An Accounting System for Water and Consumptive Use Along the Colorado River, Hoover Dam to Mexico

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Prepared in cooperation with the Bureau of Reclamation

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By SANDRA J. OWEN-JOYCE and LEE H. RAYMOND

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PLATES

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FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in)	25 4	millimeter
foot (ft)	0 3048	meter
mile (mi)	1 609	kilometer
foot per mile (ft/mi)	0 1894	meter per kilometer
	Area	
square mile (mi^2)	2 590	square kilometer
acre	0 4047	square hectometer
	Volume	
acre-foot (acre-ft)	0 001233	cubic hectometer
	Flow	
cubic foot per second (ft^3/s)	0 02832	cubic meter per second
acre-foot per square mile (acre-ft/mi^2)	0 000476	cubic hectometer pre square kilometer
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 × (°F-32)	degree Celsius (°C)
	Transmissivity	
foot squared per day (ft^2/d)	0 0929	meter squared per day

VERTICAL DATUM

Sea level. In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929

ACRONYMS

AVM	Acoustic-velocity meter
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
CAP	Central Arizona Project
CAWCD	Central Arizona Water Conservation District
CIDD	Cibola Valley Irrigation and Drainage District
CIMIS	California Irrigation Management Information System
CNWR	Cibola National Wildlife Refuge
CRIR	Colorado River Indian Reservation
IBWC	International Boundary and Water Commission
LCRAS	Lower Colorado River Accounting System
MODE	Main Outlet Drain Extension
MSS	Multispectral scanner
MWD	Metropolitan Water District of Southern California
NASQAN	National Stream-Quality Accounting Network
NIB	Northerly international boundary with Mexico
PIK	Payment-In-Kind
PVID	Palo Verde Irrigation District
SIB	Southerly international boundary with Mexico
USBR	Bureau of Reclamation
USCE	U S Army Corps of Engineers
USGS	U S Geological Survey
UTM	Universal Transverse Mercator

An Accounting System for Water and Consumptive Use Along the Colorado River, Hoover Dam to Mexico

By Sandra J Owen-Joyce *and* Lee Raymond

Abstract

An accounting system for estimating and distributing consumptive use of water by vegetation to water users was developed for the Colorado River from Hoover Dam to Mexico The accounting system is based on a water-budget method to estimate total consumptive use by vegetation from Hoover Dam to Morelos Dam Consumptive use by vegetation is apportioned to agricultural users by using percentages of total evapotranspiration by vegetation estimated for each diverter of water Evapotranspiration for each diverter is estimated from (1) digital-image analysis of data from the Landsat satellite to determine vegetation types and areas for each diverter and (2) water-use rates to determine the quantity of water used by each vegetation type Evapotranspiration is estimated for each of four reaches of the river—Hoover Dam to Davis Dam, Davis Dam to Parker Dam, Parker Dam to Imperial Dam, and Imperial Dam to Morelos Dam—to incorporate spatial variations in the weather data used to calculate water-use rates

The Lower Colorado River Accounting System was used to estimate and distribute consumptive use by vegetation in calendar year 1984, consumptive use by vegetation was 2,069,900 acre-feet. About 4,283,200 acre-feet of water was exported to California, 391,400 acre-feet was diverted to the Wellton-Mohawk area in Arizona, 1,358,100 acre-feet was used for agriculture in the flood plain of the Colorado River, 1,055,800 acre-feet was transpired by phreatophytes or evaporated from open-water surfaces along the river, and 40,600 acre-feet was consumed by domestic and municipal users in and adjacent to the flood plain Total water loss from the Colorado River in the United States below Hoover Dam during 1984 was about 7,129,100 acre-feet About 18 percent was consumptively used in Arizona, 67 percent in California, less than 1 percent in Nevada, and about 15 percent was used by phreatophytes or evaporated from open-water surfaces

The accounting system produced reliable (less than 1 percent difference from the previous method) results for 1984 when, because of an unusually large quantity of flow in the river, the computed consumptive use by vegetation was less precise than anticipated On the basis of the analysis for 1984, the accounting system should yield accurate estimates of consumptive use by agricultural users for all years To improve the estimate of consumptive use by vegetation, errors in computed flow at the mainstream gages should be further reduced More accurate computation of discharge at the major dams along the Colorado River will also facilitate the use of water budgets for subreaches of the river to refine the estimates of consumptive use by vegetation along the river Water-use rates for vegetation types that more accurately reflect spatial and temporal variability of evapotranspiration need to be developed to improve the distribution of consumptive use by vegetation, the identification of minor crops and multiple-cropped areas also needs to be improved

INTRODUCTION

The Colorado River, which has its headwaters as far north as Wyoming, discharges into the Gulf of California in Mexico (fig 1) The Colorado River drainage basin includes about 246,700 mi^2 in the United States (White and Garrett, 1987, p 319) The basin is divided into the upper and lower basins at the Compact point[1] (fig 1) The lower basin includes parts of Arizona, California, Nevada, New Mexico, and Utah The use of water for irrigation, domestic, municipal, and industrial purposes has a higher priority than the use of water for hydroelectric-power generation and recreation Power generation and recreation are managed so that availability of water for high-priority uses is not affected The river also is the source of water for a large distribution system that provides water to agricultural and densely populated areas in California and Arizona outside the study area Water is exported to parts of six counties in the coastal plain of southern California, including the cities of Los Angeles and San Diego, and to Phoenix in Arizona Along the river, the dominant influence on the distribution of water is the diversion for irrigation

The lower Colorado River system consists of the natural drainage basin of the Colorado River below Hoover Dam (site 1, pl 1), excluding the Bill Williams River basin above Alamo Dam (site 12, pl 1), the Gila River basin above the streamflow-gaging station near Dome (site 47, pl 1), and the drainage area in Mexico (fig 1) The south boundary of the study area coincides with the international boundary between the United States and Mexico Part of the international boundary is defined by the Colorado River This 23-mile reach of river is between the northerly international boundary (NIB), the point where the boundary between California and Mexico intersects the river, and the southerly international boundary (SIB), the southernmost point on the river where the boundary between Arizona and Mexico intersects the river Water delivered to the reach below the NIB is available for use by Mexico

In the United States, accounting for the use and distribution of Colorado River water in the lower basin is required by law (U S Supreme Court, 1964) In 1984 the U S Geological Survey (USGS), in cooperation with the Bureau of Reclamation (USBR), began a study to develop an accounting system for water and consumptive use along the Colorado River between Hoover Dam and Mexico (fig 2) to enable the Secretary of the Interior to meet legal responsibilities stated in a Decree (U S Supreme Court, 1964) Precise accounting of the distribution and use of water from the lower Colorado River has become increasingly important because of increasing demands for water in the United States and Mexico The Colorado River Compact of 1922 apportioned in perpetuity the exclusive beneficial consumptive use of 7 5 million acre-ft/yr of water each to the upper basin and to the lower basin (U S Congress, 1948, p A19) The Rio Grande, Colorado, and Tijuana Treaty of 1944 allotted a guaranteed annual quantity of 1 5 million acre-ft of Colorado River water to be delivered to Mexico (U S Congress, 1948, p A831—A885) Basic apportionments to the upper and lower basins and the treaty delivery to Mexico total 16 5 million acre-ft/yr, which exceeds the natural flow of the river Average annual virgin flow (estimated flow without regulation or diversion) at the Compact point (fig 1) was about 15 1 million acre-ft between 1906 and 1983 (John Billings, hydraulic engineer, Bureau of Reclamation, oral commun , 1986)

As of 1984, apportionments to the upper and lower basins were not fully used and the delivery to Mexico was fully satisfied in accordance with the treaty In the lower basin, California, with the exception of 1983, has used more than its basic apportionment of 4 4 million acre-ft/yr, using virtually all or part of the unused apportionments of Arizona and Nevada Arizona is expected to take its full apportionment of 2 8 million acre-ft/yr when the Central Arizona Project (CAP) Canal is completed in the 1990's, and Nevada is projected to use its full apportionment of 300,000 acre-ft/yr shortly after the year 2000 The upper basin is projected to use its full apportionment by 2040 (Jeffrey C Addiego, hydraulic engineer, Bureau of Reclamation, oral commun , 1986)

[1] Although the Colorado River Compact refers to this point as Lee Ferry, "* * *a point in the main stream of the Colorado River one mile below the mouth of the Paria River," this and many other U S Geological Survey reports refer to it as the Compact point to avoid confusion with the community of Lees Ferry at the confluence Lee Ferry is used in this report only when quoting the Compact (U S Congress, 1948, p A17—A22) and the Decree (U S Supreme Court, 1964)

Figure 1. Colorado River basin and study area.

