional studies, which lasted more than a year, were needed to determine the location and extent of the fault and its effect on the movement and chemical quality of the ground water. Geophysical exploration and test drilling, in cooperation with the U.S. Bureau of Reclamation, disclosed that this northwest-trending fault was a significant barrier to the movement of ground water. Incorporating the barrier effect of the fault into a second, more sophisticated electric analog model of the Yuma area made possible the satisfactory simulation of historical changes in water level in the Yuma area. The project studies in the Yuma area were supplemented by studies made at the request of and for the U.S. Section of the International Boundary and Water Commission. These later studies were concerned with determining rates and directions of

ground-water movement across segments of the international boundary under natural conditions and at various times during the development of ground-water and surface-water supplies both in Mexico and in the United States.

### ACKNOWLEDGMENTS

Many agencies, groups, and individuals furnished records and cooperated with the U.S. Geological Survey during the project studies. Appropriate acknowledgment and appreciation of this help are given in each of the separate reports on the project. In this summary report, except for the few individual acknowledgments which follow, only a general acknowledgment is made.

The U.S. Bureau of Reclamation, Yuma project office, furnished information from its files, did some exploratory drilling, financed a reflection seismic survey, contributed financially toward the construction of an electric analog model of the Yuma area, and, in addition, maintained a close working relationship with the Survey throughout the investigation. Both the U.S. Section and the Mexican Section of the International Boundary and Water Commission provided valuable data from their files. The U.S. Section also provided financial assistance toward construction of the analog model.

The cooperation of the Colorado River Indian Agency, the Upper Colorado River Commission, several private consultants, and the various irrigation districts in making available needed data from their files is gratefully acknowledged. Appreciation is also extended to the many well drillers who had drilled, or were drilling, wells in the project area for making available their logs of wells and the results of well-completion tests. Acknowledgment and appreciation are given to the many farmers and other landowners for generously permitting access to their lands and wells, for furnishing data on their wells and farming practices, and for their cooperation in the scheduling of aquifer tests. Special credit and thanks are extended to Messrs. F. H. Olmsted and D. G. Metzger for providing much of the material presented in the section on geology and the related maps.

### SUMMARY OF RESULTS

The following summary of the results of the project studies is based mainly on project reports, published as Professional Paper 486, chapters B-K, the titles of which are—

B. "Precipitation, Runoff, and Water Loss in the Lower Colorado River-Salton Sea Area"

- C. "Hydrologic Regimen of Salton Sea, California"
- D. "Lower Colorado River Water Supply—Its Magnitude and Distribution"
- E. "Salinity of Surface Water in the Lower Colorado River-Salton Sea Area"
- F. "Consumptive Use of Water by Phreatophytes and Hydrophytes near Yuma, Arizona"
- G. "Geohydrology of the Yuma Area, Arizona and California"
- H. "Geohydrology of the Parker-Blythe-Cibola Area, Arizona and California"
- I. "Analog Simulation of the Yuma, Arizona, ground-water system"
- J. "Geohydrology of the Needles area, Arizona, California, and Nevada"
- K. "Geohydrologic reconnaissance of the Imperial Valley, California"

The chapters deal with separate subjects or areas in a comprehensive manner, and the reader is referred to them for more specific and detailed information. In a few instances, data used in this summary report post-date the periods covered by the project reports in order to make this summary more current.

### MAGNITUDE AND DISTRIBUTION OF THE WATER SUPPLY

The water supply of the Colorado River system above compact point probably can be sustained at 13 million acre-feet per year over long periods of time and at 14 million acre-feet per year for most years. This supply is available for depletions above compact point and for release to the lower basin States and Mexico. The division of this gross supply between the upper and lower service areas depends in part on the existence of facilities to enable use of the water in the upper service area and on provisions of the Colorado River Compact. The actual flow at compact point probably will exceed compact requirements most of the time until the upper service area's man-caused depletion of water supplies reaches 5 million acre-feet annually—which is forecast for 1990 (U.S. Bureau of Reclamation, 1965). However, the supply is likely to be inadequate for meeting all the potential demands for water by the States before that date.

Distribution of Colorado River water below Davis Dam during 1961-63 is shown in figure 5 and is listed in table 1. Depletions of the river during the above period caused by use of water from the main stream in Arizona and California probably were comparable to depletions in 1960, which were about 1.1 million and 4.9 million acre-feet, respectively. About 1.94 million acre-feet reached the international boundary.

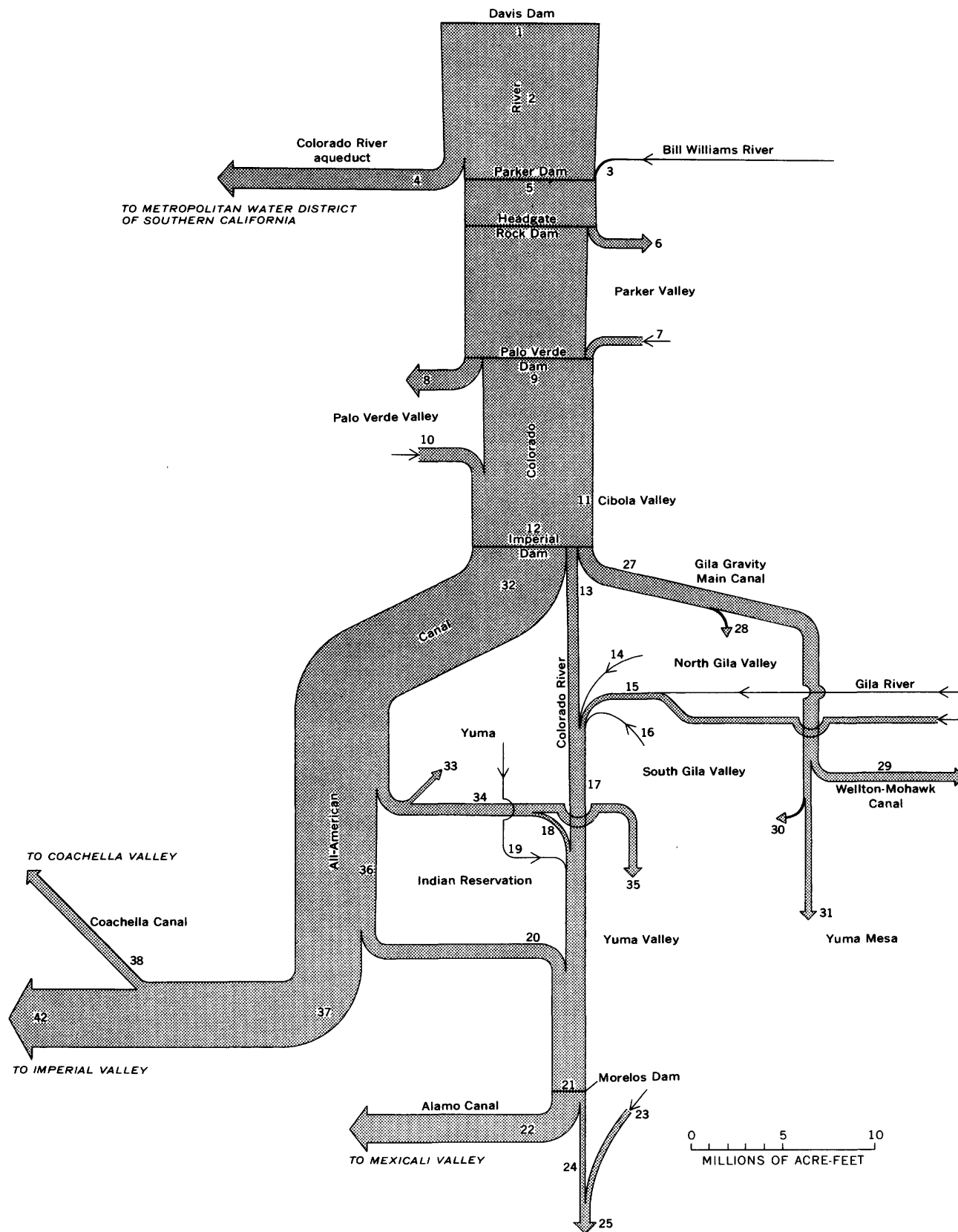


FIGURE 5.—Distribution of Colorado River water below Davis Dam, 1961-63. Widths of pattern indicate mean annual flows except those less than 100,000 acre-feet. Numbers refer to items in table 1.

TABLE 1.—Average annual flow in the lower Colorado River system, 1961-63

[Data are in acre-feet]

COLORADO RIVER BASIN	
1. Colorado River below Davis Dam, Ariz.-Nev.....	8,438,000
2. Colorado River near Topock, Ariz.....	8,221,000
3. Bill Williams River near Alamo, Ariz.....	19,860
4. Diversion to Metropolitan Water District of Southern California.....	1,078,000
5. Colorado River below Parker Dam, Ariz.-Calif. <sup>1</sup> .....	7,128,000
6. Diversion to Parker Valley, Ariz.....	463,300
7. Return flow from Parker Valley, Ariz. <sup>2</sup> .....	284,900
8. Diversion to Palo Verde Valley, Calif.....	941,900
9. Colorado River below Palo Verde Dam, Ariz.-Calif.....	5,871,000
10. Return flow from Palo Verde Valley, Calif. <sup>3</sup> .....	567,700
11. Colorado River below Cibola Valley, Ariz.....	6,438,000
12. Colorado River above Imperial Dam, Ariz.-Calif.....	6,424,000
13. Colorado River below Imperial Dam, Ariz.-Calif.....	507,400
14. Return flow from North Gila Valley, Ariz. <sup>4</sup> .....	49,900
15. Gila River near Yuma, Ariz. <sup>5</sup> .....	194,000
16. Return flow from South Gila Valley, Ariz. <sup>6</sup> .....	39,520
17. Colorado River at Yuma, Ariz.....	822,600
18. Return flow through Yuma Main Canal wasteway, Calif.....	220,800
19. Return flow from Reservation Division of Yuma project, Calif. <sup>7</sup> .....	51,500
20. Return flow through Pilot Knob powerplant and wasteway, Calif.....	645,400
21. Colorado River at northerly international boundary.....	1,772,000
22. Diversion in Alamo Canal to Mexicali Valley, Baja Calif.....	1,525,000
23. Return flow from Yuma Valley, Ariz. <sup>8</sup> .....	172,200
24. Colorado River at southerly international boundary.....	223,400
25. Total flow to Mexico at southerly boundary <sup>9</sup> .....	370,400
26. Total flow to Mexico <sup>10</sup> .....	1,920,000
27. Gila Gravity Main Canal at Imperial Dam, Ariz.-Calif.....	871,600
28. Diversion to North Gila Valley, Ariz.....	87,330
29. Diversion to Wellton-Mohawk area, Ariz.....	414,600
30. Diversion to South Gila Valley, Ariz.....	17,700
31. Diversion to Yuma Mesa, Ariz.....	310,600
32. All-American Canal near Imperial Dam, Ariz.-Calif.....	5,048,000
33. Diversion to Reservation Division of Yuma project, Calif. <sup>11</sup> .....	95,100
34. Yuma Main Canal at siphon-drop powerplant near Yuma, Ariz.....	573,700
35. Diversion to Yuma Valley, Ariz. <sup>12</sup> .....	350,000
36. All-American Canal above Pilot Knob wasteway, Calif.....	4,284,000
37. All-American Canal below Pilot Knob wasteway, Calif. (diversion to Imperial and Coachella Valleys).....	3,603,000
SALTON SEA BASIN, CALIF.	
38. Coachella Canal at head, near Greys Well.....	529,300
39. Diversion from Coachella Canal to Imperial Valley.....	2,100
40. Coachella Canal below 6A check, near Niland.....	380,500
41. Coachella Canal at milepost 87, near Mecca.....	355,000
42. All-American Canal below Coachella Canal.....	2,966,000
43. All-American Canal above East Highline Canal <sup>13</sup> .....	2,923,000
44. Total delivery to Imperial Valley (items 39 and 43).....	2,925,000
DRAINAGE TO SALTON SEA	
45. Drainage into Imperial Valley from Mexico.....	130,600
46. Inflow to Salton Sea from Imperial Valley <sup>14</sup> .....	1,270,000
47. Inflow to Salton Sea from Coachella Valley <sup>15</sup> .....	110,000

<sup>1</sup> A decrease of 15,100 acre-feet in the contents of Lake Havasu accounts for 5,000 acre-feet of this total.

<sup>2</sup> Sum of flows in six channels, of which four enter the river above Palo Verde Dam and two enter below the dam but above the gaging station (item 9).

<sup>3</sup> Sum of flows in 12 channels—partly estimated.

<sup>4</sup> Sum of flows in six channels—three tributary to the Colorado River and three tributary to the Gila River.

<sup>5</sup> Sum of flows of the Gila River near Dome, Wellton-Mohawk Main Outlet drain, and minor flows in two wasteways in the Gila Gravity Main Canal. It includes return flow from the Wellton-Mohawk area and some runoff from local storms, but does not include return flows from North and South Gila valleys.

<sup>6</sup> Sum of flows in three channels—2 tributary to the Gila River and one tributary to the Colorado River.

<sup>7</sup> Sum of flows in two channels.

<sup>8</sup> Includes flows from three wasteways to the Colorado River (25,170 acre-ft) and water that flowed or was pumped across the international boundary to canals in Sonora, Mexico (147,000 acre-ft).

<sup>9</sup> Sum of flows in the Colorado River and canals. (See footnote 8.)

<sup>10</sup> Flow reaching the international boundary (items 21 and 23) was 1,944,000 acre feet; flow leaving the boundary (items 22 and 25) was 1,895,000 acre-feet.

<sup>11</sup> Sum of flows in several small canals diverting from All-American and Yuma Main Canals. About 4,700 acre-feet of the total was diverted from Yuma Main Canal below siphon-drop powerplant and is included in item 34.

<sup>12</sup> Includes diversion for the City of Yuma.

<sup>13</sup> Sum of flows below East Highline Canal and diversions above East Highline check.

<sup>14</sup> Sum of flows in the Alamo and New Rivers and about 30 other channels.

<sup>15</sup> Sum of flows in the Whitewater River and 18 drains.

In more recent years, 1967-69, the average annual flow below Davis Dam has been very near 8 million acre-feet; depletions of the river caused by the use of main-stream water in Arizona and California have been comparable to the respective uses in 1961-63. Only slightly more than the 1.5 million acre-feet

guaranteed by the Mexican Water Treaty of 1944 has been delivered at the international boundary. Thus, in recent years a flow of about 8 million acre-feet per year has been sufficient to meet current demands. However, future demands will be considerably larger, especially when the Central Arizona Project, under which an estimated 1.2 million acre-feet per year will be diverted from the river to central Arizona, becomes operative.

