Lower Colorado River Water Supply— Its Magnitude and Distribution

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By ALLEN G. HELY

WATER RESOURCES OF LOWER COLORADO RIVER–SALTON SEA AREA

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LOWER COLORADO RIVER WATER SUPPLY—ITS MAGNITUDE AND DISTRIBUTION

By Allen G. Hely

ABSTRACT

The water supply in the lower Colorado River depends almost entirely on (a) the virgin flow at compact point (Lee Ferry), near Lees Ferry, Ariz., (b) the depletion of that flow caused by storage above compact point and use of water in the upper Colorado River service area, and (c) the provisions of the Colorado River Compact for release of water to the lower river.

The computed average annual virgin flow at compact point for the 71 water years 1896–1966 is 14,900,000 acre-feet, but for the 34 years, 1931–64, it is only 12,900,000 acre-feet. During the decade 1953–62 the virgin flow was depleted about 2 million acre-feet per year by diversion and use in the upper service area. These depletions increased sharply after 1962 and probably will continue to increase for many years.

Probability and storage analyses indicate that the water supply derived from the Colorado River system above compact point to meet all demands for depletion above that point and release to the lower river can be sustained at about 13 million acre-feet, and that 14 million acre-feet will be available most of the time.

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 development of water supplies progresses considerably and also during subsequent periods of abundant runoff.

Below compact point, the losses associated with storage and transport of water exceed the inflow from tributaries. Lake Mead provides storage capacity for regulation of the flow that cannot be regulated above compact point, and appropriate use of this capacity can increase the total usable supply below Lake Mead. However, if maximum feasible use is made of the capacity above compact point, storage in Lake Mead can contribute little if any to the dependable supply below the lake because of the large evaporation losses associated with long-term storage.

The annual depletion of the Colorado River caused by use in Arizona of water from the main stem increased from less than 200,000 acre-feet in 1915 to about 1,100,000 acre-feet in 1960. Corresponding depletions caused by use of water in California were 1,800,000 acre-feet and 4,900,000 acre-feet. In the same years the principal diversions to Mexico (via the Alamo Canal) were 240,000 acre-feet and 1,800,000 acre-feet, respectively. As a result of such increases in water use and the predominately below average runoff since 1930, flow into the Gulf of California has diminished to negligible quantities in recent years. Future distribution of the available water supply in accordance with the U.S. Supreme Court decree of 1964 will permit a large increase in the amount of Colorado River water used in Arizona and will require a decrease in the amount used in California, at least during periods of below-average runoff.

The beneficial use of water below compact point is accompanied by large losses, some avoidable and some unavoidable. Evaporation from the Colorado River and from reservoirs consumes more than a million acre-feet per year, and nearly worthless native vegetation consumes more than half a million acre-feet. Seepage from large canals between Imperial Dam and the areas served amounts to about half a million acre-feet, some of which is being recovered or is recoverable. Considerably more than a million acre-feet per year drains to the Salton Sea. Although drainage is necessary to maintain productivity of the land and is also essential to the continued existence of the sea, much of this water can be considered a loss from the standpoint of irrigation. Annual deliveries of water to Mexico during 1961–63 exceeded treaty requirements by about 400,000 acre-feet, which can be considered a loss to the United States.

With no new importation of water to the lower Colorado River and with natural water yields similar to those of 1931–64, any new diversions from the river will depend chiefly on redistribution of the available supply among the States and on more effective use of that supply. The increased effectiveness can be achieved by such means as channel improvement and canal lining; eradication of worthless or low-value vegetation; increased use of holdover surface storage for water-supply rather than power needs; more precise deliveries of water to irrigation districts and Mexico; and controlled withdrawals of ground water from aquifers near the river to utilize their storage capacity, reduce evapotranspiration losses, and provide adequate drainage of fields.

The basic allotments of water from the upper Colorado River system and the lower river by compact and treaty amount to 16,500,000 acre-feet. If these basic allotments do not include unavoidable losses from the river and reservoirs below com-

pact point, the total water supply required for their fulfillment is more than 17,500,000 acre-feet. This potential requirement exceeds the 34-year (1931–64) mean virgin flow by 4,600,000 acre-feet.

INTRODUCTION

The Colorado River basin includes about 243,000 square miles in Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming in the United States and more than 1,000 square miles in Baja California and Sonora, Mexico. As most of the drainage basin is arid or semiarid, the flow of the river is small relative to its drainage area and is insufficient to meet the potential demand for water in the service area, which includes large areas outside the drainage basin but within the same States. Competition for rights to use water from the Colorado River system has resulted in an international treaty, interstate compacts, legislation at both State and national levels, delay in planning and construction of water utilization projects, and seemingly endless conflict and litigation.

The Colorado River basin is so extensive and its hydrologic characteristics are so diverse that investigations and appraisals of the water resources for certain parts of the basin or its service area are most conveniently made separately, even though the interrelations between the parts must be recognized. This investigation and appraisal concern most of the area for which the lower Colorado River has been the principal source of water supply but includes only a part of the "Lower Basin" as defined in the Colorado River Compact.

As defined by drainage boundaries, the report area consists of the Salton Sea basin and the natural drainage area of the Colorado River below Davis Dam, Ariz.-Nev., excluding the Bill Williams River basin above the gaging station near Alamo, Ariz., the Gila River basin above the Wellton-Mohawk Irrigation and Drainage District, and the drainage area of San Cristobal Wash (a desert wash that enters the Gila River from the south just below the upper end of the irrigation district). The investigation extended into Mexico only as far as necessary to delineate the hydrologic problems and relationships near the international boundary. For reasons to be explained, the investigation included the main stem of the Colorado River up to compact point, Ariz. Figure 1 shows the relation of the 25,000-square mile report area to the entire basin and its surroundings.

This report is one of a series that constitutes an appraisal of the water resources of the area described. It concerns waters of the lower Colorado River and their disposition, which is largely by diversion for irrigation. Ground water related to the river or to irrigation with river water and the quality of the water are discussed herein only as required for a comprehensive description of the river. Separate reports on these topics are in preparation. Use of water for the generation of hydroelectric power and for recreation is given only incidental consideration because these uses have very little effect on the supply of water available for irrigation, municipal, and industrial uses. Although power generation has been a major factor in the economic feasibility of major river-development projects and recreational use of reservoirs and several reaches of river channel has become a major factor in the economy of the region, the Colorado River Compact established higher priorities for irrigation, municipal, and industrial uses.

The investigation and appraisal were made under the general supervision of C. C. McDonald, project hydrologist. Many organizations furnished records or cooperated with the Geological Survey in gathering the streamflow data used in this report. Most of the records used are contained in the annual series of reports and in compilation reports by the U.S. Geological Survey (1954, 1964), and the details of such cooperation are contained therein. The U.S. Bureau of Reclamation furnished additional records of water distribution and return flows near Yuma, Ariz.; the United States Section of The International Boundary and Water Commission furnished records of flow at the boundary; the Imperial Irrigation District furnished records for Imperial Valley, Calif., including the All-American Canal below Pilot Knob and part of the Coachella Canal, and also for the Alamo Canal in Baja California; the Coachella Valley County Water District furnished records for Coachella Valley, Calif.; and the Upper Colorado River Commission furnished estimates of virgin flow at compact point, Ariz.

THE LOWER COLORADO RIVER AND ENVIRONS

A legal division of the Colorado River service area into an "Upper Basin" and a "Lower Basin" was made by terms of the Colorado River Compact at a point on the Colorado River 1 mile downstream from the Paria River, 17 miles downstream from Glen Canyon Dam, and 29 miles downstream from the Arizona-Utah boundary. Although the compact refers to this point as Lee Ferry, this and many other Geological Survey reports refer to it as compact point to avoid confusion with stream-gaging stations that are above the confluence of the two rivers and that are named for the community of Lees Ferry at the confluence.

The features of the Colorado River system above Davis Dam that are most significant in this study are shown in figure 1. The major features below Davis Dam and the principal tracts in the report area that use Colorado River water are shown in figures 2–4.

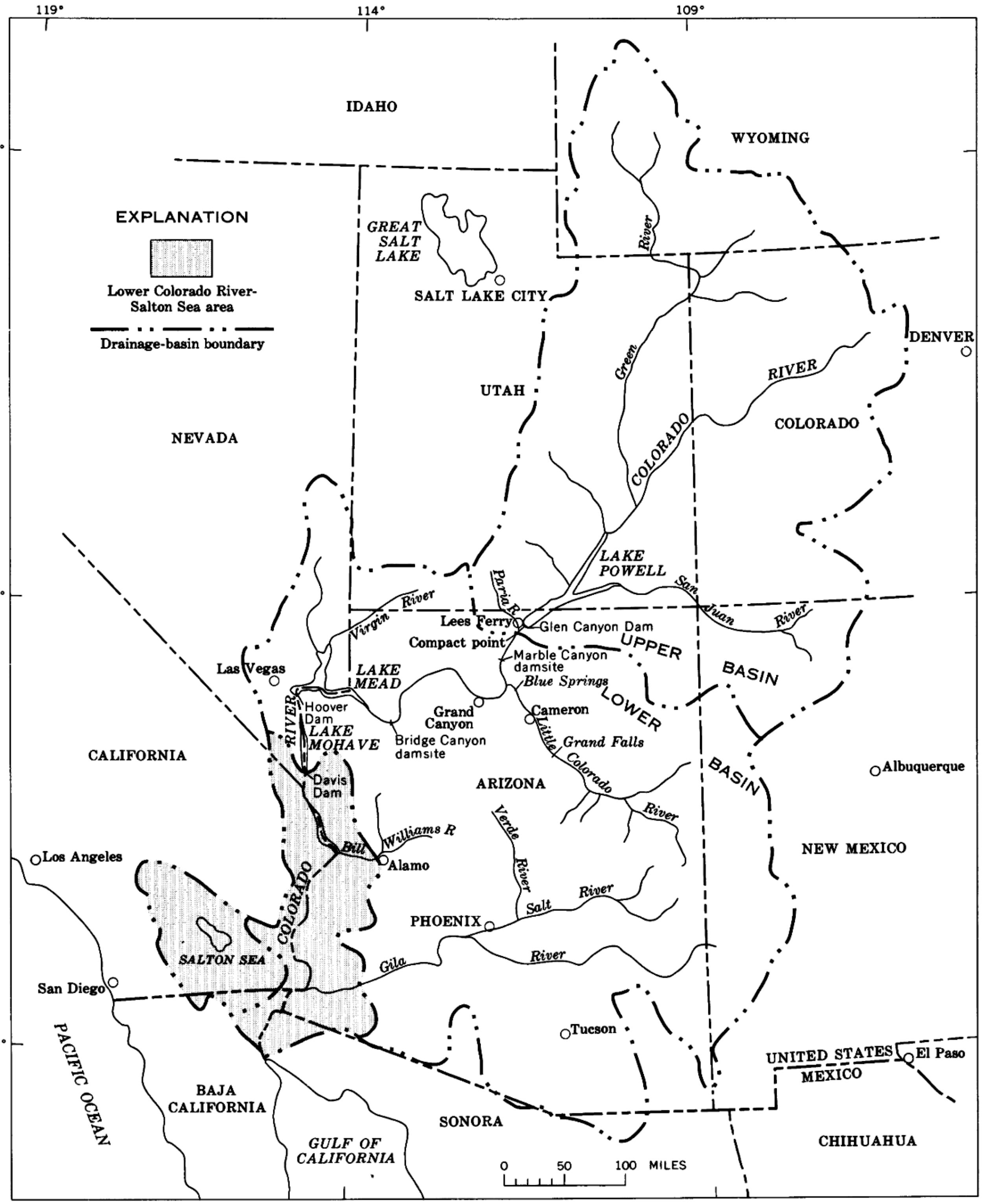

FIGURE 1.—The Colorado River basin showing report area.

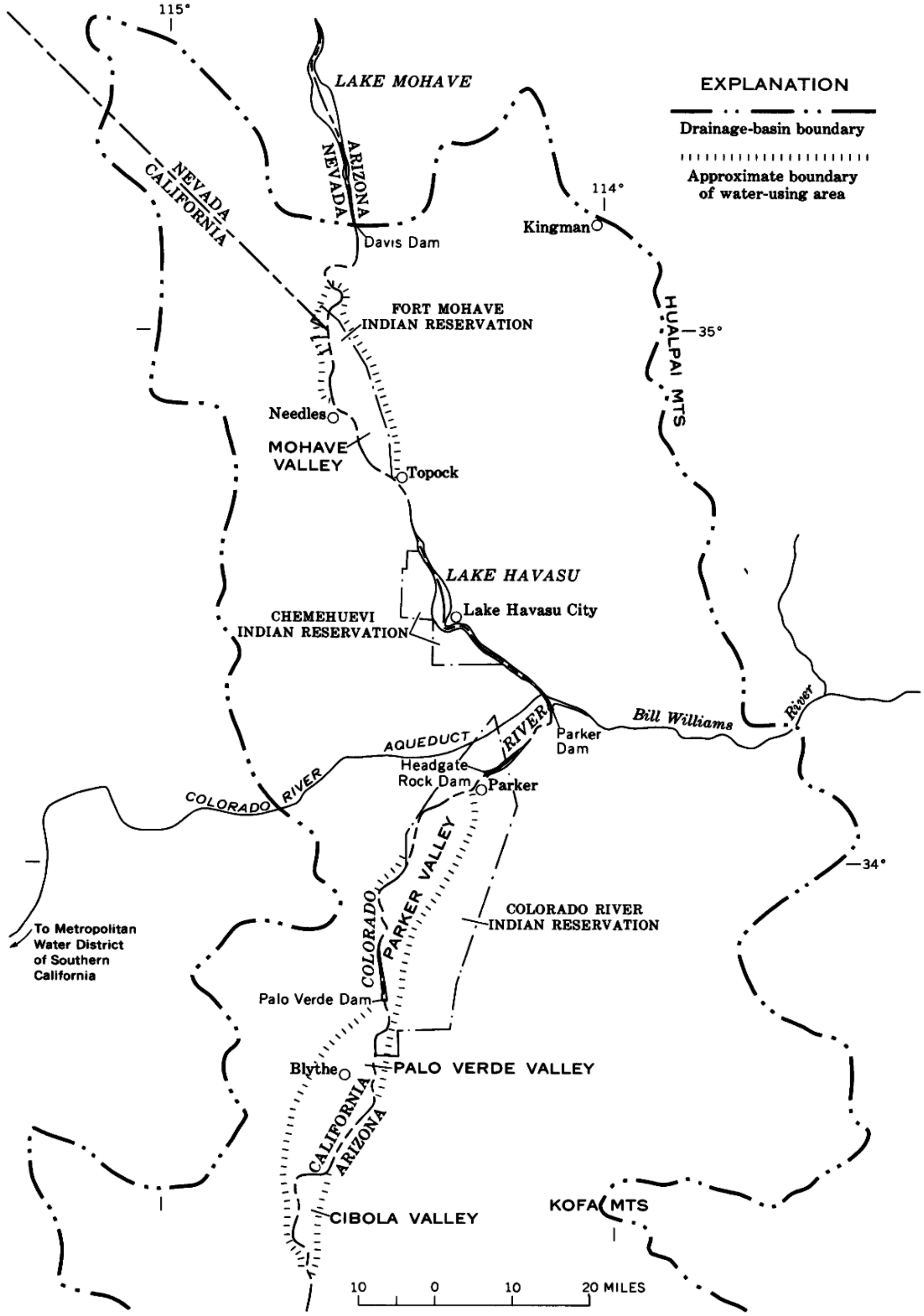

FIGURE 2.—Principal features of the Colorado River system and water-using areas from Davis Dam to Cibola Valley.

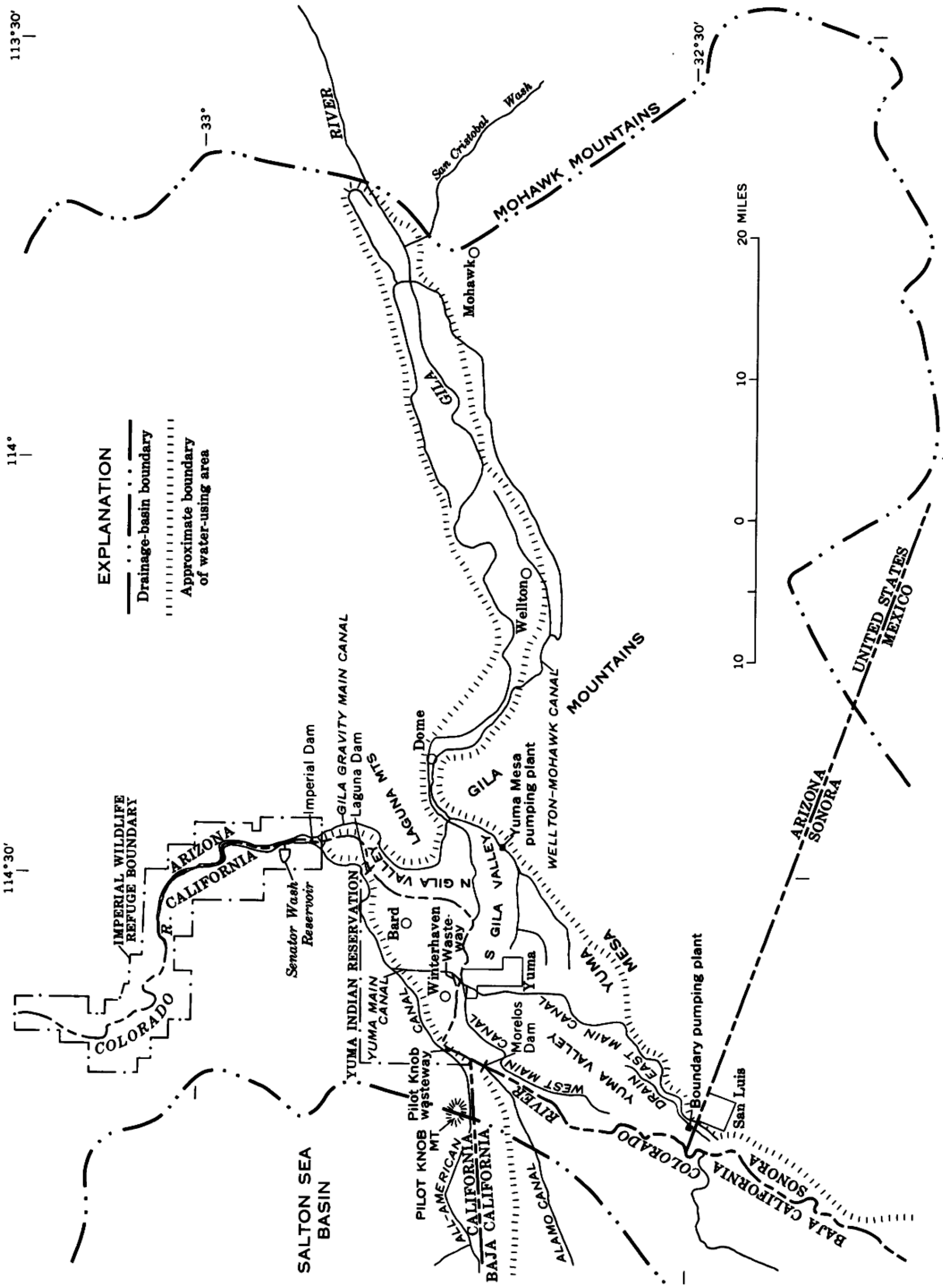

FIGURE 3.—Principal features of the Colorado River system and water-using areas below Cibola Valley.

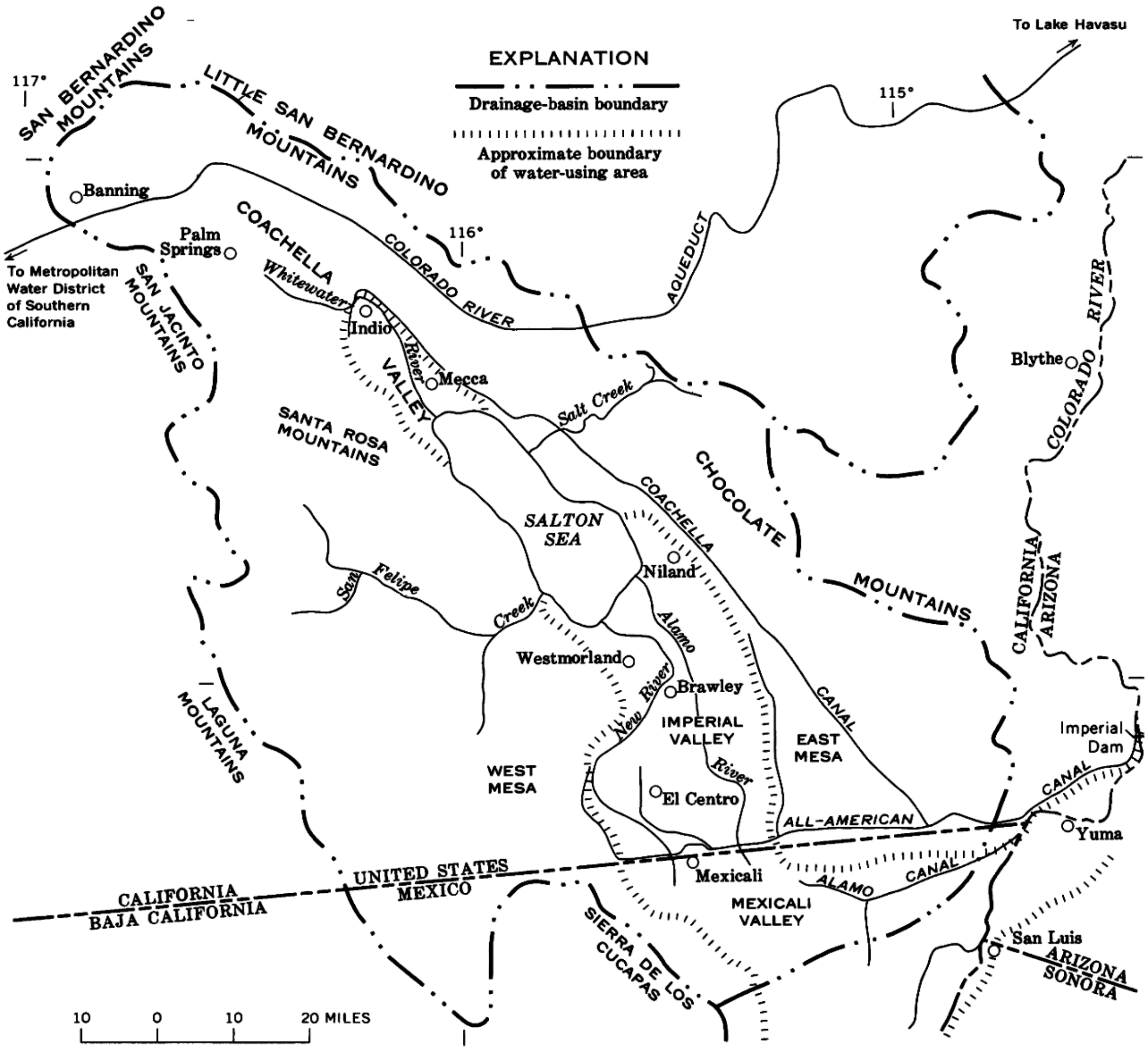

FIGURE 4.—Principal features of the Colorado River distribution system and water-using areas in the Salton Sea basin.

The Colorado River flows in deep, rugged canyons (including the famous Grand Canyon) in nearly all the 422-mile reach from compact point to Davis Dam. The only diversions from this reach are made by pumping from Lake Mead to the Boulder City–Henderson–Las Vegas area in southern Nevada.

Minor canyons alternate with fertile valleys between Davis Dam and the river's delta, which is a vast arable plain. Although this is one of the most arid parts of the United States, agriculture made possible by irrigation with Colorado River water is the mainstay of the area's economy. The productivity of the land is enhanced by a growing season that is practically continuous although frost occurs occasionally in most winters. Semitropical plants, such as citrus trees and date palms, are grown in parts of the area. A summary of the irrigated acreage in the principal tracts is given in "Appendix" (table 12).

About 6 miles below Davis Dam the Colorado River enters Mohave Valley, through which it flows 40 miles to Topock, Ariz. Most of the valley is within Arizona, and much of it is within the Fort Mohave Indian Reservation. Needles, Calif., at the western edge of the valley, is its principal city. A land inventory in 1962 by the U.S. Bureau of Reclamation (1963) indicated a total flood-plain area of 50,900 acres. Native vegetation, chiefly phreatophytes (plants that depend on shallow ground water), covered 47,600 acres. Only 3,050 acres were irrigated, although 15,700 acres were considered arable.

The 58-mile reach below Mohave Valley includes minor canyons and Chemehuevi Valley, which is now largely covered by Lake Havasu. A new town on the shore of the lake, Lake Havasu City, Ariz., was started in 1964 to provide a setting for light industry and recreation.

The next major valley (referred to in some early reports as the Great Colorado Valley) is divided into three sections—Parker, Palo Verde, and Cibola Valleys—by meanders of the river. The principal cities are Parker, Ariz., at the head of Parker Valley, and Blythe, Calif., in Palo Verde Valley. Nearly all of Parker Valley is within the Colorado River Indian Reservation. The valley includes about 110,000 acres of flood plain, 31,700 acres of which were irrigated in 1962 and most of the remainder was covered by phreatophytes. Additional land is being cleared and prepared for irrigation. Almost all of Palo Verde Valley and a small area on the adjoining mesa, a total of more than 80,000 acres, are irrigated. Phreatophytes cover minor areas along the river and along some drainage channels. During 1962, about 6,000 acres in Cibola Valley were irrigated with water pumped from the river or from wells near the river (U.S. Bureau of Reclamation, 1963), and more than 12,000 acres were covered by phreatophytes.

Below Cibola Valley the Colorado River flows about 43 miles through a minor canyon, most of which is within the Imperial Wildlife Refuge. It contains numerous small lakes and a few thousand acres of phreatophytes.

The river emerges from the mountains at Laguna Dam, 14 miles upstream from Yuma, Ariz. A few miles farther south the flood plains of the Colorado and Gila Rivers merge. Below Yuma the flood plain widens and merges with the delta, which extends westward into the Salton Sea basin and southward to the Gulf of California.