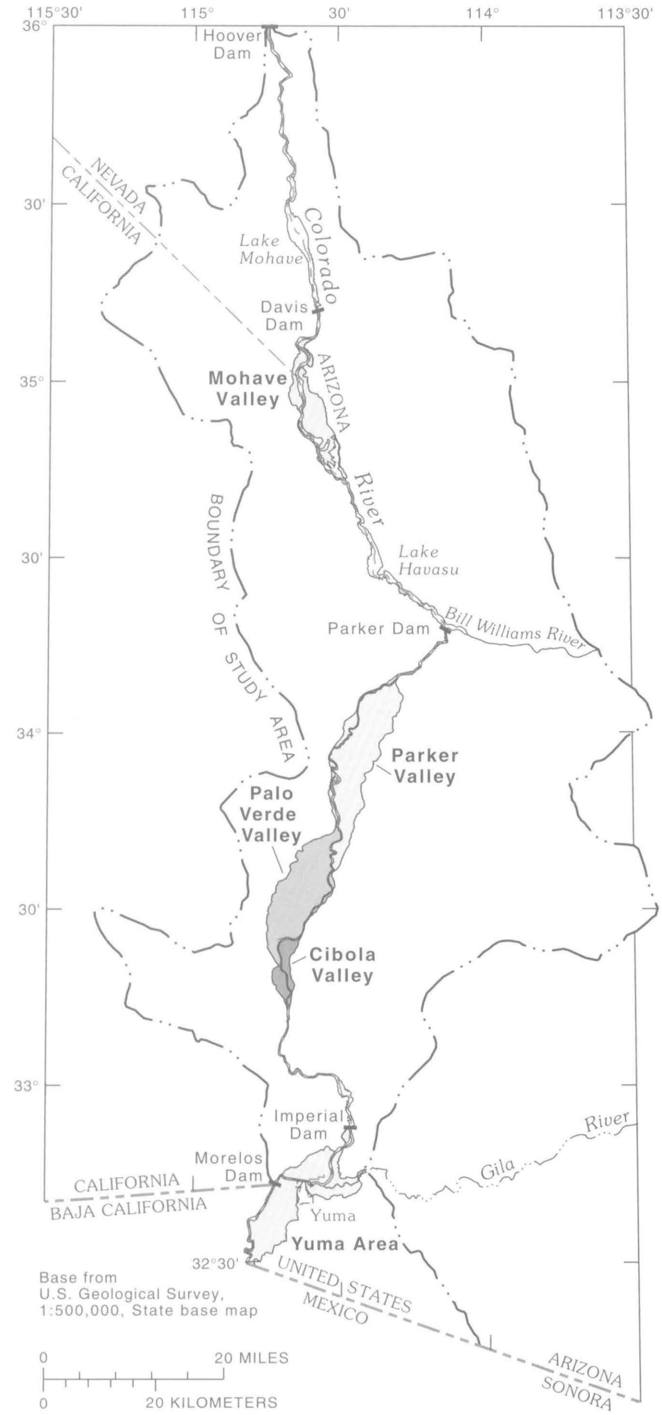


Figure 2. Lower Colorado River from Hoover Dam to Mexico and the areas (shaded) where the flood plain is used for agriculture and irrigated with water from the Colorado River.

Legal Framework

The flow of the Colorado River has been apportioned among seven basin States and Mexico by various documents and laws known, collectively, as "The Law of the River." The most significant to this study are the Colorado River Compact of 1922 and the U.S. Supreme Court Decree, 1964, *Arizona* v. *California*.

Colorado River Compact

The Colorado River Compact (Compact), signed on November 24, 1922, apportions the waters between the upper basin States and the lower basin States and acknowledges the obligation of delivery of water to Mexico (U.S. Congress, 1948, p. A17–A22). The Compact established Lee Ferry, Arizona, as the point on the Colorado River where the apportioned waters between the upper and lower basins would be measured.

The requirement for participation of the USGS and USBR is stated in Article V of the Compact as follows:

> 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 Director of the United States Geological Survey shall cooperate, ex-officio:
>
> (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.

U.S. Supreme Court Decree, 1964, *Arizona* v. *California*

The U.S. Supreme Court Decree (Decree), 1964, *Arizona* v. *California*, apportions the waters of the lower Colorado River basin to the States of California, Arizona, and Nevada in terms of consumptive use. Consumptive use is defined in the Decree as "* * *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" (U.S. Supreme Court, 1964). The Decree is specific about the responsibility of the Secretary of the Interior in providing the identification of the users of Colorado River water and publication of the quantities of diversion stated individually for each diverter Also, information about releases through regulatory structures on the river and the deliveries of water to Mexico must be provided Article V of the Decree reads as follows

> 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
>
> (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 therefore 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

The amount of data required to implement the Decree is large because consumptive use is the standard of measure and the identification of the quantity used by each diverter is required Low hydraulic-head conditions generally associated with return flows make the data collection complex The Decree defines consumptive use to include water drawn from the mainstream by underground pumping, therefore, the USBR accounts for water pumped from wells that tap the flood-plain aquifer as pumpage from the mainstream The USGS calculates the quantity of water pumped by using current-meter measurements, trajectory and orifice measurements, and power records, and by monitoring the crop acreage irrigated and applying a water-use-per-acre factor A provisional monthly table of diversions and returns is published by the USGS The USBR publishes an annual tabulation of diversions and returns to the Colorado River Most of the hydrologic information contained in the annual report is furnished by the USGS (Condes de la Torre, 1982, p 5–7)

The Decree defines tributaries as "* * *all stream systems the waters of which naturally drain into the mainstream of the Colorado River below Lee Ferry " The Decree does not affect 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—until the tributary flow reaches the mainstream

After the Decree by the U S Supreme Court (1964) set forth the apportionment of the water in the lower Colorado River, several methods were developed to estimate consumptive use along the Colorado River None of the methods, however, provided for the distribution of consumptive use among water users as specified in the Decree Evolution of the methods has reflected advances in technology, which have resulted in more reliable estimates of consumptive use by vegetation but at increased expense The technology of computer processing of remotely sensed data from satellites offered a more cost-effective technique by which vegetation types could be identified and acreages by type compiled for individual water users Therefore, a regional approach was taken to develop a system by which annual consumptive use of Colorado River water could be estimated and distributed in an equitable manner among users by combining the water-budget method and the remote-sensing technique investigated by Raymond and Rezin (1989)

Purpose and Scope

The purpose of this report is to document the Lower Colorado River Accounting System (LCRAS) developed to estimate consumptive use by vegetation of Colorado River water and to account for that use by water users Included in the report is a detailed description of (1) the distribution and use of water along the Colorado River between Hoover Dam and Mexico (see study area, figs 1 and 2) as of 1984, (2) the network of streamflow gages established and operated to meet the requirements of the Decree, and (3) the data required by the Decree and for estimating values for components of a water budget for the river The two major parts of LCRAS are described using a simplified model, followed by a detailed description of the water-budget method and the remote-sensing technique The flow components required for the water-budget method and the remotely sensed data required for the remote-sensing technique are also documented Application to calendar year 1984 illustrates the use of LCRAS, which is followed by an evaluation of the accounting system Annual data in this report are based on the calendar year

Previous Investigations

During the 1960's, comprehensive studies made by the USGS of the Colorado River area downstream from Davis Dam included reports on geology, ground-water resources, water quality, and paleohydrology Results were published as a series of chapters of USGS Professional Paper 486 (Hely and Peck, 1964, Hely and others, 1966, McDonald and Hughes, 1968, Hely, 1969, Irelan, 1971, Metzger and Loeltz, 1973, Metzger and others, 1973, Olmsted and others, 1973, Loeltz and others, 1975, McDonald and Loeltz, 1976, Patten, 1977) and by Metzger (1965, 1968) and Loeltz and McDonald (1969) These studies indicated that a substantial quantity of water applied for irrigation is returning to the Colorado River as ground-water discharge from the alluvium The States of California and Arizona have requested credit for irrigation water from their respective States that returns to the Colorado River as ground water

Methodology was not available to quantify ground-water movement through long reaches of the river adjacent to irrigated lands, therefore, the USGS developed a technique that was acceptable to the States of California, Arizona, and Nevada (Condes de la Torre, 1982, p 6) The technique involved hydraulic analyses of ground-water flow at 18 cross sections normal to the river in the Yuma area (Loeltz and Leake, 1983a, b) Extensive data were required to implement the technique, and the estimates of ground-water return flows were approximations of return flows only from each side of the river During 1983, high flows in the river destroyed about half the data-collection sites used to obtain data in the Yuma area Replacement of the data-collection sites and recalibration of the cross-sectional models were not justified because the technique did not fulfill an important requirement of the Decree, namely, the assignment of consumptive use to each water user

In Parker, Palo Verde, and Cibola Valleys, ground-water budgets were used to estimate ground-water return flow from areas under which ground water drains to the river (Leake, 1984, Owen-Joyce, 1984) Consumptive use by vegetation was estimated with a water budget for the area of each valley drained by drainage ditches Consumptive use per unit area is assumed equal for the area drained by drainage ditches and the area drained by the river, when crop data are available, adjustments are made for the unequal distribution of vegetation types (Leake, 1984, Owen-Joyce, 1984)

The USGS also investigated the remote-sensing technique of estimating consumptive use of water along the lower Colorado River Consumptive use by vegetation can be closely approximated by (1) using remote-sensing techniques to identify vegetation types and calculate acreages of each vegetation type and (2) multiplying the areas of each vegetation type by the associated water-use rate (Raymond and Rezin, 1989)

Additional studies compared the ground-water budget method and the remote-sensing technique of estimating consumptive use by vegetation Estimates of consumptive use by vegetation calculated as the residual in a ground-water budget showed reasonable agreement with estimates calculated as the product of areas of vegetation types determined from Landsat digital-image analysis and predetermined water-use rates in Palo Verde Valley (Raymond and Owen-Joyce, 1986, 1987, Owen-Joyce and Kimsey, 1987) and Parker Valley (Owen-Joyce, 1988) In both valleys, estimates of consumptive use by vegetation were within 10 percent The Palo Verde and Parker comparison studies indicated that measured diversions minus return flows underestimated consumptive use by vegetation because the drainage ditches intersect water from several sources River seepage, tributary runoff, and ground water enter the drainage ditches and are credited as surface-water return flows Because of the nature of the hydrologic system in Cibola Valley, Owen-Joyce (1990) found that the remote-sensing technique was the best available method to estimate consumptive use by vegetation during periods of rising and sustained high flows in the river

Many other studies provided information on the lower Colorado River drainage area used for this study Vegetation and wildlife habitat studies by Anderson and Ohmart (1976, 1982a, b, 1984a, b) include riparian vegetation-type maps, which were used to identify vegetation types for the image classifications A geohydrologic reconnaissance study of the Lake Mead National Recreation Area provided information on the Hoover Dam to Davis Dam reach (Bentley, 1979a, b, c, Laney, 1981) Ground-water studies provided information on areas that drain to the lower Colorado River that include Ranegras Plain (Briggs, 1969, Wilkins and Webb, 1976), Sacramento Valley (Gillespie and others, 1966, Gillespie and Bentley, 1971, Pfaff and Clay, 1981), Eldorado and Piute Valleys (Rush and Huxel, 1966), and the Bill Williams River area (Wolcott and others, 1956, Sanger and Littin, 1981) Hydrologic data reports provided information on Palo Verde Valley (Moyle and Mermod, 1978), Chuckwalla Valley (Giessner, 1963a), Rice and Vidal Valleys (Giessner, 1963b), Yuma area (U S Bureau of Reclamation, 1983, 1985a, b), and Arizona (U S Geological Survey, 1985, White and Garrett, 1986, 1987, 1988)