Considering probable upstream uses and assuming no supplemental supply from storage, the net supply of Colorado River water below Davis Dam for normal runoff conditions is estimated to be 10.2 million acre-feet for 1975 and 8.4 million acre-feet for the year 2030. For dry conditions, the corresponding supplies are estimated to be 8.2 million and 6.4 million acre-feet. Thus, for periods of normal runoff, the supply appears to be adequate for meeting the demands of recent years in the lower basin plus the demands of the Central Arizona Project for a decade or two beyond 1975. However, for protracted dry periods, the supply will be inadequate after completion of the Central Arizona Project.

The amount of water required to satisfy basic allotments below Davis Dam (8.7 million acre-ft) and the losses associated with storage and conveyance of water below the dam (900,000 acre-ft) is 9.6 million acre-feet. Comparison of these figures of supply and basic allotments shows that the supply would be adequate during periods of near normal runoff until about 1980.

## WATER LOSS

The beneficial use of water below compact point is accompanied by large losses, some of which are unavoidable. Evaporation from the river and from reservoirs consumes more than 1 million acre-feet per year, and riparian vegetation consumes more than 500,000 acre-feet per year. Annual seepage from large canals between Imperial Dam and the areas to which the water is diverted amounts to 500,000 acre-feet. About 1.3 million acre-feet per year, most of which is return flow from irrigation in Imperial Valley, drains to the Salton Sea, where it evaporates. A large part, although not all, of this drainage is necessary to maintain the productivity of the irrigated land. However, all the inflow is needed to maintain the Salton Sea—which provides substantial recreational opportunities—at its present stage.

The disposal of water that seeps from canals varies considerably. Some of the seepage from canals near the Colorado River contributes to return flow to the river and to that extent does not deplete the available



supply. However, much of the seepage from canals is used consumptively by vegetation having little or no direct economic value or it drains to areas where the water is no longer available for further beneficial consumptive use. The U.S. Bureau of Reclamation and the irrigation districts have continuing programs for determining where large-scale leakage is occurring and for reducing or eliminating such leakage.

### CONSUMPTIVE-USE RATES

Evaporation rates from the Salton Sea during the years 1961-62 computed by water-budget and energy-budget methods differed by less than 5 percent. Data obtained by these methods, together with data on windspeed and vapor-pressure differences between saturated air at the water surface and the air above the water surface, were used to establish the empirical coefficient in the simplified mass-transfer equation. The mass-transfer method was then used to determine relative rates of monthly evaporation.

Annual evaporation determined by the first two methods also was used to establish a coefficient (0.64) for comparison of average annual evaporation from three sunken pans at widely separated sites on the shores of the Salton Sea with evaporation from the sea. Use of the pans was concluded to be the most practical method for continuing the measurement of annual evaporation from the sea, even though the method is not suitable for accurate determination of monthly rates of evaporation. The computed evaporation for 1961-62 and the pan data for 1948-62 indicate that normal annual evaporation from Salton Sea is 5.78 feet (69 in.). This rate is markedly lower than that for Lake Mead, which is the nearest large body of water in a desert environment. The average annual evaporation from Lake Mead from 1948-62 was about 86 inches, or 17 inches more than the evaporation from the Salton Sea during the same period. Although some of the difference probably is due to small errors in the data used for computing the rates, most of the difference probably results from differences in salinity, in the volumes and temperatures of inflow and outflow, and in the mean distance the wind travels across the water.

Consumptive-use rates for five species of vegetation and rates of evaporation from bare soil and from free water surfaces were determined during a 6-year period, 1961-66, at two sites on the flood plain of the river between Yuma and Imperial Dam. Arrowweed, fourwing saltbush, quailbrush, and bermuda grass were grown in large tanks, each about 1,000 square feet in area, at Imperial campsite. Average yearly

water use for four species of vegetation was as follows:

Type of vegetation	Depth to water table in (ft)	Average yearly water use (in.)
Arrowweed ( <i>Pluchea sericea</i> ) . . . . .	5.5	96
Quailbrush ( <i>Atriplex lentiformis</i> ) . . . . .	3.5-5.5	44
Fourwing saltbush ( <i>Atriplex canescens</i> ) . . . . .	3.5-5.5	38
Bermuda ( <i>Cynodon dactylon</i> ) . . . . .	3.5	73

Cattail was grown in tanks, 100 square feet in area, at Mittry Lake site. Water in the tanks was maintained 0.2-0.3 foot above the land surface. Average annual use of water, including precipitation, ranged from 100 to 114 inches for tanks in which the vegetation appeared to be similar to the cattail vegetation outside the tanks.

Evaporation from bare soil tanks at Imperial campsite was found to vary greatly with depth to water below land surface. For the sand-silt-clay mixture in the tanks, which was considered to be representative of much of the flood-plain soil, annual evaporation rates averaged 20.0 inches with the water level 2 feet below land surface, 6.6 inches with the water level 3 feet below land surface, and 3.2 inches with the water level 4 feet below land surface. The foregoing rates exclude precipitation, which was significant for only a few months. Rates of evaporation for the 4-foot depth to water were lower than rates for similar depths to water computed by others in previous studies. Much of the wide range in evaporation at comparable depths indicated by other studies probably is due to differences in the degree of compaction and types of soil used in the various experiments.

The great influence of environmental factors on evaporation rates from free water surfaces was demonstrated by the large differences in rates of evaporation noted at Imperial campsite, which is relatively open to wind movement and not adjacent to open water, and at Mittry Lake site, which is surrounded by cattails and is adjacent to the lake. In 1964, the Class A pan at Imperial campsite showed a yearly rate of evaporation of 114.52 inches, whereas the same type pan at Mittry Lake site showed only 91.06 inches. The 10- by 10- by 1-foot buried tank adjacent to the standard pan at Mittry Lake site showed a yearly rate of only 66.37 inches. Differences in wind movement and air temperatures at the sites probably accounted for most of the differences in measured evaporation.

Consumptive-use rates for other species of natural vegetation and for crops were based on rates computed by Blaney and Harris (1952) but were increased somewhat for alfalfa and cotton because of higher rates indicated in studies made by Erie, French, and Harris (1965). Because of further uncertainties regarding the cropped acreages, the variations in farming practices, and the types of crops grown, a uniform rate of 3.6 acre-feet per irrigated acre per year was concluded to be a satisfactory average rate for computing consumptive use by crops in the flood plain. In intensively cultivated areas where natural vegetation occupied only a small percentage of the area, a consumptive-use rate of 2.5 acre-feet per acre per year was used for noncropped areas on the flood plain. On the Yuma Mesa, where about 20,000 acres of citrus is irrigated, consumptive use was computed on the basis of rates of use by the principal kinds of citrus that were irrigated.

### WATER BUDGETS

Consumptive-use quantities of water within selected areas were computed by both the inflow-outflow method and the area-rate method. In the inflow-outflow method, consumptive use was computed as the residual between inflow and outflow items of the water supply. Depletions indicated by streamflow records were adjusted for exports from the areas and for changes in surface-water storage. Changes in ground-water storage, except in the Yuma area, were small enough to be ignored. In the area-rate method, consumptive use was computed by summing quantities obtained by multiplying rates of use and areas to which the rates applied. Consumptive-use quantities between Davis Dam and Imperial Dam computed by each of the two methods and the average of these quantities are shown in table 2.

Differences in consumptive use computed by the two methods range from virtually nothing for the area between Davis Dam and Parker Dam to 150,000 acre-feet for each of the areas between Parker Dam and Imperial Dam, and Davis Dam and Imperial Dam. The differences between the two methods for computing consumptive use are not always in the same direction. In the areas Davis Dam to the gaging station near Topock and the gaging station near Topock to Parker Dam, the differences are wholly compensating.

Loeltz and McDonald (1969) in analyzing this problem considered the probability that the 15-year means of surface-water depletions might differ from long-term means. They found an even chance that the

15-year mean might differ from a long-term mean by 20,000 acre-feet or more, and 1 chance in 20 that it might differ by 60,000 acre-feet or more. Other possible sources of error were small consistent errors in measurement of river discharge. A consistent error of 1 percent would cause an error in the range of 80,000 to 95,000 acre-feet in the computed depletion for each of the adjacent reaches.

Depletions of streamflow between Davis Dam and Imperial Dam are shown in figure 6. Random errors of measurement are indicated by the year-to-year differences in depletion, especially when the depletion increases significantly in one reach of the river and at the same time decreases in an adjoining reach. The difference of almost 200,000 acre-feet between the average depletion for the entire reach between 1953-57 and the average depletion for 1958-62 probably results from a change or changes in measurement or computational procedure at one or more points of measurement.

Other recognized sources of error are the estimates of consumptive-use rates and acreages to which the rates apply, and the estimates of unmeasured inflow and outflow. The latter estimates are rather small, however, and are therefore not as likely to be the cause of the larger differences. Although adjustments could be made to bring about a closer agreement between the consumptive-use estimates for each of the reaches, in view of the uncertainties regarding the preciseness of most of the budget items, such adjustments were concluded to be unwarranted.

A water budget for the Yuma area, showing a comparison between the two methods for computing consumptive use for the 16-year period 1951-66, is given in table 3. The budget differs from the budgets for the areas upstream from Imperial Dam principally in that changes in ground-water storage are significant. The virtual agreement between values obtained by the two methods for the Yuma area is fortuitous because studies of variability of the yearly differences between measured inflow to and outflow from the area showed that at the 95-percent confidence level the 16-year mean might differ as much as 37,000 acre-feet from the long-term mean.

A detailed water budget for Imperial Valley, Calif. was not made because of the reconnaissance nature of the investigation of that area. An approximation of the magnitude of the budget items is shown as follows:

[Items refer to table 1]	Thousands of acre-feet
Measured inflow (items 44 and 45) . . . . .	3,056
Measured outflow (item 45) . . . . .	1,270
Residual . . . . .	1,786

TABLE 2.—*Consumptive use of water between Davis Dam and Imperial Dam*

Colorado River valley between:							
Budget items	Davis Dam and gaging station near Topock, 1950-66	Gaging station near Topock and Parker Dam, 1950-66	Davis Dam and Parker Dam 1950-66	Parker Dam and Palo gaging station 1957-66	Palo Verde Dam and Imperial Dam, below Cibola Valley, Ariz., 1957-66	Parker Dam and Imperial Dam, 1950-66	Davis Dam and Imperial Dam 1950-66
<b>Inflow-outflow method</b>							
Measured inflow minus measured outflow (average annual streamflow depletion, adjusted) . . . . .	181,000	151,000	332,000	295,000	361,000	686,000	1,018,000
Unmeasured inflow minus unmeasured outflow:							
Surface water . . . . .	15,000	19,000	34,000	6,000	27,000	44,000	78,000
Ground water . . . . .	15,000	5,000	20,000	-1,000	3,000	-8,000	12,000
Consumptive use . . . . .	211,000	175,000	386,000	300,000	391,000	722,000	1,108,000
<b>Area-rate method</b>							
Natural vegetation . . . . .	188,000	8,000	192,000	167,000	136,000	353,000	545,000
Irrigated crops . . . . .	12,000	(1)	12,000	118,000	321,000	439,000	451,000
Evaporation . . . . .	41,000	140,000	181,000	22,000	20,000	81,000	262,000
Consumptive use . . . . .	241,000	144,000	385,000	307,000	477,000	873,000	1,258,000
Consumptive use (average of both methods) . . . . .	226,000	160,000	386,000	304,000	434,000	798,000	1,183,000

<sup>1</sup>Negligible.TABLE 3.—*Consumptive use of water in Yuma area, 1951-66*  
[Mean annual quantities, in thousands of acre-feet]

<b>Inflow-outflow method</b>	
<i>Inflow</i>	
Measured:	
Surface . . . . .	+7,858
Unmeasured:	
Surface water . . . . .	+2
Ground water . . . . .	+11
<i>Outflow</i>	
Measured:	
Surface water . . . . .	-7,232
Unmeasured:	
Ground water . . . . .	-70
<i>Change in storage</i>	
Unmeasured:	
Ground water . . . . .	-80
Consumptive use . . . . .	489
<b>Area-rate method</b>	
Natural vegetation and other noncropland . . . . .	99
Irrigated crops . . . . .	367
Evaporation . . . . .	20
Consumptive use . . . . .	486
Consumptive use (average of both methods) . . . . .	488

The residual represents consumptive use on 432,000 acres of cropland plus consumptive use in unplanted areas within the irrigated tracts. The rate of 4.1

acre-feet per acre, computed on the basis of cropland alone, is therefore somewhat higher than the consumptive-use rate for crops that would be obtained if the other acreages and rates of use within the irrigated tracts were included in the computations.

### CHEMICAL QUALITY OF THE COLORADO RIVER

Under virgin conditions and prior to the closure of Hoover Dam, the chemical quality of the lower Colorado River varied substantially from season to season and year to year. Dissolved solids probably ranged from slightly less than 200 to more than 2,000 mg/l (milligrams per litre), and consisted mainly of calcium and bicarbonate at lower concentration levels and calcium, sodium sulfate, and chloride at higher concentration levels.