The area between the mountains and the international boundary, called the Yuma area in this report, is divided into several parts by geographic features. On the Arizona side of the Colorado River the flood plain between the mountains and Yuma is divided by the Gila River into North and South Gila Valleys. Yuma Valley extends from Yuma to the southerly international (Arizona-Sonora) boundary and is separated from South Gila Valley by Yuma Mesa, a terrace that is generally 70–80 feet higher than the adjacent valleys. The flood plain on the California side of the river includes the irrigable lands of the Yuma Indian Reservation, about an equal amount of non-Indian land, and the small towns of Bard and Winterhaven. The principal city within this area is Yuma, Ariz. San Luis, Sonora, is just south of the southerly international boundary at the lower end of Yuma Valley. Nearly 100,000 acres, including most of the flood plains and part of the Yuma Mesa, are irrigated; phreatophytes occupy an additional 13,000 acres. A small area in Sonora, south of San Luis along the east bank of the river, is irrigated by return flow from Yuma Valley and by pumping from the river or from wells.

About 12 miles east of Yuma at a narrow gap between the Gila and Laguna Mountains, the lower Gila River valley joins the common valley of the Gila and Colorado Rivers. Colorado River water has been diverted by pumping since 1952 to serve the Wellton-Mohawk area, which extends about 50 miles along the Gila River from the gap to a point a few miles east of the Mohawk Mountains. The Wellton-Mohawk Irrigation and Drainage District contains about 75,000 acres of irrigable land, and since 1959 the irrigated acreage has exceeded 50,000. Several thousand acres are covered with phreatophytes.

The delta of the Colorado River extends across the long structural trough that contains the Gulf of California and the Salton Sea, which is more than 230 feet below mean sea level. The delta has gradually risen to about 40 feet above mean sea level, forming a divide which prevents waters of the gulf from reaching the Salton Sea basin. Levees along the north side of the river and the numerous storage reservoirs in the Colorado River basin now prevent any uncontrolled flow of Colorado River water into the Salton Sea basin. However, a large part of the delta and other areas in the Salton Sea basin are irrigable by gravity diversion from the river. Drainage from the Salton Sea basin collects in the Salton Sea and is dissipated by evaporation.

The area between the Salton Sea and the international boundary, known as Imperial Valley, consists of a central part underlain by fine sediments and a terrace at each side (East Mesa and West Mesa) underlain by coarser sediments. The central part includes nearly half a million acres of irrigated land, the principal cities of El Centro and Brawley, and half a dozen smaller towns.

The area south of the international boundary is an extension of Imperial Valley and has sometimes been included in the area designated by that term. However, the irrigated part of the delta in Baja California is now generally known as Mexicali Valley. The city of Mexicali, which had an estimated population of about 100,000 in 1964, is the principal city of Baja California and the largest in the report area. About half a million acres are irrigated with water from the Colorado River or from ground-water reservoirs that are recharged either by irrigation water or by seepage from the river and canals.

Coachella Valley is a picturesque intermontane valley northwest of the Salton Sea. The ground-water resources were developed early in this century at many places in the valley and are still a principal source of supply for the upper part of the valley. Because of declining water levels, Colorado River water was imported to the lower part of the valley beginning about 1948 and now serves more than 60,000 acres. The principle cities are Banning, at the head of the valley in San Gorgonio Pass; Palm Springs, a resort city in the upper part of the valley; and Indio, in the lower part of the valley. More than a dozen smaller towns are scattered throughout the valley.

WATER-CONTROL AND DISTRIBUTION SYSTEMS

A discussion of problems relating to the lower Colorado River necessarily involves many elements of the water-control and distribution systems. Consequently, the dams and their associated reservoirs, major canals, and an aqueduct are briefly described in the following paragraphs. The locations are indicated in figures 1–4.

All figures of reservoir storage capacity in this report refer to volumes within surface reservoirs, although these volumes are supplemented by the ground-water capacity of large volumes of surrounding materials within the zone of fluctuation of reservoir levels. The effects of such supplemental bank storage, however, are not clearly defined because they vary with the physical characteristics of the materials and with the rapidity and magnitude of reservoir fluctuations. Furthermore, the gradual reduction of the volumes within reservoirs by the accumulation of sediment tends to offset the gain from ground-water (bank) storage.

Glen Canyon Dam and Lake Powell.—Glen Canyon Dam, 17 miles upstream from compact point, near Lees Ferry, Ariz., regulates practically all the natural surface outflow from the drainage area above compact point. Lake Powell (total usable capacity 25,000,000 acre-ft, of which 20,900,000 acre-ft is generally active) is the principal reservoir of the Colorado River Storage Project, which includes five other reservoirs upstream (existing or authorized as of 1968) with a combined active capacity of more than 6,000,000 acre-feet. Storage in Lake Powell began in 1963; storage in two of the other reservoirs began in 1962. The rated capacity of the powerplant at Glen Canyon Dam is 900,000 kw (kilowatts).

The primary purpose of regulating the flow at compact point is to enable greater use of water upstream rather than downstream. During years of very low runoff after the initial filling of the lake, most of the flow of headwater streams can be utilized above compact point and withdrawals from storage can provide for the releases to the lower river required by the Colorado River Compact. Without Lake Powell, any substantial development after 1962 of water supplies for use above compact point would not have been practicable because of the obligations to release water to the lower river.

Hoover Dam and Lake Mead.—Hoover Dam, Ariz.-Nev. (originally known as Boulder Dam) is 353 miles downstream from compact point and 303 miles upstream from Imperial Dam. It was the first large river-control project on the Colorado River, and it made possible most of the later developments downstream. The river has been almost completely controlled below the dam since storage began in 1935.

The usable capacity of Lake Mead for flood control, irrigation and municipal supply, and power generation was 28,000,000 acre-feet in 1935 and 27,200,000 acre-feet in 1949 (Thomas, 1954, table 1). The rated capacity of the powerplant is 1,344,800 kw. All diversions of Colorado River water to Nevada are made by pumping from the lake.

Davis Dam and Lake Mohave.—Davis Dam, Ariz.-Nev., is 67 miles downstream from Hoover Dam, near the head of Mohave Valley. The usable capacity of Lake Mohave for power generation, for regulation of the variable flow released at Hoover Dam, and for regulation of flow at the international boundary as required by a treaty between the United States and Mexico is 1,810,000 acre-feet. Storage began in January 1950. The powerplant has a rated capacity of 225,000 kw.

Colorado River aqueduct.—The water pumped from Lake Havasu into the Colorado River aqueduct, built and operated by the Metropolitan Water District of Southern California, is one of several supplies for the south coastal basins. The aqueduct was constructed in two stages, which were completed in 1941 and 1960, respectively. Pumping to reservoirs began in 1939, before completion of the first stage. The Metropolitan Water District originally included 11 cities and served 1,600,000 people, but by 1961 it included 91 cities and served 7,500,000 people (Smith and Brewer, 1961).

Parker Dam and Lake Havasu.—Parker Dam, Ariz.-Calif., is 88 miles downstream from Davis Dam, just below the Bill Williams River, and 147 miles upstream from Imperial Dam. The usable capacity of Lake Havasu is 619,400 acre-feet, but, except in emergencies, the capacity available for reregulation of streamflow is only 180,000 acre-feet because the dam was built primarily to create a pool from which water could be pumped to the Colorado River aqueduct. Storage began in 1938. The rated capacity of the powerplant is 120,000 kw.

Headgate Rock Dam.—Headgate Rock Dam, Ariz.-Calif., 14 miles downstream from Parker Dam, controls diversions to Parker Valley for the Colorado River Indian Reservation. The storage capacity of its reservoir is negligible. Prior to completion of the dam in 1942, diversions were made by pumping from the river.

Palo Verde Dam.—The diversion to Palo Verde Valley is made at Palo Verde Dam, Ariz.-Calif., 59 miles downstream from Parker Dam and 89 miles upstream from Imperial Dam. The dam, completed in December 1957, replaced a rock weir that had been used since 1945. No appreciable storage capacity was associated with either structure.

Imperial Dam.—Diversions at Imperial Dam, 26 miles upstream from the northerly international (California-Baja California) boundary, supply the Yuma and Wellton-Mohawk areas and Imperial and Coachella Valleys. Also, much of the water scheduled for delivery to Mexico is diverted here and returned to the river through the siphon-drop powerplant (near Yuma) or Pilot Knob powerplant (near the northerly boundary). Diversions began in 1938, but some areas now served by diversions made at this point were served until 1954 by diversions made at Laguna Dam, 5 miles downstream.

Several days are required for water to travel the great distances from the regulating reservoirs to Imperial Dam (147 miles from Lake Havasu and 236 miles from Lake Mohave). Because of changes in weather or other unforeseen circumstances, the need for water at Imperial Dam sometimes differs from the amounts released several days earlier on the basis of water orders. The capacity required for reregulation to avoid water shortage or waste is not available in the reservoir above Imperial Dam because of sedimentation and the negligibly small operating range of water levels. A small auxiliary reservoir (built in 1965) in Senator Wash, about 2 miles above Imperial Dam, provides 13,400 acre-feet of storage capacity. Water is pumped to the reservoir, but part of the power required is recovered by generating power from the water as it returns to the river.

Gila Gravity Main Canal.—The Gila Gravity Main Canal receives water through a settling basin at the east end of Imperial Dam and delivers it to the North Gila Valley, the Wellton-Mohawk Canal system (which includes three pumping plants and serves the Wellton-Mohawk area), the South Gila Valley, and a pumping plant that lifts water to the Yuma Mesa, all in Arizona. Diversions began in 1943.

All-American Canal system.—Water diverted at the west end of Imperial Dam passes through desilting works into the All-American Canal, which serves areas in both Arizona and California and also supplies water for the generation of hydroelectric power at several plants. Diversions began in 1938, but until 1940 the water was used only for priming the canal.

Several small diversions from both the All-American Canal and a major branch, the Yuma Main Canal, serve the California part of the Yuma area. Most of the water diverted into the Yuma Main Canal passes through the siphon-drop powerplant. Water for irrigation of Yuma Valley passes under the Colorado River in an inverted siphon, and the water not needed in Yuma Valley returns to the river through the Yuma Main Canal (California) wasteway.

The All-American Canal extends southward along the west edge of the river valley to Pilot Knob, where part of the flow returns to the river through Pilot Knob powerplant and wasteway. The canal then turns westward along the international boundary into the Salton Sea basin. About 16 miles west of Pilot Knob, water is diverted into the Coachella Canal to serve the lower part of Coachella Valley and the remaining water continues westward to serve Imperial Valley. Hydroelectric power is generated at several drop structures between Pilot Knob and Imperial Valley.

Laguna Dam.—Prior to construction of Imperial Dam, all diversions to the Yuma area were made at Laguna Dam, 5 miles downstream from Imperial Dam. The Dam was completed in 1909, and it served part of the Yuma area until 1954. It has no present diversion functions, but it may help to prevent excessive streambed scour from uncontrolled local floods, and it affords limited capacity for reregulation of flows passing Imperial Dam.

Morelos Dam and Alamo Canal.—Morelos Dam, Ariz.-Baja California, 1.1 miles downstream from the northerly international boundary and 27 miles downstream from Imperial Dam, was built by the Mexican Government in 1950 to control diversions to Alamo Canal without the use of facilities in the United States.

Prior to 1941 the Alamo Canal (originally known as Imperial Canal) supplied both Mexicali Valley in Baja California and Imperial Valley in California. Diversions from the Colorado River were made at several locations near the site of Morelos Dam and were controlled only by headgates. After construction of the All-American Canal, the Alamo Canal continued to serve Mexicali Valley, and from 1941 to 1950 water could be delivered to the Alamo Canal from the All-American Canal through Pilot Knob wasteway and a connecting canal that is now plugged.

Return-flow channels.—Surplus water and drainage from irrigated tracts near the Colorado River return to the river in a large and varying number of surface channels. Drainage of most tracts is accomplished by tile drains or open ditches, but the Wellton-Mohawk area and parts of the Yuma area are drained by pumping ground water. Drainage from the Wellton-Mohawk area flowed in a lined channel to the Gila River at a point near its mouth from 1961 until 1965, when the channel was extended to Morelos Dam. Provision is made for directing the flow into the Colorado River either above or below the dam as requested by Mexico. The surplus water in East Main canal in Yuma Valley flows across the international boundary and drainage from the valley is pumped from the main drain into a canal at the boundary for use in Mexico without return to the river.

Proposed developments.—The major proposed water-supply developments related to the lower Colorado River include (a) high dams for power generation at Marble Canyon and Bridge Canyon damsites, between Glen Canyon Dam and Lake Mead; (b) facilities for diverting an average of 1,200,000 acre-feet per year by pumping from Lake Havasu into an aqueduct serving central Arizona; and (c) improved efficiency of water transport and use through such means as deepening and straightening the river channel, lining canals, eradicating phreatophytes, and utilizing ground-water reservoirs that are recharged with Colorado River water.

These items have been proposed independently, but recently most of them have been incorporated into several plans to meet the water needs of the lower Colorado River service area or even larger areas, as exemplified by plans of the U.S. Bureau of Reclamation (1964 a–c). In addition to items such as those noted above, these regional plans generally contemplate ultimate importation of water to make up the deficiency in the Colorado River supply. The intent of such plans is to assure a sufficient supply of water from the main stem of the Colorado River or from new imports to satisfy an annual consumptive use of at least 7,500,000 acre-feet in Arizona, California, and Nevada and delivery of 1,500,000 acre-feet to Mexico.

LEGAL CONTROLS

The need for specific apportionment of waters of the Colorado River system was recognized early in the present century. Under the generally applied doctrine of prior appropriation, the first beneficial use of unappropriated water established a legal right to continued use. The rapid development of Colorado River water supplies for certain areas threatened the future supply for other less rapidly growing areas, which then sought to establish permanent water rights by compact, legislation, and court decree. Also, after construction of the All-American Canal, Mexico sought protection from excessive depletion of the river by diversions in the United States.

Interpretation of the law applying to the Colorado River is highly controversial and is beyond the scope of this report. Nevertheless, knowledge of some of the provisions of certain documents is essential to an understanding of the water problems because distribution of the water is subject to such provisions. Brief comments on four documents are given in the following paragraphs. The full text of the Colorado River Compact and the most pertinent parts of the Mexican treaty and of the U.S. Supreme Court decree of 1964 are included in "Appendix" for convenient reference.

The Colorado River Compact, 1922.—The distribution of waters of the Colorado River system between the Upper and Lower Basins (service areas) is subject to the provisions of the Colorado River Compact of 1922 (sometimes called the Sante Fe Compact). The compact was ratified in 1923 by six of the seven States involved; it became effective in 1929 by presidential proclamation, in accordance with a provision of the Boulder Canyon Project Act, and it was ratified by the seventh State, Arizona, in 1944.

The compact apportions water from the Colorado River system to the Upper Basin and the Lower Basin and also provides for the satisfaction of any water rights of Mexico that "the United States of America shall hereafter recognize * * *". Among the provisions most pertinent to the lower Colorado River is that of Article III paragraph (d): "The States of the Upper Division will not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75,000,000 acre-feet for any period of ten consecutive years reckoned in continuing progressive series beginning with the first day of October next succeeding the ratification of this compact." Other provisions applying to release of additional water from the Upper Basin have been interpreted in different ways and, hence, cannot be reliable guides to the flow of the lower river until some of the disputed issues have been settled.

Boulder Canyon Project Act, 1928.—In the Boulder Canyon Project Act, the Congress of the United States authorized several actions including the following: (a) Approval of the Colorado River Compact with ratification by only six of the seven States involved, (b) construction and operation of a dam (Hoover Dam) in Black or Boulder Canyon for the storage of water and of a main canal and appurtenant structures (All-American Canal and Imperial Dam) to deliver water to Imperial and Coachella valleys, (c) contracts between the Secretary of the Interior and water and power users for the storage and delivery of water, the generation and delivery of power, and the collection of revenues to reimburse the United States for costs incurred, and (d) an agreement among Arizona, California, and Nevada for a specified apportionment of Colorado River water. No agreement was concluded, but the specified apportionment was confirmed by the U.S. Supreme Court in 1964.

Rio Grande, Colorado, and Tijuana Treaty, 1944.—The distribution of waters of the Colorado River between the United States and Mexico is subject to provisions of the Rio Grande, Colorado, and Tijuana Treaty, signed in 1944 and ratified by both countries in 1945. The treaty allots to Mexico, "A guaranteed annual quantity of 1,500,000 acre-feet" and, when surplus water is available, "additional waters of the Colorado River system to provide a total quantity not to exceed 1,700,000 acre-feet * * * a year." Also, it requires that delivery of the water allotted to Mexico be made in accordance with schedules prepared by the Mexican Section of the International Boundary and Water Commission subject to limitations specified in the treaty.

Decree of the U.S. Supreme Court, 1964, Re: Arizona *v.* California, Colorado River.—The distribution of water from the main stem of the Colorado River below compact point among the States of Arizona, California, and Nevada is subject to provisions of the U.S. Supreme Court Decree of 1964.

The decree provides, "If sufficient mainstream water is available for release * * * to satisfy 7,500,000 acre-feet of annual consumptive use in the aforesaid three states, then of such 7,500,000 acre-feet of consumptive use, there shall be apportioned 2,800,000 acre-feet for use in Arizona, 4,400,000 acre-feet for use in California, and 300,000 acre-feet for use in Nevada."

If surplus water is available, 50 percent of the surplus is apportioned to California and 50 percent to Arizona, except that Nevada may contract for additional deliveries of up to 4 percent of the surplus, and then Arizona's share of the surplus will be reduced to 46 percent.

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If less than 7,500,000 acre-feet of water from the main stem of Colorado River is available for apportionment among the three States, "the Secretary of the Interior, after providing for satisfaction of present perfected rights in the order of their priority dates without regard to state lines * * * may apportion the amount remaining * * * in such a manner as is consistent with the Boulder Canyon Project Act * * * and with other applicable federal statutes, but in no event shall more than 4,400,000 acre-feet be apportioned for use in California."

STUDIES OF THE WATER SUPPLY

Studies of the water supply in the lower Colorado River logically begin with the record of streamflow at compact point, nears Lees Ferry, Ariz., for the following reasons: (a) Most of the water that reaches the lower river is runoff from mountainous areas above compact point; (b) since the closure of Glen Canyon Dam in 1963, the flow below the dam has been subject to regulation in accordance with provisions of the Colorado River Compact; (c) the most effective guide to future streamflow characteristics is obtained by separating the effects of man's activities from those of natural phenomena, and this separation can be achieved more accurately and more readily at compact point than at points below Lake Mead, especially for the period prior to 1963; and (d) the streamflow record (including estimates) for compact point is one of the longest in the Colorado River basin and has been the subject of many previous studies.

The analysis of streamflow at compact point is based on water years ending September 30. Water years are commonly used because in most parts of the United States September 30 is near the end of the growing season and is usually near the time of minimum storage of moisture in various forms.

Below compact point, increases in storage, which are chiefly a result of inflow from the upper river, generally begin in late spring instead of October. Below Davis Dam, the growing season is practically continuous, and the minimum water demand is near the end of the calendar year. Also, most water users maintain operating records by calendar years rather than water years. Consequently, the calendar year was used for analyses of all records below compact point and for comparisons involving such flows and those at compact point.

Streamflow in the lower Colorado River is modified so much by storage reservoirs that annual flows and average flows for periods of several years are the most significant units in a water-supply study. Although short-term flood flows of local origin may cause damage in the report area, data concerning such floods are too meager for effective analysis.

All streamflow records used in the following analyses are from U.S. Geological Survey water-supply papers except as otherwise noted.

COLORADO RIVER AT COMPACT POINT, NEAR LEES FERRY, ARIZ.

The streamflow at compact point depends on the virgin (natural) flow, the depletion of that flow by activities of man, reservoir storage, and the provisions of the Colorado River Compact. This report summarizes data on the actual flows, estimated depletions, and the virgin flows computed as the sum of actual flows and depletions. Analysis of the virgin-flow data provides estimates of the probable magnitude of future virgin flows, but the distribution of such flows can be determined only for assumed conditions regarding depletions and operation of reservoirs and for assumed interpretations of the compact.

ACTUAL FLOW, 1896–1966

Annual flows of the Colorado River at compact point since 1923 have been computed as the sum of flows measured at stream-gaging stations on the Colorado River and the Paria River above their confluence. Because the streamflow record for Colorado River began in 1921, it was necessary to estimate only the relatively small flow in the Paria River for 1921–22 to complete the record at compact point since 1921.

The Engineering Advisory Committee to the Upper Colorado River Basin Compact Commission estimated annual flows at compact point for 1914–20 on the basis of records of flow at other points on the Colorado River and its major tributaries; the U.S. Bureau of Reclamation (1954) used these estimates and made similar estimates for 1896–1913 for studies of the water supply. The estimated flows, particularly those for the earliest years, are necessarily less reliable than the computed flows for the years since 1921, nevertheless, they are of sufficient reliability to assist in defining long-term streamflow characteristics at this key point on the Colorado River.

The variations in actual flow reflect variations in both virgin flow and depletion as described in the following sections. Annual streamflow data are listed in "Appendix" (table 6) and are summarized in table 1.

TABLE 1.—*Summary of annual streamflow, in millions of acre-feet, at compact point, near Lees Ferry, Ariz., 1896–1966*

[Regulated actual flow after 1962 excluded]

Streamflow	Water years	Actual flow	Virgin flow
Minimum annual	1934	4.397	5.64
Maximum annual	1907	22.00	--------
	1917	--------	24.0
Minimum 5-year mean	1931–35	9.146	10.7
Maximum 5-year mean	1905–09	17.69	--------
	1917–21	--------	19.4
Minimum 10-year mean	1931–40	10.15	11.8
Maximum 10-year mean	1914–23	16.86	18.8
Minimum 30-year mean	1931–60	11.28	[1] 13.2
	1934–63	--------	13.1
Maximum 30-year mean	1903–32	15.63	17.3
34-year average	1931–64	--------	12.9
67-year average	1896–1962	13.39	15.1
71-year average	1896–1966	--------	14.9

[1] Minimum to 1962, corresponding to minimum actual flow for the same period.

MAN-CAUSED DEPLETION ABOVE COMPACT POINT

Natural processes and the activities of man both cause depletion of streamflow in arid regions. As consumptive use is involved in the terms of the Colorado River Compact, knowledge regarding the man-caused depletion of the natural water supply in the upper Colorado River system is essential for equitable division of the water supply between the Upper and Lower Basins.

The principal components of the man-caused depletion are (a) evapotranspiration resulting from irrigation or other uses within the drainage basin, (b) diversions to areas outside the basin, and (c) evaporation from reservoirs. Such depletions began before the first streamflow records. The irrigated acreage within the drainage basin increased from 310,000 in 1896 to 1,020,000 in 1910 to 1,425,000 in 1960. Water exports increased from relatively insignificant amounts prior to 1905 to more than 500,000 acre-feet in 1960. Evaporation from reservoirs was relatively small prior to 1962, when the reservoir storage was less than 2 million acre-feet. All these depletions are increasing, and evaporation is a much more significant item since the partial filling of Lake Powell and other major reservoirs.

The Engineering Advisory Committee to the Upper Colorado River Basin Compact Commission used the available hydrologic data to estimate the depletion during the 32-year period 1914–45. The U.S. Bureau of Reclamation (1954, p. 145) used the committee's data to derive a series of annual depletions for the same period and used similar data to estimate annual depletions from 1896 to 1913. The Bureau of Reclamation and the Upper Colorado River Commission (successor to the Compact Commission) made similar estimates for later years. Some investigators have used estimates slightly different from those described, but the differences generally are insignificant. Although such estimates have been used for many years, no estimates have been accepted by the Upper Colorado River Commission as official.

Figure 5 shows the estimated depletion in selected years plotted against the corresponding virgin flow. It shows a progressive but irregular increase of depletion with time and a variation of depletion with virgin flow. The lines in figure 5 should be considered as illustrative and approximate rather than definitive. As downward extensions of the lines indicate depletion exceeds the supply at very low flows, such extensions cannot be valid.

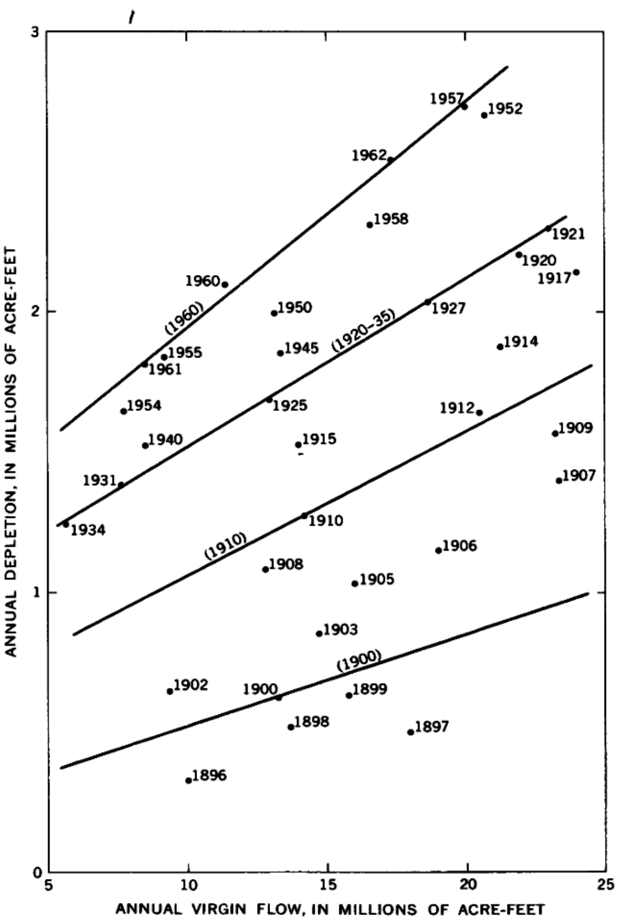

FIGURE 5.—Approximate relations of annual depletion of streamflow to annual virgin flow at compact point, 1896–1962. Points for many years omitted to avoid congestion. Adapted from Yevdjevich (1961, fig. 6).