Acknowledgments

The authors gratefully acknowledge the cooperation of the many residents of the area who granted permission to work on their property and supplied information about their wells, pumps, and croplands Special appreciation is extended to the State agencies that furnished information for the study Arizona Department of Water Resources, Colorado River Board of California, and Colorado River Commission of Nevada

The USBR provided information on the management of the lower Colorado River, USBR Project lands, boundaries for water users, and flow and river-stage data as well as manpower Special thanks go to Ronald J Effertz, Jeffrey C Addiego, Earl E Burnett, Carl F Mayrose, Richard L Sampson, Laurie Barker, Sonya Nadalinski, and Steven W Pedretti for the above information

Water-use information was provided by many people and agencies, some of which include the various Chambers of Commerce, City Planning offices, and Yuma Metropolitan Planning Organization Gary Bunney and Linda Rowell of Lake Mead National Recreation Area provided pumpage, number of visitors, and water-use data for Willow Beach, Cottonwood Cove, and Katherine

Bud Weiser and R D Johnson of Mohave Valley Irrigation and Drainage District provided water-level data for the District observation-well network John Algot of the Fort Mojave Tribe provided water-level data for the observation-well network monitored by the tribe

Conrad B Kresge, Billy D Martin, Rodney McVey, and Thomas Claw of the U S Bureau of Indian Affairs (BIA) provided irrigation and agricultural data for the Colorado River Indian Reservation Hydrologic and crop data were collected by the BIA and included regulatory waste to drainage ditches, irrigation-water deliveries, and acreages by crop type

Roger E Henning, Gerald M Wolford, Jr , and Gerald M Davisson of the Palo Verde Irrigation District provided irrigation and agricultural data The Palo Verde Irrigation District collected hydrologic and crop data, which included monthly water levels in wells, monthly stage measurements in drainage ditches, spillage from canals, and crop type and acreage for each field in the valley These data were used to calculate water budgets and change in ground--water storage and to calibrate vegetation classifications from Landsat digital-image analysis

Wayne Sprawls of the Cibola Valley Irrigation and Drainage District provided agricultural data, including crop types and acreages by crop type Wes Martin of Cibola National Wildlife Refuge and Ronald E Swan provided information and gave permission to monitor an observation-well network on and near the wildlife refuge

The Arizona State Land Department, Resource Analysis Division, provided all computer resources for the image analyses Special thanks go to William

H Bayham, Director, and Steve B Miller for their assistance and support Additional computer services were provided by the Arizona Department of Water Resources

A Task Force on Unmeasured Return Flows to the Colorado River was formed in July 1970 to provide input from interested agencies into investigations along the lower Colorado River that pertain to the 1964 Decree The task force includes representatives from the States of California, Arizona, and Nevada, BIA, USBR, and USGS Meetings are held when necessary to discuss work in progress or completed, to resolve problems that arise, and to exchange data and information The authors wish to acknowledge the cooperation of the representatives that served on the Task Force from 1984 to 1989

DESCRIPTION OF THE STUDY AREA

The Colorado River reach between Hoover Dam and Mexico was divided into subreaches at the major dams because digital data sets from multiple Landsat images were large and because agricultural lands cover much of the flood-plain areas within the subreaches between the dams, in Mohave Valley, Parker Valley, Palo Verde Valley, Cibola Valley, and the Yuma area (fig 2) The subreaches are referred to in this report by the names of the dams that bound the subreach In all the subreaches, except for Imperial Dam to Morelos Dam, the agricultural lands are between the dams Morelos Dam, with an associated streamflow-gaging station upstream at the NIB where water leaves the United States, is where Mexico diverts Colorado River water Agricultural lands in the United States adjacent to the reach between the NIB and SIB streamflow-gaging stations are south of Morelos Dam in Yuma Valley but are inclusive to this reach because of irrigation with water diverted from the river at Imperial Dam

Between Hoover Dam and Mexico, water from the Colorado River is used mainly for agriculture and by phreatophytes on the flood plain, that part of the Colorado River valley inundated by floods prior to the construction of the dams Phreatophytes are riparian vegetation that obtain water from the river and from the shallow alluvial aquifer that is hydraulically connected to the river Crops are grown on the cultivated areas, more than one crop is grown on some of these areas during a given year (multiple-cropped areas) In this report, the net vegetated area includes the cultivated area and the area of phreatophytes The total vegetated area includes the net vegetated area and the additional effective area where there are multiple crops

The cultivated area is 70 3 percent of the net vegetated area (table 1) The net vegetated area was classified by using digital-image data from the Landsat satellite in 1984 In a few areas, crops are grown on older alluvial terraces adjacent to the flood plain Most of the water used to irrigate croplands is diverted or pumped directly from the river Water also is pumped from wells in Mohave Valley, the Yuma area, and on the terraces that are hydraulically connected to the river

In addition to crops, several types of phreatophytes that vary in density cover the uncultivated flood-plain areas of the valleys and the narrow river banks in the canyon reaches between the valleys In the reaches between the dams, phreatophytes cover from 23 9 to 100 percent of the net vegetated area (table 1) Only small areas of phreatophytes are scattered between Hoover Dam and Davis Dam, where the principal use of the river is for recreation The river also supplies water for domestic, municipal, and industrial use Agricultural, domestic, municipal, and industrial water uses are allocated to users, whereas water use by phreatophytes is not allocated

Hoover Dam to Davis Dam

The reach of the Colorado River between Hoover Dam and Davis Dam is in the Lake Mead National Recreation Area (pl 2) The river is confined by bedrock, and riparian vegetation is sparse except on the small areas of alluvium that are present at the mouths of tributary streams (pl 1) Small quantities of water are pumped for use in the recreation area Water is stored in Lake Mohave behind Davis Dam During low lake stage, water flows 10 to 12 mi between Hoover Dam and the north end of Lake Mohave, whereas Lake Mohave is backed up to Hoover Dam during high lake stage (Bentley, 1979a, p 21)

Davis Dam to Parker Dam

In the reach between Davis Dam and Parker Dam, Mohave Valley begins about 6 mi below Davis Dam near Bullhead City, where the flood plain of the river widens, and extends about 40 mi to Topock, where the river enters a canyon (fig 3) Most of the

Table 1. Crop and phreatophyte areas and evapotranspiration calculated from vegetation classifications of Landsat satellite digital images in the reaches between the dams along the lower Colorado River, Hoover Dam to Mexico, 1984

River reach and vegetation type	Net vegetated area, in acres[1]	Percentage of net vegetated area	Evapotranspiration, in acre-feet[2]	Percentage of total evapotranspiration
Hoover Dam to Davis Dam:				
Crops	0	0 0	0	0 0
Phreatophytes	706	100 0	2,983	100 0
Total (rounded)	706		2,980	
Davis Dam to Parker Dam.				
Crops	20,981	54 6	111,379	57 1
Phreatophytes	17,416	45 4	83,589	42 9
Total (rounded)	38,397		195,000	
Parker Dam to Imperial Dam:				
Crops	163,556	76 1	654,948	71 0
Phreatophytes	51,400	23 9	267,377	29 0
Total (rounded)	214,956		922,300	
Imperial Dam to Morelos Dam:				
Crops	90,494	66 0	346,060	60 8
Phreatophytes	46,614	34 0	223,447	39 2
Total (rounded)	137,108		569,500	
Hoover Dam to Morelos Dam:				
Crops	275,031	70 3	1,112,387	65 8
Phreatophytes	116,136	29 7	577,396	34 2
Total (rounded)	391,167		1,689,800	

[1]Summarized from tables 26, 28, 30, and 32
[2]Summarized from tables 27, 29, 31, and 33

flood plain is on the Arizona side of the river Land is divided in a checkerboard pattern between the Fort Mohave Indian Reservation and the States, which include private ownership (pl 2) All the agricultural lands in this reach are in Mohave Valley Water is used for agriculture by the Fort Mohave Indian Reservation and the Mohave Valley Irrigation and Drainage District The river supplies water to population centers at Needles, California, Laughlin, Nevada, and Bullhead City, Riviera, Bermuda City, Golden Shores, and Lake Havasu City, Arizona (pl 2) Topock Marsh is at the south end of the valley and is part of Havasu National Wildlife Refuge (pl 2) The refuge continues south of Topock to north of Lake Havasu City The river flows in a bedrock-lined channel until it widens into the north end of Lake Havasu in Chemehuevi Valley From Lake Havasu City to Parker Dam, Lake Havasu State Park bounds the river on the Arizona side Part of the reach on the California side of the river is within the Chemehuevi Indian Reservation (pl 2). Between Davis Dam and Parker Dam, the principal consumptive use of water from the Colorado River is the diversion and exportation to California through the Colorado River aqueduct and to Arizona through the CAP Canal (pl 1)