At Grand Canyon, where the chemical quality of the Colorado River is representative of the chemical quality of water that enters Lake Mead, the weighted average dissolved-solids concentration for the 40-year period 1926-65 was about 600 mg/l. The outflow from Lake Mead is more highly mineralized than is the inflow, and the dissolved-solids concentration increases downstream. Between Hoover and Imperial

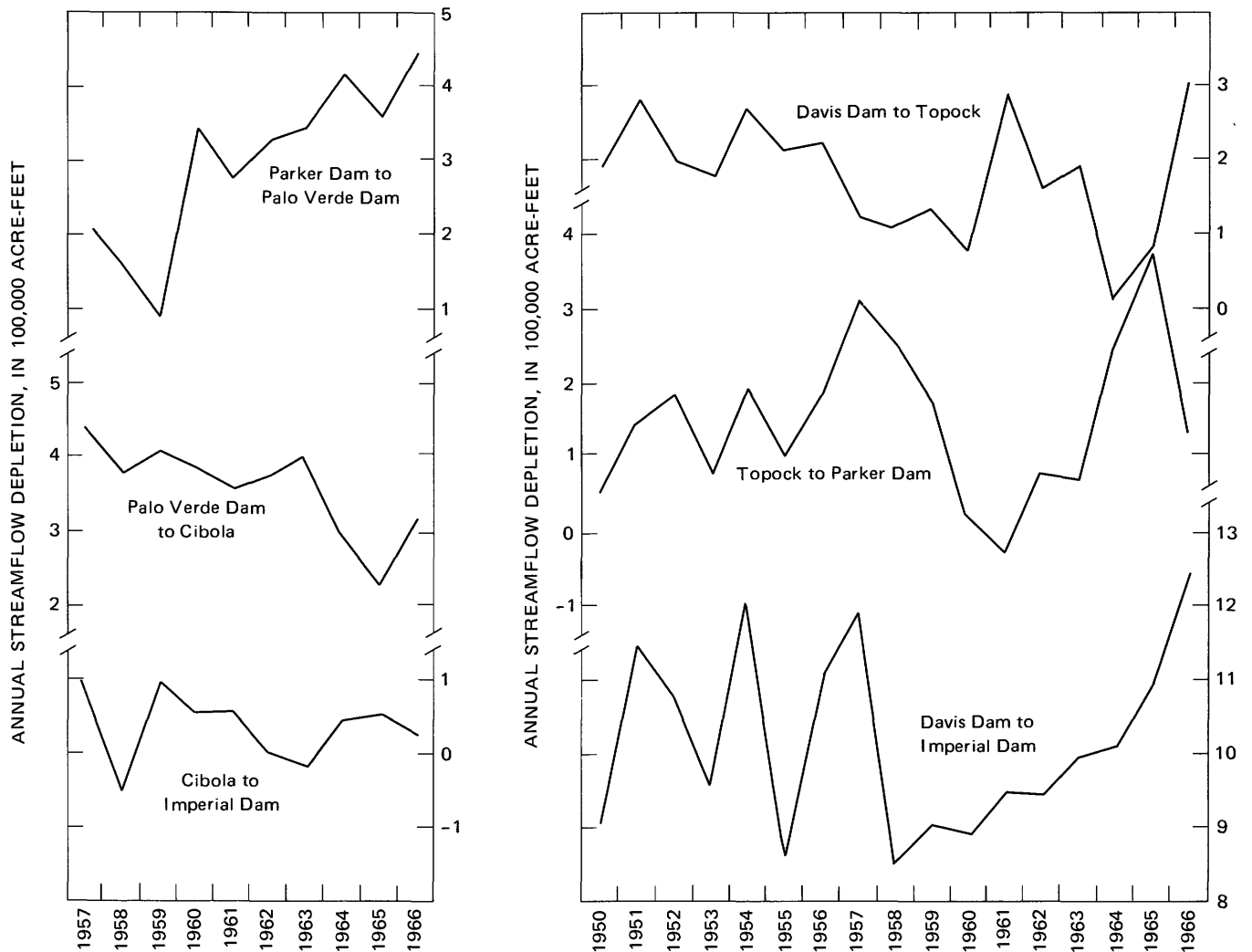


FIGURE 6.—Depletions of streamflow between Davis Dam and Imperial Dam

Dams, the dissolved-solids concentration generally has ranged between 600 and 900 mg/l (tables 4, 5). The higher dissolved-solids concentrations immediately below Hoover Dam result mainly from evaporation from the surface of Lake Mead and solution of salts from its bed. These adverse effects are offset in part by precipitation of calcium carbonate in the lake; also, the solution of salts from the bed of the lake appears to be substantially less in recent years than during the first few years after the lake was formed.

A marked increase in the annual diversion of the Colorado River aqueduct during 1961-65 further lessened the quantity of water available in the main stream for dilution of somewhat saline return flows from irrigated areas downstream from Parker Dam. Development of new lands for irrigation, especially in Parker Valley, increased the quantity of dissolved salts in return flow to the river, thereby also contributing to the increasing salinity of the river

below Parker Valley. An indication of the increasing salinity of the river water between Hoover and Imperial Dams is shown by the increase in the difference between the dissolved-solids concentration below Hoover Dam and at Imperial Dam for the three 5-year periods listed in the following table. Further increases in the differences between the sums of dissolved solids at the two sampling sites can be expected as the annual depletion of the river

Sampling site	Sum of dissolved solids (mg/l), by water years		
	1941-45	1951-55	1961-55
Colorado River below Hoover Dam . . . . .	703	658	714
Colorado River at Imperial Dam . . . . .	726	706	824
Difference . . . . .	23	48	110

TABLE 4.—Annual weighted-average chemical analyses for Colorado River below Hoover Dam, Ariz.-Nev.

[Results in milligrams per litre unless otherwise indicated. \* (estimated) signifies concentrations determined indirectly instead of by weighting individual analyses]

Water year	Total flow (acre-ft)	Mean discharge (cfs)	Silica (SiO <sub>2</sub> )	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO <sub>3</sub> )	Sulfate (SO <sub>4</sub> )	Chloride (Cl)	Fluoride (F)	Nitrate (NO <sub>3</sub> )	Dissolved solids			Hardness as CaCO <sub>3</sub>		Specific conductance (microhmhos at 25°C)
													Residue at 180°C	Sum		Calcium, magnesium	Noncarbonate	
														Milligrams per liter	Tons per acre-ft			
1935	5,556,000	7,674	13	82	29	108	5.8	169	268	101	0.3	3.3	693	694	0.94	324	185	*1,070
1936	6,282,000	8,653	13	78	24	85	5.7	152	242	72	.3	2.7	596	599	.81	293	168	*907
1937	5,826,000	8,048	10	102	25	93	5.4	157	314	74	.....	3.1	703	704	.96	358	229	*1,060
1938	6,168,000	8,519	11	103	25	90	5.7	153	314	69	.....	2.8	696	696	.95	360	234	*1,040
1939	8,473,000	11,700	13	102	26	93	6.1	158	321	72	.3	3.2	712	716	.97	362	232	*1,070
1940	7,694,000	10,600	13	110	28	98	5.2	159	348	77	.3	3.0	761	762	1.03	390	259	1,140
1941	11,730,000	16,200	11	110	28	98	6.4	153	355	79	.3	3.0	766	767	1.04	390	264	1,140
1942	17,880,000	24,690	12	103	27	98	.....	156	329	72	.4	2.6	719	722	.98	367	239	1,080
1943	12,500,000	17,260	13	95	26	89	.....	158	303	64	.3	3.2	673	673	.92	344	214	1,010
1944	14,450,000	19,910	12	92	28	90	5.9	159	299	70	.4	3.4	679	677	.92	344	214	1,030
1945	12,940,000	17,870	*12	*93	*30	95	.....	*166	*302	*77	.....	*3.0	*696	*695	.95	*356	*220	*1,060
1946	11,290,000	15,600	*10	*89	*30	90	.....	*162	*288	*75	.....	*2.5	*664	*662	.90	*346	*212	*1,030
1947	10,660,000	14,730	*12	*90	*29	96	.....	*161	*294	*78	.....	*1.8	*688	*680	.92	*344	*212	*1,040
1948	12,750,000	17,570	*11	*88	*27	89	.....	*157	*281	*71	.....	*1.8	*649	*646	.88	*330	*202	*985
1949	13,200,000	18,230	*11	*85	*25	84	.....	*156	*263	*67	.....	*1.8	*615	*615	.84	*315	*187	*939
1950	12,940,000	17,870	*11	*84	*26	81	.....	*158	*257	*66	.....	*1.9	*606	*606	.82	*316	*187	*927
1951	9,981,000	13,790	13	84	28	90	.....	167	267	72	.....	2.0	663	639	.90	324	188	977
1952	14,370,000	19,800	*13	83	27	*90	*4.5	*160	*273	*72	.....	*2.1	652	*645	.89	318	187	974
1953	12,780,000	17,650	*13	83	23	82	*4.2	*162	*253	*62	.....	*2.0	632	*604	.86	302	168	938
1954	10,690,000	14,760	*13	88	25	90	*5.0	*164	*274	*73	.....	*2.1	677	*652	.92	322	188	1,010
1955	9,276,000	12,810	*13	102	27	106	*5.0	*167	*320	*94	.....	*2.2	778	*753	1.06	366	228	1,150
1956	7,818,000	10,770	*13	104	32	117	*5.3	170	*350	*103	.....	*3.7	837	*813	1.14	391	252	1,230
1957	8,088,000	11,170	*12	96	31	110	*5.3	171	*320	*98	.....	*2.2	791	*760	1.08	367	227	1,170
1958	12,270,000	16,940	11	87	24	86	4.2	158	269	71	.3	2.9	661	634	.90	316	186	985
1959	9,757,000	13,480	11	84	24	81	4.0	158	261	67	.3	3.2	622	614	.85	308	178	944
1960	9,251,000	12,740	11	88	25	87	3.9	158	*270	*72	.....	*2.5	656	*639	.89	322	193	983
1961	8,661,000	11,960	10	92	27	92	4.6	160	288	*82	.4	3.5	694	680	.94	340	210	1,040
1962	8,304,000	11,470	12	101	26	98	4.3	162	*311	*87	.3	3.5	725	727	.99	359	226	1,090
1963	8,810,000	12,170	10	98	24	96	4.3	160	290	86	.3	2.7	700	691	.95	343	212	1,050
1964	8,234,000	11,340	10	93	27	97	4.3	154	292	90	.....	1.2	703	691	.96	328	202	1,030
1965	7,917,000	10,940	10	101	29	115	5.4	156	335	108	.4	1.6	814	782	1.11	371	243	1,210

increases. The concentration of dissolved-solids in the Colorado River at the northerly international boundary is substantially greater than it is at Imperial Dam mainly because moderate saline return flows from irrigation and ground water pumped by drainage wells are discharged into the river, the flow of which is greatly reduced by diversion to the All-American Canal and Gila Gravity Main Canal at Imperial Dam.

## GEOLOGY

### LANDFORMS

The lower Colorado River-Salton Sea area is characterized by barren, rugged mountains a few hundred to several thousand feet high separated by broad desert basins in which lie the present flood plains of the Colorado River and its principal southern tributary, the Gila River. The types of landforms in the project area are shown in figures 7-10. In the Needles and Parker-Blythe-Cibola areas, the landforms are grouped as (1) mountains and hills, (2)

piedmont slopes and dissected uplands, (3) river flood plain, and (4) sand dunes (figs. 7, 8). In the Yuma area the landform types are similar, except that the second type is described as mesas and piedmont slopes (fig. 9). In Imperial Valley the types are (1) mountains and hills, (2) low hills and dissected uplands, (3) mesas and piedmont slopes, (4) young lakebed (most of central Imperial Valley), and (5) sand dunes (fig. 10).

The mountains and hills are chiefly rugged exposures of hard igneous (plutonic and volcanic) rocks and metamorphic rocks but, in the Yuma area, include less rugged exposures of semiconsolidated nonmarine sedimentary rocks.

In the Imperial Valley area the low hills and dissected uplands consist of exposures of slightly to strong deformed semiconsolidated marine and nonmarine sedimentary rocks. Within the area shown in figure 10 these rocks are generally finer grained than the semiconsolidated nonmarine sedimentary rocks of the Yuma area and, in places, form colorful badlands.

TABLE 5.—Annual weighted average chemical analyses for Colorado River at Imperial Dam, Ariz.-Calif.

[Results in milligrams per litre unless otherwise indicated. \* (estimated) signifies concentrations determined indirectly instead of by weighting individual analyses]

Water year	Total flow (acre-ft)	Mean discharge (cfs)	Silica (SiO <sub>2</sub> )	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO <sub>3</sub> )	Sulfate (SO <sub>4</sub> )	Chloride (Cl)	Fluoride (F)	Nitrate (NO <sub>3</sub> )	Dissolved solids			Hardness as CaCO <sub>3</sub>		Specific conductance (micromhos at 25°C)
													Residue at 180°C	Sum		Calcium, magnesium	Noncarbonate	
													Milligrams per liter	Tons per acre-ft				
1941	11,060,000	15,270	*12	*110	*28	*107	*5.5	*153	*363	*87	*0.3	*2.5	788	791	1.08	*390	*264	*1,200
1942	16,980,000	23,460	*12	*103	*27	*105	4.1	*156	*336	*79	*.3	*1.9	743	742	1.01	*368	*240	*1,120
1943	10,820,000	14,950	14	96	26	97		158	312	72	.3	1.8	696	698	.95	346	217	1,050
1944	13,240,000	18,230	11	92	28	98	4.1	165	306	76	.3	2.5	699	700	.95	344	210	1,070
1945	11,800,000	16,300	11	91	29	99	5.3	163	300	82	.3	1.5	699	701	.95	346	212	1,070
1946	10,160,000	14,040	13	87	30	98	5.9	160	295	83	.2	1.0	692	692	.94	340	210	1,050
1947	9,714,000	13,420	12	92	31	104	4.1	165	310	89	.2	1.3	726	725	.99	357	222	1,100
1948	11,730,000	16,160	13	89	28	100	3.3	165	292	82	.2	1.5	690	690	.94	337	202	1,060
1949	12,270,000	16,940	13	88	28	89	6.4	165	281	74	.3	1.8	663	663	.90	334	200	1,010
1950	11,500,000	15,890	13	84	27	88	2.9	163	265	75	.3	1.4	637	637	.87	320	187	985
1951	7,766,000	10,730	14	86	28	101	5.2	172	281	87	.3	1.1	706	688	.94	330	188	1,050
1952	13,040,000	17,970	14	85	29	100	4.4	169	283	84	.3	1.4	700	684	.93	331	192	1,050
1953	11,970,000	16,540	14	83	29	95	4.2	170	273	79	.4	1.4	680	663	.90	326	186	1,020
1954	8,950,000	12,360	16	86	28	105	4.5	171	287	87	.3	1.3	726	699	.95	330	190	1,070
1955	8,398,000	11,600	16	95	33	121	5.2	170	333	106	.3	1.5	818	795	1.08	372	233	1,200
1956	6,323,000	8,710	15	106	34	137	5.6	173	375	126	.4	1.7	917	886	1.20	404	262	1,340
1957	6,279,000	8,673	13	110	34	130	5.4	175	364	126	.4	1.1	884	870	1.18	414	270	1,340
1958	10,707,000	14,790	20	93	27	117	4.9	171	304	97	.6	1.9	763	750	1.02	343	203	1,140
1959	8,246,000	11,390	*17	91	25	107	*4.5	164	*288	*96	*.4	*1.7	746	710	.97	330	196	1,080
1960	7,338,000	10,110	*18	93	26	112	*4.7	163	*299	*104	*.4	*1.6	764	739	1.01	339	205	1,130
1961	6,527,000	9,016	*16	98	27	126	*4.9	167	*323	*117	*.4	*2.0	821	797	1.08	356	218	1,220
1962	6,220,000	8,591	16	99	29	133	*5.5	164	328	126	.6	1.8	814	820	1.12	366	232	1,260
1963	6,612,000	9,133	15	100	27	129	*5.2	167	326	118	.6	1.2	799	804	1.09	360	224	1,240
1964	6,076,000	8,370	16	95	28	131	*5.1	165	324	122	.5	1.4	835	806	1.10	352	216	1,240
1965	5,766,000	7,964	16	104	31	150	*5.7	168	364	142	.4	1.1	912	894	1.22	387	249	1,380