The depletions increased rapidly for a few years after 1963 because of the increased evaporation from reservoirs, and they may increase gradually for an indefinite period because of increasing water use. Future depletions probably will not correlate as closely with virgin flows as in the past because evaporation will depend primarily on the aggregate storage rather than on the current virgin flow. The increase in depletions may be limited by such factors as a short growing season, relatively small acreage of arable land within the drainage basin, and the high cost of diverting water to areas outside the drainage basin. If the increase is not limited by such factors, it will be limited by provisions of the Colorado River Compact for release of water to the lower river.

It is obviously not possible to predict precisely the rate at which depletions above compact point will increase, nor the date when they will reach the limit imposed by the compact, but the following estimates by the U.S. Bureau of Reclamation (1965, p. 236) are illustrative of present forecasts:

Year	*Estimated depletion, in acre-feet*
1975	4,220,000
1990	5,100,000
2000	5,430,000
2030	5,800,000

VIRGIN FLOW, 1896–1966

The U.S. Bureau of Reclamation and the Upper Colorado River Commission have computed the virgin flow [1] of the Colorado River at compact point by adding the previously described depletions to the measured or estimated streamflow for the period 1896–1966. Prior to 1963, the effects of storage above compact point were relatively small, the average depletion was less than 13 percent of the actual flow, and annual depletions seldom exceeded 20 percent of the actual flow. Consequently, the computed virgin flows are only slightly less reliable than the corresponding figures of actual flow. As future depletions increase, the need for accurate determination of depletions will increase.

Both actual and virgin annual flows are shown graphically in figure 6; they are listed in "Appendix" (table 6) and are summarized in table 1. One of the most notable characteristics of this record is that mean annual flows for periods of about 30 years (1903–32 and 1931–64) differ by as much as 4,400,000 acre-feet, or 30 percent of the 71-year mean flow.

As the amount of water in storage at any time depends on the flow during preceding years, progres-

[1] Although the Commission has used these figures, it has not accepted any figures of virgin flow as official.

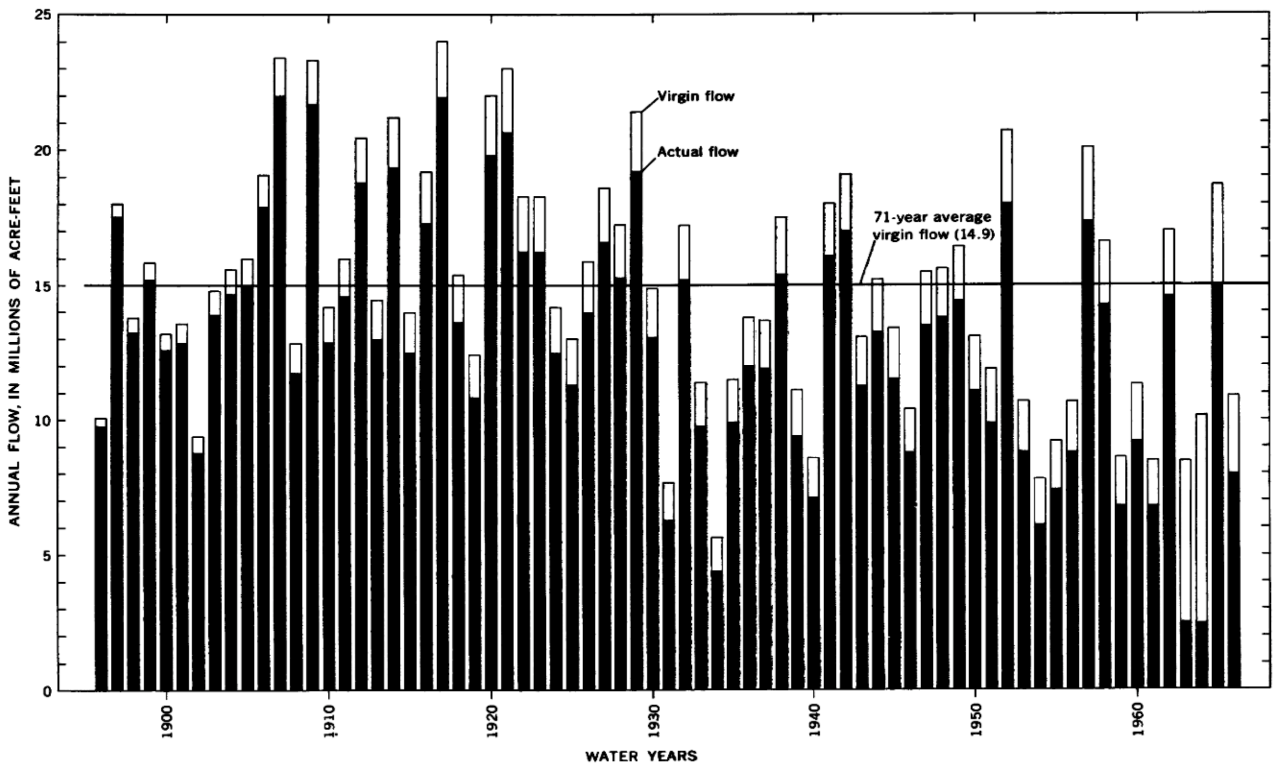

FIGURE 6.—Annual flow of the Colorado River at compact point, 1896–1966. A new regime for the actual flow began with the closure of Glen Canyon Dam in 1963.

sive averages of annual flows for periods of 5 or 10 years are useful indicators of water-supply conditions. The 10-year average is particularly important at compact point because of the provision in the Colorado River Compact referring to the aggregate flow in any 10-year period. Figure 7 shows the progressive 10-year average, and also the progressive change in the average for the period of record beginning in 1896.

PROBABLE FUTURE VIRGIN FLOW

The principal objective of computing virgin flows at compact point is information regarding future flow, which is required for most effective planning and operation of the river-control system. Reliable forecasts, the most useful type of information, have been limited to periods of a year or less and have required current data such as the water content of the snowpack in early spring. In the absence of long-term forecasts, the most useful information concerns the probable magnitudes of future multiyear means of the virgin flow.

Conventional methods of probability analysis are readily applicable to the annual virgin flows of the Colorado River. The cumulative frequency plot in figure 8 indicates only moderate scatter about the straight line representing the normal distribution; hence, the assumption that annual flows are normally distributed about the mean is well supported. The only other assumption involved in the application of statistical principles to annual flows concerns the true long-term mean. In probability theory this true mean is the mean for a period of infinite length. In hydrologic studies, however, the true mean generally is assumed to be the mean for a period of only a few centuries which does not reflect the major changes of climate and runoff that have occurred during periods of thousands of years.

Statistical analysis of multiyear means involves greater uncertaintly because annual flows fail to fulfill one criterion of a normal distribution (that each item is independent) when they are arranged in chronological order rather than order of magnitude as in figure 8.

The record of virgin flows at compact point exhibits a tendency for high flows to persist during some periods and for low flows to persist during others. Some arrays of random numbers exhibit the same tendency, however, and a persistence effect is not considered real unless

FIGURE 7.—Progressive averages of annual virgin flow at compact point.

the tendency for such grouping is greater in the annual virgin flows than is expected in a random array. Hence, evaluation of a persistence effect must be made as a probability rather than a certainty.

A persistence effect in virgin flows may be a natural result of similar persistence in annual or winter totals of precipitation in the upper Colorado River basin. Moreover, the lag between precipitation and runoff resulting from the natural storage capacity of the drainage basin would cause persistence in virgin flows even though the distribution of precipitation were random. Multiyear means of flows that are affected by persistence are more variable than corresponding unaffected means. The hydrologic literature exhibits a wide range of opinion on the nature and magnitude of persistence in both precipitation and runoff, and available records are not long enough to assure the validity of any particular assumption. Because of these uncertainties, probability statements derived from multiyear means of virgin flow should be considered useful approximations rather than the equivalent of conventional probability statements.

Leopold (1959) presented a semiempirical probability analysis in which he computed the variability of multiyear means from records for many streams in the United States and Europe. His study indicates that multiyear means of virgin flow of Colorado River at compact point are much more variable than similar means for a random array. The results are not conclusive, however, because of the small number of independent multiyear means in each record (for example, there are only three independent 20-year means in the 61-year record he used for compact point).

Additional information was gained from an intensive statistical study of precipitation and runoff in the upper Colorado River basin (Brittan, 1961; Julian, 1961; Yevdjevich, 1961). Julian concluded that winter precipitation totals probably exhibit no persistence effect. Yevdjevich concluded that the persistence effect in annual streamflow data for 14 small drainage basins in or near the upper Colorado River basin is relatively small. He concluded also that the water in natural storage at the end of a year would significantly influence the flow in only one succeeding year.

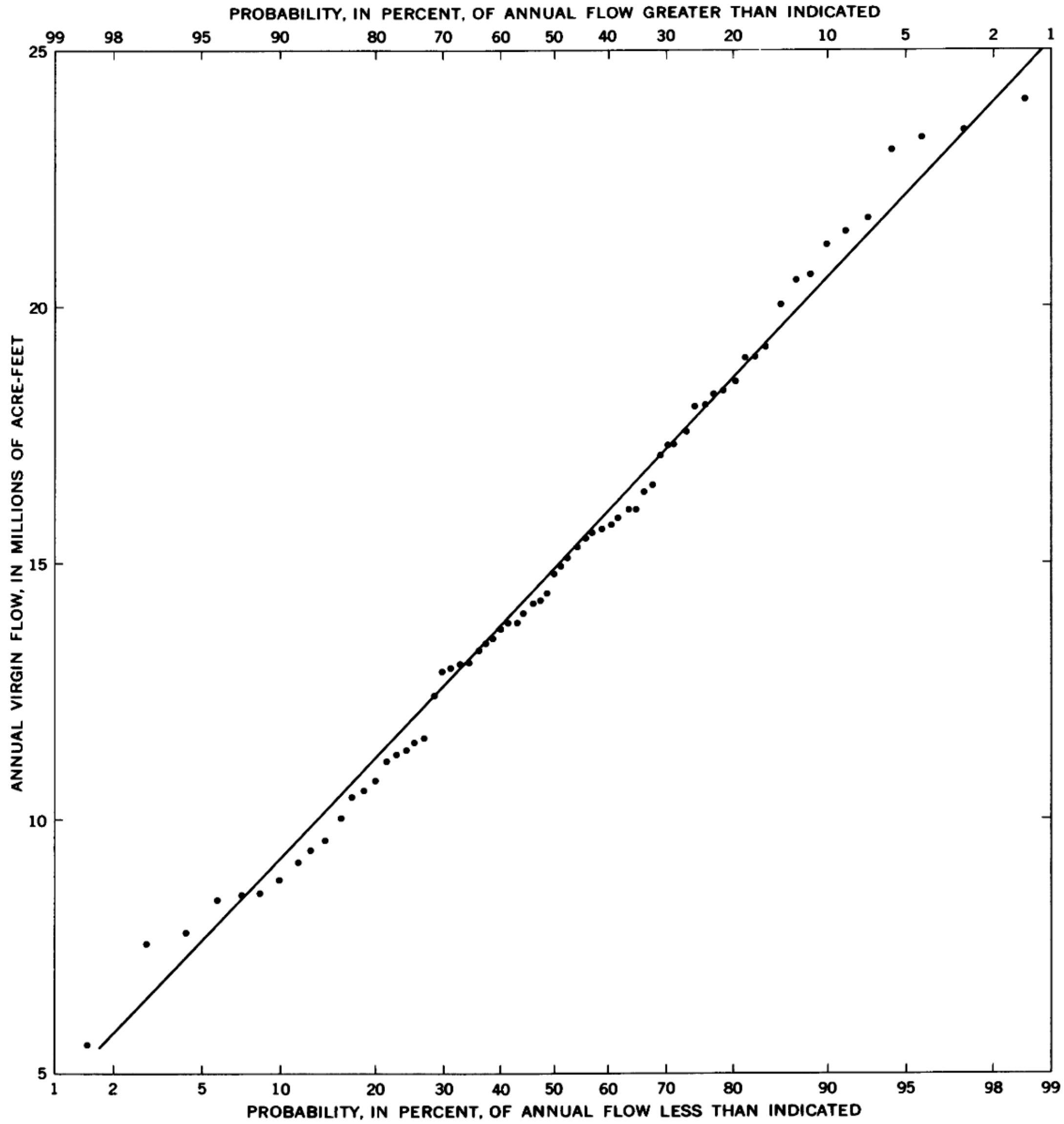

FIGURE 8.—Cumulative frequency diagram of annual virgin flow at compact point, 1896–1964. The dots represent annual flows; the straight line represents the normal distribution of items with the same mean and standard deviation as those computed from the annual flows.

On the basis of these and perhaps other similar studies, several investigators have assumed that the virgin flows can be represented by a mathematical model implying that a particular annual flow equals a random component plus the preceding annual flow multiplied by the first-order serial correlation coefficient. If the assumed model is a valid representation of the annual flows, this coefficient is a measure of the persistence effect. Unfortunately, however, the first-order serial-correlation coefficient computed from available streamflow records is a very imprecise estimate of the true (long-term) coefficient. Using calculated or estimated coefficients, Julian (1961), Brittan (1961), and others have found that such autoregressive or Markov models produce fair representations of annual streamflow sequences.

N. C. Matalas (written commun. 1965) of the Geological Survey used a Markov model with a coefficient of 0.20 (pratically the same as his calculated value, 0.206) to make a probability analysis of the virgin flows at compact point for 1896–1964. With this coefficient he calculated that the 69 serially-correlated flows were equivalent to only 44 uncorrelated (independent) items in defining confidence limits for the mean. Table 2 shows the resulting confidence limits for multiyear means at various levels of probability. Limits for 30-year means were computed by the author in the same manner as Matalas computed other limits. The table indicates an 80-percent chance, for example, that a future 20-year mean will be greater than 13,200,000 acre-feet and less than 16,500,000 acre-feet.

TABLE 2.—*Confidence limits for multiyear means of virgin flow at compact point*

Length of period	Probability, in percent	Confidence limits, in millions of acre-feet
10 years	80	12.0 –17.8
	95	9.82–19.9
	99	6.95–22.8
20 years	80	13.2 –16.5
	95	12.2 –17.5
	99	11.1 –18.6
30 years	80	13.5 –16.3
	95	12.7 –17.1
	99	11.9 –17.9
Long term	80	14.0 –15.8
	95	13.5 –16.2
	99	13.1 –16.7

PROBABLE FUTURE REGULATED WATER SUPPLY

Since 1963 the water supply, represented by the previously described virgin flows at compact point, has been modified by the effects of storage in major reservoirs. A total capacity of 25 million acre-feet—of which 20 million are in Lake Powell and the remainder in other reservoirs upstream—is considered available for long-term regulation of the river at compact point (Mosk, 1959).

The potential effects of such storage are conveniently illustrated by comparing cumulative virgin flows with cumulative draft from that flow (the sum of all man-caused depletions plus the release to the lower river). As such accumulations tend to be very large, more convenient results for graphical analysis are obtained by cumulating the departure from a convenient value near the mean.

The irregular graph in figure 9 represents the cumulative departure from 15 million acre-feet of annual virgin flows for the period October 1, 1895, to September 30, 1966. The upward trend for 1903–29 indicates annual flows generally exceeding 15 million acre-feet and the downward trend after 1930 indicates flows less than that amount.

Figure 9 demonstrates that during the period 1903–29 the flow in excess of 15 million acre-feet per year was more than sufficient to fill all presently existing reservoirs in the Colorado River System above Davis Dam. With a hypothetical annual withdrawal of 15 million acre-feet (including reservoir evaporation), the surplus would have reached 60 million acre-feet by the end of 1922 and 74 million acre-feet by 1929. Following 1929, flows have been predominately below normal; the average for the 34-year period 1931–64 was 12,900,000 acre-feet. Assuming that the effective storage capacity of 25 million acre-feet above compact point was full in 1930, a uniform annual draft of 13,700,000 acre-feet (as shown by the inclined line in fig. 9) theoretically could have been maintained during the period 1930–66. The reservoirs would have been full in 1952 and empty in 1964.

Although techniques similar to those illustrated by figure 9 have long been standard for analysis of storage requirements or effects, the validity of the results depends on the sequential occurrence of historical flows. Failure to include an estimate of the probability of future deficiencies is a critical weakness. To obtain more meaningful evaluations, increasing attention is being given to application of probability theory to storage analyses. Such applications are hampered by the previously described uncertainty regarding effects of persistence in the annual flows—an uncertainty that lessens, but does not destroy, the usefulness of the results.

In a general study of reservoir storage, Hardison (1966) developed some draft-storage relations that are applicable to the Colorado River near Lakes Powell and Mead. Starting with the assumption of independent (uncorrelated) annual flows, he developed general relations of uniform annual draft to storage capacity and streamflow variability for each of several probabilities of deficiency and for each of three distributions that commonly apply to annual flows (fig. 10). Each of the three variables in these relations is expressed as a dimensionless ratio—draft and storage as ratios to the mean annual flow, and variability as an index that differs with the type of distribution. The storage capacity considered here is the carryover capacity required to smooth out annual fluctuations; it does not include storage required to smooth out seasonal fluctuations.

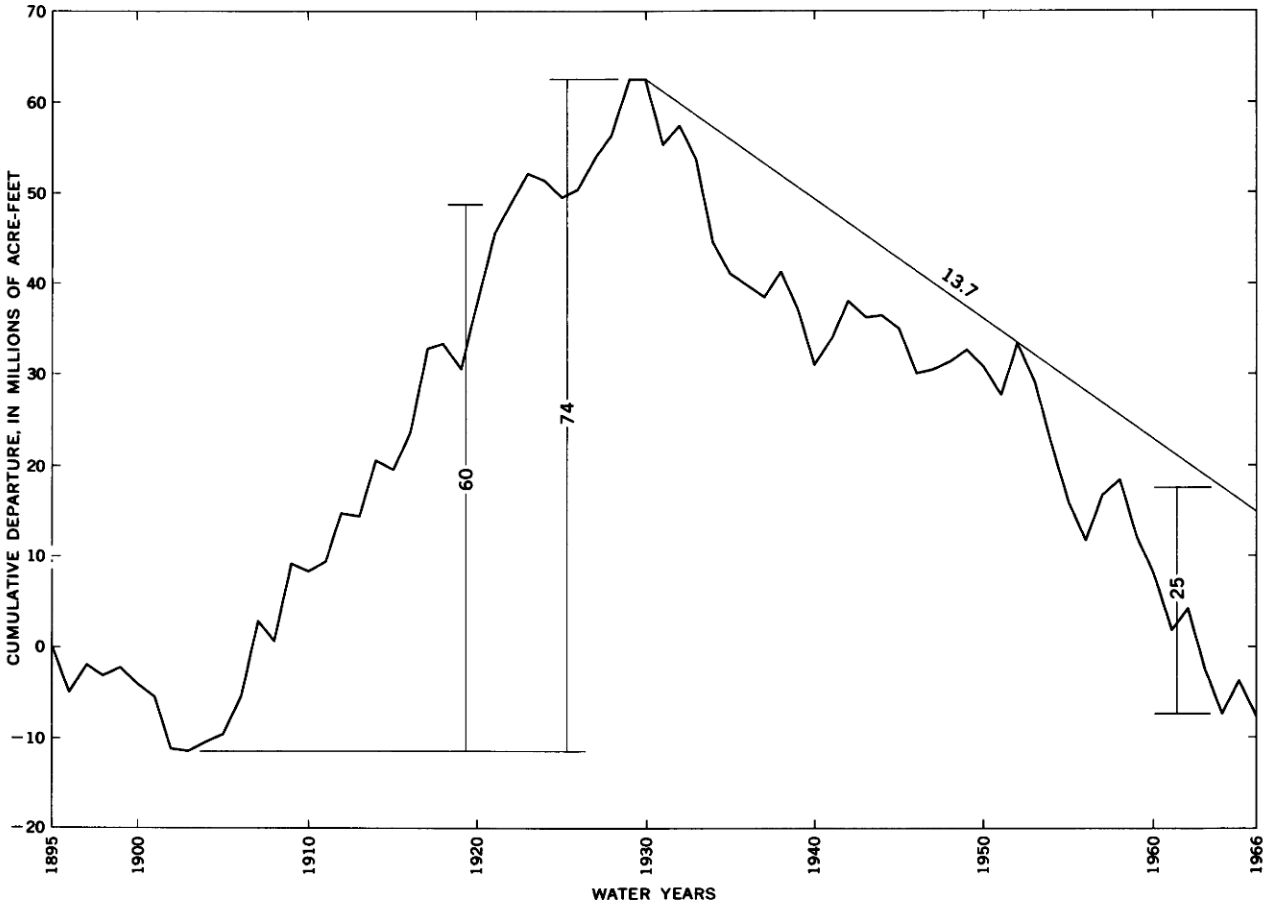

FIGURE 9.—Graphical storage analysis of the virgin flow of the Colorado River at compact point, 1895–1966. The irregular graph represents the cumulative departure of annual virgin flows from 15 million acre-feet. The inclined line represents a uniform annual draft of 13,700,000 acre-feet.

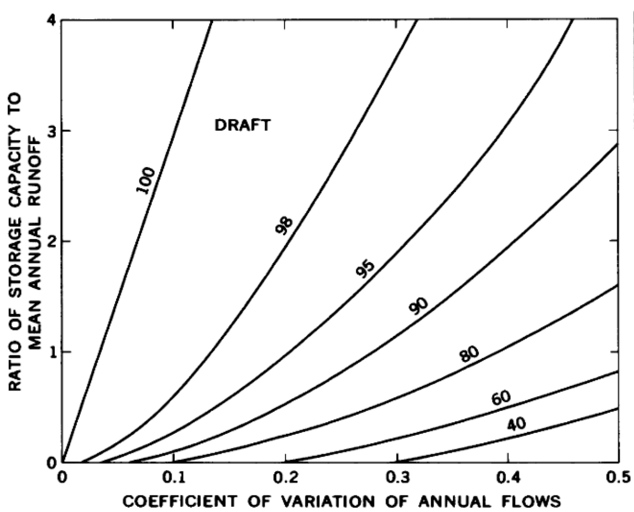

FIGURE 10.—Dimensionless draft-storage-variability relations. The family of curves represents uniform annual draft, in percent of mean annual runoff; carryover storage capacity is indicated as a ratio to mean annual runoff; and streamflow variability is represented by the coefficient of variation of annual flows. This diagram is for a 2-percent chance of deficiency and for normally distributed, independent annual flows. Similar diagrams apply for other chances of deficiency and other distributions. (After Hardison, 1966.)

To apply these dimensionless relations to the Colorado River it is necessary to select relations for the proper distribution, which was shown to be normal (fig. 8), and a proper index of variability. For normal distributions this index is the coefficient of variation (ratio of the standard deviation to the mean). In his probability analysis of virgin flows, N. C. Matalas used 14,878,000 acre-feet for the mean and 4,405,000 acre-feet for the standard deviation; the corresponding coefficient of variation is 0.30. For this coefficient and a specific level of probability, the relation curves show unique values of draft and storage ratios. Conversion of these ratios to annual amounts of draft and storage provided the data to define the solid curves in figure 11, which therefore would represent the relations of uniform annual draft to carry-over storage capacity applicable to the virgin flow of Colorado River if the annual flows were independent.

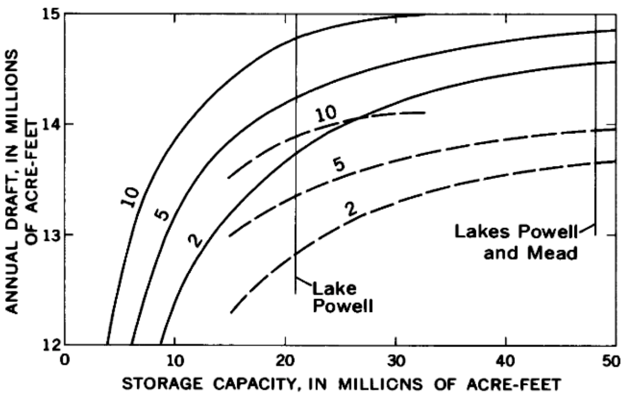

FIGURE 11.—Relations of uniform annual draft to carry-over storage capacity for virgin flow of the Colorado River near compact point. The solid curves represent relations for independent annual flows and for 10-, 5-, and 2-percent chance of deficiency (derived from Hardison's dimensionless ratios). The dashed curves represent approximate relations with streamflow persistence (draft from solid curves reduced by 6 percent of mean annual flow). The vertical lines represent the active storage capacity of Lake Powell and the combined capacity of Lakes Powell and Mead.

Hardison also studied the effect of serial correlation of annual flows, which he considered to be a measure of the persistence effect. He concluded that, for the flow at 180 stream-gaging stations in the United States with an average serial-correlation coefficient of 0.17, the serial correlation would reduce the draft corresponding to a specific storage capacity by about 5 percent of the mean annual flow. If this conclusion is valid, the reduction corresponding to the serial-correlation coefficient of 0.20, used by Matalas in the analysis of virgin flows, is about 6 percent.[2] Thus, the dashed curves in figure 11, representing approximate relations with persistence effect, were derived by lowering the solid curves 893,000 acre-feet.

Figure 11 illustrates the well-known principle that as storage capacity available for regulation of flow at a particular point increases each succeeding increment of storage is accompanied by a smaller increment of the allowable draft. This is true even when evaporation from reservoirs is included in the draft, as in figure 11. The corresponding increments of usable draft (withdrawals in surface channels or pipes) decrease even more rapidly because evaporation losses tend to increase with increasing capacity.

The capacity available for carryover storage is somewhat less than the 25 million acre-feet used in figure 9 because of the requirements for seasonal storage. Hardison's data (Löf and Hardison, 1966, table 7) indicate that the seasonal requirement for 2-percent chance of deficiency is less than 5 million acre-feet, which is less than the capacity of reservoirs above Lake Powell. Assuming the active capacity of Lake Powell (20,900,000 acre-ft) is available for carryover storage, figure 11 suggests that the regulated water supply from the upper Colorado River basin seldom will be less than 13 million acre-feet and will exceed 14 milion acre-feet most of the time.