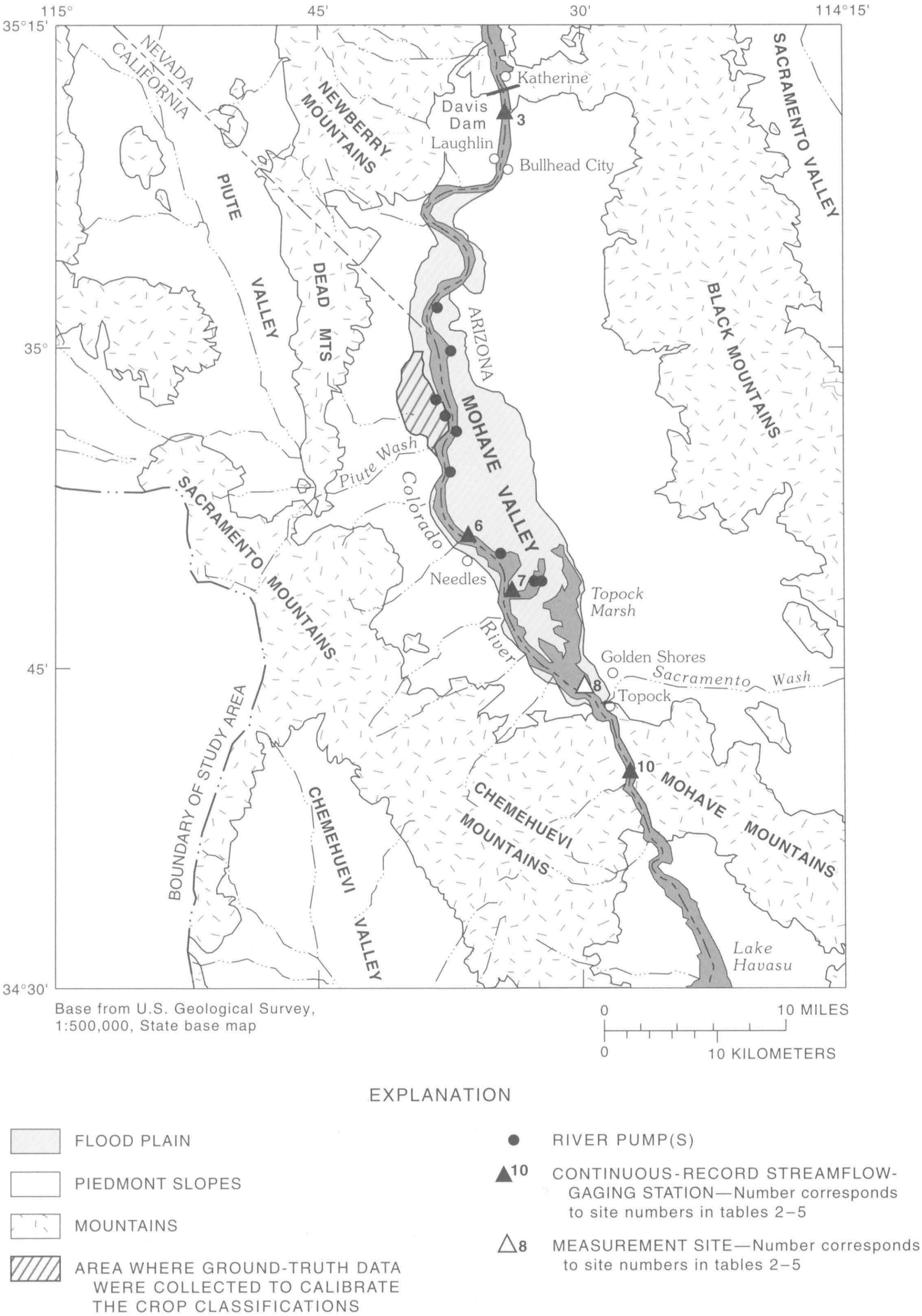


Figure 3. Flood-plain areas, location of streamflow-gaging stations and measurement sites, and crop-calibration area in Mohave Valley.

Parker Dam to Imperial Dam

Between Parker Dam and Imperial Dam, one continuous flood-plain area is divided by meanders of the river into Parker, Palo Verde, and Cibola Valleys, which contain about 60 percent of the agricultural area below Davis Dam Parker Valley is between the cities of Parker and Ehrenberg, Arizona (fig 4) In Parker Valley, most of the flood plain lies in the Colorado River Indian Reservation (CRIR) (pl 2) on the Arizona side of the river (fig 4) At Headgate Rock Dam, water is diverted from the river to croplands in Arizona Water is pumped from the river to small farms on both sides of the river The population centers are Parker and Poston, Arizona Palo Verde Valley is between Palo Verde Dam and the old river channel on the California side of the river (fig 5) The agricultural area, which covers most of Palo Verde Valley, is in the Palo Verde Irrigation District (PVID) (pl 2) Water is diverted from the river at Palo Verde Dam The population centers are Blythe, East Blythe, Palo Verde, and Ripley, California Cibola Valley is southeast of Palo Verde Valley on the Arizona side of the river (fig 5) Most of the flood plain is in Arizona, however, after channelization and realignment of the Colorado River were completed in 1970, part of the flood plain is now west of the river (fig 5) Agricultural lands are divided between Cibola Valley Irrigation and Drainage District (CIDD) and Cibola National Wildlife Refuge (CNWR) (pl 2) Water is pumped from the river at various sites (fig 5) The population centers are Cibola and a concentration of houses along the boundary between the refuge and CIDD, which parallels the road along the base line (fig 5) South of Cibola Valley, the flood plain narrows and the river flows to Imperial Dam through an area of phreatophytes The Cibola National Wildlife Refuge extends southward from the valley to the boundary with the Imperial National Wildlife Refuge In three areas east and south of Parker, in Vidal Valley, and on Palo Verde Mesa, agricultural lands are on the terraces above the flood plain These agricultural lands are assumed to be using Colorado River water because much of the water was pumped from wells that are downgradient from and hydraulically connected to the river

Imperial Dam to the Border with Mexico

The Yuma area begins at Imperial Dam, includes the flood plains of the Colorado and Gila Rivers and Yuma Mesa, and extends to the southerly international boundary with Mexico (SIB) The Yuma area is divided by geographic features that correspond to the agricultural-area boundaries Laguna Valley is between Imperial and Laguna Dams (fig 6) and includes Mittry Lake Wildlife Area and part of the Yuma Proving Ground (pl 2) The flood plain below Imperial Dam on the Arizona side of the river, east of the city of Yuma, and northeast of Yuma Mesa is divided into the North and South Gila Valleys by the Gila River Yuma Valley is south of the city of Yuma, west of Yuma Mesa, and southeast of Morelos Dam On the California side of the river are the lands of the Fort Yuma Indian Reservation, which include the Reservation Division and the Bard Water District, and some non-Indian land The Yuma Island area consists of land between an abandoned channel and the current channel of the Colorado River where the California-Arizona border has been determined to be west of the river, which results in some Arizona land being on the California side of the river (pl 2) Most of the irrigation water is diverted at Imperial Dam and distributed to both sides of the river through an extensive network of canals Additional water is pumped directly from the river at various sites or indirectly from the river at many wells The population centers are Yuma, the Marine Corps Air Station, Somerton, Gadsden, and San Luis in Arizona, and Winterhaven and Bard in California

Measurement of Flow

The USGS operates continuous-recording streamflow-gaging stations at each regulatory structure controlled by the United States, major diversions into canals at diversionary structures, and major returns from drainage ditches (figs 7 and 8) The flow data are published annually in USGS Water-Data Reports (White and Garrett, 1986, 1987, 1988) Most of the streamflow-gaging stations are or were operated to meet the requirements of Decree accounting (table 2) Other streamflow-gaging stations are operated to meet the needs of other agencies (table 3)

An appraisal of the streamflow-gaging stations operated by the USGS to meet the requirements of Decree accounting determined the justification,