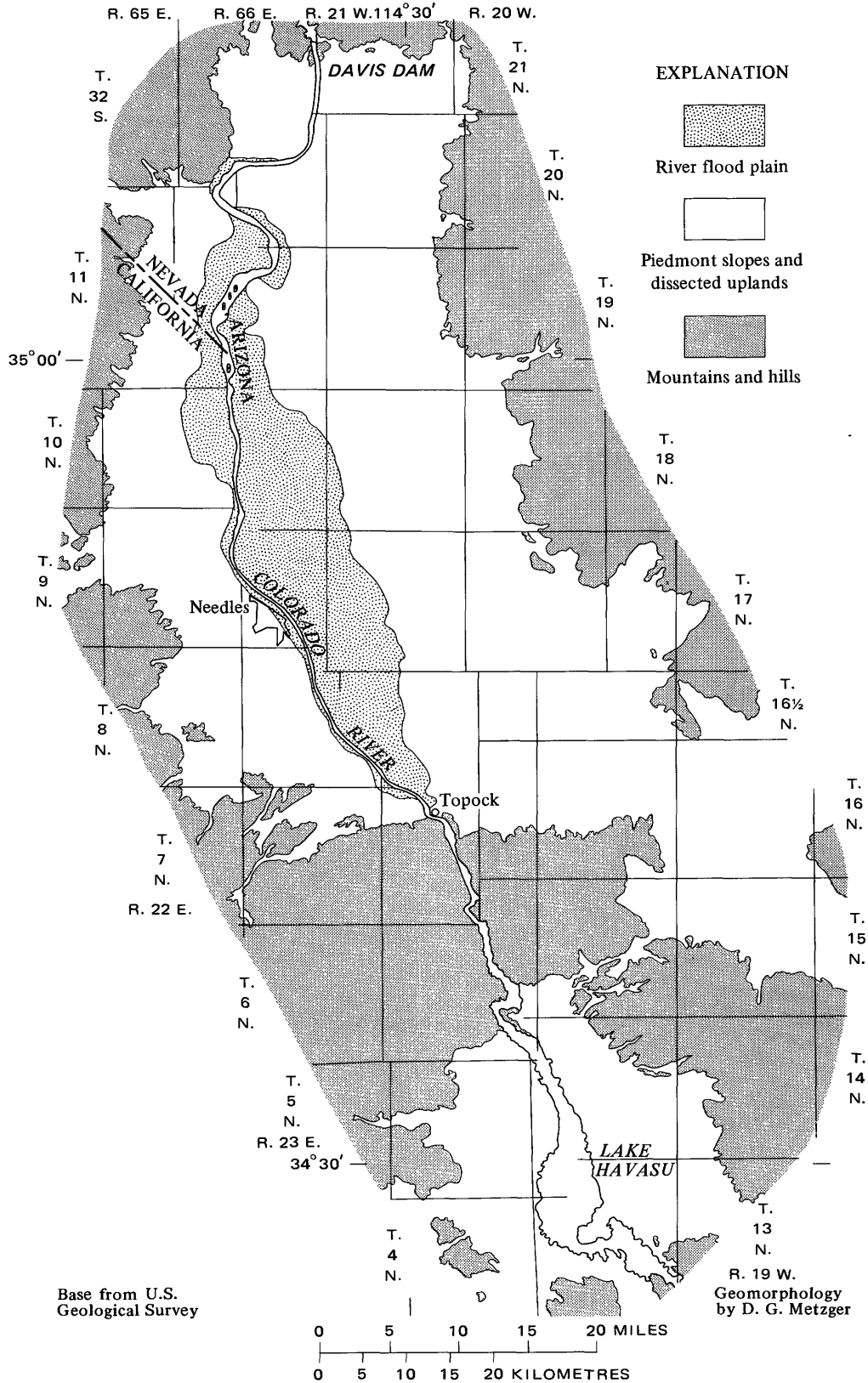
The mountains and hills of the lower Colorado River-Salton Sea area are flanked by broad piedmont slopes having gradients ranging from 200 feet per mile to less than 10 feet per mile. At many places near the flood plains the piedmont slopes merge with, or are more sharply bounded by, river terraces and other slopes of low gradient, which locally are termed "mesas." Yuma Mesa in the Yuma area and East Mesa and West Mesa in the Imperial Valley area are the most extensive of these gently sloping surfaces; narrower terraces extend along the margins of the Colorado River flood plain north of the Yuma area. Also grouped with the piedmont slopes in the Needles and Parker-Blythe-Cibola areas are dissected uplands underlain by nonmarine and marine sedimentary rocks. In the Yuma area exposures of similar rocks are more rugged and hilly than in the Needles and Parker-Blythe-Cibola areas and are grouped instead with mountains and hills (fig. 9).

Upstream from Yuma the Colorado River flood plain ranges in width from less than 1 mile, where it is flanked by mountains and hills, to about 9 miles; downstream from Yuma the flood plain widens to merge with the broad fan-shaped subaerial delta of the

Colorado River, which separates the Gulf of California from Imperial Valley. The flood plain ranges in altitude from about 90 feet above mean sea level at the southerly international boundary to more than 500 feet in the northern part of the Needles area. Generally, the flood plain is 50 to 80 feet below the adjacent river terraces, such as Yuma Mesa.

Central Imperial Valley is the bed of prehistoric Lake Cahuilla, whose shorelines are 42 to 50 feet above mean sea level. At some places, particularly along the southwest margin of the Salton Sea, the old lakebed has been modified slightly by alluvial processes; the resulting surfaces are shown in figure 10 as mesas and piedmont slopes. The lakebed slopes north-northwestward from the international boundary to the Salton Sea at an average gradient of 1.7 feet per mile and is dissected by the Alamo and New Rivers, which have cut trenches as much as 40 feet deep into the soft silty lacustrine deposits.

In the lower Colorado River-Salton Sea area, as in most desert areas, wind is an important agent of erosion and deposition, especially where sandy alluvial or shoreline materials are exposed. The thicker accumulations of windblown sand are shown in figures



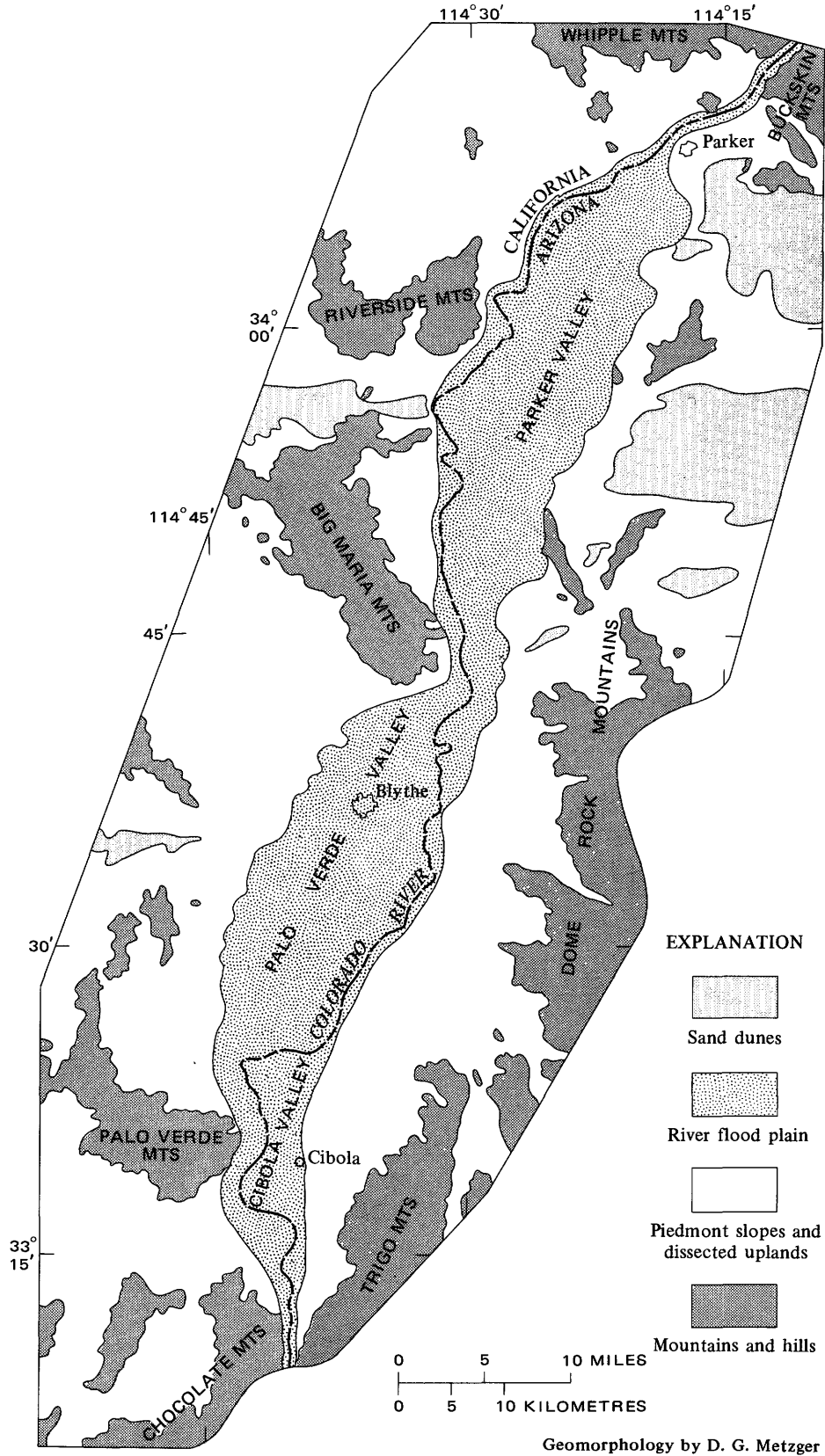
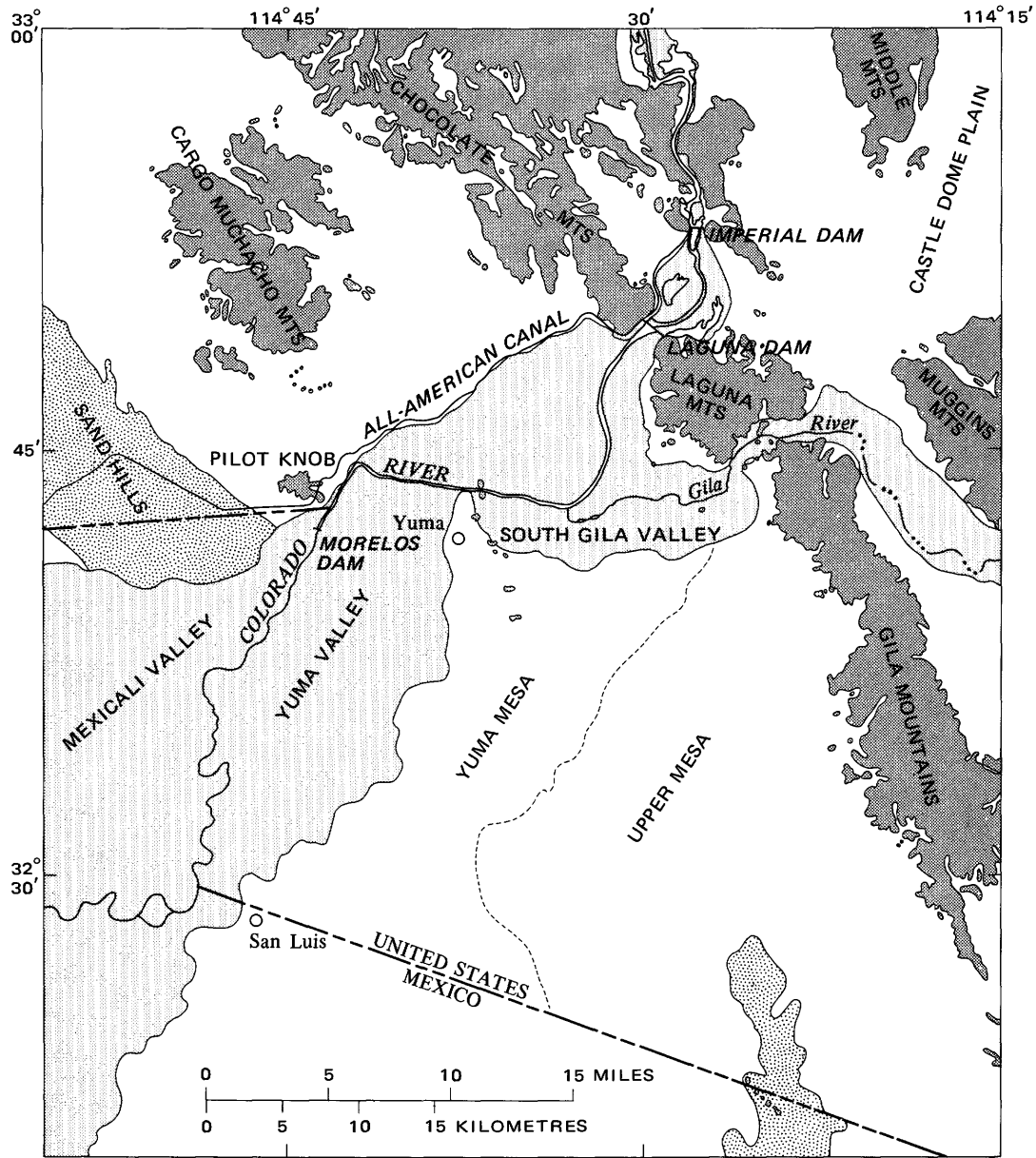


FIGURE 8.—Landforms in the Parker-Blythe-Cibola area.