As previously described, the distribution of this regulated water supply from the upper Colorado River system (which should not be confused with that from the entire Colorado River system) to the upper and lower service areas depends on legal considerations, the existence of facilities in the upper service area to enable beneficial use of its share of the water, and the magnitude of the regulated supply. For example, if the annual man-caused depletions above compact point should average 5 million acre-feet (about double those prevailing about 1960) when sufficient water is available, a regulated annual supply of 14 million acre-feet would provide 9 million acre-feet at compact point. Flow would be limited to the legal minimum, which conflicting claims place at either 7,500,000 or 8,250,000 acre-feet, whenever the regulated annual supply is equal to or less than either 12,500,000 or 13,250,000 acre-feet, respectively. Similarly, if these annual depletions above compact point should reach the 7,500,000 acre-feet specified in the Colorado River Compact (article III, paragraph a, see "Appendix"), the flow at compact point would be limited to the legal minimum except during wet periods when the total supply (regulated and unregulated) exceeds either 15,000,000 or 15,750,000 acre-feet.

COLORADO RIVER BETWEEN COMPACT POINT AND DAVIS DAM

Between compact point and Davis Dam the flow of the Colorado River is modified by highly variable inflows, evaporation from the river and reservoirs, diversions from Lake Mead, and storage in Lakes Mead and

[2] In a general appraisal of storage requirements in the United States (Löf and Hardison, 1966), Hardison used a reduction of 3 percent rather than the 6 percent used herein or the 5 percent he considered to be the average. The same correction was applied for all streams and the lower value was selected to avoid overcorrection where the persistence effect is small.

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Mohave. Since 1935 the modifications have been dominated by the effects of man's activities rather than by natural runoff and water loss. Because the effects of man's activities change markedly, analysis of long-term records of flow in the lower river can add little to the knowledge of future streamflow characteristics.

A more fruitful approach to the prediction of future water supply is the determination of average gains or losses between compact point and the site for which information is desired. The average annual inflow to Lake Mead can be closely approximated by adding a relatively small increment to the corresponding flow at compact point, and the average annual flow at Davis Dam can be similarly approximated by subtracting a relatively small net loss from the corresponding flow at compact point and adjusting the result for the effects of change in storage in reservoirs below compact point.

GAINS AND LOSSES

Average gains and losses for various reaches between compact point and Davis Dam are determined from streamflow records for Colorado River and tributaries and from records of diversion and surface storage. (See "Appendix," tables 7–9, 11.)

Gaging stations have been maintained on Colorado River near Grand Canyon, Ariz. (87 miles downstream from compact point), since 1922, below Hoover Dam since 1933, and below Davis Dam since 1949. Gains and losses in streamflow between these stations are shown in table 3. All figures in this table are based on calendar years rather than the water years used in the preceding analyses of the flow at compact point. The period 1935–49, following closure of Hoover Dam but prior to closure of Davis Dam, includes the period of filling of Lake Mead. Adjustments are made for surface storage only; bank storage, although believed to be significant, has not been determined with sufficient reliability for use in this study. Both Lake Mead and Lake Mohave (above Davis Dam) were in existence during the period 1950–62, but storage in Lake Powell (above Glen Canyon Dam) did not begin until 1963. Regulation in Lake Powell may influence channel losses between Glen Canyon Dam and Lake Mead.

TABLE 3.—*Gains and losses between compact point, and Davis Dam, Ariz.-Nev.*

Gaging station or increment	Drainage area (sq mi)	Average annual flows and increments (millions of acre-ft)		
		1935–49 (15 yr)	1950–62 (13 yr)	1923–62 (40 yr)
Compact point	109,500	12.39	10.68	11.96
Increment	28,300	+.31	+.20	+.31
Grand Canyon	137,800	12.70	10.88	12.77
Increment	30,000	−.52	−.44	
Hoover Dam (adjusted) [1]		12.18	10.44	
Hoover Dam (actual)	167,800	10.68	10.20	
Increment	1,500		−.11	
Davis Dam (adjusted) [2]			10.09	
Davis Dam (actual)	169,300		9.960	

[1] Adjusted for change in contents of Lake Mead (storage began in 1935).
[2] Adjusted for change in contents of Lake Mohave (storage began in 1950).

The average annual net losses between compact point and Hoover Dam were 210,000 acre-feet during 1935–49 and 240,000 acre-feet during 1950–62 (obtained by combining increments in table 3). Since construction of Davis Dam, the additional loss between Hoover and Davis Dams has been 110,000 acre-feet. Hence, for runoff conditions similar to those of 1935–62, the net loss from compact point to Davis Dam would be about 335,000 acre-feet.

Future losses in this reach will be affected by variations in runoff from tributary areas and consumptive use of water within those areas. Higher runoff during wet periods will tend to decrease the losses, but increasing use of water will tend to increase them. The local use of tributary flows has been increasing and is expected to continue increasing for many years. Diversions to Nevada from the Colorado River or Lake Mead began in 1932 and gradually increased to 20,000 acre-feet per year in 1955. These diversions may eventually equal Nevada's basic allotment of 300,000 acre-feet per year. Thus, losses during long relatively dry periods may eventually be more than double present losses.

Satisfactory accuracy of the increments in table 3 is indicated by comparison of each increment with other increments and with independent estimates based on streamflow records for tributaries and computed evaporation losses.

The Little Colorado River drains approximately 95 percent of the area between compact point and Grand Canyon and contributes nearly 100 percent of the inflow. This river has been measured since 1925 either at Grand Falls (96 miles upstream from the mouth) or near Cameron, Ariz. (45.4 miles upstream from the mouth), and at both places simultaneously for more than 8 years. During the periods of simultaneous records, the flow near Cameron exceeded that at Grand Falls by about 6 percent. Consequently, annual flows near Cameron prior to the period of record were estimated as 106 percent of those measured at Grand Falls. Furthermore, occasional measurements of Blue Springs, in the canyon of the Little Colorado River below the Cameron gaging station, indicate that the flow of the river at its mouth exceeds that near Cameron by a nearly constant amount of 220 cubic feet per second (159,000 acre-ft per yr).

Annual contributions to the Colorado River determined in this manner average 350,000 acre-feet and range from 190,000 to 780,000 acre-feet. The average annual evaporation loss between compact point and Grand Canyon is about 27,000 acre-feet, estimated on the basis of data presented by Meyers (1962, table 4); hence, the corresponding net gain is 320,000 acre-feet, which is close to the 310,000 acre-feet shown in table 3 for 1923–62. Similar computations indicate a net gain of 340,000 acre-feet during 1935–49 (compared with 310,000 in table 3) and 260,000 acre-feet during 1950–62 (compared with 200,000 in table 3).

In the reach between Grand Canyon and Hoover Dam, the loss generally exceeds the inflow, which is only partly measured. The gross annual loss during 1950–62 was about 890,000 acre-feet, which included 837,000 acre-feet evaporated from Lake Mead (measured by either energy-budget or mass-transfer method, March 1952–December 1962), 37,000 acre-feet evaporated from the river above Lake Mead (based on data presented by Meyers, 1962) and 17,000 acre-feet diverted from the lake for use in Nevada. If the net loss of 440,000 acre-feet (table 3) is subtracted from the gross loss an average annual inflow (including precipitation on the water surface) of 450,000 acre-feet during 1950–62 is indicated. If the same gross loss occurred during 1935–49, the corresponding inflow was about 370,000 acre-feet.

Streamflow records for Bright Angel Creek, the Virgin River, and Las Vegas Wash, and occasional measurements of large springs feeding Tapeats and Havasu Creeks in the Grand Canyon together account for about 250,000 acre-feet of inflow between Grand Canyon and Hoover Dam, and precipitation on the water surface accounts for about 65,000 acre-feet. The balance of the computed inflow may reasonably be accounted for by unmeasured inflow.

EFFECTS OF STORAGE BELOW COMPACT POINT

Lake Mead enabled virtually complete regulation of the Colorado River at Hoover Dam during the relatively dry period from the closure of the dam in 1935 until 1963. Smaller reservoirs below Hoover Dam reregulate the fluctuating releases associated with power generation and aid delivery of water as needed in both the United States and Mexico. Since the construction of large reservoirs above compact point, much of the primary river regulation occurs there, and a substantial part of the capacity of Lake Mead has become available for additional regulation. Although this extra capacity may not be needed for some fairly long periods, the streamflow has been sufficient at times to fill all reservoirs (fig. 9).

Since only minor amounts of inflow occur between Glen Canyon and Hoover Dams, it is appropriate to consider the effects of the combined capacity of Lakes Powell and Mead on the uniform annual draft from virgin flow and to compare these with the effect of Lake Powell alone. For a 2-percent chance of deficiency, figure 11 indicates an increase in draft of about 800,000 acre-feet when Lake Mead is included. For a 5-percent chance of deficiency, the corresponding increase is about 600,000 acre-feet. As all drafts involved in these computations include evaporation, it is necessary to subtract the evaporation from Lake Mead to find the net effect on usable draft. Evaporation consumed 806,000 acre-feet per year during 1952–66 and may consume a somewhat smaller amount if lake levels are lower during future periods.

The net effect on the water supply of storage in Lake Mead will be a substantial increase in allowable draft during long wet periods; but if Lake Powell is used to its full potential, storage in Lake Mead will not appreciably increase the firm supply. In practice, however, the function of river regulation probably will be shared by all major reservoirs to maintain maximum effectiveness for some of their many other uses.

COLORADO RIVER AND TRIBUTARIES BELOW DAVIS DAM

Below Davis Dam the Colorado River is primarily a part of a vast distribution system, which is discussed in later sections. Aside from numerous desert washes that rarely contribute appreciable quantities of water to the Colorado River and channels that convey return flows from irrigation diversions, there are only two tributaries below Davis Dam, the Bill Williams and Gila Rivers.

BILL WILLIAMS RIVER

The Bill Williams River drains about 5,200 square miles in west-central Arizona and flows into Havasu Lake above Parker Dam. Its drainage basin is sparsely populated, and only 9,100 acres were irrigated in 1963, chiefly by pumping ground water. A considerable part of the runoff occurs during infrequent floods; some of the runoff cannot be adequately controlled by Lake Havasu under normal operating conditions but will be controlled by a reservoir (construction began in 1965) on the Bill Williams River near Alamo, about 34 miles above Lake Havasu.

The flow of the Bill Williams River has been measured at Planet, about 6 miles above Lake Havasu, from 1929 to 1945 and near Alamo since 1939 (table 8). The records of annual flows at the two sites correlate well, and during the period of simultaneous records the average flow at Planet was about 84 percent of the flow near Alamo. On the basis of records at both sites and this relation, the average annual flow at Planet for 1929–62 is estimated to be about 70,000 acre-feet. The annual flows range from negligible amounts in many years to 400,000 acre-feet in 1941. A bar graph of the annual flows is shown in figure 12.

GILA RIVER

The Gila River, which is the largest tributary to the Colorado River below compact point, drains 57,950 square miles, chiefly in central and southern Arizona but including about 5,600 in New Mexico and about 1,100 in Sonora, Mexico. Its drainage basin includes the major cities of Phoenix and Tucson, Ariz., more than 100 smaller cities, and about a million acres of farm lands irrigated with water from the Gila River system and the aquifiers underlying the basin. For many years the annual consumptive use of water in the basin has greatly exceeded the average annual runoff. The high rate of consumptive use has been sustained by annual withdrawals of ground water several times as great as the annual replenishment.

A bar graph in figure 12 represents the annual flow of the Gila River near Dome (table 8), in the gap where the Gila River enters the lower Colorado River valley. This flow does not include return flows from irrigation in North and South Gila Valleys or the flow in the Wellton-Mohawk Main Outlet drain, which was constructed in 1961 to convey the effluent from drainage wells in the Wellton-Mohawk area to the Colorado River. The graph illustrates both the extreme variability of the flow and the decline caused by development of irrigation within the basin. The only flow between 1941 and the wet winter of 1965–66 was surface drainage from irrigation in the Wellton-Mohawk area or runoff from occasion local storms.

Although average annual water use exceeds the average streamflow and the major irrigation storage reservoirs (combined capacity, nearly 3,500,000 acre-ft.) seldom fill completely, a recurrence of runoff similar to

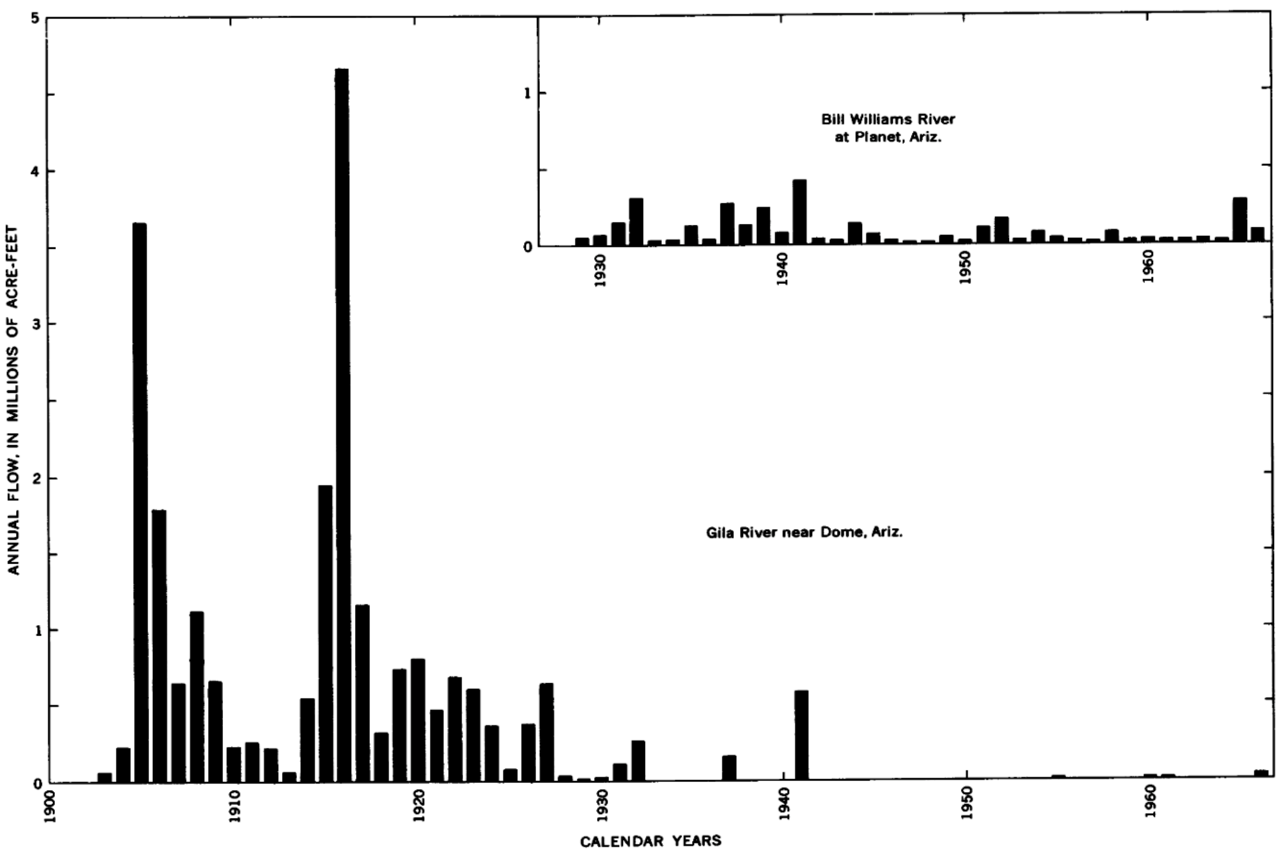

FIGURE 12.—Annual flows of the Bill Williams and Gila Rivers.

that of 1916 (1,665,000 acre-ft.) would almost certainly cause considerable spill from several reservoirs. Painted Rock reservoir, 126 miles upstream from the mouth, provides nearly 2,500,000 acre-feet of additional capacity for control of floods that originate above the dam. Release of water from this reservoir or infrequent uncontrolled floods from the 7,300-square-mile drainage area downstream can cause appreciable flow into the Colorado River at times.

As the confluence of the Gila and Colorado Rivers is below all storage reservoirs and below all but one of the major diversions (Alamo Canal), there is little opportunity to use any flood flow that may occur in the Gila. Thus, the contribution of the Gila River to the usable water supply in the Colorado River must be considered negligible. The infrequent controlled releases from Painted Rock reservoir may help to supply the current requirements of Mexico if the resulting flows at the mouth of the Gila River can be coordinated with releases from the storage reservoirs on the Colorado River.

COLORADO RIVER BELOW ALL MAJOR DIVERSIONS

A synthesized record of the flow of the Colorado River below all major diversions (fig. 13) illustrates the downward trend of the residual flow, caused chiefly by an increasing use of water from the Colorado River. The residual flows during 1935–39 were unusually low largely because of the initial filling of Lake Mead. The low flows during 1959–62 indicate a nearly complete utilization of the Colorado River; consequently, future increases in beneficial use of water from the basin may depend largely on increasing the efficiency of use.

The annual flows shown in figure 13 are about the

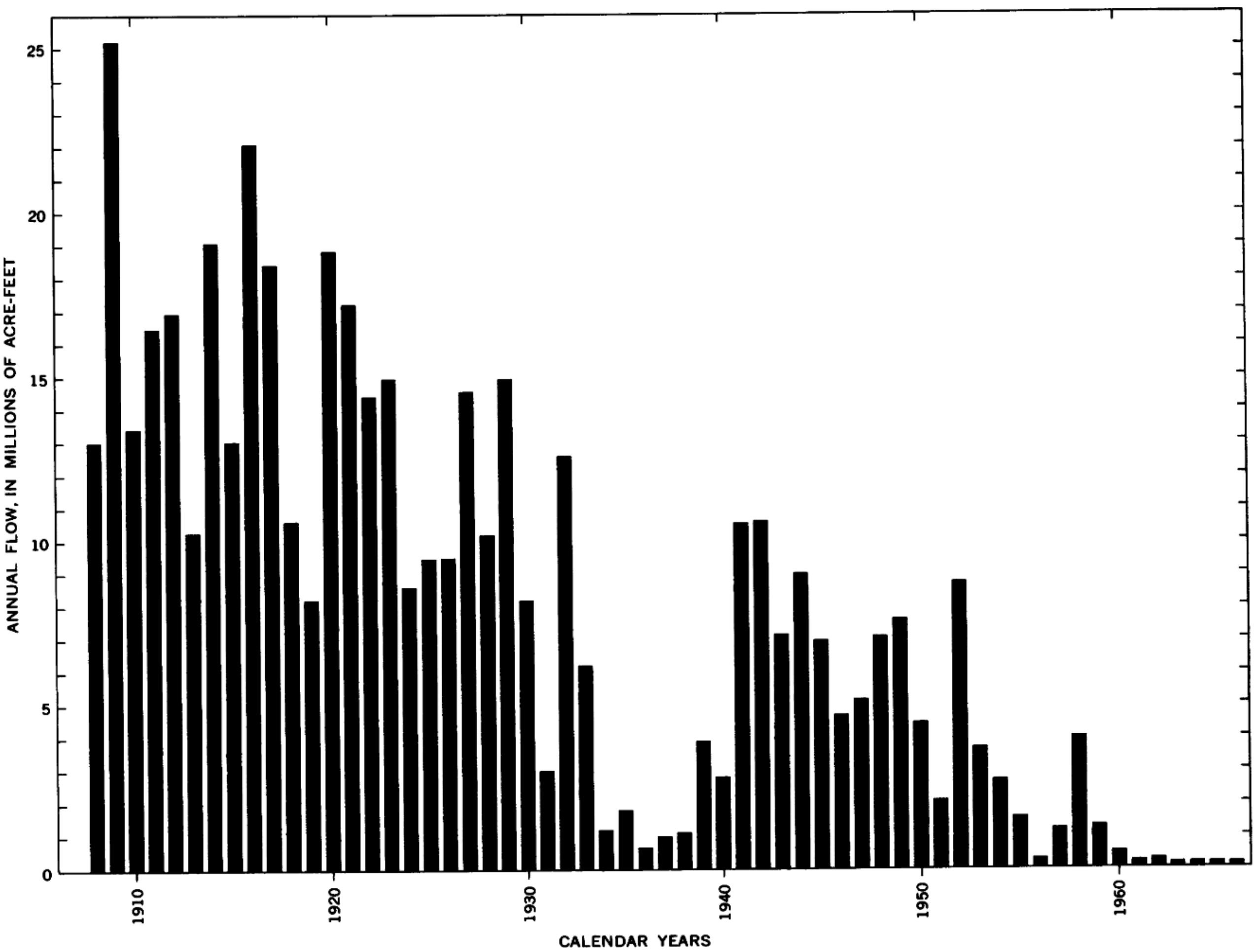

FIGURE 13.—Annual flow of the Colorado River below all major diversions.

same as the annual flows into the Gulf of California, except those for periods of very low flow when small diversions and return flows below Alamo Canal may have caused appreciable differences between the respective flows. These residual flows were obtained by subtracting the flow of Alamo Canal from the flow of the Colorado River above the canal. The site of the diversion has varied but generally has been within a few miles of the present site, 1.1 miles downstream from the northerly international (California–Baja California) boundary (fig. 3).

Diversion through Alamo Canal began in 1901, but continuous records of the diversion (table 10) did not begin until 1908, following a period of about 2 years of uncontrolled diversion into the Salton Sea. Since 1951, a record of the flow above the canal at the northerly boundary (table 7) has been maintained by the International Boundary and Water Commission. An equivalent record for 1934–50, computed by adding flows in two drains and two wasteways (constructed after 1911) to the flows of the Colorado River at Yuma, was published for "Colorado River and Pilot Knob wasteway at Rockwood Gate, Calif." (U.S. Geol. Survey, 1954). A similar record for 1912–33, compiled for this report, required the estimation of small return flows for 12 years. Prior to 1912, annual flows at Yuma were practically the same as those at the northerly boundary.

DISTRIBUTION OF COLORADO RIVER WATER

Irrigation has been a major goal in the development of the lower Colorado River and is still the dominant influence on distribution of the water. Other uses are increasing, however, and large quantities of water are lost by evaporation and nonbeneficial transpiration.

Diversions from the Colorado River below Davis Dam serve areas adjoining or near the river in Arizona and much of the densely populated area in southern California. A large part of the water diverted to areas within the Colorado River basin returns to the river and can be diverted again, but only a negligible part of the water diverted for use outside the basin returns to the river.

The net diverson (difference between gross diversion and return flow in surface channels) commonly is used as an index of the streamflow depletion or consumptive use of water associated with a particular diversion. Although such net diversion is a satisfactory index of actual consumptive use under favorable circumstances, it is a very unreliable index when relatively large quantities of water enter or leave the particular area as ground-water seepage or contribute to changes in ground-water storage within the area. Furthermore, there are few adequate records of return flows prior to 1960 because there was no scarcity of water for then current uses.

GROSS DIVERSIONS

Figure 14 illustrates the progressive increase of diversions from the lower Colorado River. It is necessarily based on gross diversions because of the scarcity of return-flow data needed to determine net diversions. The following paragraphs describe these diversions and their relation to the total water supply of the respective areas.

The only major diversion between Hoover Dam and Parker Dam is the diversion from Lake Havasu through the Colorado River aqueduct to the south coastal basins of California. This diversion, which began in 1939, supplements other water supplies from both local and distant sources.

All water diverted between Parker Dam and Imperial Dam (except for numerous small diversions by pumps, chiefly in Cibola Valley) is delivered to Parker and Palo Verde Valleys. Diversions to Parker Valley began in 1870, but there are no records for years prior to 1915. Annual diversions were less than 40,000 acre-feet per year until after the completion of Headgate Rock Dam in 1942, when they began to increase rapidly. Diversions to Palo Verde Valley began before 1900, but there are no records for years prior to 1922. These diversions are the only water supplies for the respective valleys except for the local ground water, which is affected by seepage to or from the river and by irrigation of crops with river water.

Diversions from the Colorado River to the Yuma area began about 1900 and have been made by several means, including gravity diversion at both ends of Imperial and Laguna Dams, temporary gravity diversions, and pumping. Diversions to the Wellton-Mohawk area, in the lower part of the Gila River valley, began in 1952. Records on which approximate total diversions to the Yuma and Wellton-Mohawk areas can be based began in 1908. These totals are gross diversions for irrigation; they do not include water returned to the river through the Yuma Main Canal wasteway or Pilot Knob powerplant and wasteway, most of which was diverted for power generation. These diversions, like those to the Parker and Palo Verde Valleys, are the only water supplies for the Yuma and Wellton-Mohawk areas except the local ground-water supply, which is affected by seepage to or from the Colorado and Gila Rivers and by irrigation of crops with river water.