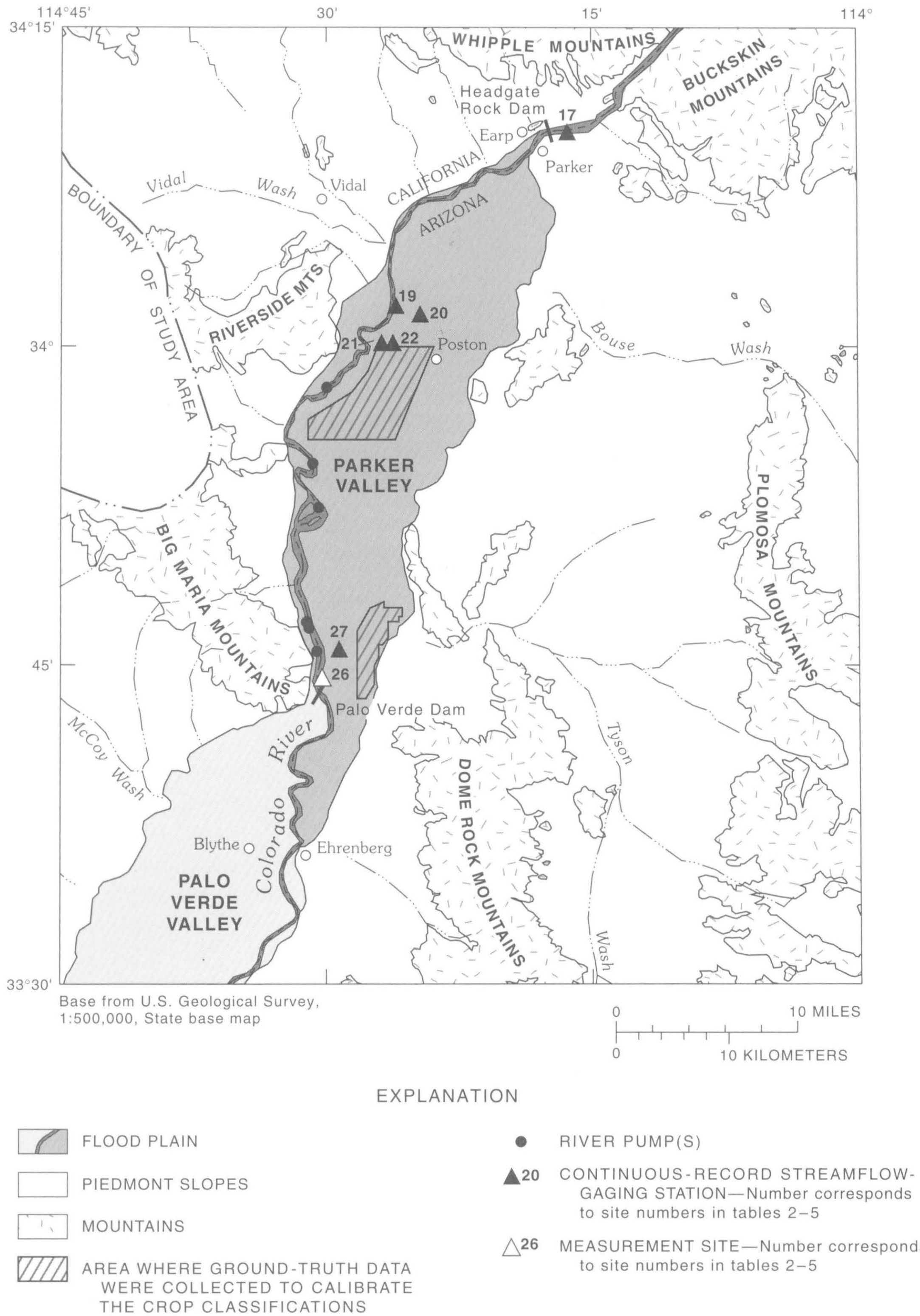
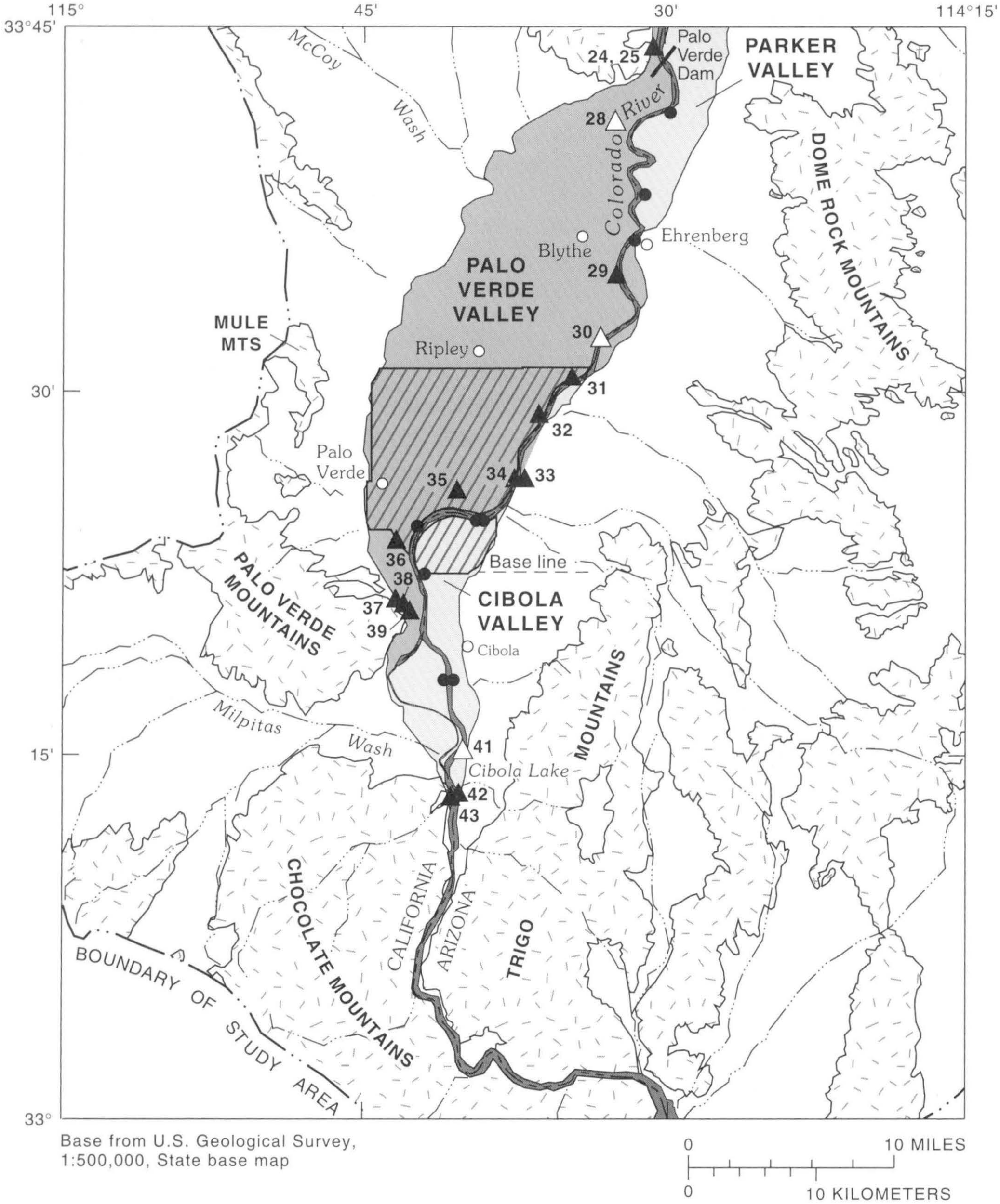


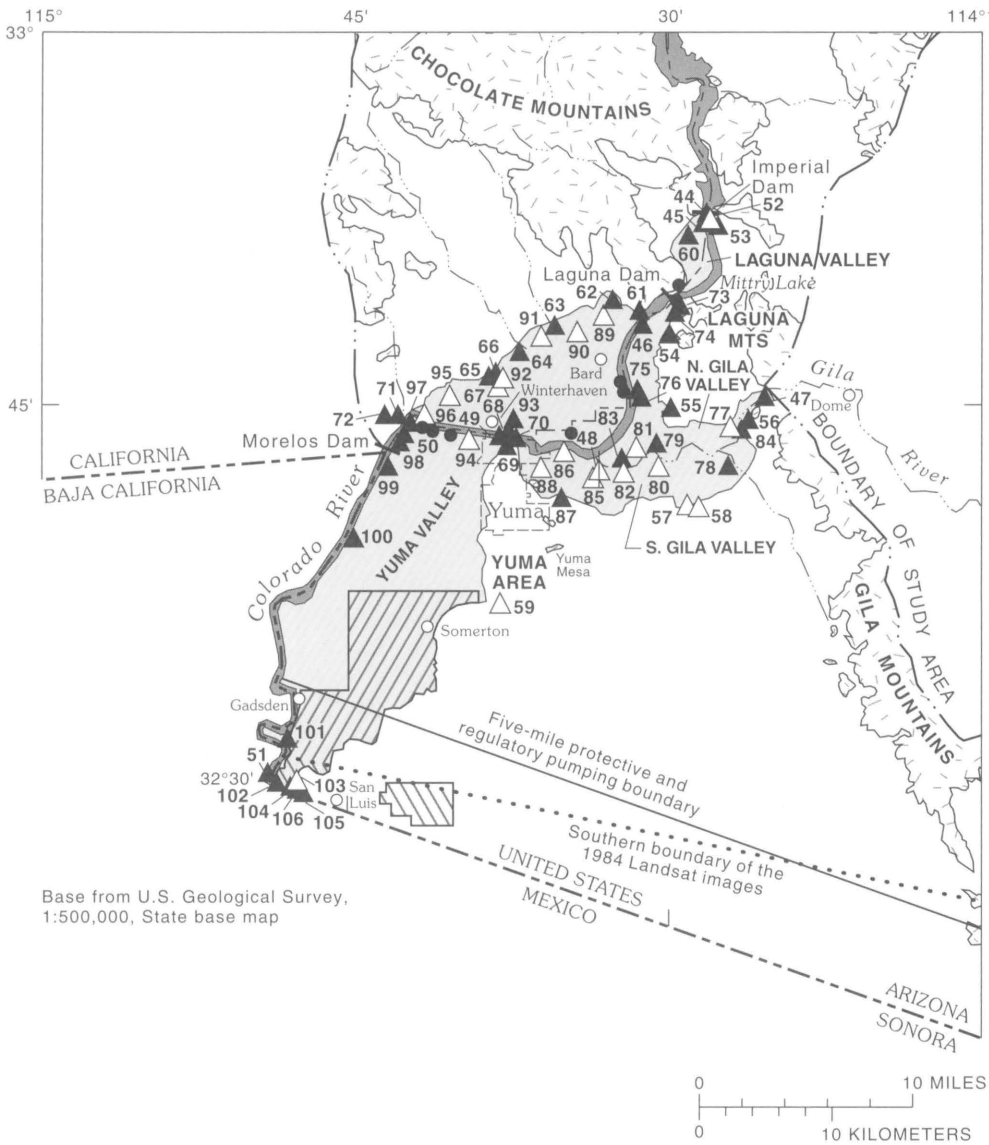
Figure 4. Flood-plain areas, location of streamflow-gaging stations and measurement sites, and crop-calibration areas in Parker Valley.



EXPLANATION

- FLOOD PLAIN
- PIEDMONT SLOPES
- MOUNTAINS
- AREA WHERE GROUND-TRUTH DATA WERE COLLECTED TO CALIBRATE THE CROP CLASSIFICATIONS
- ● RIVER PUMP(S)
- 29▲ CONTINUOUS-RECORD STREAMFLOW-GAGING STATION—Number corresponds to site numbers in tables 2–5
- △41 MEASUREMENT SITE—Number corresponds to site numbers in tables 2–5

Figure 5. Flood-plain areas, location of streamflow-gaging stations and measurement sites, and crop-calibration areas in Palo Verde and Cibola Valleys.



EXPLANATION

- FLOOD PLAIN
- PIEDMONT SLOPES
- MOUNTAINS
- AREA WHERE GROUND-TRUTH DATA WERE COLLECTED TO CALIBRATE THE CROP CLASSIFICATIONS
- AREA WHERE CROP DATA WERE COLLECTED BECAUSE THE AREA WAS NOT ON THE LANDSAT IMAGES
- ● RIVER PUMP(S)
- 4▲ CONTINUOUS-RECORD STREAMFLOW-GAGING STATION—Number corresponds to site numbers in tables 2–5
- △59 MEASUREMENT SITE—Number corresponds to site numbers in tables 2–5
- 48 DISCONTINUED STREAMFLOW-GAGING STATION—Number corresponds to site numbers in tables 2–5

Figure 6. Flood-plain areas, location of streamflow-gaging stations and measurement sites, and crop-calibration areas in the Yuma area.