Geomorphology by F. H. Olmsted

EXPLANATION



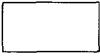

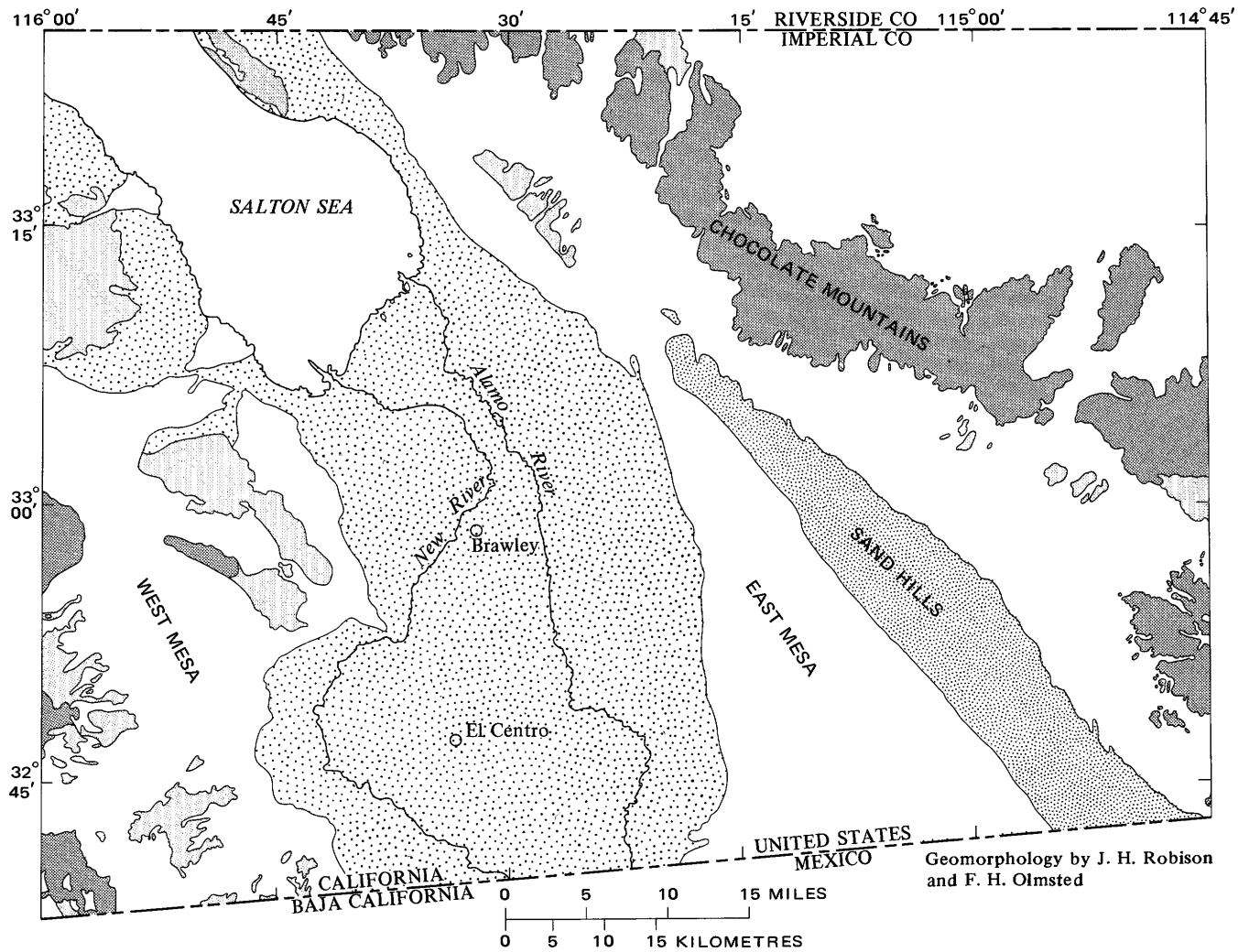
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|--|---|
| <p> Sand dunes<br/><i>Thick accumulations of windblown sand. Thin sheets and small dunes not shown</i></p> <p> River flood plains<br/><i>Exposures of younger deposits of the Colorado and Gila Rivers</i></p> | <p> Mesas and piedmont slopes<br/><i>Undissected to strongly dissected alluvial surfaces and river terraces. Includes exposures of older deposits of the Colorado and Gila Rivers and local ephemeral streams and also thin sheets of windblown sand and small dunes</i></p> <p> Mountains and hills<br/><i>Rugged exposures of pre-Tertiary crystalline rocks and Tertiary volcanic rocks; less rugged exposures of Tertiary sedimentary rocks</i></p> |
|--|---|


FIGURE 9.—Landforms in the Yuma area.


WATER RESOURCES OF LOWER COLORADO RIVER – SALTON SEA AREA





Geomorphology by J. H. Robison and F. H. Olmsted


EXPLANATION

- 

**Sand dunes**  
*Thick accumulations of windblown sand. Thin sheets and small dunes not shown*
- 

**Low hills and dissected uplands**  
*Exposures of slightly to strongly deformed sedimentary rocks of the late Tertiary and Quaternary age, in places forming colorful badlands*
- 

**Young lakebed**  
*Bed of prehistoric Lake Cahuilla where essentially unmodified by alluvial processes*
- 

**Mountains and hills**  
*Rugged exposures of dense pre-Tertiary crystalline rocks and Tertiary volcanic rocks. Includes domes of obsidian at south end of Salton Sea*
- 

**Mesas and piedmont slopes**  
*Undissected to slightly dissected alluvial surfaces and terraces. Includes thin sheets of windblown sand, small dunes, and young lakebed where modified by alluvial processes*

FIGURE 10.—Landforms in the Imperial Valley area.

7-10 as sand dunes; thinner sheets, generally less than 10 feet thick, are not differentiated from the surfaces on which they lie. The largest and most extensive dunes are the Sand Hills of the southeastern Imperial

Valley area, which form a belt more than 40 miles long and generally about 5-6 miles wide. Some of the dunes are 300 feet thick.

#### ROCK UNITS AND OCCURRENCE OF GROUND WATER

The earth materials of the lower Colorado River-Salton Sea area comprise a basement complex of pre-Tertiary crystalline rocks, an overlying sequence of slightly to moderately deformed sedimentary and volcanic rocks of Tertiary age, and virtually undeformed alluvial and windblown deposits of late Tertiary and Quaternary age, which were deposited after the Colorado River entered the area. The crystalline rocks include a wide variety of metamorphic, plutonic, and dike rocks. All are dense and contain only small amounts of water in fractures and weathered zones. The sedimentary and volcanic rocks of Tertiary age vary lithologically from slightly consolidated nonmarine and marine beds and volcanic-ash beds to dense lava flows and beds of welded tuff; they are similarly variable in water-bearing characteristics. Some of the coarse-grained nonmarine beds are capable of yielding moderate amounts of fresh ground water. Other, indurated beds, such as the lava flows and welded tuff, are as poorly watered bearing as the pre-Tertiary crystalline rocks and, like the crystalline rocks, may form the floor and walls of the ground-water reservoir. The virtually undeformed alluvial deposits (including some lake deposits in Imperial Valley) constitute the upper, principal part of the ground-water reservoir in the area. The beds of coarse sand and gravel, deposited chiefly by the Colorado River, are highly permeable and yield copious quantities of water to irrigation wells and other large wells.

#### NEEDLES AND PARKER-BLYTHE-CIBOLA AREAS

In the Needles and Parker-Blythe-Cibola areas, the bedrock that forms the boundaries of the ground-water reservoir is made up of igneous and metamorphic rocks, including metamorphosed Paleozoic and Mesozoic rocks, and it also includes deformed indurated sedimentary and volcanic rocks of Tertiary age. Where exposed, these rocks form the mountains and hills shown in figures 7 and 8.

The rock units exposed as piedmont slopes and dissected uplands (figs. 7, 8) include Miocene(?) fanglomerate, Bouse Formation, and older alluviums of the Colorado River and its tributaries. Locally, these units are overlain by eolian sand and sand dunes. Younger alluvium of the Colorado River underlies the river flood plain (figs. 7, 8).

The Miocene(?) fanglomerate consists mainly of a cemented, poorly sorted gravel composed of angular to subrounded pebbles and some fine-grained material. The fanglomerate is believed to have come from a nearby source, and it antedates the Colorado river. Locally, the fanglomerate is a good aquifer. For example, wells near Parker, Ariz., that tapped this aquifer yielded 15 (gal/min)/ft of drawdown.

The Bouse Formation of Pliocene age was deposited in an embayment of the Gulf of California, and it extends not only upstream along the present Colorado River north of the Needles area, but also into adjacent desert basins. The Bouse comprises a basal limestone overlain by interbedded clay, silt, and sand and a distinctive tufa. The maximum known thickness is more than 760 feet beneath the central part of Parker Valley. The lower part of the formation is generally poorly permeable, but the upper part is fairly permeable where sand is more abundant. A sandy zone in the Bouse in Parker Valley yielded water at the rate of 13 (gal/min)/ft of drawdown.

As the water in the Bouse Formation embayment began to recede, the Colorado River entered the project area. Eventually, the river eroded much of the Bouse Formation, and, although the mountains rose relative to the basins, the rate of rise was so slow that the river was able to maintain its course by cutting downward into the dense rocks of the mountains, thereby carving the present intervalley canyons.

The deposits of the Colorado River and its tributaries are divided into older and younger alluviums, which represent several long periods of degradation and aggradation by the Colorado River. Because of the several periods of degradation, much of the original thickness of the alluvial deposits has been eroded from the area. Although the alluviums represent distinctive geologic units, they are sufficiently permeable to constitute a common aquifer. The greatest saturated thickness of the alluviums is about 600 feet, near Blythe, Calif.; elsewhere, the thickness is much less.

The most abundant material in the alluviums is sand, and properly constructed wells that tap sufficient thickness of clean medium to coarse sand yield water at a rate of a few tens of gallons per minute per foot of drawdown. Where saturated, coarse gravel of the alluviums is the most productive water-yielding material in the area. Yields of more than 100 (gal/min)/ft of drawdown have been obtained from wells tapping coarse-gravel aquifers.

#### YUMA AREA

The crystalline rocks of pre-Tertiary age form the boundaries of the ground-water reservoir in the Yuma

area. The ground-water reservoir consists of two major subdivisions—the poorly water-bearing rocks of Tertiary age and the water-bearing deposits of Pliocene to Holocene age.

The first subdivision—the lower part of the reservoir—includes the sedimentary and minor volcanic rocks that were deposited before the Colorado River entered the area. In generally ascending order, the rock units are (1) nonmarine sedimentary rocks, (2) volcanic rocks, (3) older marine sedimentary rocks, (4) Bouse Formation (younger marine sedimentary rocks), (5) transition zone, and (6) conglomerate of Chocolate Mountains. At most places these units either contain highly mineralized water, are too poorly permeable, or lie at too great a depth to be significant potential sources of ground water. However, in the northern part of the area some of the coarse-grained nonmarine sedimentary rocks and a conglomerate in the basal part of the Bouse Formation are moderately permeable and contain fresh water (less than 1,800 mg/l dissolved solids).

The second subdivision, or upper part of the ground-water reservoir, consists of (1) older alluvium, (2) younger alluvium, and (3) windblown sand. The older alluvium underlies most of the mesas and piedmont slopes and represents several depositional cycles, separated by periods and erosion. The younger alluvium represents the most recent depositional cycle. It underlies the flood plains of the Colorado and Gila Rivers, the ephemeral washes of the piedmont slopes, and the much more extensive alluvial fans adjacent to the western Cargo Muchacho Mountains and in southern Gila Mountains. The windblown sand forms dunes, the largest of which are the Sand Hills west of Yuma and an unnamed set of dunes just north of the southerly international boundary (fig. 9). Windblown sand also forms thin sheets on Yuma Mesa and Upper Mesa and forms small dunes in Yuma Valley and on the flood plain northeast of Yuma; these are not shown in figure 9.

Beneath the central part of the Yuma area, the upper part of the ground-water reservoir also is divided hydrologically into three zones, which are, in ascending order: The wedge zone, the coarse-gravel zone, and the upper, fine-grained zone. Outside the central area the coarse-gravel zone is absent in most places, and the upper part of the reservoir is not divided but is classified instead as older alluvium undivided.

The wedge zone is composed of older alluvium and extends to depths of about 2,500 feet south and southwest of Yuma. The lower part of the zone contains more silt and clay than the upper part, but in

general the fine-grained strata are not sufficiently extensive or thick to cause significant hydraulic separation. The upper part of the zone locally contains coarse-gravel strata similar to those in the overlying coarse-gravel zone.

The coarse-gravel zone, which is the principal aquifer beneath the river flood plains and Yuma Mesa, is a complex of gravel bodies of different ages, deposited by the Colorado and Gila Rivers. Beneath Yuma Mesa the coarse-gravel zone is within the upper part of the older alluvium, but beneath the flood plains the zone may include a basal gravel of the younger alluvium. The zone ranges in the thickness from 0 to possibly more than 150 feet; its top lies at an average depth of 100 feet beneath the flood plains and 170 to 180 feet beneath Yuma Mesa.

The upper, fine-grained zone includes both the younger alluvium beneath the river flood plains and the uppermost part of the older alluvium beneath Yuma Mesa. The zone averages about 100 feet in thickness beneath the flood plains and 170 to 180 feet beneath Yuma Mesa. Sand and silt are the most abundant materials, although beds of silty and sandy clay and sandy gravel are extensive in parts of the area. Some clay beds in the zone underlie areas of several tens of square miles but do not appear to cause significant hydraulic separation, probably because they are fairly sandy in places.

#### IMPERIAL VALLEY AREA

The pre-Tertiary crystalline rocks of the Imperial Valley area are overlain by trough-filling deposits estimated, on the basis of geophysical evidence, to be more than 20,000 feet thick locally. These deposits are dominantly nonmarine and, beneath the central part of the valley, mostly Pliocene to Holocene in age. For hydrologic purposes, the deposits are grouped into three broad categories: (1) a lower sequence composed chiefly of nonmarine sedimentary rocks of early to middle Tertiary age but also including volcanic rocks and minor marine sedimentary rocks; (2) a middle marine unit, the Imperial Formation, of late Tertiary (Miocene or Pliocene) age; and (3) an upper sequence composed of predominantly nonmarine deposits of late Tertiary (Pliocene) and Quaternary age. The upper sequence constitutes the main part of the ground-water reservoir beneath Imperial Valley.

The lower sequence, exposed in the mountains and hills on the margins of the valley, is, if present, far too deep beneath the central part of the valley to be a possible source of ground water. Moreover, the rocks there would be expected to have extremely low permeability and to contain saline water.

The marine Imperial Formation may be in part equivalent to the Bouse Formation of the Yuma, Parker-Blythe-Cibola, and Needles areas. Although the formation is exposed on the west side of Imperial Valley, the Imperial Formation has not been recognized in several oil test wells, as much as 13,443 feet deep, in the central part of the valley. If present, the Imperial Formation would form an effective floor of the upper part of the ground-water reservoir, owing to its generally low permeability and probable content of saline water.

The upper sequence, which overlies the Imperial Formation, is predominantly nonmarine but includes some marine strata and evaporite beds representing, respectively, periodic incursions of the Gulf of California and intermittent lakes. In the marginal parts of the Imperial Valley area, the nonmarine deposits are of local derivation, but most of the deposits in the central part of the valley were brought in by the Colorado River. In general, the deposits of the Colorado River are finer grained and better sorted than the locally derived deposits.

### CHEMICAL QUALITY OF GROUND WATER

Chemical analyses of samples of ground water obtained within short distances of one another in the project area often show a wide range in the percentage and concentration of the six ionic constituents that make up the bulk of the dissolved solids. Except for relatively small quantities of ground water that were derived locally, the water in the valleys upstream from the Yuma area is derived almost wholly from the Colorado River, whereas in the Yuma area the water is derived from both the Colorado and the Gila Rivers.