Diversions to Imperial and Mexicali Valleys began in 1901; continuous records began in 1908. Prior to completion of the All-American Canal in 1940, water was

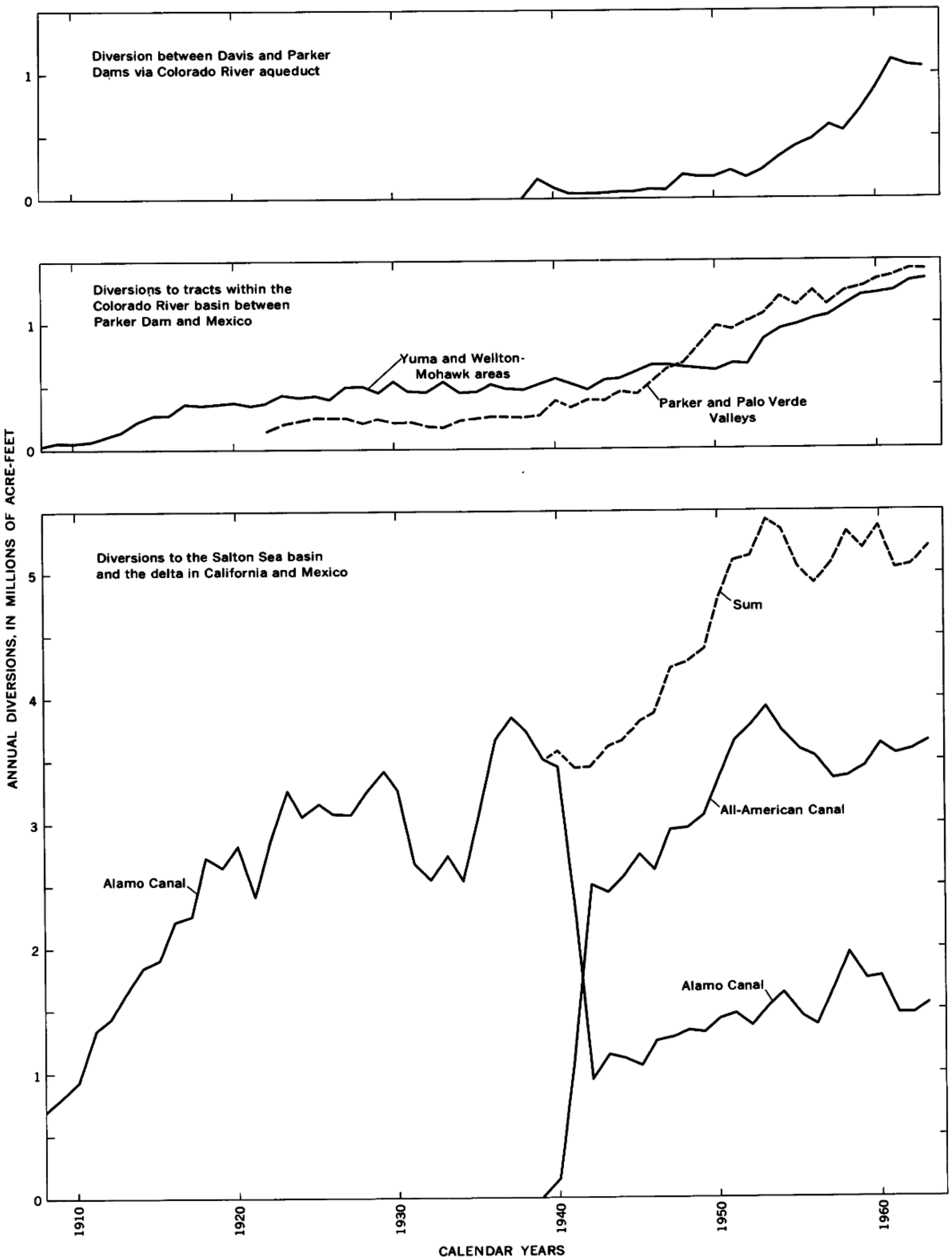

FIGURE 14.—Principal diversions from the Colorado River below Davis Dam, 1908–63.

diverted through the Alamo (Imperial) Canal for use on both sides of the international boundary. During 1916–21, supplemental diversions were made from a distributary of the Colorado River at Volcano Lake, near the western edge of the delta in Baja California. The rapid increases in diversions during the first half of this century were interrupted in the drought of 1931–34 but were resumed after regulation of the river was accomplished by closure of Hoover Dam in 1935.

Since 1941 the All-American Canal has supplied all water used in Imperial Valley in California, and since 1948 it has also supplied water to the lower part of Coachella Valley. The graph for the All-American Canal (fig. 14) shows the flow below Pilot Knob powerplant and wasteway; therefore, it does not include water diverted through the All-American Canal to the Yuma area, water returned to the river at or above Pilot Knob, or water lost by evaporation and seepage above Pilot Knob. The graph for Alamo Canal after 1941 shows the principal diversion to Mexico but does not include small diversions from the river below the canal or return flow from Yuma Valley used for irrigation near San Luis, Sonora.

The Colorado River and the related ground-water bodies are the only supplies available in Imperial and Mexicali Valleys. Wells in the central part of Imperial Valley yield very little water, which is generally of poor quality, but usable ground-water supplies underlie parts of the East Mesa (fig. 4). Water is withdrawn from many wells in Mexicali Valley.

Ground water that originates from precipitation on nearby mountains is the principal supply for the upper part of Coachella Valley (fig. 4) and was the principal supply for the lower part of the valley until importation of Colorado River water began about 1948. The Coachella Valley County Water District has contracted for delivery of additional surface water from northern California whenever such supply becomes available.

NET DIVERSIONS

The gross diversions shown in figure 14 for the Colorado River aqueduct and the All-American Canal below Pilot Knob are good approximations of the streamflow depletion caused by these diversions. The gross diversion through the aqueduct generally exceeded the net diversion by less than 2 percent. As previously described, the diversions to Imperial and Coachella Valleys were determined for a point below Pilot Knob wasteway and so excluded both the return flows and the unrecovered losses from the canal above the wasteway. As some of the losses are attributable to this diversion, the streamflow depletions were slightly greater than the indicated diversions.

Available records indicate that return flows from areas adjoining the river are commonly more than half the gross diversions. For example, figure 15 shows the

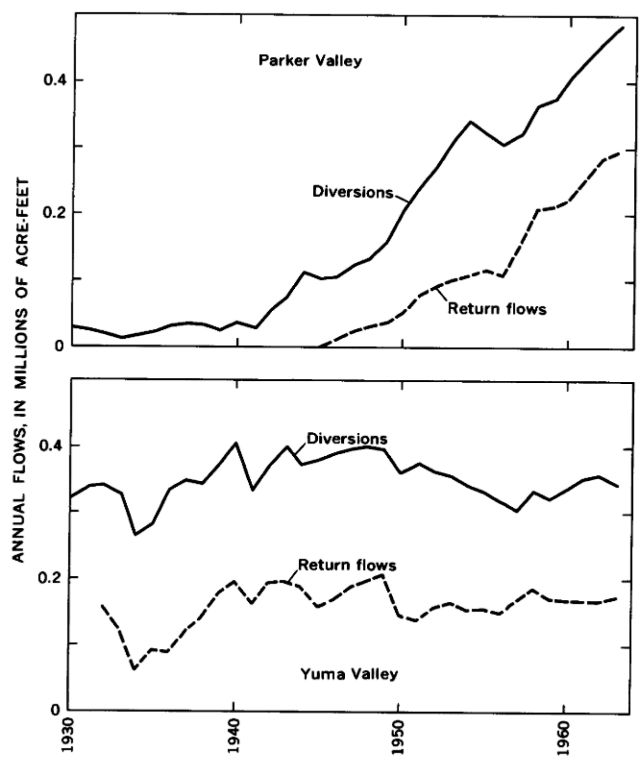

FIGURE 15.—Annual diversions and return flows for Parker Valley and Yuma Valley, 1930–63.

annual diversions and return flows (hence, the magnitude of net diversions) for Parker and Yuma Valleys, for which the longest records are available. The graph for Parker Valley illustrates the usual absence of return flow when diversions are small and the progressive increase of return flow as the gross diversion increases.

Figure 16 illustrates the approximate depletion of the flow of the Colorado River caused by use of water from the main stem in the States of Arizona and California and also the principal diversions to Baja California in four selected years. Losses from the river associated with the storage and conveyance of water are not included. Accurate determination of these depletions for years prior to 1960, particularly those prior to 1941, is impossible not only because of a scarcity of return-flow records but also because some canals supplied tracts in more than one State; nevertheless, quantities that are sufficiently accurate for this illustration were estimated on the basis or available records of diversions, return flows, and irrigated acreage.

The diversions in Alamo Canal for 1915 and 1930 were prorated between California and Baja California in proportion to the irrigated acreage in each State. In 1915 about 12 percent of the acreage served by the canal was in Baja California, and by 1928 about 32 percent was in that State (Adams and others, 1930, p. 86). The percentage for 1930 was assumed to be the same as that for 1928.

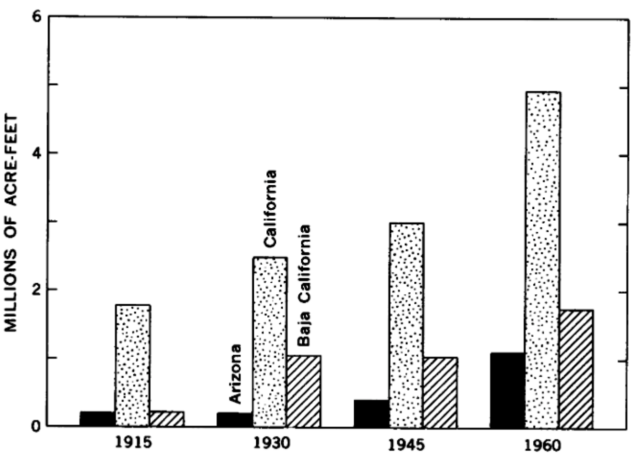

FIGURE 16.—Depletion of the lower Colorado River in selected years, by States.

The bars shown (fig. 16) for Baja California represent the principal diversions to Mexico; they do not include the effects of return flow below Morelos Dam, diversions from the river below the dam in both Sonora and Baja California, or water crossing the Arizona-Sonora boundary.

The distribution of Colorado River water in accordance with requirements of the Mexican treaty of 1944 and the U.S. Supreme Court decree of 1964 will require changes in the existing distribution indicated in figure 16 unless additional water is provided. In 1960, annual diversions to Baja California exceeded the guaranteed quantity of 1,500,000 acre-feet for Mexico, and depletions in California exceeded the basic allowance of 4,400,000 acre-feet; but depletions in Arizona were still less than half the basic allowance of 2,800,000 acre-feet.

DISTRIBUTION OF FLOW DURING 1961–63

The pattern of distribution of Colorado River water has been changing since the first diversions were made and is still changing as new water-supply and irrigation projects are completed or old ones altered. As flows for a single year may be affected by abnormal circumstances, and as average flows for a long period may be affected by excessive change of the distribution pattern within the period, the distribution is best represented by average flows for a period of only a few years.

Table 4 and figure 17 summarize the average annual flows throughout the distribution system below Davis Dam for the period 1961–63. The annual flows during the period varied within a relatively narrow range. The most notable differences between average flows for this period and those for other recent periods are: (a) Flow of Gila River near its mouth was markedly greater after 1960 because of pumping from drainage wells in the Wellton-Mohawk area and in South Gila Valley, and (b) return flow through Yuma Main Canal wasteway was markedly less after 1960.

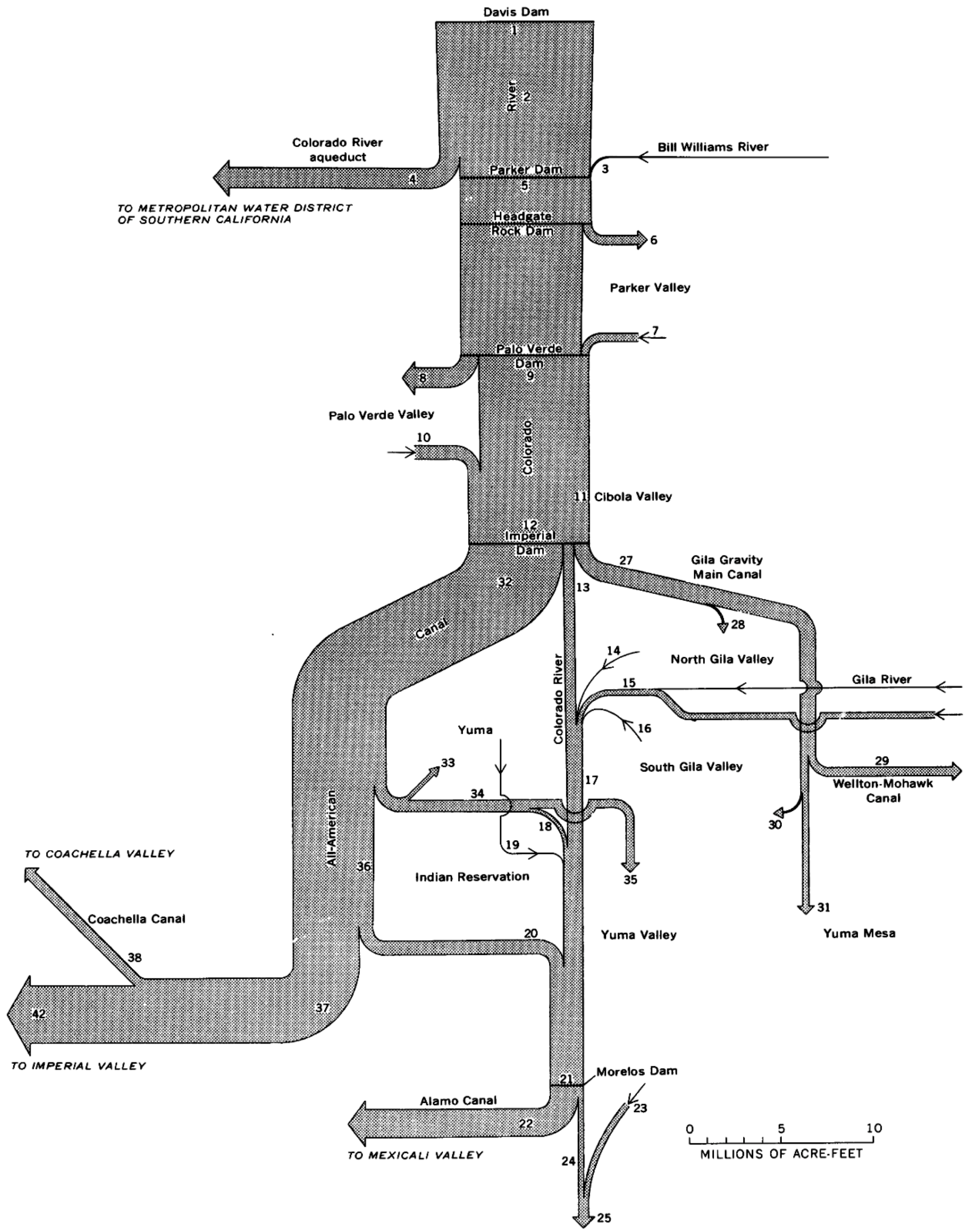

FIGURE 17.—Distribution of Colorado River water below Davis Dam, 1961–63. Widths of pattern indicate mean annual flows except those less than 100,000 acre-feet. Numbers refer to items in table 4.

TABLE 4.—*Average annual flow in the lower Colorado River system, 1961–63*

		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.[1]	7,128,000
6.	Diversion to Parker Valley, Ariz	463,300
7.	Return flow from Parker Valley, Ariz.[2]	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.[3]	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.[4]	49,900
15.	Gila River near Yuma, Ariz.[5]	194,000
16.	Return flow from South Gila Valley, Ariz.[6]	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.[7]	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.[8]	172,200
24.	Colorado River at southerly international boundary	223,400
25.	Total flow to Mexico at southerly boundary [9]	370,400
26.	Total flow to Mexico [10]	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.[11]	95,100
34.	Yuma Main Canal at siphon-drop powerplant near Yuma, Ariz	573,700
35.	Diversion to Yuma Valley, Ariz.[12]	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 [13]	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 [14]	1,270,000
47.	Inflow to Salton Sea from Coachella Valley [15]	110,000

[1] A decrease of 15,100 acre-feet in the contents of Lake Havasu accounts for 5,000 acre-feet of this total.
[2] 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).
[3] Sum of flows in 12 channels—partly estimated.
[4] Sum of flows in six channels—three tributary to the Colorado River and three tributary to the Gila River.
[5] Sum of flows of the Gila River near Dome, Wellton-Mokawk 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.
[6] Sum of flows in three channels—2 tributary to the Gila River and one tributary to the Colorado River.
[7] Sum of flows in two channels.
[8] 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).
[9] Sum of flows in the Colorado River and canals. (See footnote 8.)
[10] 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.
[11] Sum of flows in several small canals diverting from All-American and Yuma Main Canals. About 4,700 acre-feet of his total was diverted from Yuma Main Canal below siphon-drop powerplant and is included in item 34.
[12] Includes diversion for the City of Yuma.
[13] Sum of flows below East Highline Canal and diversions above East Highline check.
[14] Sum of flows in the Alamo and New Rivers and about 30 other channels.
[15] Sum of flows in the Whitewater River and 18 drains.

Additional information concerning the distribution of Colorado River water can be derived from the data in table 4, but figures so derived must be interpreted with caution. For example, the difference of 14,000 acre-feet between items 11 and 12 is much smaller than probable errors of measurement involved in either item; consequently, it is not a dependable estimate of depletion between Cibola Valley and Imperial Dam. Some applications of table 4 are discussed in the following section.

WATER USE AND WATER LOSS

The use of water from the lower Colorado River has been accompanied by large losses, some avoidable and others unavoidable. Although the previously described streamflow data afford little direct information concerning such losses or the efficiency of water use, information can be obtained from water-budget studies based on the streamflow data and computations or estimates of evaporation and consumptive use by vegetation.

The term "consumptive use" denotes water returned to the atmosphere by evaporation and transpiration or incorporated in vegetation or industrial products. Consumptive use for an irrigated tract includes evaporation from canals and bare soil and transpiration from areas of native vegetation that are too small to be considered separately. It should be noted, however, that the amount of water required for irrigation of crops in an arid region without impairment of the soil productivity exceeds the consumptive use. Sufficient water must be applied to remove excess minerals from the soil; also, some waste is involved in any practical method of applying water to the crops.

A water budget is an accounting based on the fact that outflow from a specific area or water body during a specific period is equal to the inflow plus the decrease (or minus the increase) in storage. The unqualified terms "inflow" and "outflow" generally refer to water entering or leaving a budget area by any means; but in the following budgets, precipitation is accounted for by subtracting it from evaporation and transpiration instead of entering it as an inflow item. Changes in storage include changes in both surface and groundwater storage where applicable. Changes in soil moisture, which must be included in a comprehensive budget for a land area, are ignored herein because they are unknown and their effects probably are negligible.

The residual required to balance a water budget is affected by the net error in all other budget terms and by any term omitted because it was small or unknown. Hence, the residual is most reliable as an estimate of stream depletion or consumptive use when the ratio of residual to probable net error is greatest.

Water budgets for several segments of the study area, described in the following sections, have been developed. As Colorado River water is the primary concern of this report, the budget areas are limited to the river and to land where river water or closely related ground water is consumed. Budgets to determine conveyance losses from major canals are treated separately because these losses are reflected in budgets for the encompassing areas.

CONVEYANCE LOSSES FROM LARGE CANALS

The distribution of water throughout an irrigation system involves losses by evaporation and seepage, especially when unlined canals convey water for long distances in desert terrain. Evaporation from large unlined canals generally is small in relation to the seepage. For example, seepage from the canals listed in table 5 is roughly 30 times the estimated evaporation.

The disposition of water that seeps from canals varies with location and circumstances. Seepage may become part of the evapotranspiration loss from the encompassing area, or it may become part of a local water supply. Thus, the seepage may influence the distribution of water within a specific area as much as it influences the overall water loss.

Seepage from canals near the Colorado River contributes to return flow and usually is indistinguishable from return flow caused by irrigation. Part of the seepage from the All-American and Coachella Canals enters the Salton Sea, and part of it recharges shallow aquifers that may contain water of either better or worse quality than that of the canal water.

Seepage losses vary considerably because of erosion of seepage channels, activities of burrowing animals, deposition of sediment, canal maintenance activities, and changes in the extent of saturated sediments beneath and adjacent to the canals. Seepage from some reaches of the All-American Canal system has shown a tendency to decline, probably because of changes in the extent of saturated sediments.

Table 5 summarizes the losses by evaporation and seepage from several reaches of the major canals below Imperial Dam. The losses were calculated from the data in table 4. The percentages in the last column are used as a basis for judging the reliability of the calculated losses. Thus, an error of 1 percent in the determination of canal flow would produce an error of less than 4 percent in the calculated loss from the upper reach of Coachella Canal but would produce an error of more than 30 percent in the calculated loss from the upper reach of the All-American Canal. In fact, the loss calculated for a nearly identical reach of the All-American Canal—Imperial Dam to the gaging station above Pilot Knob wasteway—is 100,000 acre-feet instead of the 140,000 acre-feet shown in table 5.

TABLE 5.—*Water losses from major canals, 1961–63*

Canal reach	Length of reach (miles)	Average annual loss	
		Acre-feet	Percentage of flow at head of reach
Gila Gravity Main Canal			
Imperial Dam to Yuma Mesa	21	[1] 41,000	4.7
All-American Canal			
Imperial Dam to Pilot knob [2]	21	140,000	2.8
Pilot Knob to East High Line Canal [3]	37	150,000	4.2
Coachella Canal			
Head to 6A check, near Niland	49	150,000	28
6A check to mile post 87, near Mecca	38	25,000	6.6

[1] Includes minor amounts of gate leakage or spill at two wasteways.
[2] Below Pilot knob wasteway (item 37 of table 4.
[3] First major diversion to Imperial Valley.

LOWER COLORADO RIVER AREA—DAVIS DAM TO MEXICO

Davis Dam to Imperial Dam.—O. J. Loeltz and C. C. McDonald, U.S. Geological Survey (written commun., 1967), developed water budgets for the reach extending from Davis Dam to Imperial Dam and for the two subreaches that meet at Parker Dam. Although the computed residuals for the subreaches are less accurate indicators of consumptive use than that for the longer reach, they are useful indicators of the distribution of such use. Loeltz and McDonald also computed the corresponding annual consumptive use using experimental data on rates of consumptive use and acreages of various crops, native vegetation, and water surface. Their results are summarized in the following tabulation.

[Mean annual quantities, in acre-ft, 1950–66]

	Davis Dam to Parker Dam	Parker Dam to Imperial Dam	Davis Dam to Imperial Dam
Water budget			
Inflow:			
Measured:			
Surface	9,581,000	8,578,000	9,581,000
Unmeasured:			
Surface	73,000	71,000	144,000
Subsurface	15,000	16,000	31,000
Change in storage:			
Measured	−8,000	------------	−8,000
Unmeasured			
Outflow:			
Measured:			
Surface	9,253,000	7,890,000	8,565,000
Unmeasured:			
Subsurface	0	10,000	10,000
Residual (consumptive use)	424,000	765,000	1,189,000
Consumptive use			
Irrigated cropland (3.6 acre-ft per acre)	11,000	440,000	451,000
Native vegetation	188,000	353,000	541,000
Water surface (6.75 acre-ft per acre)	181,000	81,000	262,000
Total	380,000	874,000	1,254,000
Average for two methods	402,000	820,000	1,222,000

All measured flows in the water budgets were derived from stream flow records in the same manner as items in table 4. Records of the flow at (above) Imperial Dam prior to 1961, however, were adjusted by deducting 100,000 acre-feet per year because of unmeasured inflow between the dam and the station at Yuma, the record for which was used in compiling those records for Imperial Dam. Later records were compiled from flows measured at the dam.

All unmeasured flows in the budgets were estimated. Although these small quantities are subject to large percentage errors, the errors probably are less significant than the small percentage errors affecting the large measured quantities. Estimates of surface runoff were based on the analysis of runoff made by Hely (Hely and Peck, 1964) and records of runoff for nearby desert areas. The average annual rate of runoff was estimated to be 16 acre-feet per square mile. Unmeasured ground-water inflow was assumed to equal the net recharge to aquifers in the area tributary to the Colorado River valley, which was estimated on basis of annual precipitation by methods developed by Eakin (1961). In this method, annual recharge was computed as a percentage of annual precipitation above a base, the percentage increasing with annual precipitation.

The measured change in storage is the average annual decrease in the contents of Lake Havasu, which is equivalent to an addition to inflow or a deduction from outflow in a water budget. The unmeasured change, chiefly in ground-water storage, is unknown but believed to be negligible.

The probable reliability of the residuals for the 17-year period as estimates of long-term residuals could be determined by statistical analysis of residuals for annual budgets. However, for the reach from Davis Dam to Imperial Dam, the measured quantities in the 17-year budget account for 86 percent of the total residual. Hence, analysis of the annual residuals computed using only measured quantities serves nearly as well. Loeltz and McDonald made such an analysis of annual residuals for the reach from Davis Dam to Imperial Dam and concluded that (a) the annual residuals probably are normally distributed; and (b) at the 95 percent confidence level, the computed residual (1,024,000 acre-ft for measured quantities) is within 69,000 acre-feet of the long-term residual.

The consumptive-use estimates in the lower part of the tabulation were derived from acreages of each type of water-using area and appropriate rates of use by each type. Data for the principal areas of cropland were obtained from annual crop reports of the Colorado River Indian Reservation and the Palo Verde Irrigation District. Data on other cropland and native vegetation were obtained from an inventory of land use in 1962 (U.S. Bureau of Reclamation, 1963). The area of water surface was derived from areal photographs.

The average annual rate of water use by the crops usually grown in these areas was estimated to be 3.6 acre-feet per acre on the basis of studies by Blaney and Harris (1952) and Erie, French, and Harris (1965). The consumptive use by native vegatation above Parker Dam is from a preliminary estimate by the U.S. Bureau of Reclamation (1963); the use below Parker Dam is equal to the Bureau's preliminary estimate, 327,000 acre-feet, plus 26,000 acre-feet (estimated by Loeltz and McDonald, written commun., 1967) used on 6,000 acres in Palo Verde valley, which was not included in the Bureau's land inventory. The net evaporation from water surfaces was derived by subtracting the mean annual precipitation, 5 inches (Hely and Peck, 1964, pl. 3), from the mean annual lake evaporation, 86 inches, determined by the U.S. Weather Bureau (1959, pl. 2).

Although the areas covered by various types of native vegetation are known only for 1962, the consumptive use during that year probably is close to the mean consumptive use during the budget period. The known increase of irrigated acreage has been accompanied by clearing of native vegetation. This tendency for reduction of native vegetation may have been at least partly compensated by the well-known tendency for native vegetation to spread and increase in density. Loeltz and McDonald estimated that consumptive use increased 0.8 acre-foot per acre when land was cleared and irrigated. The net result probably was a relatively small increase of consumptive use during the budget period.

Considering the uncertainties involved in computation of consumptive use and the effect of probable errors on the water-budget residual, the results obtained by the two methods are in close agreement.

Imperial Dam to Mexico.—The water-using area between Imperial Dam and Mexico includes several distinct units (fig. 3). For water-budget studies, however, a simpler division into two units with hydraulic connection only in the narrow gap at the north end of the Gila Mountains is more appropriate. These units are the Wellton-Mohawk area extending upstream from the gap along the Gila River, and the Yuma area along the Colorado River.