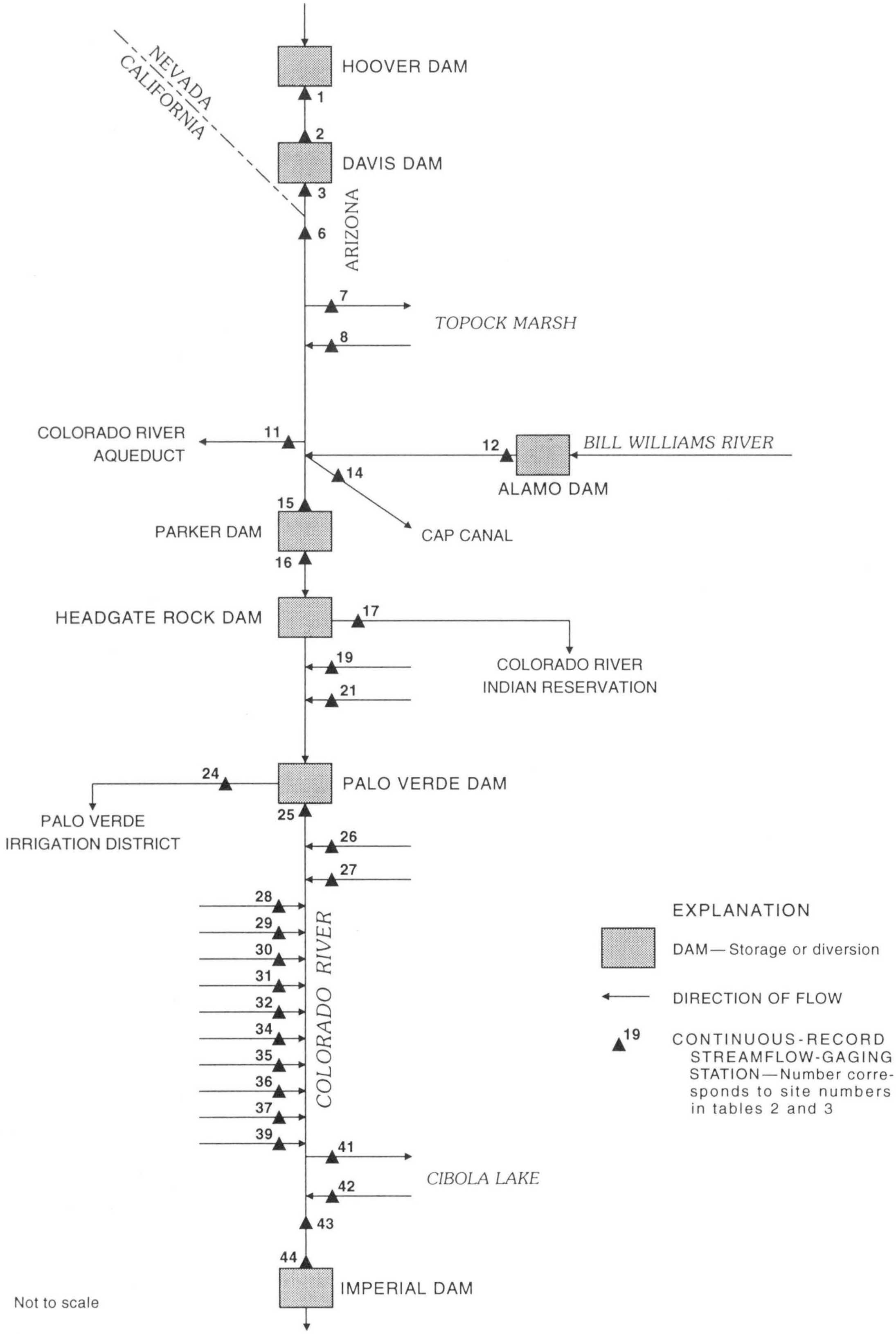


Figure 7. Streamflow-gaging stations operated in 1984 from Davis Dam to Imperial Dam.

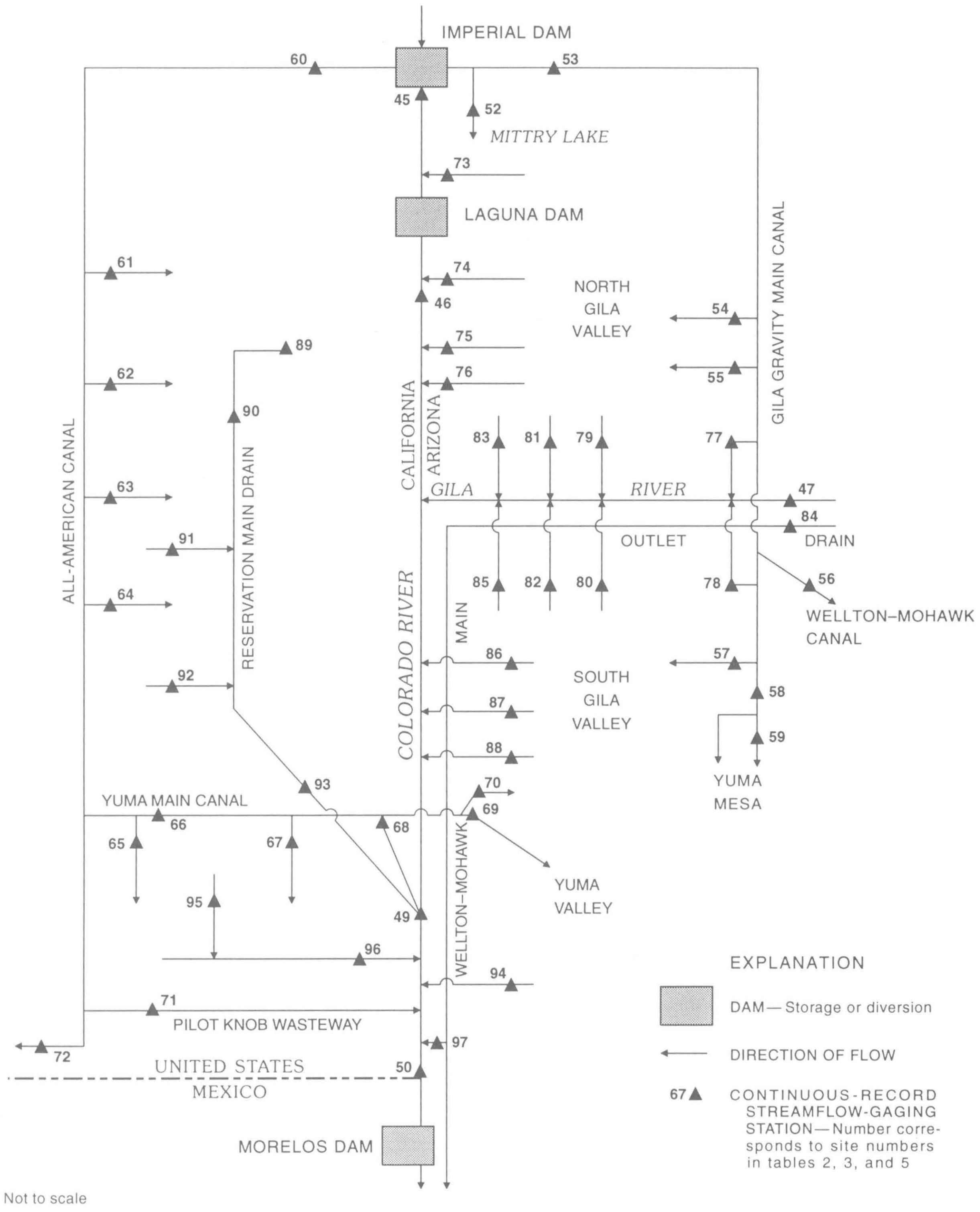


Figure 8. Streamflow-gaging stations operated in 1984 from Imperial Dam to the northerly international boundary with Mexico.

Table 2. Evaluation of data collected at streamflow-gaging stations operated by the U S Geological Survey

[Station name CAP, Central Arizona Project, CRIR, Colorado River Indian Reservation PVID, Palo Verde Irrigation District Justification D, U S Supreme Court Decree (1964), N, Justification for station no longer valid See text for detailed explanation Purpose R releases from regulatory structures, D, diversion from the river at a diversionary structure for use in the drainage basin, RF, return flow from irrigation that discharges into drainage ditches, E, diversion of water for export out of the drainage basin Accuracy E, about 95 percent of the daily discharges are within 5 percent of the true value, G, about 95 percent of the daily discharges are within 10 percent, F, about 95 percent of the daily discharges are within 15 percent, P, about 95 percent of the daily discharges have less than "F" accuracy Is all the flow defined by the purpose of the gage measured? Y yes, N, no]

Site number[1]	Station number	Station name	Justification	Purpose	Accuracy	Is all the flow defined by the purpose of the gage measured?
1	09421500	Colorado River below Hoover Dam	D	R	E	N
3	09423000	Colorado River below Davis Dam	D	R	G	Y
7	09423550	Topock Marsh inlet near Needles	D	D	G	N
8	09423650	Topock Marsh outlet near Topock	D	RF	P	N
11	09424150	Colorado River aqueduct near Parker Dam	D	E	G	Y
14	09426650	CAP Canal at Havasu Pumping Plant near Parker	D	E	G	Y
16	09427520	Colorado River below Parker Dam	D	R	G	Y
17	09428500	CRIR Main Canal near Parker	D	D	G	Y
19	09428505	Gardner Lateral spill near Parker	D	RF	F	Y
20	09428508	Upper Main drain near Poston[2]	D	RF	F	Y
21	09428510	CRIR Poston wasteway near Poston	D	RF	F	Y
22	09428511	Poston wasteway spill gates[2]	D	RF	F	Y
24	09429000	Palo Verde Canal near Blythe	D	D	G	Y
25	09429010	Colorado River at Palo Verde Dam	D	R	G	Y
26	09429030	Palo Verde drain near Parker	D	RF	F	N
27	09429060	CRIR Lower Main drain near Parker	D	RF	F	N
28	09429130	PVID Olive Lake drain near Blythe	D	RF	F	N
29	09429155	PVID F Canal spill near Blythe	D	RF	F	Y
30	09429160	PVID D-10-11-2 spill near Blythe	D	RF	F	Y
31	09429170	PVID D-10-11-5 spill near Blythe	D	RF	F	Y
32	09429180	PVID D-23 spill near Blythe	D	RF	F	Y
34	09429190	PVID D-23-1 spill near Blythe	D	RF	F	Y
35	09429200	PVID C Canal spill near Blythe	D	RF	F	Y
36	09429210	PVID C-28 upper spill near Blythe	D	RF	F	Y
37	09429220	PVID Outfall drain near Palo Verde	D	RF	G	N
38	09429225	PVID Anderson drain near Palo Verde[3]	D	RF	F	Y
39	09429230	PVID C-28 lower spill near Blythe	D	RF	F	Y
41	09429280	Cibola Lake inlet near Cibola	N	---	--	N
42	09429290	Cibola Lake outlet near Cibola	N	---	--	N
44	09429490	Colorado River above Imperial Dam	N	---	--	--
45	09429500	Colorado River below Imperial Dam	D	R	G	Y
46	09429600	Colorado River below Laguna Dam	D	R	G	Y
52	09522400	Mittry Lake diversion at Imperial Dam	D	D	G	N
53	09522500	Gila Gravity Main Canal at Imperial Dam	D	D	G	Y
54	09522600	North Gila Main Canal	D	D	G	Y
55	09522650	North Gila Main Canal No 2	D	D	G	Y
56	09522700	Wellton-Mohawk Canal	D	E	G	Y
57	09522800	South Gila Main Canal	D	D	G	Y
58	09522850	Gila Gravity Main Canal at pumping plant	D	D	G	Y
59	09522900	Unit B Main Canal	D	D	G	Y