The observed wide range in chemical quality of ground water in areas where the source obviously was the Colorado River can be explained as the result of one or more of the following processes: (1) Concentration of dissolved solids by evapotranspiration, (2) softening, (3) carbonate precipitation, (4) sulfate reduction, (5) hardening, (6) re-solution of precipitated salts, (7) oxidation of dissolved organic substances, and (8) mixing of waters of different chemical composition.

By beginning with a weighted average chemical analysis of recent Colorado River water and by using several combinations of the first five processes carried out to various degrees, most types and dissolved-solids concentrations of ground water derived from the Colorado River can be duplicated. Sulfate reduction appears to be a major process in the

chemical alteration of Colorado River water to a water containing fewer dissolved solids than the river.

Chemical analyses of water from wells in the Needles area suggest that the ground water there is generally of better quality than that in the downstream valleys. About half of the 95 ground-water samples analyzed contained dissolved solids of less than 1,000 mg/l and 6 had less than 500 mg/l. On the other hand, 6 analyses showed dissolved-solids concentrations between 2,000 and 3,290 mg/l.

Ground water acceptable for domestic use, public supply, or irrigation can be found at some depth in most parts of the Parker-Blythe-Cibola area. However, there are areas beneath which water of satisfactory quality is limited to thin strata or is not available. Much of the shallow ground water beneath the flood plain is relatively poor in quality except near the river or where it has been freshened as a result of irrigation. Shallow ground water in the nonirrigated southern part of Parker Valley commonly is several times more mineralized than river water. Shallow ground water of poor quality is also common beneath the nonirrigated land in Cibola Valley and in the southern part of the Palo Verde Valley.

In Parker Valley water from the principal gravel zone is generally similar to, but somewhat more mineralized than, present-day Colorado River water. However, near the eastern margin of Parker Valley south of Bouse Wash, in the southern part of Palo Verde Valley, and in Cibola Valley, the water in the principal gravel zone contains sufficient chloride to make it unfit for most domestic uses and is marginal to unsatisfactory for sustained irrigation. Near Blythe, Calif., water beneath the principal gravel zone contains considerably less sulfate and somewhat less dissolved solids than Colorado River water. Beneath the piedmont slopes, where local recharge moves toward the flood plain, the chemical quality of the ground water is commonly different from, and less concentrated than, Colorado River water.

Fluoride concentrations in excess of limits recommended by the U.S. Public Health Service (1962, p. 8) for drinking water on interstate carriers have been noted in many samples of water obtained from units older than the Colorado River deposits, such as the Bouse Formation and the Miocene(?) fanglomerate.

Fresh water (less than 1,800 mg/l dissolved solids) extends to depths of more than 2,500 feet in the south-central and southwestern parts of the Yuma area. Most of this water is in the wedge zone, but the overlying, more permeable coarse-gravel zone yields

much more water to wells. In the northern part of the area the water in the wedge zone is substantially fresher than that in the coarse-gravel zone, but in the southern part the chemical quality of the water in the two zones is virtually identical.

Ground water in the coarse-gravel zone beneath South Gila Valley and beneath eastern North Gila Valley generally contains more than 1,800 mg/l but less than 3,600 mg/l of dissolved solids. Elsewhere in the northern part of the Yuma area, the water in the coarse-gravel zone contains less than 1,800 mg/l. Water in the overlying fine-grained zone locally is more highly mineralized than water in the coarse-gravel zone. Beneath Yuma Valley the chemical quality of water in the coarse-gravel zone and in the overlying fine-grained zone is not well known, but the freshest water (commonly containing less than 900 mg/l of dissolved solids) occurs near the Colorado River.

Beneath the irrigated parts of Yuma Mesa, the ground water is similar to Colorado River water in which the dissolved solids have become concentrated by evapotranspiration. Outside the irrigated area and at depths beneath the irrigated area sufficiently deep that the native water has not been displaced by the infiltration of irrigation water, the concentration of dissolved-solids is less than 1,800 mg/l, and chloride, rather than sulfate, is the major anion.

Infiltration of local runoff has resulted in a few limited zones, such as the one beneath Fortuna Wash, 12 miles east of Yuma, where a lens of water containing only a few hundred milligrams per litre of dissolved solids has displaced water containing a much higher concentration of dissolved solids.

Beneath most areas in central Imperial Valley, the ground water contains sufficient dissolved solids to make it unsatisfactory as either a domestic or an irrigation supply. Several test wells, drilled to depths of as much as 1,000 feet, in the southern and western parts of central Imperial Valley yielded water containing 5,000 mg/l or more of dissolved solids.

The largest known body of fresh ground water in the Imperial Valley area is beneath the southeastern part of East Mesa. Fresh water extends from a few tens of feet below land surface to more than a 1,000 feet below land surface near the head of the Coachella Canal. The other principal areas of fresh ground water are on the west side of the valley. They are in the Lower Borrego Valley, the San Felipe Creek area, and the Coyote Wells area. Ground water beneath the developed part of the Coyote Wells area generally contains less than 400 mg/l of dissolved solids. Water from this area is hauled by tank truck to communities

as far away as Calexico, Calif., and Mexicali, Baja California, Mexico, for drinking water.

### HYDRAULIC PROPERTIES OF ROCKS

Analyses of test-drilling data, pumping tests, and the specific capacities of existing wells indicate that some of the gravel deposits of both the Colorado and Gila Rivers, whether classified as younger or older alluviums, are highly transmissive. The more permeable deposits, commonly 10-70 feet thick, have hydraulic conductivities of about 10,000 (gal/d)/ft<sup>2</sup>. Transmissivities of these deposits, computed from pumping tests of wells, ranged from about 100,000 or 200,000 (gal/d)/ft to about 1 million (gal/d)/ft.

Hydraulic-conductivity values of sand strata range widely but generally are a few hundred gallons per day per square foot. However, some clean sands at moderate depths have conductivities of 1,000 (gal/d)/ft<sup>2</sup> or more.

Transmissivity values for the younger and older alluviums of the Colorado river and its tributaries in the Yuma area are shown in figure 11. The values are the sums of transmissivity values computed for the coarse-gravel zone and the wedge zone that were simulated in the electric analog model of the Yuma areas. Practically all ground-water movement in the Yuma area occurs in these zones.

Large-diameter wells that tap 10 feet or more of the highly permeable gravel can be expected to yield 30 or more (gal/min)/ft of drawdown. Specific capacities of several hundred gallons per minute per foot of drawdown are obtainable in some parts of all the major river valleys. A few of the more favorably located wells in the Yuma area have specific capacities of about 400 (gal/min)/ft of drawdown. Wells that tap 100 feet or more of clean medium to coarse sand commonly have specific capacities of a few tens of gallons per minute per foot of drawdown. In the central part of Imperial Valley, where sand and silt constitute most of the water-bearing material, specific capacities range from a fraction of a gallon to several gallons per minute per foot of drawdown.

### GROUND-WATER RESOURCES VIRGIN CONDITIONS

Under virgin (natural) conditions the principal source of ground water in the lower Colorado River basin was the Colorado River. Sources of recharge directly from precipitation, from the infiltration of tributary streams, and from underflow from tributary areas were only very minor. Recharge from the Colorado River occurred by direct infiltration and by

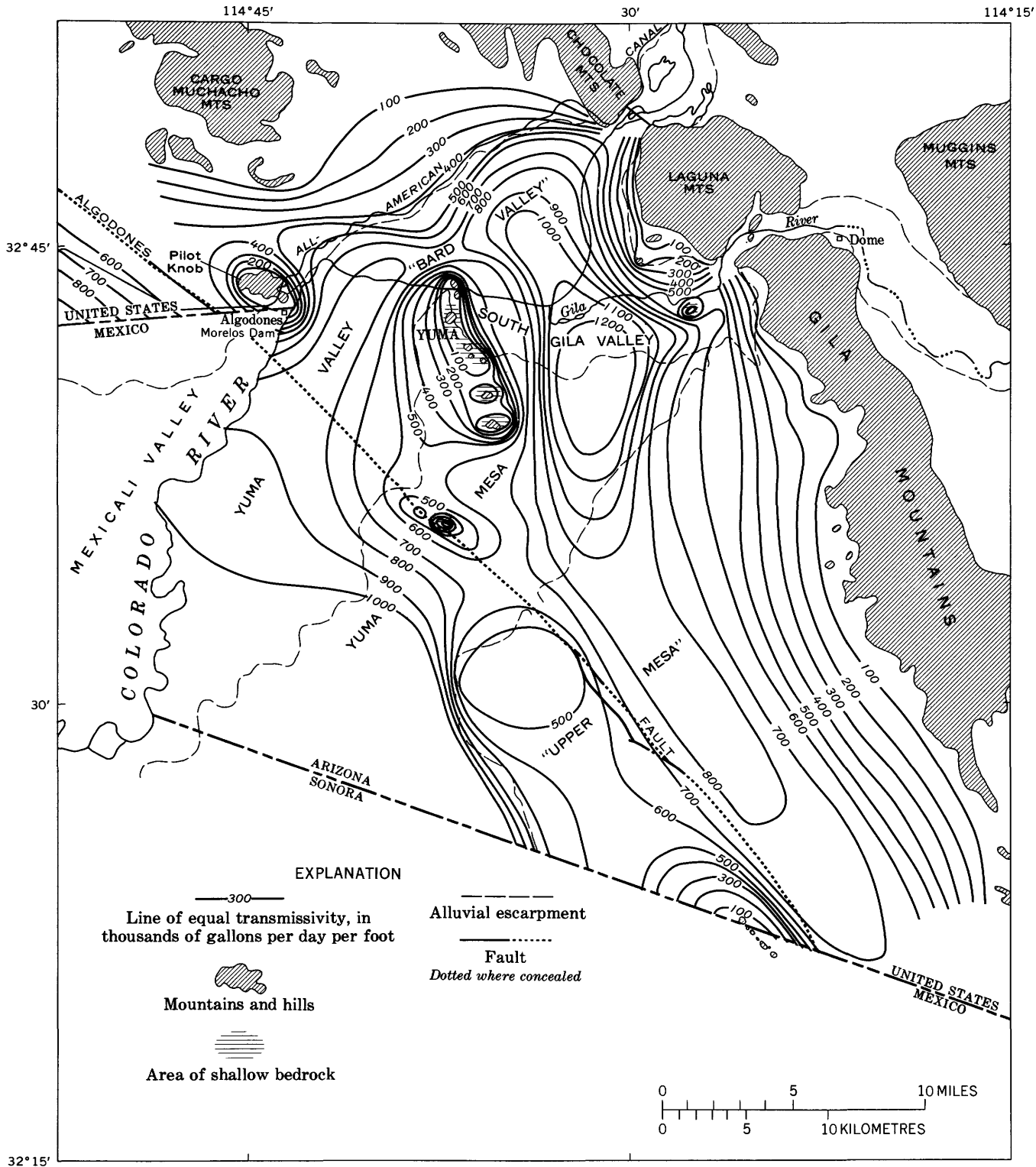


FIGURE 11.—Transmissivity values for the younger and older alluviums in the Yuma area.

infiltration in flooded areas. The latter was a significant source of recharge in the lower lying parts of the flood plain because, prior to the construction of

upstream reservoirs, the river annually flooded substantial parts of the plain and filled abandoned channels.

The recharge both from direct infiltration of water from the river and from floodwater was consumptively used mainly by transpiration of natural vegetation or by evaporation from wet soil. Discharge by transpiration of natural vegetation in Yuma Valley is estimated to have been between 100,000 and 150,000 acre-ft/yr. Half this discharge is estimated to have been supplied by direct infiltration from the river. Direct infiltration of river water which supplied evapotranspiration requirements of natural vegetation in Parker Valley was about 100,000 acre-ft/yr. Similar conditions existed in the other major flood-plain valleys. Thus, under virgin conditions, the Colorado River was a losing stream throughout much of its course through the major river valleys.

#### CONDITIONS DURING DEVELOPMENT

The completion of Hoover Dam in 1935 provided a major control for river flows, thereby eliminating both the annual floods that formerly inundated the lower lying lands of the downstream valleys and the recharge from infiltration of floodwater.

Although irrigation by diverting river water to the various valleys had been practiced since before the turn of the century, the newly acquired ability to adequately control flows encouraged the rapid expansion of irrigation agriculture. By 1960 most of the flood-plain valleys in the Yuma area, the flood plain of Palo Verde Valley, and the central part of Imperial Valley were nearly fully developed, and almost 20,000 acres on the Yuma Mesa was being irrigated. Irrigation was being practiced on a limited scale in Mohave and Cibola Valleys and on a moderate scale in Parker Valley. Canals for conveying large quantities of river water to remote areas had been completed. As a result, the ground-water system, which, under virgin conditions, had been recharged from flooding, now was recharged from infiltration of water diverted from the river which was not used consumptively by crops. In Mohave and Cibola Valleys this recharge was negligible, but in Parker Valley it was about 200,000 acre-ft/yr. In Palo Verde Valley and in the flood-plain valleys of the Yuma area, the recharge ranged from 2 to 5 acre-feet per acre irrigated per year, or from about one hundred thousand to several hundred thousand acre-feet annually.

A notable example of the additional recharge to ground water that resulted from an expansion irrigated acreage is the increase in ground-water recharge beneath Yuma Mesa. From 1942, when only 1,500 acres was irrigated, until 1954, when about 17,000 acres was irrigated, the yearly recharge

increased from 8,000 to 177,000 acre-feet. For the 5-year period beginning in 1960, the recharge averaged 226,000 acre-ft/yr but for the next several years declined to somewhat less than 200,000 acre-ft/yr, mainly because of improved irrigation practices.