Because of its separation from the Colorado River floodplain, the Wellton-Mohawk area was not included in either the detailed ground-water studies by the Geological Survey or the inventory of land use by the Bureau of Reclamation. Furthermore, ground water in the area has two major sources (the Gila River and the Colorado River) rather than the single major source for most other units of the study area. The available information is insufficient for compilation of a reliable, complete water budget.

Marked changes in the hydrologic regimen of the Wellton-Mohawk area occurred about 1950, when Colorado River water began to replace the local ground water as the irrigation supply, and in 1961, when drainage by pumping ground water began. The following tabulation of measured inflows and outflow and the corresponding residuals illustrate some effects of the last of these changes and compares the changing regimen for the Wellton-Mohawk area with the more stable regimen for the Yuma area.

[Mean annual quantities, in acre-ft.]

	Wellton-Mohawk area	Yuma area	Combined area
	Calendar years 1957–59		
Measured inflow	332, 800	8, 414, 000	8, 413, 000
Measured outflow	1, 500	7, 771, 000	7, 438, 000
Residual	331, 000	643, 000	975, 000
	Calendar years 1961–63		
Measured inflow	414, 600	6, 618, 000	6, 424, 000
Measured outflow	194, 000	5, 913, 000	5, 498, 000
Residual	221, 000	705, 000	926, 000

The inflow and outflow figures for 1961–63 were derived from table 4, and those for 1957–59 were derived from an unpublished compilation for that period. As explained in the discussion of water budgets for areas above Imperial Dam, the published figures of flow at the dam prior to 1961 were adjusted by deducting 100,000 acre-feet per year.

None of the residuals in this tabulation is a valid estimate of consumptive use because of the omission of important items, particularly changes of storage. Each is a fair estimate of the depletion of Colorado River caused chiefly by the use of its water in the area.

Using the same average rate of consumptive use by cropland (3.6 acre-ft per acre) as that used for areas above Imperial Dam, the average consumptive used by cropland in the Wellton-Mohawk area was computed by C. C. McDonald and O. J. Loeltz of the U.S. Geological Survey (written commun., 1967), as 168,000 acre-feet per year during 1957–59 and 192,000 acre-feet per year during 1961–63. The use by native vegetation is unknown but probably substantial.

During 1957–59 nearly all the Colorado River water diverted to the Wellton-Mohawk area remained there; unused water percolated into the underlying aquifer which had been depleted by pumping prior to 1950. Consequently, the residual nearly equals the inflow. By 1960 the ground-water level had risen sufficiently to cause substantial return flow in surface channels, and by 1961 drainage by pumping began. Because of the substantial outflow during 1961–63, the residual was markedly less than in 1957–59 even though the inflow was greater.

In the Yuma area, the acreages of cropland and native vegetation have been relatively stable for many years, and considerable information on the movement and storage of ground water (described in a later chapter) has been gathered since 1960. Using this information and methods previously described, C. C. McDonald and O. J. Loeltz of the U.S. Geological Survey (written commun., 1967), compiled the following water budget and estimates of consumptive use for the calendar years 1951–66.

[Mean annual quantities, in acre-ft, 1951–66]

Water budget	
Inflow:	
Measured:	
Surface	7, 858, 000
Unmeasured:	
Surface	2, 000
Subsurface	17, 000
Change in storage:	
Unmeasured:	
Subsurface	+80, 000
Outflow:	
Measured:	
Surface	7, 232, 000
Unmeasured:	
Subsurface	70, 000
Residual (consumptive use)	495, 000
Consumptive use	
Irrigated cropland	367, 000
Native vegetation	53, 000
Other land areas, including city of Yuma	46, 000
Water surface	20, 000
Total	486, 000
Average for two methods	490, 000

Measured items in the water budget were determined by unpublished compilations similar to table 4. The small, unmeasured surface inflow was estimated in the same manner as the corresponding items in budgets for areas above Imperial Dam. The estimated subsurface inflow consists of 10,000 acre-feet at Imperial Dam, 3,000 acre-feet at the gap where the Gila River enters the Colorado River valley, and 4,000 acre-feet from all other tributary areas. The subsurface outflow crosses the international boundary southward into Sonora and westward into Baja California. The increase in storage was caused chiefly by irrigation of the very sandy soils on the Yuma Mesa, southeast of Yuma, Ariz.

Studies of variability of the yearly differences between measured inflow to and outflow from the Yuma area, made in a manner similar to that previously described for the reach Davis Dam to Imperial Dam, indicated that with 95-percent confidence the 16-year average annual difference is within 37,000 acre-feet of the long term mean. As the total residual required to balance the water budget is 79 percent of the difference between measured inflow and outflow, this range of probable error may be reasonably applied to the total residual also.

Summary of stream depletions, Davis Dam to Mexico.—Diversions to the metropolitan areas of southern California through the Colorado River aqueduct have increased gradually from a few thousand acre-feet in 1946 to about 1,100,000 acre-feet in each year after 1960. Diversions to the Salton Sea basin through the All-American Canal have varied between 3 million and 4 million acre-feet per year since 1945. The consumptive use in areas along the Colorado River was relatively stable and near 1,900,000 acre-feet per year during the 17-year period 1950–66. The flow to Mexico has exceeded the guaranteed quantity of 1,500,000 acre-feet per year in every year since 1944. The excess averaged nearly half a million acre-feet, but the excess has been sharply reduced in recent years. Practically no water has flowed into the Gulf of California since 1959 without having been diverted at least once.

The 1,900,000 acre-feet consumed in areas along the Colorado River includes about a million acre-feet used by crops, nearly 600,000 acre-feet used by native vegetation (excluding unknown use in the Wellton-Mohawk area), and nearly 300,000 acre-feet evaporated from water surfaces.

The consumptive use of water by cropland is increasing because of the increase of irrigated acreage and the growth of recently planted citrus trees. The largest potential increase of irrigated acreage is in the Colorado River Indian Reservation, where about 75,000 acres of arable land were undeveloped in 1962 (U.S. Bureau of Reclamation, 1963). Most of this land, however, was covered with native vegetation that used large quantities of water. Hence, the increase in consumptive use by cropland will be at least partly compensated for by a decrease in consumptive use by native vegetation.

Flow to Mexico exceeding treaty requirements was a natural result of streamflow exceeding existing needs in the United States. This flow commonly exceeded requirements, however, even during periods of water shortage because of insufficient regulating capacity near Imperial Dam, release of relatively high flows for short periods to move sediment deposits below the dam, and return flows from the Yuma and Wellton-Mohawk areas. Better regulation of the flow by use of Senator Wash Reservoir and more efficient use of return flows probably will tend to keep the excess flows below the relatively low level achieved in 1966 (about 200,000 acre-ft).

The potential water salvage by channelizing the river, eradicating the native vegetation from nonarable flood plains that are not within wildlife refuges, and recovering ground water in the Yuma area has been estimated by the U.S. Bureau of Reclamation (1964c) as 510,000 acre-feet. If this much salvage is achieved, the future annual depletions of the Colorado River between Davis Dam and Mexico may be nearly 500,000 acre-feet less than those of 1961–63.

This potential reduction of depletion below Davis Dam approximately balances the potential increase of depletion above the dam (p. D20); so the future depletion in the entire reach from compact point to Mexico (excluding diversions out of the Colorado River valley) may not differ greatly from the 2,200,000 acre-feet indicated for recent years. The proposed diversion to central Arizona is not included in the depletion discussed here because that diversion would involve removal of water from the budget area with no return flow and, consequently, would be similar to diversions to southwestern California.

SALTON SEA BASIN

The gross annual diversion for 497,000 acres in Imperial and Coachella Valleys during 1961–63 was 3,603,000 acre-feet (item 37 of table 4), or about 7.2 acre-feet per acre irrigated. This rate of use, however, is affected by high conveyance losses below Pilot Knob (table 5) and the discharge of all unconsumed water to the Salton Sea.

These large losses are excluded from the following water budget for the irrigated land in Imperial Valley:

[Items refer to table 4]

	Acre-feet
Measured inflow (items 44 and 45)	3,056,000
Measured outflow (item 46)	1,270,000
Residual	1,786,000

The residual represents an average consumptive use on 432,000 acres of 4.1 acre-feet per acre (including uses in unplanted areas within the irrigated tract).

A similar computation for the area in Coachella Valley served by Colorado River water indicates an apparent consumptive use of 3.8 acre-feet per acre. This figure may differ from the actual consumptive use by crops because it includes consumptive use by native vegetation and an increase in ground-water storage but excludes ground-water inflow from adjacent areas.

The principal losses involved in the use of Colorado River water in the Salton Sea basin are conveyance losses from canals and discharge to the Salton Sea, but neither of these can be evaluated adequately by itself. As stated in the discussion of conveyance losses from canals, part of the seepage recharges aquifers and may be recoverable (some may be recovered in Mexico), and another part reaches the Salton Sea through drainage channels. The feasibility of reducing seepage losses is under investigation by the Bureau of Reclamation. Although some of the discharge to the Salton Sea represents a loss to the irrigation districts, considerable discharge is necessary to maintain soil productivity. Also, the sea is sustained almost entirely by the inflow from irrigation districts. Consequenlty, an evaluation of any programs that would reduce discharge from the districts must consider the effects of such programs on the hydrologic regimen of the Salton Sea (Hely and others, 1966).

INTERRELATION OF SURFACE WATER AND GROUND WATER

As the Colorado River traverses extensive deposits of saturated alluvium, water levels in the alluvium obviously must affect the regimen of the river. Under conditions of excessive uncontrolled withdrawal of ground water from the floodplain the river would lose substantial quantities of water to the underlying alluvium. Under such conditions nearly all of the ground-water recharge would be derived from the river either by direct seepage or by application of river water for irrigation; hence, the pumping of ground water from the floodplain and adjacent areas can add little to the long-term water supply available from the lower Colorado River. Prudent use of ground water, however, can markedly influence the ultimate disposition of this total supply. Losses by seepage from a particular area or by nonbeneficial use can be decreased by lowering the water level in some areas. Withdrawals of ground water add to the usable supply for the duration of such withdrawals (except when the water is of very poor quality).

Preceding discussions have indicated that the pumping of ground water is intimately related to irrigation drainage and water salvage in some areas and that this pumping is increasing. Another potentially important use of such pumping is for additional stabilization of the water supply available below Davis Dam.

To obtain maximum benefit from such short-term augmentation of the usable supply by withdrawals from storage, ground-water storage capacity should be used in the same manner as surface storage—drawn upon when other supplies are insufficient and replenished when other supplies are abundant—so long as this can be done without serious interference with streamflow.

Storage of water beneath the ground prevents the loss by evaporation that tends to nullify the benefits of long-term storage in surface reservoirs. However, many other problems concerning the characteristics of the ground-water reservoirs and the economics of well-field development and operation, all of which are beyond the scope of this report, are involved. Also, management of ground-water storage may require legal controls or authorizations that do not now exist.

Artificial recharge of aquifers to enable optimum use of their storage capacity has been employed experimentally and practically since about 1895 (Todd, 1959), and its use is increasing. For example, 32.4 percent of the water diverted through the Colorado River aqueduct in 1960 was used to recharge depleted aquifers in southwestern California (Smith and Brewer, 1961).

Some aspects of the conjunctive use of surface and subsurface reservoirs and the management of ground-water basins have been discussed in publications of the American Society of Civil Engineers (1961, 1964); an investigation of the use of aquifers in San Joaquin Valley, Calif., for storage of surplus surface water has been described by Davis, Lofgren, and Mack (1964). Investigations of several aquifers near the lower Colorado River and of the chemical quality of the water therein are in progress (1968).

A rough estimate of the potentially usable ground-water storage capacity between Davis Dam and Mexico can be derived as follows. If the area of ground-water development is assumed to be 150,000 acres and to have recoverable water occupying 15 percent of the volume of alluvium, each 10-foot change in the average water level within the developed area would correspond to 225,000 acre-feet (or a change of about 45 ft in water level would correspond to 1,000,000 acre-ft). Although it would be theoretically possible to reserve most of this storage for use during the most critical periods, the impossibility of forecasting the magnitude and duration of streamflow deficiencies and the economics of well fields preclude such ideal use. However, without doubt prudent ground-water development can significantly improve the efficiency of water use and stability of the supply.

DEFICIENCY OF THE COLORADO RIVER SUPPLY

The potential demand for water in the service area of the lower Colorado River system greatly exceeds presently foreseeable supplies. Thousands of formerly irrigated acres in the Gila River basin near Phoenix, Ariz., have been abandoned for lack of water; in vast areas rates of water use greatly exceeding the average annual replenishment of the supplies are sustained by continuing withdrawals from rapidly dwindling ground-water storage; other areas could be made productive if water were available.

Despite the evident water shortages, the population in parts of the service area has been increasing at phenomenal rates. This has been possible partly because water requirements of urban and irrigated areas of equal size are roughly the same. Urban growth in the south coastal basins in California, however, has involved interbasin transfers of water within the water-short Southwest (including that through the Colorado River aqueduct), and facilities now (1968) under construction will enable transfer from water-surplus areas in northern California. The deficiency of the Colorado River supply is not expected to deter urban growth in the report area, but it will deter expansion of irrigation. The necessary urban supplies will be derived by conversion from irrigation uses if necessary.

As satisfaction of all potential water demands in the service area is practically impossible, current planning is often based on the arbitrary goal established by the Colorado River Compact and the Boulder Canyon Project Act at times when the available streamflow records indicated a considerably larger mean virgin flow of Colorado River than present records indicate. This goal is to provide sufficient water in the lower Colorado River, or equivalent imports to the service area, to provide for delivery of Mexico's guaranteed allotment and for annual consumptive use of 2,800,000 acre-feet in Arizona, 4,400,000 acre-feet in California, and 300,000 acre-feet in Nevada. These prospective uses in Arizona and Nevada are much greater than current uses, but the prospective use in California is less than current use. Some proposals involve much larger quantities of water and much larger service areas.

The regulated water supply derived from the drainage basin above compact point is near 13 million acre-feet during dry periods, such as 1931–64, and 15 million acre-feet during periods of normal runoff. The additional supply derived from inflow to the Colorado River between compact point and Davis Dam probably will be less than 500,000 acre-feet (assuming an increase in the consumptive use of tributary flows) during dry periods and slightly greater during periods of normal runoff. Hence, the corresponding gross supplies at Davis Dam are near 13,500,000 acre-feet and 15,500,000 acre-feet.

To obtain the net supply available at Davis Dam the probable depletions above the dam must be substracted from these totals. These depletions, as estimated by the U.S. Bureau of Reclamation (1965, p. 236), are listed below.

[Amounts given in acre-ft]

Year	1975	1990	2000	2030
Depletion above compact point	4,220,000	5,100,000	5,430,000	5,800,000
Evaporation from Lake Mead (and Colorado River)	898,000	872,000	835,000	853,000
Net use in Nevada	100,000	150,000	200,000	300,000
Net loss in Lake Mohave	110,000	110,000	110,000	110,000
Total depletion above Davis Dam	5,328,000	6,232,000	6,575,000	7,063,000

For normal runoff conditions, the corresponding net supply at Davis Dam would be about 10,200,000 acre-feet in 1975 and 8,400,000 acre-feet in 2030. For dry conditions, the corresponding supplies would be 8,200,000 acre-feet and 6,400,000 acre-feet.

The amount of water required to satisfy basic allotments below Davis Dam (8,700,000 acre-ft) and the losses associated with storage and conveyance of water below the dam (about 900,000 acre-ft) is 9,600,000 acre-feet. The usable part of the small inflow below Davis Dam probably is little greater than the excess flow to Mexico that will be necessary to effect delivery of the guaranteed quantity as requested by Mexico. Hence, these two small quantities are ignored in this discussion.

Comparison of these figures of supply and demand shows that the supply is adequate only for periods of near normal runoff prior to about 1980. For dry conditions (exemplified by 1931–64) near the year 2030, the deficiency would be about 3,200,000 acre-feet. If depletions above compact point should reach the 7,500,000 acre-feet specified in the Colorado River Compact, the deficiency might be as much as 4,900,000 acre-feet.

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APPENDIX

Given on the following pages are the Colorado River Compact and parts of the Rio Grande, Colorado, and Tijuana Treaty, quoted from a compilation by Witmer (1956), and parts of the decree by the Supreme Court of the United States, reproduced from an original publication of the Court (1964).

COLORADO RIVER COMPACT, 1922

[Quoted from a compilation by Witmer (1956)]

The States of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming, having resolved to enter into a compact under the Act of the Congress of the United States of America approved August 19, 1921 (42 Statutes at Large, page 171), and the Acts of the Legislatures of the said States, have through their Governors appointed as their Commissioners:

W. S. Norviel for the State of Arizona,
W. F. McClure for the State of California,
Delph E. Carpenter for the State of Colorado,
J. G. Scrugham for the State of Nevada,
Stephen B. Davis, Jr., for the State of New Mexico,
R. E. Caldwell for the State of Utah,
Frank C. Emerson for the State of Wyoming,

who, after negotiations participated in by Herbert Hoover appointed by The President as the representative of the United States of America, have agreed upon the following articles:

ARTICLE I

The major purposes of this compact are to provide for the equitable division and apportionment of the use of the waters of the Colorado River System; to establish the relative importance of different beneficial uses of water; to promote interstate comity; to remove causes of present and future controversies; and to secure the expeditious agricultural and industrial development of the Colorado River Basin, the storage of its waters, and the protection of life and property from floods. To these ends the Colorado River Basin is divided into two Basins, and an apportionment of the use of part of the water of the Colorado River System is made to each of them with the provision that further equitable apportionments may be made.

ARTICLE II

As used in this compact—

(a) The term "Colorado River System" means that portion of the Colorado River and its tributaries within the United States of America.

(b) The term "Colorado River Basin" means all of the drainage area of the Colorado River System and all other territory within the United States of America to which the waters of the Colorado River System shall be beneficially applied.

(c) The term "States of the Upper Division" means the States of Colorado, New Mexico, Utah, and Wyoming.

(d) The term "States of the Lower Division" means the States of Arizona, California, and Nevada.

(e) The term "Lee Ferry" means a point in the main stream of the Colorado River one mile below the mouth of the Paria River.

(f) The term "Upper Basin" means those parts of the States of Arizona, Colorado, New Mexico, Utah, and Wyoming within and from which waters naturally drain into the Colorado River System above Lee Ferry, and also all parts of said States located without the drainage area of the Colorado River System which are now or shall hereafter be beneficially served by waters diverted from the System above Lee Ferry.

(g) The term "Lower Basin" means those parts of the States of Arizona, California, Nevada, New Mexico, and Utah within and from which waters naturally drain into the Colorado River System below Lee Ferry, and also all parts of said States located without the drainage area of the Colorado River System which are now or shall hereafter be beneficially served by waters diverted from the System below Lee Ferry.

(h) The term "domestic use" shall include the use of water for household, stock, municipal, mining, milling, industrial, and other like purposes, but shall exclude the generation of electrical power.

ARTICLE III

(a) There is hereby apportioned from the Colorado River System in perpetuity to the Upper Basin and to the Lower Basin, respectively, the exclusive beneficial consumptive use of 7,500,000 acre-feet of water per annum, which shall include all water necessary for the supply of any rights which may now exist.

(b) In addition to the apportionment in paragraph (a), the Lower Basin is hereby given the right to increase its beneficial consumptive use of such waters by one million acre-feet per annum.

(c) If, as a matter of international comity, the United States of America shall hereafter recognize in the United States of Mexico any right to the use of any waters of the Colorado River System, such waters shall be supplied first from the waters which are surplus over and above the aggregate of the quantities specified in paragraphs (a) and (b); and if such surplus shall prove insufficient for this purpose, then, the burden of such deficiency shall be equally borne by the Upper Basin and the Lower Basin, and whenever necessary the States of the Upper Division shall deliver at Lee Ferry water to supply one-half of the deficiency so recognized in addition to that provided in paragraph (d).

(d) The States of the Upper Division will not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75,000,000 acre-feet for any period of ten consecutive years reckoned in continuing progressive series beginning with the first day of October next succeeding the ratification of this compact.

(e) The States of the Upper Division shall not withhold water, and the States of the Lower Division shall not require the delivery of water, which cannot reasonably be applied to domestic and agricultural uses.

(f) Further equitable apportionment of the beneficial uses of the waters of the Colorado River System unapportioned by paragraphs (a), (b), and (c) may be made in the manner provided in paragraph (g) at any time after October first, 1963, if and when either Basin shall have reached its total beneficial consumptive use as set out in paragraphs (a) and (b).

(g) In the event of a desire for a further apportionment as provided in paragraph (f) any two signatory States, acting through their Governors, may give joint notice of such desire to the Governors of the other signatory States and to The President of the United States of America, and it shall be the duty of the Governors of the signatory States and of The President of the United States of America forthwith to appoint representatives, whose duty it shall be to divide and apportion equitably between the Upper Basin and Lower Basin the beneficial use of the unapportioned water of the Colorado River System as mentioned in paragraph (f), subject to the legislative ratification of the signatory States and the Congress of the United States of America.

ARTICLE IV

(a) Inasmuch as the Colorado River has ceased to be navigable for commerce and the reservation of its waters for navigation would seriously limit the development of its Basin, the use of its waters for purposes of navigration shall be subservient to the uses of such waters for domestic, agricultural, and power purposes. If the Congress shall not consent to this paragraph, the other provisions of this compact shall nevertheless remain binding.

(b) Subject to the provisions of this compact, water of the Colorado River System may be impounded and used for the generation of electrical power, but such impounding and use shall be subservient to the use and consumption of such water for agricultural and domestic purposes and shall not interfere with or prevent use for such dominant purposes.

(c) The provisions of this article shall not apply to or interfere with the regulation and control by any State within its boundaries of the appropriation, use, and distribution of water.

ARTICLE V

The chief official of each signatory State charged with the administration of water rights, together with the Director of the United States Reclamation Service and the Drector of the Unted States Geologcal Survey shall cooperate, ex-offico:

(a) To promote the systematic determination and coordination of the facts as to flow, appropriation, consumption, and use of water in the Colorado River Basin, and the interchange of available information in such matters.

(b) To secure the ascertainment and publication of the annual flow of the Colorado River at Lee Ferry.

(c) To perform such other duties as may be assigned by mutual consent of the signatories from time to time.

ARTICLE VI

Should any claim or controversy arise between any two or more of the signatory States: (a) with respect to the waters of the Colorado River System not covered by the terms of this compact; (b) over the meaning or performance of any of the terms of this compact; (c) as to the allocation of the burdens incident to the performance of any article of this compact or the delivery of waters as herein provided; (d) as to the construction or operation of works within the Colorado River Basin to be situated in two or more States, or to be constructed in one State for the benefit of another State; or (e) as to the diversion of water in one State for the benefit of another State; the Governors of the States affected, upon the request of one of them, shall forthwith appoint Commissioners with power to consider and adjust such claim or controversy, subject to ratification by the Legislatures of the States so affected.

Nothing herein contained shall prevent the adjustment of any such claim or controversy by any present method or by direct future legislative action of the interested States.

ARTICLE VII

Nothing in this compact shall be construed as affecting the obligations of the United States of America to Indian tribes.

ARTICLE VIII

Present perfected rights to the beneficial use of waters of the Colorado River System are unimpared by this compact. Whenever storage capacity of 5,000,000 acre-feet shall have been provided on the main Colorado River within or for the benefit of the Lower Basin, then claims of such rights, if any, by appropriators or users of water in the Lower Basin against appropriators or users of water in the Upper Basin shall attach to and be satisfied from water that may be stored not in conflict with Article III.

All other rights to beneficial use of waters of the Colorado River System shall be satisfied solely from the water apportioned to that Basin in which they are situate.

ARTICLE IX

Nothing in this compact shall be construed to limit or prevent any State from instituting or maintaining any action or proceeding, legal or equitable, for the protection of any right under this compact or the enforcement of any of its provisions.

ARTICLE X

This compact may be terminated at any time by the unanimous agreement of the signatory States. In the event of such termination all rights established under it shall continue unimpaired.

ARTICLE XI

This compact shall become binding and obligatory when it shall have been approved by the Legislatures of each of the signatory States and by the Congress of the United States. Notice of approval by the Legislatures shall be given by the Governor of each signatory State to the Governors of the other signatory States and to the President of the United States, and the President of the United States is requested to give notice to the Governors of the signatory States of approval by the Congress of the United States.

IN WITNESS WHEREOF, the Commissioners have signed this compact in a single original, which shall be deposited in the archives of the Department of State of the United States of America and of which a duly certified copy shall be forwarded to the Governor of each of the signatory States.

Done at the City of Sante Fe, New Mexico, this twenty-fourth day of November, A.D. One Thousand Nine Hundred and Twenty-two.

W. S. NORVIEL
W. F. MCCLURE
DELPH E. CARPENTER
J. G. SCRUGHAM
STEPHEN B. DAVIS, JR.
R. E. CALDWELL
FRANK C. EMERSON

Approved:
HERBERT HOOVER

[Quoted from a compilation by Witmer (1956). Only those parts of the treaty that deal directly with delivery of Colorado River water to Mexico, Articles 10, 11, and 15, are reproduced herein.

Since the construction in 1950 of Morelos Dam in the limitrophe section of the river, at the head of Alamo Canal the water referred to in paragraph (c) of Article 11 and Schedule II of Article 15 has been delivered to Alamo Canal through the river channel rather than the canal connecting Pilot Knob wasteway to Alamo Canal.]

III—COLORADO RIVER

ARTICLE 10

Of the waters of the Colorado River, from any and all sources, there are allotted to Mexico:

(a) A guaranteed annual quantity of 1,500,000 acre-feet (1,850,234,000 cubic meters) to be delivered in accordance with the provisions of Article 15 of this Treaty.

(b) Any other quantities arriving at the Mexican points of diversion, with the understanding that in any year in which, as determined by the United States Section, there exists a surplus of waters of the Colorado River in excess of the amount necessary to supply uses in the United States and the guaranteed quantity of 1,500,000 acre-feet (1,850,234,000 cubic meters) annually to Mexico, the United States undertakes to deliver to Mexico, in the manner set out in Article 15 of this Treaty, additional waters of the Colorado River system to provide a total quantity not to exceed 1,700,000 acre-feet (2,096,931,000 cubic meters) a year. Mexico shall acquire no right beyond that provided by this subparagraph by the use of the waters of the Colorado River system, for any purpose whatsoever, in excess of 1,500,000 acre-feet (1,850,234,000 cubic meters) annually.