Table 2 Evaluation of data collected at streamflow-gaging stations operated by the U S Geological Survey—*Continued*

Site number[1]	Station number	Station name	Justification	Purpose	Accuracy	Is all the flow defined by the purpose of the gage measured?
60	09523000	All-American Canal near Imperial Dam	D	D	G	Y
61	09523200	Reservation Main Canal	D	D	G	Y
62	09523400	Titsink Canal	D	D	G	Y
63	09523600	Yaqui Canal	D	D	G	Y
64	09523800	Pontiac Canal	D	D	G	Y
65	09523900	Walapai Canal	D	D	G	Y
66	09524000	Yuma Main Canal at Siphon-Drop Powerplant near Yuma	D	D	G	Y
67	09524500	Diversions from Yuma Main Canal between Siphon-Drop Powerplant and Yuma Main Canal wasteway	D	D	G	Y
68	09525000	Yuma Main Canal wasteway at Yuma	D	D	P	Y
69	09525500	Yuma Main Canal below Colorado River siphon at Yuma	D	D	G	Y
70	09526000	Diversions from Yuma Main Canal for municipal supply for Yuma	D	D	G	Y
71	09527000	Pilot Knob Powerplant and wasteway near Pilot Knob	D	RF	G	Y
72	09527500	All-American Canal below Pilot Knob wasteway	D	E	G	Y
73	09527900	Mittry Lake outlet channel near Yuma	N	---	--	N
74	09528600	Laguna Canal wasteway	D	RF	G	Y
75	09528800	Levee Canal wasteway	D	RF	G	Y
76	09529000	North Gila drain No 1	D	RF	F	Y
77	09529050	North Gila drain No 3 near Yuma	N	---	--	N
78	09529100	Fortuna wasteway near Yuma	N	---	--	N
79	09529150	North Gila Main Canal wasteway	D	RF	G	Y
80	09529160	South Gila Pump Outlet Channel No 3 near Yuma	D	RF	G	Y
81	09529200	Bruce Church drain	D	RF	F	Y
82	09529240	South Gila Pump Outlet Channel No 2 near Yuma	D	RF	G	N
83	09529250	Bruce Church wasteway	D	RF	G	Y
84	09529300	Wellton-Mohawk Main Outlet drain near Yuma	N	---	--	--
85	09529360	South Gila Pump Outlet Channel No 1 near Yuma	D	RF	G	Y
86	09529400	South Gila drain No 2 near Yuma	N	---	--	N
87	09529420	South Gila Terminal wasteway	D	RF	G	Y
88	09529440	South Gila Pump Outlet Channel No 4	D	RF	G	Y
89	09529600	Reservation drain No 7	N	---	--	--
90	09529700	Reservation Main drain No 6	N	---	--	--
91	09529800	Reservation drain No 2	N	---	--	--
92	09529900	Reservation drain No 3	N	---	--	--
93	09530000	Reservation Main drain No 4	D	RF	F	Y
94	09530200	Yuma Mesa Outlet drain at Yuma	D	RF	G	Y
95	09530400	Reservation drain No 11	N	---	--	--
96	09530500	Drain 8-B near Yuma	D	RF	P	Y
97	09531800	Main Outlet Drain Extension above Morelos Dam (MODE 2)	N	---	--	--

[1]Locations plotted on figures 3–6 and plate 1

[2]Sites 20 and 22 are used to compute the flow at site 21

[3]Site 38 was discontinued when Palo Verde Irrigation District destroyed the drain in May 1984

Table 3. Streamflow-gaging stations operated by the U S Geological Survey for other agencies

[Agency MWD, Metropolitan Water district of Southern California, USCE, U S Army Corps of Engineers, USBR, Bureau of Reclamation]

Site number[1]	Station number[2]	Station name	Agency
2	09422500	Lake Mohave at Davis Dam	MWD
6	09423500	Colorado River at Needles	MWD
12	09426000	Bill Williams River below Alamo Dam	USCE
15	09427500	Lake Havasu near Parker Dam	MWD
43	09429300	Colorado River below Cibola Valley (at Adobe Ruins)[3]	USBR
47	09520500	Gila River near Dome	USBR
48	09529700	Gila River near mouth[4]	USBR
49	09521100	Colorado River below Yuma Main Canal wasteway at Yuma	USBR

[1]Locations plotted on plate 1 or figure 6
[2]Assigned by the U S Geological Survey
[3]U S Geological Survey discontinued site September 30, 1988 Bureau of Reclamation began operating station as river-stage gage
[4]U S Geological Survey discontinued site June 30, 1983

purpose, and accuracy of the discharge record and evaluated each gage as to whether all the flow that is defined by the purpose of the gage is measured (table 2) For example, to avoid backwater from the river, some gages on drainage ditches are located some distance upstream from the river Such locations mean that flows entering ditches between the gages and the river are unmeasured For stations where additional explanation is required to describe why the data are not fully representative of the intended purpose of the site, see the sections in this report entitled "Dams and Reservoirs," "Diversions," "Return Flows," and "Tributary Inflow " LCRAS uses data collected at many existing measurement sites operated by the USGS but also uses data collected at sites for other agencies and data collected by other agencies

The USBR operates river-stage gaging stations (table 4) and uses data from some of the streamflow-gaging stations operated by the USGS along the lower Colorado River for water management River-stage data are used to route water downstream to users and to monitor the inflow of storm runoff from tributaries to the river that would require modifications to releases at the dams River-stage data also are used to estimate the quantity of inflow from tributary runoff for use in LCRAS

Occasional flow measurements are made of water pumped from the river or pumped from wells on the flood plain Diversion of river water by pumps in the river or pumps in wells on the flood plain is computed by the USGS from power records Pumpage data are published annually by the U S Bureau of Reclamation (1985d, 1986a)

Table 4. River-stage gaging stations operated by the Bureau of Reclamation

Site number[1]	Station number[2]	Station name
4	([3])	Colorado River at Big Bend
5	([3])	Colorado River at Boy Scout Camp
9	([3])	Colorado River at Gasline Bridge
10	09424000	Colorado River near Topock (at RS-41)
13	09426620	Bill Williams River near Parker (below Mineral Wash)[4]
18	([3])	Colorado River at Parker
23	([3])	Colorado River at Water Wheel
33	09429188	Colorado River at Taylor Ferry
40	([3])	Colorado River at Lower Cibola Bridge

[1]Locations plotted on plate 1
[2]Assigned by the U S Geological Survey
[3]No U S Geological Survey streamflow-gaging station numbers were assigned to these sites

The International Boundary and Water Commission (IBWC) operates continuous-recording streamflow-gaging stations in the Colorado River at the NIB (site 50, fig 6) and SIB (site 51, fig 6) with Mexico and at sites (sites 98–106, fig 6) between the NIB and the SIB to fulfill the requirements of a treaty with Mexico and to account for the quantity of water that is delivered each year to Mexico (table 5) The IBWC uses the data to compute the inflow to Morelos Dam, where water is diverted for use in Mexico Flow measured at the NIB upstream from Morelos Dam and return flows to the river between the NIB and SIB are used in LCRAS Flow and related data are published annually in the Western Water Bulletin by the International Boundary and Water Commission, United States and Mexico (1984)

Table 5 Streamflow-gaging stations operated by the International Boundary and Water Commission to fulfill treaty requirements with Mexico

Site number[1]	Station number[2]	Station name
50	09522000	Colorado River at Northerly International Boundary above Morelos Dam near Andrade
51	09522200	Colorado River at Southerly International Boundary near San Luis
98	09531850	Cooper wasteway
99	09531900	Main Outlet Drain Extension below Morelos Dam (MODE 3)
100	09532500	Eleven Mile wasteway
101	09533000	Twenty-one Mile wasteway
102	09533300	Wellton-Mohawk Bypass drain at Arizona-Sonora Boundary
103	09534000	Main drain at Southerly International Boundary near San Luis
104	09534300	West Main Canal wasteway
105	09534500	East Main Canal wasteway
106	09534550	Two-Forty-Two well field lateral near San Luis

[1]Locations plotted on figure 6
[2]Assigned by the U S Geological Survey

LOWER COLORADO RIVER ACCOUNTING SYSTEM

The Lower Colorado River Accounting System (LCRAS) is a method that estimates and distributes consumptive use by vegetation to water users along the lower Colorado River LCRAS is composed of two major parts (fig 9) First, the water-budget method is used to estimate annual consumptive use by vegetation between Hoover Dam and Morelos Dam Second, annual consumptive use by vegetation is distributed to agricultural water users by using a remote-sensing technique from which percentages of total evapotranspiration are estimated for each diverter from digital-image analysis of satellite images, estimated water-use rates by vegetation types, and digitized boundaries for diverters LCRAS combines the output from the water budget with the output from the remote-sensing technique to apportion annual consumptive use by vegetation of water from the lower Colorado River by point of diversion, diverter, and State as required by Supreme Court Decree The LCRAS computer program, which runs on a microcomputer, is documented by von Allworden and others (1991)