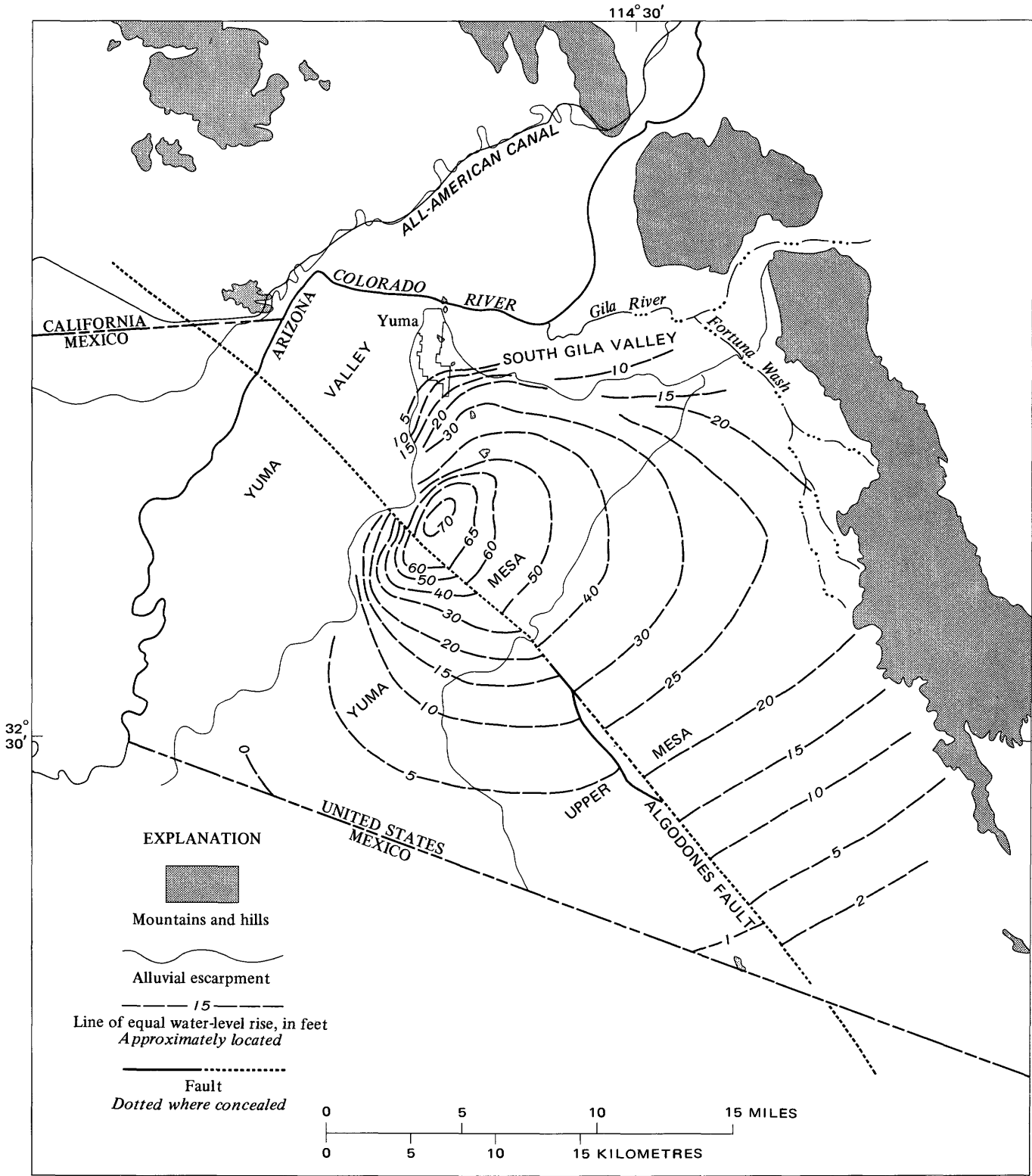
The initial effect of increased recharge from irrigation in all areas was a rise in ground-water levels. Eventually, water levels in parts of each area rose into the root zone sufficiently to impair crop growth. Drainage systems, some of which were extensive, were constructed to keep water levels at satisfactory depths. Thus, much of the increase in ground-water recharge from irrigation eventually was balanced by a similar increase in ground-water discharge to drains or to drainage wells.

Increases in ground-water storage that resulted from increased recharge were generally limited to the quantities of water contained in a 5 to-10-foot-thick volume of the flood-plain deposits, because rises in excess of the above range generally caused water levels to invade the root zone of crops, which then prompted remedial action for lowering water levels.

One area where the preceding generalization does not hold is Yuma Mesa, where, prior to the beginning of irrigation development, water levels were more than 70 feet below land surface. Changing much of the mesa from a desert area to a highly developed irrigated area resulted in the building of a large ground-water mound, the extent and thickness of which are shown in figure 12. By 1960 the mound contained about 1.3 million acre-feet of water in the United States alone.

Southward extension of the mound is curtailed by the barrier effect of the Algodones fault that probably exists at depth below the Yuma Mesa. The westward and northward extent of the mound was curtailed by pumping of drainage wells in the flood plain adjacent to the northern and western boundaries of the mesa. In the late 1950's, before the drainage wells were being pumped in the flood plain at the northern edge of the mesa, the apex of the mound was so near land surface that a tile drainage system was installed in a limited area near the apex to lower water levels to acceptable depths. Increased pumping of drainage wells in the flood plain adjacent to the western margin of the mesa and the pumping of newly constructed drainage wells adjacent to the northern margin of the mesa during the next decade lowered water levels in the higher parts of the mound sufficiently to cause the tile drainage system to become inoperative. Average annual pumpage from drainage wells increased from 19,000 acre-feet during 1948-52 to 120,000 acre-feet





Base from U.S. Geological Survey

Hydrology by O. J. Loeltz

FIGURE 12.—Change in water level beneath Yuma Mesa, 1925-66

during 1963–66. Had not these drainage wells been adjacent flood-plain agricultural areas would have used to the extent that they were, large areas of the been waterlogged.

## GROUND-WATER MOVEMENT

The direction and the quantity of ground-water movement have been changed greatly in some areas because of developments by man. In most of the river valleys where irrigation with Colorado River water is extensive, water levels beneath the flood plain have risen above the levels that existed under virgin conditions. Generally, this rise of water levels has reduced the direct infiltration of river water that occurred under virgin conditions, but in some reaches, the rise has been sufficient to reverse the direction of the interflow between the river and the ground-water reservoir. For example, in the reach between Imperial Dam and the northerly international boundary, the river is now receiving water from the ground-water reservoir, whereas under virgin conditions the river was supplying water to the ground-water reservoir. Reversals of this type have also occurred in Palo Verde Valley and, to a lesser extent, in Parker Valley. On the other hand, man's activities have increased the infiltration rate from the river to the ground-water reservoir in some reaches. Probably the most noteworthy example is the Needles area, where infiltration from the river was increased by higher river stages that resulted from aggradation of the river channel upstream from Lake Havasu after completion of Parker Dam.

The water-level-contour maps of the principal areas indicate reaches where ground water is moving toward or away from the river. Further studies and additional data are needed if a more precise determination is to be made of where and at what rates interchange between ground water and the river occurs. Water-level contours in figure 13 indicate that the river probably is losing water throughout the reach north of Needles. Similarly, contours in figure 14 indicate that some ground water probably is discharging to the river in the reach in the upper half of Parker Valley; however, in most of the rest of the reach in Parker Valley the river is losing water to the ground-water reservoir.

Water-level contours for Palo Verde Valley indicate that some of the river reaches, especially in the northern part of the valley, are receiving ground-water discharge. In the southern part of the valley, the relation between the river and the ground-water system is less clear. In Cibola Valley the river apparently is losing a considerable amount of water to areas east of the river.

Water-level contours for the delta region (fig. 15), which includes the Yuma area, indicate that ground water is discharging to the river upstream from the northerly international boundary. The average yearly

discharge to the river during 1960-63, on the basis of ground-water parameters, is estimated to be 72,000 acre-feet. The contours also indicate westward movement of ground water from Yuma Valley. However, because of local conditions most of the ground water does not discharge into the river but continues to move westward into the Mexicali Valley. This outflow averaged 33,000 acre-ft/yr during 1960-63. Southward movement across the international boundary east of the river during 1960-63 is estimated to have been 35,000 acre-ft/yr on the basis of the distribution of annual outflow from the ground-water mound beneath Yuma Mesa during the same period. Had the estimate been made on the basis of transmissivities and indicated hydraulic gradients, as was done for a 1970 study, the estimated outflow would have been about 6,000 acre-feet more. Readjustments of the other quantities of westward and northward outflow from the mound that would be required to keep the total outflow unchanged would not be unreasonable and would reduce the imbalance in the water budget for the Yuma Valley subarea. If estimates of outflow are to be used as a basis for comparison between the outflow during selected periods covered by the present study and outflows for future periods, the computations should be based solely on transmissivity and hydraulic gradients so that both values will have a common base.

The movement of ground water in Imperial Valley, as inferred from water-level contours (fig. 16), is generally westward and northwestward toward the Salton Sea. Much of the discharge, except that from the shallow deposits, is by upward leakage either to drains or to the lower reaches of the Alamo and New Rivers. A large part of the leakage from the All-American Canal, estimated at 150,000 acre-feet annually in 1961-63 for the 37-mile reach west of Pilot Knob, moves southward from the canal across the international boundary into Mexicali Valley. Prior to the construction of the canal, the rate of movement of ground water was much less, and the movement generally was parallel to the international boundary.

## CHANGES IN THE HYDROLOGIC ENVIRONMENT

During the past 40 years the hydrologic environment of the lower Colorado River has been altered greatly by man in his attempts to utilize more fully the flow of the river. Consequently, during the 10-year period of the lower Colorado River study, many changes occurred that necessitated a shift in emphasis on certain phases of the investigation.

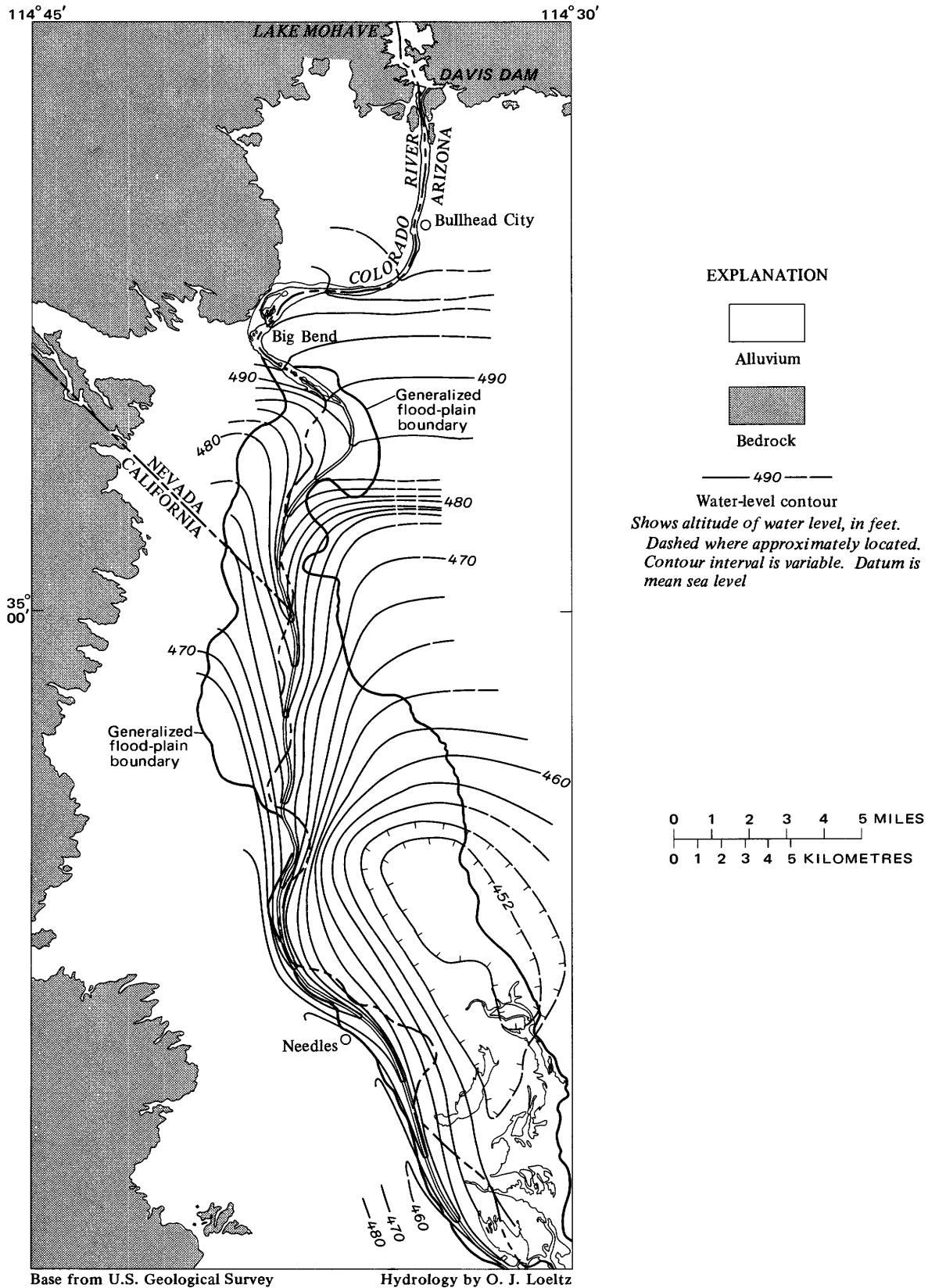


FIGURE 13.—Generalized water-level contours during 1962-69 in Mohave Valley, Ariz.-Calif.-Nev.