In the event of extraordinary drought or serious accident to the irrigation system in the United States, thereby making it difficult for the United States to deliver the guaranteed quantity of 1,500,000 acre-feet (1,850,234,000 cubic meters) a year, the water allotted to Mexico under subparagraph (a) of this Article will be reduced in the same proportion as consumptive uses in the United States are reduced.

ARTICLE 11

(a) The United States shall deliver all waters allotted to Mexico wherever these waters may arrive in the bed of the limitrophe section of the Colorado River, with the exceptions hereinafter provided. Such waters shall be made up of the waters of the said river, whatever their origin, subject to the provisions of the following paragraphs of this Article.

(b) Of the waters of the Colorado River alloted to Mexico by subparagraph (a) of Article 10 of this Treaty, the United States shall deliver, wherever such waters may arrive in the limitrophe section of the river, 1,000,000 acre-feet (1,233,489,000 cubic meters) annually from the time the Davis dam and reservoir are placed in operation until January 1, 1980 and thereafter 1,125,000 acre-feet (1,387,675,000 cubic meters) annually, except that, should the main diversion structure referred to in subparagraph (a) of Article 12 of this Treaty be located entirely in Mexico and should Mexico so request, the United States shall deliver a quantity of water not exceeding 25,000 acre-feet (30,837,000 cubic meters) annually, unless a larger quantity may be mutually agreed upon, at a point, to be likewise mutually agreed upon, on the international land boundary near San Luis, Sonora, in which event the quantities of 1,000,000 acre-feet (1,233,489,000 cubic meters) and 1,125,000 acre-feet (1,387,675,000 cubic meters) provided hereinabove as deliverable in the limitrophe section of the river shall be reduced by the quantities to be delivered in the year concerned near San Luis, Sonora.

(c) During the period from the time the Davis dam and reservoir are placed in operation until January 1, 1980, the United States shall also deliver to Mexico annually, of the water allotted to it, 500,000 acre-feet (616,745,000 cubic meters), and thereafter the United States shall deliver annually 375,000 acre-feet (462,558,000 cubic meters), at the international boundary line, by means of the All-American Canal and a canal connecting the lower end of the Pilot Knob Wasteway with the Alamo Canal or with any other Mexican canal which may be substituted for the Alamo Canal. In either event the deliveries shall be made at an operating water surface elevation not higher than that of the Alamo Canal at the point where it crossed the international boundary line in the year 1943.

(d) All the deliveries of water specified above shall be made subject to the provisions of Article 15 of this Treaty.

* * * * *

ARTICLE 15

A. The water allotted in subparagraph (a) of Article 10 of this Treaty shall be delivered to Mexico at the points of delivery specified in Article 11, in accordance with the following two annual schedules of deliveries by months, which the Mexican Section shall formulate and present to the Commission before the beginning of each calendar year.

Schedule I

Schedule I shall cover the delivery, in the limitrophe section of the Colorado River, of 1,000,000 acre-feet (1,233,489,000 cubic meters) of water each year from the date Davis dam and reservoir are placed in operation until January 1, 1980 and the delivery of 1,125,000 acre-feet (1,387,675,000 cubic meters) of water each year thereafter. This schedule shall be formulated subject to the following limitations:

With reference to the 1,000,000 acre-foot (1,233,489,000 cubic meter) quantity:

(a) During the months of January, February, October, November and December the prescribed rate of delivery shall be not less than 600 cubic feet (17.0 cubic meters) nor more than 3,500 cubic feet (99.1 cubic meters) per second.

(b) During the remaining months of the year the prescribed rate of delivery shall be not less than 1,000 cubic feet (28.3 cubic meters) nor more than 3,500 cubic feet (99.1 cubic meters) per second.

With reference to the 1,125,000 acre-foot (1,387,675,000 cubic meter) quantity:

(a) During the months of January, February, October, November and December the prescribed rate of delivery shall be not less than 675 cubic feet (19.1 cubic meters) nor more than 4,000 cubic feet (113.3 cubic meters) per second.

(b) During the remaining months of the year the prescribed rate of delivery shall be not less than 1,125 cubic feet (31.9 cubic meters) nor more than 4,000 cubic feet (113.3 cubic meters) per second.

Should deliveries of water be made at a point on the land boundary near San Luis, Sonora, as provided for in Article 11, such deliveries shall be made under a sub-schedule to be formulated and furnished by the Mexican Section. The quantities and monthly rates of deliveries under such sub-schedule shall be in proportion to those specified for Schedule I, unless otherwise agreed upon by the Commission.

Schedule II

Schedule II shall cover the delivery at the boundary lines by means of the All-American Canal of 500,000 acre-feet (616,745,000 cubic meters) of water each year from the date Davis dam and reservoir are placed in operation until January 1, 1980 and the delivery of 375,000 acre-feet (462,558,000 cubic meters) of water each year thereafter. This schedule shall be formulated subject to the following limitations:

With reference to the 500,000 acre-foot (616,745,000 cubic meter) quantity:

(a) During the months of January, February, October, November and December the prescribed rate of delivery shall be not less than 300 cubic feet (8.5 cubic meters) nor more than 2,000 cubic feet (56.6 cubic meters) per second.

(b) During the remaining months of the year the prescribed rate of delivery shall be not less than 500 cubic feet (14.2 cubic meters) nor more than 2,000 cubic feet (56.6 cubic meters) per second.

With reference to the 375,000 acre-foot (462,558,000 cubic meter) quantity:

(a) During the months of January, February, October, November and December the prescribed rate of delivery shall be not less than 225 cubic feet (6.4 cubic meters) nor more than 1,500 cubic feet (42.5 cubic meters) per second.

(b) During the remaining months of the year the prescribed rate of delivery shall be not less than 375 cubic feet (10.6 cubic meters) nor more than 1,500 cubic feet (42.5 cubic meters) per second.

B. The United States shall be under no obligation to deliver, through the All-American Canal, more than 500,000 acre-feet (616,745,000 cubic meters) annually from the date Davis dam and reservoir are placed in operation until January 1, 1980 or more than 375,000 acre-feet (462,558,000 cubic meters) annually thereafter. If, by mutual agreement, any part of the quantities of water specified in this paragraph are delivered to Mexico at points on the land boundary otherwise than through the All-American Canal, the above quantities of water and the rates of deliveries set out under Schedule II of this Article shall be correspondingly diminished.

C. The United States shall have the option of delivering, at the point on the land boundary mentioned in subparagraph (c) of Article 11, any part or all of the water to be delivered at that point under Schedule II of this Article during the months of January, February, October, November, and December of each year, from any source whatsoever, with the understanding that the total specified annual quantities to be delivered through the All-American Canal shall not be reduced because of the exercise of this option, unless such reduction be requested by the Mexican Section, provided that the exercise of this option shall not have the effect of increasing the total amount of scheduled water to be delivered to Mexico.

D. In any year in which there shall exist in the river water in excess of that necessary to satisfy the requirements in the United States and the guaranteed quantity of 1,500,000 acre-feet (1,850,234,000 cubic meters) allotted to Mexico, the United States hereby declares its intention to cooperate with Mexico in attempting to supply additional quantities of water through the All-American Canal as such additional quantities are desired by Mexico, if such use of the Canal and facilities will not be detrimental to the United States, provided that the delivery of any additional quantities through the All-American Canal shall not have the effect of increasing the total scheduled deliveries to Mexico. Mexico hereby declares its intention to cooperate with the United States by attempting to curtail deliveries of water through the All-American Canal in years of limited supply, if such curtailment can be accomplished without detriment to Mexico and is necessary to allow full use of all available water supplies, provided that such curtailment shall not have the effect of reducing the total scheduled deliveries of water to Mexico.

E. In any year in which there shall exist in the river water in excess of that necessary to satisfy the requirements in the United States and the guaranteed quantity of 1,500,000 acre-feet (1,850,234,000 cubic meters) allotted to Mexico, the United States Section shall so inform the Mexican Section in order that the latter may schedule such surplus water to complete a quantity up to a maximum of 1,700,000 acre-feet (2,096,931,000 cubic meters). In this circumstance the total quantities to be delivered under Schedules I and II shall be increased in proportion to their respective total quantities and the two schedules thus increased shall be subject to the same limitation as those established for each under paragraph A of this Article.

F. Subject to the limitations as to rates of deliveries and total quantities set out in Schedules I and II, Mexico shall have the right, upon thirty days notice in advance to the United States Section, to increase or decrease each monthly quantity prescribed by those schedules by not more than 20% of the monthly quantity.

G. The total quantity of water to be delivered under Schedule I of paragraph A of this Article may be increased in any year if the amount to be delivered under Schedule II is correspondingly reduced and if the limitations as to rates of delivery under each schedule are correspondingly increased and reduced.

SUPREME COURT OF THE UNITED STATES

No. 8, ORIGINAL

STATE OF ARIZONA, PLAINTIFF
v.
STATE OF CALIFORNIA, ET AL., DEFENDANTS

DECREE.—MARCH 9, 1964.

It is ORDERED, ADJUDGED AND DECREED that

I. For purposes of this decree:

(A) "Consumptive use" means diversions from the stream less such return flow thereto as is available for consumptive use in the United States or in satisfaction of the Mexican treaty obligation;

(B) "Mainstream" means the mainstream of the Colorado River downstream from Lee Ferry within the United States, including the reservoirs thereon;

(C) Consumptive use from the mainstream within a state shall include all consumptive uses of water of the mainstream, including water drawn from the mainstream by underground pumping, and including but not limited to, consumptive uses made by persons, by agencies of that state, and by the United States for the benefit of Indian reservations and other federal establishments within the state;

(D) "Regulatory structures controlled by the United States" refers to Hoover Dam, Davis Dam, Parker Dam, Headgate Rock Dam, Palo Verde Dam, Imperial Dam, Laguna Dam and all other dams and works on the mainstream now or hereafter controlled or operated by the United States which regulate the flow of water in the mainstream or the diversion of water from the mainstream;

(E) "Water controlled by the United States" refers to the water in Lake Mead, Lake Mohave, Lake Havasu and all other water in the mainstream below Lee Ferry and within the United States;

(F) "Tributaries" means all stream systems the waters of which naturally drain into the mainstream of the Colorado River below Lee Ferry;

(G) "Perfected right" means a water right acquired in accordance with state law, which right has been exercised by the actual diversion of a specific quantity of water that has been applied to a defined area of land or to definite municipal or industrial works, and in addition shall include water rights created by the reservation of mainstream water for the use of federal establishments under federal law whether or not the water has been applied to beneficial use;

(H) "Present perfected rights" means perfected rights, as here defined, existing as of June 25, 1929, the effective date of the Boulder Canyon Project Act;

(I) "Domestic use" shall include the use of water for household, stock, municipal, mining, milling, industrial, and other like purposes, but shall exclude the generation of electrical power;

(J) "Annual" and "Year," except where the context may otherwise require, refer to calendar years;

(K) Consumptive use of water diverted in one state for consumptive use in another state shall be treated as if diverted in the state for whose benefit it is consumed.

II. The United States, its officers, attorneys, agents and employees be and they are hereby severally enjoined:

(A) From operating regulatory structures controlled by the United States and from releasing water controlled by the United States other than in accordance with the following order of priority:

(1) For river regulation, improvement of navigation, and flood control;

(2) For irrigation and domestic uses, including the satisfaction of present perfected rights; and

(3) For power;

Provided, however, that the United States may release water in satisfaction of its obligations to the United States of Mexico under the treaty dated February 3, 1944, without regard to the priorities specified in this subdivision (A);

(B) From releasing water controlled by the United States for irrigation and domestic use in the States of Arizona, California and Nevada, except as follows:

(1) If sufficient mainstream water is available for release, as determined by the Secretary of the Interior, to satisfy 7,500,000 acre feet of annual consumptive use in the aforesaid three states, then of such 7,500,000 acre feet of consumptive use, there shall be apportioned 2,800,000 acre feet for use in Arizona, 4,400,000 acre feet for use in California, and 300,000 acre feet for use in Nevada;

(2) If sufficient mainstream water is available for release, as determined by the Secretary of the Interior, to satisfy annual consumptive use in the aforesaid states in excess of 7,500,000 acre feet, such excess consumptive use is surplus, and 50% thereof shall be apportioned for use in Arizona and 50% for use in California; provided, however, that if the United States so contracts with Nevada, then 46% of such surplus shall be apportioned for use in Arizona and 4% for use in Nevada;

(3) If insufficient mainstream water is available for release, as determined by the Secretary of the Interior, to satisfy annual consumptive use of 7,500,000 acre feet in the aforesaid three states, then the Secretary of the Interior, after providing for satisfaction of present perfected rights in the order of their priority dates without regard to state lines and after consultation with the parties to major delivery contracts and such representatives as the respective states may designate, may apportion the amount remaining available for consumptive use in such manner as is consistent with the Boulder Canyon Project Act as interpreted by the opinion of this Court herein, and with other applicable federal statutes, but in no event shall more than 4,400,000 acre feet be apportioned for use in California including all present perfected rights;

(4) Any mainstream water consumptively used within a state shall be charged to its apportionment, regardless of the purpose for which it was released;

(5) Notwithstanding the provisions of Paragraphs (1) through (4) of this subdivision (B), mainstream water shall be released or delivered to water users (including but not limited to, public and municipal corporations and other public agencies) in Arizona, California, and Nevada only pursuant to valid contracts therefor made with such users by the Secretary of the Interior, pursuant to Section 5 of the Boulder Canyon Project Act or any other applicable federal statute;

(6) If, in any one year, water apportioned for consumptive use in a state will not be consumed in that state, whether for the reason that delivery contracts for the full amount of the state's apportionment are not in effect or that users cannot apply all of such water to beneficial uses, or for any other reason, nothing in this decree shall be construed as prohibiting the Secretary of the Interior from releasing such apportioned but unused water during such year for consumptive use in the other states. No rights to the recurrent use of such water shall accrue by reason of the use thereof;

(C) From applying the provisions of Article 7 (d) of the Arizona water delivery contract dated February 9, 1944, and the provisions of Article 5 (a) of the Nevada water delivery contract dated March 30, 1942, as amended by the contract dated January 3, 1944, to reduce the apportionment or delivery of mainstream water to users within the States of Arizona and Nevada by reason of any uses in such states from the tributaries flowing therein;

(D) From releasing water controlled by the United States for use in the States of Arizona, California, and Nevada for the benefit of any federal establishment named in this subdivision (D) except in accordance with the allocations made herein; provided, however, that such release may be made notwithstanding the provisions of Paragraph (5) of subdivision (B) of this Article; and provided further that nothing herein shall prohibit the United States from making future additional reservations of mainstream water for use in any of such States as may be authorized by law and subject to present perfected rights and rights under contracts theretofore made with water users in such State under Section 5 of the Boulder Canyon Project Act or any other applicable federal statute:

(1) The Chemehuevi Indian Reservation in annual quantities not to exceed (i) 11,340 acre feet of diversions from the mainstream or (ii) the quantity of mainstream water necessary to supply the consumptive use required for irrigation of 1,900 acres and for the satisfaction of related uses, whichever of (i) or (ii) is less, with a priority date of February 2, 1907;

(2) The Cocopah Indian Reservation in annual quantities not to exceed (i) 2,744 acre feet of diversions from the mainstream or (ii) the quantity of mainstream water necessary to supply the consumptive use required for irrigation of 431 acres and for the satisfaction of related uses, whichever of (i) or (ii) is less, with a priority date of September 27, 1917;

(3) The Yuma Indian Reservation in annual quantities not to exceed (i) 51,616 acre feet of diversions from the mainstream or (ii) the quantity of mainstream water necessary to supply the consumptive use required for irrigation of 7,743 acres and for the satisfaction of related uses, whichever of (i) or (ii), is less, with a priority date of January 9, 1884;

(4) The Colorado River Indian Reservation in annual quantities not to exceed (i) 717,148 acre feet of diversions from the mainstream or (ii) the quantity of mainstream water necessary to supply the consumptive use required for irrigation of 107,588 acres and for the satisfaction of

related uses, whichever of (i) or (ii) is less, with priority dates of March 3, 1865, for lands reserved by the Act of March 3, 1865 (13 Stat. 541, 559); November 22, 1873, for lands reserved by the Executive Order of said date; November 16, 1874, for lands reserved by the Executive Order of said date, except as later modified; May 15, 1876, for lands reserved by the Executive Order of said date; November 22, 1915, for lands reserved by the Executive Order of said date;

(5) The Fort Mohave Indian Reservation in annual quantities not to exceed (i) 122,648 acre feet of diversions from the mainstream or (ii) the quantity of mainstream water necessary to supply the consumptive use required for irrigation of 18,974 acres and for the satisfaction of related uses, whichever of (i) or (ii) is less, and, subject to the next succeeding proviso, with priority dates of September 18, 1890, for lands transferred by the Executive Order of said date; February 2, 1911, for lands reserved by the Executive Order of said date; provided, however, that lands conveyed to the State of California pursuant to the Swamp and Overflowed Lands Act [9 Stat. 519 (1850)] as well as any accretions thereto to which the owners of such land may be entitled, and lands patented to the Southern Pacific Railroad pursuant to the Act of July 27, 1866 (14 Stat. 292) shall not be included as irrigable acreage within the Reservation and that the above specified diversion requirement shall be reduced by 6.4 acre feet per acre of such land that is irrigable; provided that the quantities fixed in this paragraph and paragraph (4) shall be subject to appropriate adjustment by agreement or decree of this Court in the event that the boundaries of the respective reservations are finally determined;

(6) The Lake Mead National Recreation Area in annual quantities reasonably necessary to fulfill the purposes of the Recreation Area, with priority dates of March 3, 1929, for lands reserved by the Executive Order of said date (No. 5105), and April 25, 1930, for lands reserved by the Executive Order of said date (No. 5339);

(7) The Havasu Lake National Wildlife Refuge in annual quantities reasonably necessary to fulfill the purposes of the Refuge, not to exceed (i) 41,839 acre feet of water diverted from the mainstream or (ii) 37,339 acre feet of consumptive use of mainstream water, whichever of (i) or (ii) is less, with a priority date of January 22, 1941, for lands reserved by the Executive Order of said date (No. 8647), and a prority date of February 11, 1949, for land reserved by the Public Land Order of said date (No. 559);

(8) The Imperial National Wildlife Refuge in annual quantities reasonably necessary to fulfill the purposes of the Refuge not to exceed (i) 28,000 acre feet of water diverted from the mainstream or (ii) 23,000 acre feet of consumptive use of mainstream water, whichever of (i) or (ii) is less, with a priority date of February 14, 1941;

(9) Boulder City, Nevada, as authorized by the Act of September 2, 1958, 72 Stat. 1726, with a priority date of May 15, 1931;

Provided further, that consumptive uses from the mainstream for the benefit of the above-named federal establishments shall, except as necessary to satisfy present perfected rights in the order of their priority dates without regard to state lines, be satisfied only out of water available, as provided in subdivision (B) of this Article, to each state wherein such uses occur and subject to, in the case of each reservation, such rights as have been created prior to the establishment of such reservation by contracts executed under Section 5 of the Boulder Canyon Project Act or any other applicable federal statute.

III. The States of Arizona, California and Nevada, Palo Verde Irrigation District, Imperial Irrigation District, Coachella Valley County Water District, Metropolitan Water District of Southern California, City of Los Angeles, City of San Diego, and County of San Diego, and all other users of water from the mainstream in said states, their officers, attorneys, agents and employees, be and they are hereby severally enjoined:

(A) From interfering with the management and operation, in conformity with Article II of this decree, of regulatory structures controlled by the United States;

(B) From interfering with or purporting to authorize the interference with releases and deliveries, in conformity with Article II of this decree, of water controlled by the United States;

(C) From diverting or purporting to authorize the diversion of water from the mainstream the diversion of which has not been authorized by the United States for use in the respective states; and provided further that no party named in this Article and no other user of water in said states shall divert or purport to authorize the diversion of water from the mainstream the diversion of which has not been authorized by the United States for its particular use;

(D) From consuming or purporting to authorize the consumptive use of water from the mainstream in excess of the quantities permitted under Article II of this decree.

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V. The United States shall prepare and maintain, or provide for the preparation and maintenance of, and shall make available, annually and at such shorter intervals as the Secretary of the Interior shall deem necessary or advisable, for inspection by interested persons at all reasonable times and at a reasonable place or places, complete, detailed and accurate records of:

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(A) Releases of water through regulatory structures controlled by the United States;

(B) Diversions of water from the mainstream, return flow of such water to the stream as is available for consumptive use in the United States or in satisfaction of the Mexican treaty obligation, and consumptive use of such water. These quantities shall be stated separately as to each diverter from the mainstream, each point of diversion, and each of the States of Arizona, California and Nevada;

(C) Releases of mainstream water pursuant to orders therefor but not diverted by the party ordering the same, and the quantity of such water delivered to Mexico in satisfaction of the Mexican Treaty or diverted by others in satisfaction of rights decreed herein. These quantities shall be stated separately as to each diverter from the mainstream, each point of diversion, and each of the States of Arizona, California and Nevada;

(D) Deliveries to Mexico of water in satisfaction of the obligations of Part III of the Treaty of February 3, 1944, and, separately stated, water passing to Mexico in excess of treaty requirements;

(E) Diversions of water from the mainstream of the Gila and San Francisco Rivers and the consumptive use of such water, for the benefit of the Gila National Forest.

VI. Within two years from the date of this decree, the States of Arizona, California, and Nevada shall furnish to this Court and to the Secretary of the Interior a list of the present perfected rights, with their claimed priority dates, in waters of the mainstream within each state, respectively, in terms of consumptive use, except those relating to federal establishments. Any named party to this proceeding may present its claim of present perfected rights or its opposition to the claims of others. The Secretary of the Interior shall supply similar information, within a similar period of time, with respect to the claims of the United States to present perfected rights within each state. If the parties and the Secretary of the Interior are unable at that time to agree on the present perfected rights to the use of mainstream water in each state, and their priority dates, any party may apply to the Court for the determination of such rights by the Court.

* * * * * * * * * * * *

VIII. This decree shall not affect:

(A) The relative rights *inter sese* of water users within any one of the states, except as otherwise specifically provided herein;

(B) The rights or priorities to water in any of the Lower Basin tributaries of the Colorado River in the States of Arizona, California, Nevada, New Mexico and Utah except the Gila River System;

(C) The rights or priorities, except as specific provision is made herein, of any Indian Reservation, National Forest, Park, Recreation Area, Monument or Memorial, or other lands of the United States;

(D) Any issue of interpretation of the Colorado River Compact.

IX. Any of the parties may apply at the foot of this decree for its amendment or for further relief. The Court retains jurisdiction of this suit for the purpose of any order, direction, or modification of the decree, or any supplementary decree, that may at any time be deemed proper in relation to the subject matter in controversy.

MR. JUSTICE DOUGLAS dissents.

MR. JUSTICE HARLAN and MR. JUSTICE STEWART dissent to the extent that the decree conflicts with the views expressed in the dissenting opinion of MR. JUSTICE HARLAN, 373 U. S. 546, 603.

THE CHIEF JUSTICE took no part in the consideration or decision of this case.

TABLES OF BASIC DATA

In the tables that follow, streamflow data are from the U.S. Geological Survey (1954, 1964, 1961–68), except as noted. The details of cooperation in collecting previously published data are given in those reports.

TABLE 6.—*Annual flow of Colorado River at compact point, near Lees Ferry, Ariz., 1896–1966, in millions of acre-feet*

Water year	Actual flow	Virgin flow	Water year	Actual flow	Virgin flow	Water year	Actual flow	Virgin flow	Water year	Actual flow	Virgin flow
1896	9.760	10.09	1914	19.34	21.22	1932	15.29	17.24	1950	11.06	13.07
1897	17.50	18.01	1915	12.50	14.03	1933	9.745	11.36	1951	9.831	11.88
1898	13.30	13.82	1916	17.32	19.20	1934	4.397	5.640	1952	17.98	20.68
1899	15.25	15.87	1917	21.89	24.04	1935	9.911	11.55	1953	8.805	10.68
1900	12.60	13.23	1918	13.65	15.36	1936	11.97	13.80	1954	6.116	7.766
1901	12.90	13.58	1919	10.86	12.46	1937	11.90	13.74	1955	7.307	9.146
1902	8.740	9.393	1920	19.74	21.95	1938	15.44	17.54	1956	8.750	10.79
1903	13.95	14.81	1921	20.72	23.02	1939	9.394	11.08	1957	17.34	20.07
1903	14.70	15.64	1922	16.30	18.31	1940	7.082	8.601	1958	14.26	16.57
1905	15.00	16.03	1923	16.26	18.27	1941	16.05	18.15	1959	6.756	8.597
1906	17.96	19.12	1924	12.48	14.20	1942	17.03	19.12	1960	9.192	11.29
1907	22.00	23.40	1925	11.34	13.03	1943	11.26	13.10	1961	6.674	8.491
1908	11.76	12.86	1926	14.01	15.85	1944	13.22	15.15	1962	14.79	17.33
1909	21.71	23.28	1927	16.59	18.62	1945	11.54	13.41	1963	2.52	8.400
1910	12.97	14.25	1928	15.32	17.28	1946	8.744	10.42	1964	2.43	10.10
1911	14.62	16.03	1929	19.22	21.43	1947	13.51	15.47	1965	14.97	18.60
1912	18.88	20.52	1930	13.07	14.88	1948	13.69	15.62	1966	7.87	10.80
1913	12.99	14.47	1931	6.388	7.769	1949	14.36	16.40			

NOTE.—Records of actual flow for 1896–1913 and records of virgin flow for 1896–1945 are those published by the U.S. Bureau of Reclamation (1954, p. 145, 146). Records of virgin flow for 1946–66 were furnished by the Upper Colorado River Commission (written commun. 1967).