WATER RESOURCES OF LOWER COLORADO RIVER – SALTON SEA AREA

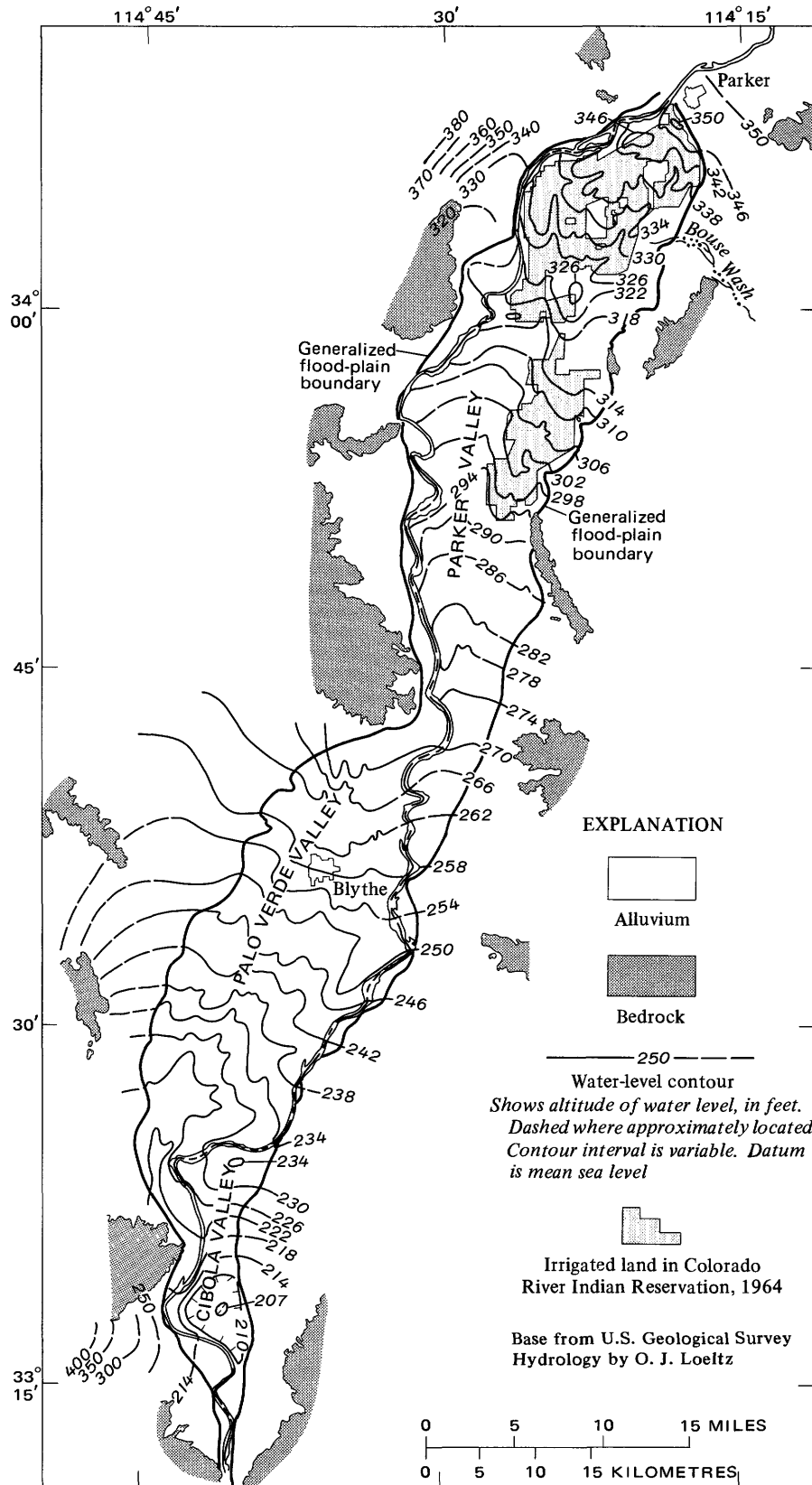
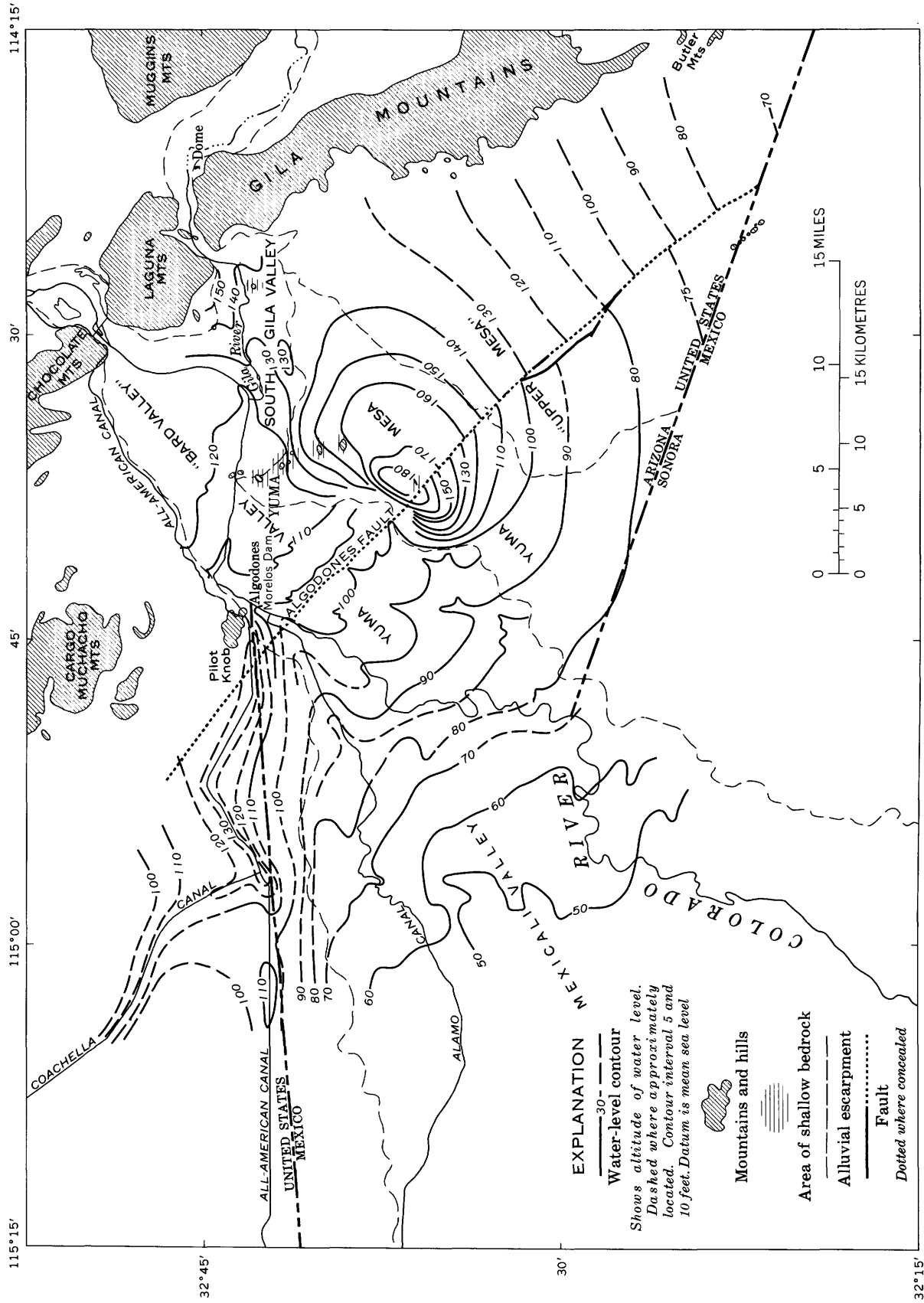


FIGURE 14.—Generalized water-level contours in Parker-Blythe-Cibola area, 1964.



Hydrology by O. J. Loeltz

FIGURE 15.—Average water-level contours in the delta region in December 1965.

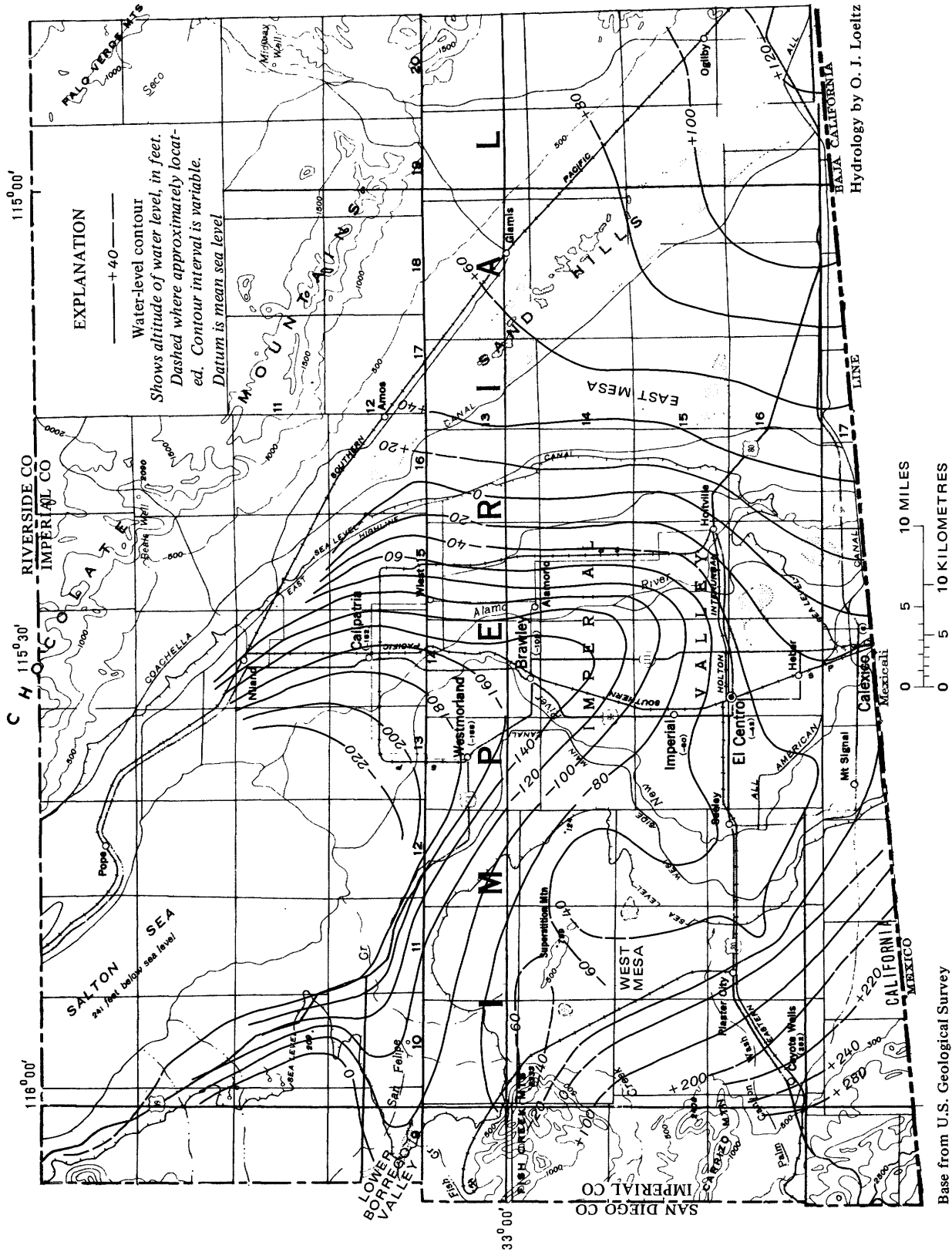


FIGURE 16.—Water-level contours of main body of ground water in Imperial Valley, 1965

A large increase in irrigated acreage in the Colorado River Indian Reservation in Parker Valley followed the change from short-term to long-term leasing of agricultural land. Development of the new land caused a marked increase in return flows and in the annual load of salt from Parker Valley to the Colorado River.

Many applications for acquiring land on the Palo Verde Mesa, west of Blythe, Calif., under terms of the Desert Land Act were filed during the investigation. The effects of pumping ground water for irrigation of these lands on the ground-water supplies in the flood plain east of the mesa and the long-term effects on the depletion of the Colorado River were questions that arose during the investigation.

Pumping of ground water for irrigation on the Yuma Mesa increased from virtually nothing in 1960 to about 30,000 acre-feet in 1969. This pumping, by private citizens outside the irrigation district boundaries, utilized some of the recharge to the area that resulted from irrigating 20,000 acres of citrus with Colorado River water. A determination of the effects of this pumping and further planned developments on the ground water stored beneath the mesa and on the ground-water outflow from the mesa to Yuma Valley and across the international boundary into Mexico was a phase of the investigation that was not anticipated at the beginning of the project studies.

In the South Gila Valley in the Yuma area, Colorado River water was made available for irrigating some 9,000 acres of land that until 1965 had been irrigated solely by pumping ground water. Pumpage from drainage wells, sumps, and drains adjacent to the Yuma Mesa increased from about 70,000 acre-feet in 1960 to 146,000 acre-feet in 1969. The disposal of this drainage water and an additional 200,000 acre-feet of moderately saline (4,000-6,000 mg/l) pumped return flow from the Wellton-Mohawk area beginning in 1961 necessitated a much more careful monitoring of these flows and their salinities to permit their disposal in a manner satisfactory, on a temporary basis, to interests in both the United States and Mexico.

Pumpage for irrigation in Mexicali Valley increased from about 700,000 acre-feet in 1960 to almost 1 million acre-feet near the end of the decade. This increase in pumpage, in addition to the increase from about 300,000 acre-feet in 1956 to the 700,000 acre-feet in 1960 steepened the hydraulic gradients across the limitrophe (international boundary) section of the river. As a consequence, extensive studies, which included the use of the electric analog model of the Yuma area, were made to determine the overall effects of the pumping in Mexicali Valley on the flow of ground water across the international boundary.

The filling of newly created Lake Powell during the project resulted in changes in the surface-water regimen of the river and also affected the chemical quality of the river downstream from the lake.

Other changes in regimen resulted from the large-scale channel-improvement program of the U.S. Bureau of Reclamation. Improvement of channel geometry, alinement, and dredging operations were completed for several reaches in the project area. Some of the realinement and dredging operations resulted in significant changes in the relation between the river and the ground-water reservoir.

## CONTINUING PROBLEMS AND PROPOSED INVESTIGATIONS

Distribution of the available supply of Colorado River water in an equitable manner to all parties dependent on that water will always pose some problems. These distributions are intrastate, interstate, and international and will become more difficult as the increasing demands for water equal and eventually exceed the available supply.

In recent years major interests in all the basin States have been coming to the conclusion that the solution of the water-supply problems of the Southwest requires a regional approach. Accordingly, in 1965 the governors of 11 western States directed the organization of the Western States Water Council, comprising representatives of the 7 Colorado River basin States and the 4 Pacific Northwest States, to seek the solution of water problems on a West-States basis.

Further recognition of the need for a regional approach was the passage by Congress and the signing into law by the President on September 30, 1968, the Colorado River Basin Project Act (Public Law 90-537), the major features of which are—

1. The Central Arizona Project and several Upper Colorado River Basin projects are authorized for construction and the Dixie Project in southern Utah is reauthorized.
2. Existing Arizona, California, and Nevada contractors for water receive a priority of deliveries over the Central Arizona Project.
3. The United States assumes the responsibility of meeting the Mexican Treaty water deliveries when the flow of the river is augmented by 2.5 million acre-feet or more of water per year.
4. The Secretary of the Interior is to study water supply and requirements and develop a plan for

meeting the water needs of the West, but any study for importing water from any other natural river drainage basin to the Colorado River basin must be delayed 10 years.

5. A basin fund is established to help repay future augmentation costs.
6. Priorities are established for the operation of the major Colorado River reservoirs.

Adequate augmentation of the water supply from sources outside the basin, however, could not become a reality for several decades even if such a decision were finally made. First, it would be necessary to achieve regionwide concurrence of its desirability; and second, many years would be required to obtain the necessary authorization, to arrange adequate financing, and to design and construct the extensive facilities that would be needed.

Methods for augmenting the freshwater supply other than by importing fresh water are in limited use or being investigated. Weather modification, specifically cloud seeding to increase precipitation in a given area at a given time, is being used successfully in more areas and with greater frequency than was true just a few years ago. Studies are being made by the University of California at Riverside to determine if ground water can be desalinated in conjunction with the development of the geothermal resources of Imperial Valley. Initial studies at the University of Arizona suggests that the capture of solar energy as a heat source for generating electricity by means of steam turbines may be economically feasible. If so, the solar energy falling on the vast expanse of desert in the lower Colorado River valley would be sufficient to generate enough power to meet the needs of the entire Southwest for the foreseeable future and also to desalinate tens of millions of acre-feet of sea water annually. These possibilities need to be studied further.

In the meantime, present measures should be continued and new measures undertaken for reducing insofar as is economically feasible unnecessary losses and waste of the present supply.

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