TABLE 7.—*Annual flows of the lower Colorado River, 1902–66, in millions of acre-feet*

Calendar year	At compact point, Ariz.	Near Grand Canyon, Ariz.	Below Hoover Dam, Ariz.-Nev.	Below Davis Dam, Ariz.-Nev.	Near Topock, Ariz.	Below Parker Dam, Ariz.-Calif.	Below Palo Verde Dam Ariz.-Calif.	Below Cibola Valley, Ariz.	At (above) Imperial Dam, Ariz.-Calif.	At Yuma, Ariz. [1]	At international boundary: Northerly [2]	At international boundary: Southerly
1902										7.960		
1903									11.3	11.33		
1904									9.87	10.12		
1905									16.1	19.71		
1906				19.15					17.7	19.48		
1907									24.8	25.48		
1908									12.6	13.69		
1909									25.3	25.97		
1910									14.1	14.33		
1911									17.6	17.84		
1912									18.2	18.36	18.5	
1913									12.0	11.77	12.1	
1914	19.62								20.6	20.64	20.97	
1915	11.96								13.1	14.64	14.84	
1916	18.31								18.9	23.14	23.31	
1917	20.96				20.88				19.9	20.61	20.74	
1918	13.78				15.22				13.2	13.15	13.32	
1919	10.57				12.97				10.5	10.74	10.91	
1920	20.10				20.09				21.1	21.45	21.6	
1921	20.50				21.99				19.5	19.44	19.6	
1922	16.09				18.57				16.9	17.02	17.25	
1923	16.97	17.98			19.17				18.0	17.84	18.14	
1924	11.70	11.99			12.70				11.6	11.35	11.67	
1925	12.39	12.78			12.63				13.0	12.40	12.7	
1926	13.08	13.55			13.34				12.6	12.20	12.6	
1927	17.56	18.24			18.07				17.5	17.12	17.6	
1928	14.73	14.97			14.61				14.0	12.78	13.5	
1929	19.62	19.85			19.39				18.8	17.50	18.4	
1930	12.41	12.76			12.64				12.0	10.61	11.4	
1931	6.229	6.594			6.605				6.08	4.831	5.71	
1932	15.17	15.82			15.96				15.3	14.20	15.1	
1933	9.751	10.04			10.19				9.48	8.016	8.92	
1934	3.967	4.186	4.513		4.316				3.69	2.384	3.224	
1935	10.28	10.62	6.359		6.040	6.091			5.601	4.038	5.007	
1936	12.14	12.47	5.943		5.675	5.629			4.916	3.465	4.382	
1937	12.01	12.54	6.018		5.768	5.950			5.315	3.995	4.870	
1938	15.66	15.86	6.764		6.580	6.009			5.464	4.170	4.915	
1939	8.872	9.090	8.645		8.314	8.417			7.840	6.557	7.381	
1940	7.617	8.035	7.973		7.790	7.656			6.979	5.437	6.248	
1941	17.89	18.79	14.89		14.51	14.75			14.02	11.73	12.74	
1942	14.81	14.92	15.76		15.36	15.20			14.71	10.48	11.55	
1943	11.44	11.62	12.72		12.16	12.08			11.35	7.272	8.310	
1944	13.03	13.33	14.43		13.87	13.84			13.21	6.612	10.10	
1945	11.79	12.11	12.51		11.94	12.03			11.39	6.462	8.001	
1946	8.772	9.12	10.58		10.23	10.14			9.486	3.804	5.885	
1947	14.07	14.35	10.96		10.71	10.66			10.04	4.243	6.370	
1948	12.90	13.01	13.05		12.91	12.65			12.04	6.260	8.330	
1949	14.62	14.62	13.57		13.32	13.06			12.57	6.565	8.770	
1950	10.81	10.84	12.02	10.83	10.64	10.47			9.906	3.464	5.810	4.417
1951	9.916	9.934	9.87	9.256	8.973	8.672			8.053	2.764	3.639	2.234
1952	17.92	18.11	15.82	15.76	15.56	15.41			14.82	9.192	10.15	8.648
1953	8.748	8.803	11.30	11.16	10.98	10.65			10.05	4.095	5.224	3.736
1954	6.183	6.297	10.51	10.41	10.14	9.671			9.03	3.196	4.346	2.697
1955	6.981	7.286	8.588	8.836	8.617	8.141			7.708	2.118	3.058	1.659
1956	8.667	8.774	7.813	7.743	7.519	6.869			6.266	.8812	1.638	.2572
1957	18.73	18.91	9.323	9.008	8.882	7.997	6.959	7.342	7.344	1.167	2.853	1.089
1958	13.17	13.46	11.88	11.74	11.63	10.89	9.858	10.35	10.50	2.951	5.908	3.908
1959	7.074	7.308	9.282	9.196	9.059	8.186	7.180	7.689	7.695	.9333	3.051	1.312
1960	8.804	9.154	8.996	8.763	8.683	7.794	6.533	7.063	7.107	.7024	2.338	.5441
1961	7.341	7.739	8.586	8.329	8.035	6.975	5.760	6.350	6.293	.6830	1.672	.1769
1962	14.46	14.84	8.615	8.453	8.288	7.159	5.878	6.460	6.458	.8605	1.810	.3081
1963	[3] 1.404	[3] 1.629	8.533	8.533	8.339	7.251	5.974	6.504	6.522	.9243	1.834	.1852
1964	[3] 3.256	[3] 3.578	8.159	8.020	8.006	6.652	5.308	5.948	5.903	.8624	1.502	.098
1965	[3] 9.995	[3] 11.77	7.792	7.735	7.652	6.356	5.224	5.777	5.724	.7298	1.524	.102
1966	[3] 7.710	[3] 8.226	7.777	8.169	7.863	6.682	5.388	5.905	5.849	.5888	1.420	.102

[1] Above Yuma Main Canal wasteway.

[2] Figures show flow reaching the northerly boundary, including flow diverted to Alamo Canal. Figures for years prior to 1951 are sums of flow of Colorado River at Yuma and return flows between Yuma and northerly boundary. Figures for 1912–33 and 1950 not previously published. Figures for 1912–13, 1920–21, 1925–30 include estimates of minor return flows.

[3] Affected by storage in Lake Powell.

TABLE 8.—*Annual flows of principal tributaries to the lower Colorado River, 1903–66, in acre-feet*

Calendar year	Little Colorado River, Ariz.		Bright Angel Creek near Grand Canyon, Ariz.	Virgin River at Littlefield, Ariz.	Bill Williams River, Ariz.		Gila River near Dome, Ariz.
	At Grand Falls	Near Cameron			Near Alamo	At Planet	
1903							60,990
1904							222,900
1905							3,665,000
1906							1,792,000
1907							633,800
1908							1,112,000
1909							661,400
1910							224,000
1911							267,400
1912							232,900
1913						29,390	73,780
1914						80,590	558,200
1915						113,800	1,946,000
1916							4,665,000
1917							1,155,000
1918							329,700
1919							739,900
1920							801,000
1921							478,500
1922							674,100
1923							589,700
1924			22,560				376,700
1925			19,340				77,870
1926	173,600		31,750				387,100
1927	390,100		34,420				635,400
1928	95,060		28,950				22,910
1929	515,600		21,980			36,710	4,870
1930	181,700		20,530	213,600		52,800	13,630
1931	197,900		16,550	106,000		130,300	110,700
1932	429,800		42,960	384,300		307,100	259,500
1933	160,400		16,170	116,300		11,840	0
1934	37,740		13,770	77,350		12,400	169
1935	217,900		31,590	162,200		110,400	5,910
1936	167,900		25,430	144,400		22,250	0
1937	340,900		42,890	234,200		253,200	153,700
1938	160,300		44,590	281,700		113,000	45,900
1939	83,450		25,780	148,700		231,200	3,540
1940	191,100		31,630	179,400	81,090	68,670	0
1941	587,700		65,760	426,800	481,500	399,200	589,700
1942	90,420		28,380	186,500	21,910	23,930	0
1943	102,500		33,490	179,200	21,900	14,220	0
1944	132,600		25,880	180,500	136,300	114,900	0
1945	155,600		26,630	181,100	74,120	60,000	0
1946	136,100		23,200	168,900	20,730		0
1947	165,700		18,170	131,400	10,510		420
1948	130,900	132,600	19,020	110,800	7,800		0
1949	261,700	285,400	20,760	163,400	58,580		0
1950	40,190	40,400	21,500	118,000	7,150		0
1951		59,380	15,440	112,000	95,550		6,360
1952		347,600	43,800	267,200	157,600		1,160
1953		54,420	14,560	97,540	7,260		958
1954	110,200	112,700	16,460	139,900	63,460		1,460
1955	149,700	191,400	12,790	133,400	35,270		12,110
1956	18,550	19,260	16,080	81,700	6,980		308
1957	194,300	201,500	27,820	133,000	16,410		223
1958	145,400	151,600	47,040	272,000	61,080		877
1959	107,300	100,800	14,010	90,650	17,080		3,350
1960		143,200	18,580	84,370	23,080		17,770
1961		33,650	18,700	107,500	6,330		11,790
1962		161,300	21,050	136,800	19,080		3,280
1963		79,020	14,480	84,810	34,180		7,210
1964		168,900	14,630	86,370	32,130		103
1965		256,300	25,470	159,200	273,800		323
1966		201,000	28,620	163,800	81,390		39,830

TABLE 9.—*Annual diversions and return flows, Lake Mead to Imperial Dam, 1915–66, in acre-feet*

Calendar year	Diversions from Lake Mead		To Metropolitan Water District, Calif.[3]	Colorado River Indian Reservation, Ariz.		Palo Verde Valley, Calif.	
	To Las Vegas and Henderson, Nev.[1]	To Boulder City, Nev.[2]		Diversion[4]	Return flow[5]	Diversion[6]	Return flow
1915				7,290			
1916				9,380			
1917				9,440			
1918				16,010			
1919				18,500			
1920				20,350			
1921				15,340			
1922				18,620		131,100	
1923				23,480		180,500	
1924				25,440			
1925				26,000		225,700	
1926				32,960		212,000	
1927				27,680		213,800	
1928				30,330		169,600	
1929				29,040		201,700	
1930				27,640		179,600	
1931				25,000		181,500	
1932				21,440		162,500	
1933				18,010		164,600	
1934				21,190		194,400	
1935				23,230		194,300	
1936		705		30,360		225,400	
1937		700		33,600		220,500	
1938		780		29,190		226,700	
1939		833	172,500	25,030		253,600	
1940		999	95,710	37,390		360,200	
1941		1,038	30,700	30,320		305,300	
1942	2,950	1,400	31,140	56,320		340,100	
1943	16,990	1,730	34,630	79,130		313,200	
1944	12,880	1,585	51,630	113,900		335,400	
1945	6,360	1,552	58,350	101,600		331,400	
1946	5,392	1,682	80,400	105,700	13,700	408,700	
1947	6,132	1,737	85,360	124,700	25,900	484,800	
1948	4,868	1,921	194,200	134,800	31,600	558,900	
1949	4,511	2,047	178,600	161,000	42,500	652,700	
1950	5,718	2,163	179,400	209,700	51,400	767,700	
1951	6,764	2,303	231,400	243,600	81,500	705,800	
1952	8,533	2,545	175,100	278,200	93,500	728,800	
1953	11,050	2,592	228,300	314,300	104,800	765,600	
1954	17,140	2,742	341,200	341,900	109,000	861,100	
1955	17,750	2,575	417,100	323,000	118,900	811,700	
1956	21,700	2,743	481,500	307,600	112,300	947,100	
1957	18,020	2,376	595,200	320,900	159,100	824,400	
1958	17,780	2,435	540,200	367,500	208,800	873,900	
1959	16,500	2,593	707,900	378,000	212,500	916,800	
1960	18,070	2,627	894,200	412,800	227,400	918,600	
1961	19,110	2,369	1,103,000	438,600	267,700	943,200	550,000
1962	21,360	2,626	1,073,000	466,800	288,600	952,800	580,400
1963	24,490	2,721	1,057,000	484,500	298,500	929,800	572,800
1964	22,300	2,992	1,137,000	455,600	275,700	727,900	530,100
1965	19,890	2,762	1,178,000	416,700	253,100	774,000	424,600
1966			1,146,000	461,200	259,800	799,300	431,200

[1] Pumping began in 1942.
[2] Pumping began in 1932.
[3] Pumping began in 1939.
[4] Figures shown for 1915–36 are for fiscal years ending June 30 (U.S. Geol. Survey, 1954). Diversions began in 1870.
[5] Flow began in 1946.
[6] Diversions began about 1879.

TABLE 10.—*Annual diversions and return flows at and below Imperial Dam, 1908–66, in acre-feet*

Calendar year	Gila Gravity Main Canal at Imperial Dam [1]	North Gila Valley Canal at Laguna Dam [2]	All American Canal near Imperial Dam [3]	Yuma Canal at Laguna Dam [4]	Reservation Division of Yuma Project, Calif.: Diversion [5]	Reservation Division of Yuma Project, Calif.: Return flow [6]	Yuma Main Canal Wasteway [7]	Yuma Valley, Ariz.: Yuma Main Canal below siphon [8]	Yuma Valley, Ariz.: Return flow to river [9]	Yuma Valley, Ariz.: Flow across southerly boundary [10]	All American Canal above Pilot Knob Wasteway [11]	Pilot Knob powerplant and Wasteway [7]	Coachella Canal at head [12]	All American Canal below Coachella Canal [12]	Alamo Canal at head (Morelo Dam) [13]
1908															709,700
1909															800,700
1910				4,000											932,800
1911				25,290											1,353,000
1912				69,050											1,434,000
1913				337,400		8,920									1,667,000
1914				520,000		12,490	313,500								1,863,000
1915				439,600		13,200	185,900								1,913,000
1916				390,700		20,190	146,800								2,219,000
1917				452,500		15,910	114,900								2,270,000
1918				467,400		17,860	152,500								2,719,000
1919				478,100		18,950	151,300								2,657,000
1920				468,900			149,900								2,822,000
1921				482,000			176,900								2,420,000
1922				546,600		10,690	219,600								2,890,000
1923				672,900		11,640	289,800								3,275,000
1924				665,600		11,740	307,100	272,900	59,660	75,820					3,078,000
1925				647,100			274,500	283,800	65,280	74,090					3,159,000
1926				704,700			352,500	272,100	61,090	75,320					3,091,000
1927				949,500			496,500	349,200	97,840	83,750					3,089,000
1928				1,182,000			728,000	298,900	102,300						3,272,000
1929				1,234,000			841,200	280,300	110,200						3,424,000
1930				1,320,000			815,600	323,400	108,800						3,281,000
1931				1,293,000			879,700	343,400	73,070						2,693,000
1932				1,330,000			913,700	343,300	101,000	53,380					2,562,000
1933				1,368,000			890,600	331,000	77,560	44,410					2,746,000
1934				1,226,000		10,000	829,800	265,800	31,580	29,380					2,050,000
1935				1,368,000		12,000	957,200	280,000	55,900	34,140					3,141,000
1936		50,000		1,370,000		12,000	905,100	333,500	36,060	52,180					3,660,000
1937		54,000		1,300,000		12,840	861,500	350,300	61,050	57,050					3,872,000
1938		49,000	793	1,169,000		13,410	731,400	346,900	49,690	91,430					3,737,000
1939		48,000	58,140	1,243,000		23,640	776,900	372,200	83,000	95,790	26,850	21,460			3,502,000
1940		46,000	180,900	1,314,000		24,170	786,600	405,000	103,400	92,120	133,000	0			3,454,000
1941		38,000	1,910,000	778,400		41,610	959,400	336,000	65,140	95,760	1,217,000	780			2,241,000
1942		40,000	3,965,000	79,250		42,930	1,025,000	370,300	92,350	103,600	2,502,000	0			955,800
1943	27,380	35,000	3,942,000	77,780		33,550	1,014,000	400,400	91,060	104,100	2,455,000	0			1,152,000
1944	60,920	37,000	4,423,000	76,210		32,070	1,043,000	376,900	86,930	103,200	2,958,000	408,300	17,600	2,445,000	1,107,000
1945	98,080	36,000	4,452,000	340,700		37,990	794,500	378,700	76,450	82,470	3,459,000	705,700	150,000	2,516,000	1,065,000
1946	146,600	40,000	5,404,000	90,330		45,970	1,012,000	388,700	77,420	91,600	3,957,000	1,023,000	128,000	2,697,000	1,255,000
1947	144,600	42,000	5,532,000	77,960		55,980	1,040,000	397,200	76,290	110,300	3,981,000	1,030,000	109,200	2,633,000	1,297,000
1948	148,900		5,558,000	24,990	35,690	59,560	943,000	403,300	81,340	127,500	4,028,000	1,064,000	164,800	2,699,000	1,324,000
1949	134,700		5,827,000		60,390	60,990	1,042,000	396,600	85,260	110,200	4,185,000	1,111,000	197,800	2,762,000	1,313,000
1950	150,200		6,250,000		65,180	61,330	980,100	360,700	47,440	98,860	4,676,000	1,305,000	346,500	2,939,000	1,434,000
1951	183,400		5,066,000		77,750	69,400	854,000	375,500	35,280	105,400	3,651,000	0	487,900	3,067,000	1,463,000
1952	281,100		5,302,000		82,250	71,510	967,400	385,000	39,760	118,100	3,781,000	0	495,600	3,203,000	1,381,000
1953	399,800		5,467,000		82,740	76,130	984,500	357,700	46,180	117,800	3,935,000	24,630	525,400	3,353,000	1,524,000
1954	472,900	75,000	5,278,000		88,630	71,180	1,006,000	344,300	37,550	118,200	3,711,000	90	561,800	3,096,000	1,628,000
1955	578,700		5,024,000		85,520	72,280	851,000	330,900	38,740	117,400	3,598,000	115	572,100	2,927,000	1,445,000
1956	619,500		4,767,000		88,250	69,620	653,300	318,100	29,500	119,300	3,525,000	10,500	547,800	2,907,000	1,396,000
1957	652,600		5,524,000		82,680	65,100	817,400	306,200	34,630	132,100	4,162,000	805,000	498,200	2,782,000	1,696,000
1958	728,200		6,823,000		77,400	61,390	1,023,000	338,000	36,520	147,500	5,316,000	1,945,000	491,900	2,731,000	1,962,000
1959	788,900		5,978,000		91,460	54,760	1,001,000	329,400	31,250	145,500	4,485,000	1,036,000	492,900	2,840,000	1,747,000
1960	794,400		5,652,000		95,210	50,440	754,100	338,900	28,100	145,600	4,386,000	765,000	493,300	2,984,000	1,771,000
1961	818,400		5,037,000		91,340	51,640	470,700	351,000	26,250	144,900	4,022,000	441,400	508,300	2,957,000	1,484,000
1962	880,200		5,068,000		97,800	51,490	75,950	355,900	23,790	147,000	4,421,000	794,400	554,400	2,951,000	1,489,000
1963	916,200		5,040,000		96,220	51,310	115,900	343,200	25,480	149,000	4,398,000	700,400	525,300	2,991,000	1,601,000
1964	896,200		4,566,000		96,500	46,990	105,900	335,600	14,630	143,200	3,993,000	585,500	503,400	2,770,000	1,408,000
1965	852,600		4,562,000		84,770	40,690	131,700	314,300	8,867	134,800	3,203,000		501,500	2,624,000	1,427,000
1966	880,000		4,694,000		91,890	39,290	121,700	318,100	7,570	128,000	3,366,000		468,100	2,818,000	1,403,000

1 Flow began in 1943.
2 Served North Gila Valley, Ariz. Flow began about 1912, and the canal was sealed about 1954. Annual flows were estimated; those for 1948–53 are not considered to be reliable. Figure for 1954 is from unpublished records of the Imperial Irrigation District.
3 Flow began in 1938.
4 Served all or parts of the Yuma Project (Reservation Division, Calif., and Yuma Valley, Ariz.). Flow began in 1910, and the canal was sealed in 1948.
5 Sum of several small diversions from All American and Yuma Main Canals. The Yuma Canal supplied additional, unknown quantities of water to the Reservation Division prior to 1949. First diversion about 1910.
6 Flow began in 1912. Sum of flows in Reservation Main drain (California drainage canal) and Drain 8B (Araz drain), in which flow began in 1948.
7 Return of water diverted primarily for power generation or delivery to Mexico rather than irrigation in the United States. Flow in the Yuma Main Canal began about 1912; in Pilot Knob, 1939.
8 Flow began in 1912. Diversions to Yuma Valley by pumping from Colorado River at Yuma (the principal supply for the valley from 1907 to 1912) were as follows: 1907—7,160; 1908—23,160; 1909—48,980; 1910—42,010; 1911—47,280; 1912—26,830; 1913—1,180.
9 Flow began about 1913. Sum of flows in Cooper (flow began in 1927), Eleven-mile (flow began about 1913), and Twenty-one mile (flow began in 1939) wasteways.
10 Flow began about 1914. Sum of flows across boundary in East Main Canal (flow began about 1914), Main Drain (flow began in 1917), and West Main Canal (1924–44).
11 Flow began in 1939. Subtract flow in next column to obtain the diversion to Imperial and Coachella Valleys, Calif.
12 Flow in Coachella Canal began about 1944; in All American Canal, about 1940. Records furnished by Imperial Irrigation District.
13 Flow began in 1901. Figures for 1951–63 furnished by the International Boundary and Water Commission. The figures listed above include water diverted from Colorado River at or near the site of Morelos Dam and water delivered through the All American Canal and Pilot Knot wasteway. Additional diversions to Alamo Canal from Colorado River at Volcano Lake, in Mexico, were made as follows: 1916—17,310; 1917—142,400; 1918—157,700; 1919—197,500; 1920—274,400; 1921—115,400.

NOTE.—Return flow through the Wellton-Mohawk Main Outlet drain began in 1961. Annual flows, in acre-feet, for the calendar years 1961–66 were as follows: 139,700; 215,100; 200,700 ;181,000; 186,100; and 216,900.

TABLE 11.—*Year-end usable contents of reservoirs below compact point, 1934–66, in thousands of acre-feet*

Calendar year	Lake Mead [1]	Lake Havasu [2]	Calendar year	Lake Mead [1]	Lake Mohave	Lake Havasu [2]
1934	0	----------	1949	19,900	0	667.7
1935	3,673	----------	1950	18,259	1,030	614.8
1936	[3] 6,339	----------	1951	17,846	1,596	636.0
1937	12,248	0	1952	19,780	1,610	582.4
1938	20,394	481.5	1953	17,000	1,695	615.4
1939	20,562	518.2	1954	12,750	1,701	612.3
1940	20,320	411.0	1955	11,394	1,439	605.5
1941	24,090	406.3	1956	11,951	1,474	546.3
1942	23,040	496.1	1957	20,842	1,595	539.8
1943	21,670	579.1	1958	21,973	1,649	547.7
1944	20,310	578.7	1959	19,553	1,657	555.2
1945	19,720	576.7	1960	19,286	1,620	549.9
1946	17,904	621.0	1961	18,025	1,682	541.6
1947	20,645	603.8	1962	22,980	1,699	540.0
1948	19,908	596.5	1963	16,007	1,553	534.8
			1964	11,136	1,588	539.3
			1965	15,233	1,738	556.7
			1966	15,481	1,574	538.4

[1] Figures of contents prior to 1949 are based on a survey completed in 1940; those after Oct. 1, 1949, are based on a survey made during 1948–49.
[2] Figures of contents prior to 1956 are based on the original survey of Lake Havasu; those after Oct. 1, 1956, are based on a resurvey of the upper 20 feet in 1957.
[3] Usable contents were reduced 3,207,000 acre-feet May 1, 1936, by permanent closing of temporary outlet gates.

TABLE 12.—*Approximate irrigated acreage in principal water-using areas for selected years*

[Data for 1914–50 from U.S. Bureau of Reclamation (1953), acreages outside irrigation districts and Indian reservations in 1962 were determined by a land-use survey (U.S. Bureau of Reclamation, 1963); acreages in Yuma Mesa and Reservation Division, 1955, and for North and South Gila Valleys, 1960–65, are from unpublished crop reports by U.S. Bureau of Reclamation. Acreages for Yuma Valley, 1960, and for Imperial and Coachella Valleys, 1955–60, are from Colorado River Board of California (1962); those for Imperial and Coachella Valleys, 1965, from crop reports of respective irrigation districts, and for Colorado River Indian Reservation, 1960–65, from crop reports of Bureau of Indian Affairs. Other data from Geological Survey reports on surface water of the United States]

Name of area	1914	1920	1925	1930	1935	1940	1945	1950	1955	1960	1965
Colorado River Indian Reservation, Ariz.	460	4,030	5,280	6,250	3,870	4,230	6,890	22,100	27,600	28,000	31,900
Palo Verde Valley, Calif.	30,700	30,700	33,600	26,000	25,000	34,400	41,700	55,100	70,300	75,900	84,300
North and South Gila Valleys, Ariz.[1]	400	1,080	3,630	5,440	5,420	8,100	7,070	15,300	----------	17,600	16,700
Wellton-Mohawk area, Ariz.[2]								0	31,000	54,100	58,000
Yuma Mesa, Ariz.[3]		0	670	1,400	1,380	1,470	1,620	9,230	17,200	19,800	20,200
Yuma Valley, Ariz.	19,800	42,900	43,600	45,600	44,700	44,200	45,400	47,400	45,500	45,600	46,300
Reservation Division of Yuma Project, Calif.	5,370	11,700	12,300	10,300	8,030	7,310	8,150	8,830	10,200	10,600	10,600
Imperial Valley, Calif.			359,000	439,000	404,000	417,000	394,000	430,000	475,000	434,000	433,000
Coachella Valley, Calif.[4]							0	11,100	47,700	55,500	59,900

NOTE.—During 1962, an additional area of 21,400 acres outside of irrigation districts and Indian reservations (14,000 acres above Imperial Dam and 7,400 acres below) was irrigated by pumping from the Colorado River or from wells near the river. Because of differences in methods of reporting irrigated acreage, some of the acreages may not be strictly comparable with other acreages in this table or with similar acreages published elsewhere.

[1] Acreages shown include those irrigated by pumping from wells in South Gila Valley.
[2] Acreages shown were irrigated with Colorado River water. This area was irrigated first by diversions from Gila River and later by pumping from wells. In 1943 about 7,800 acres were irrigated with ground water, but use of ground water ceased before 1960.
[3] Acreages include those in Yuma Mesa Auxiliary Division (unit B).
[4] Acreages irrigated with Colorado River water. Ground water was used in other parts of the valley.

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