The following sections describe the development of the algorithms used in LCRAS The water-budget equation that estimates consumptive use by vegetation is described first, followed by a description of the algorithms used to apportion consumptive use by vegetation to water users using estimates of evapotranspiration Each part includes definitions of all the components used in the method

Estimation of Consumptive Use by Vegetation

The water-budget method can be used to account for streamflow depletion (outflow) from a specific area during a specified period as inflow minus change in storage Change in storage includes change in reservoir storage and change in storage in the alluvial aquifer that is hydraulically connected to the river (fig 9) A water budget for the lower Colorado River includes the following independent components (figs 9 and 10) (1) flow in the river at the upstream boundary, (2) flow in the river at the downstream boundary, (3) change in reservoir storage, (4) water exported out of the study area, (5) consumptive use by vegetation, (6) open-water evaporation, (7) precipitation, (8) tributary inflow, (9) domestic, municipal, and industrial consumptive use, (10) return flow to the river below the downstream boundary from a diversion in the budget reach, and (11) change in storage in the alluvial aquifer The first five components make up more than 90 percent of the budgeted water Of the five principal components, only consumptive use by vegetation is not directly measured A water budget is considered a valid method because the errors of measurement of the major components do not mask the computed amount of consumptive use by vegetation

A water budget that estimates total consumptive use of water from the Colorado River between Hoover Dam (upstream boundary) and Morelos Dam (downstream boundary) for a finite time interval can be expressed as

$$CU_{ci} = IF - OF - \frac{\Delta S_r}{\Delta t} - \frac{\Delta S_a}{\Delta t}, \quad (1)$$

where

CU_{ci} = total consumptive use, in acre-feet, of Colorado River water,

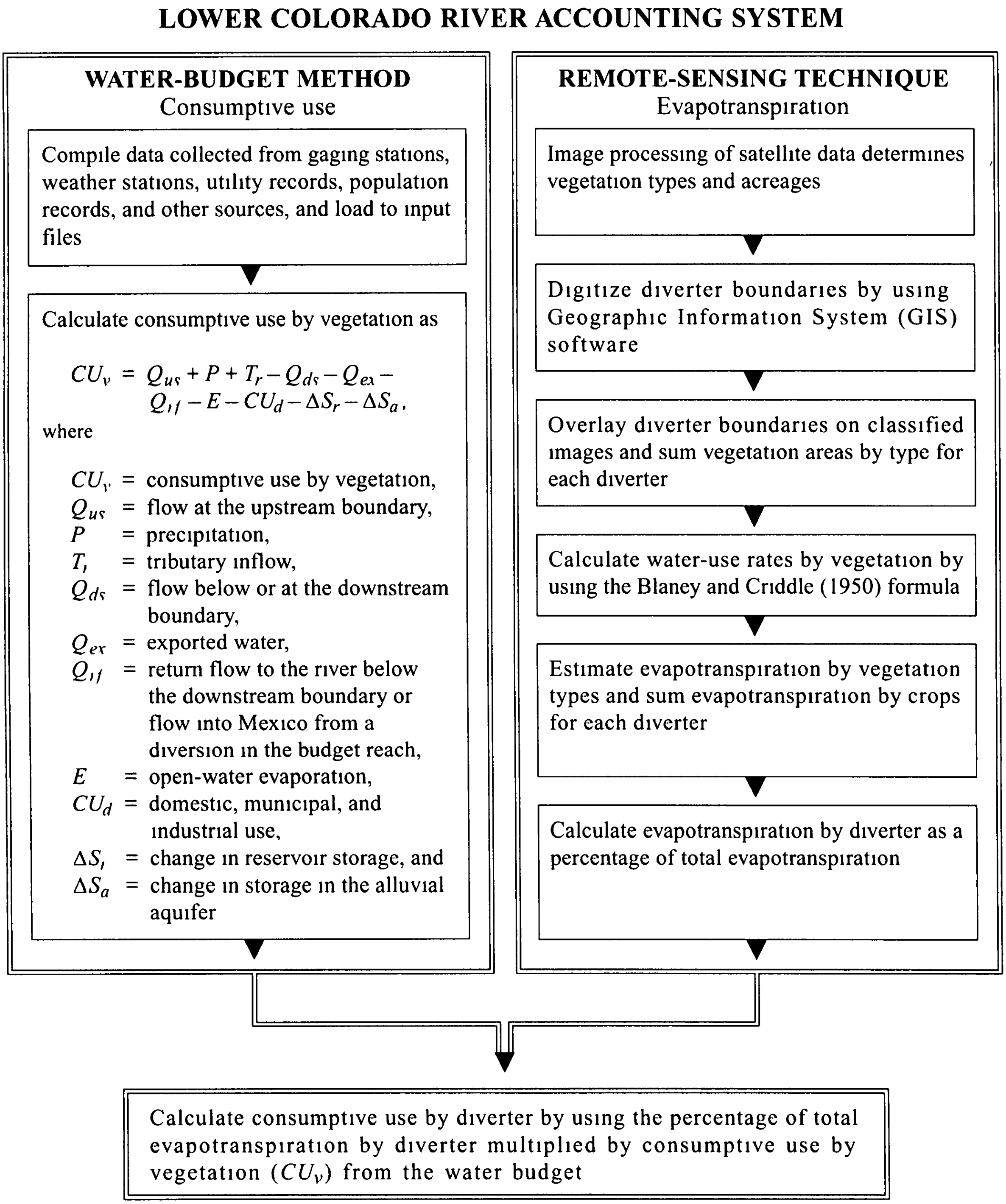


Figure 9. Flow chart of the Lower Colorado River Accounting System

IF = total inflow, in acre-feet, to the reach,

OF = total outflow other than CU_{ct}, in acre-feet, from the reach,

ΔS_r = change in reservoir storage, in acre-feet, in the reach,

ΔS_a = change in storage in the alluvial aquifer, in acre-feet, in the reach, and

Δt = time interval (one calendar year for this study)

Total inflow to the reach can be expressed as

$$IF = Q_{us} + P + T_r , \tag{2}$$

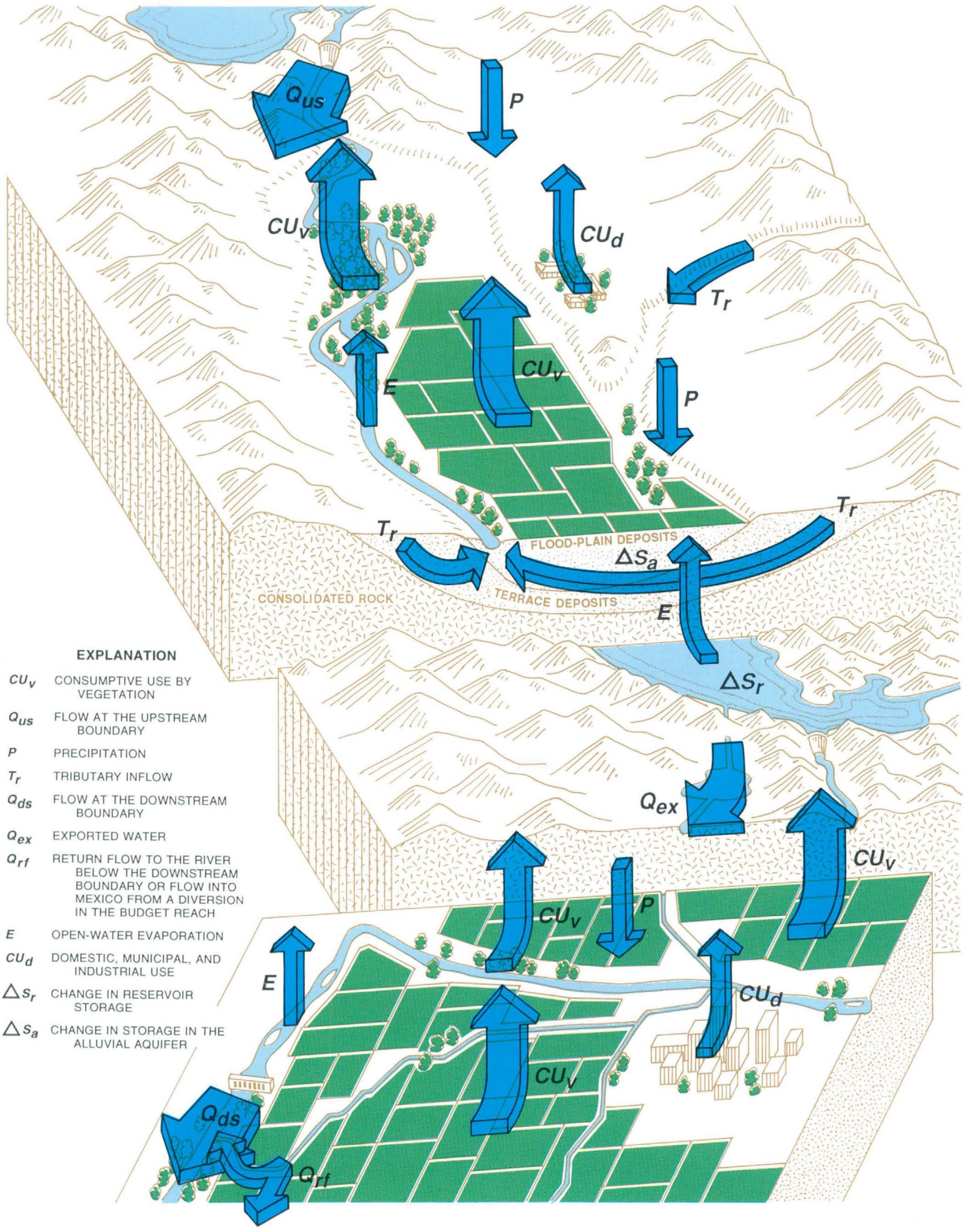


Figure 10. Flow components for a water-budget reach of the river.

where

Q_{us} = flow in the Colorado River, in acre-feet, at the upstream boundary of the reach,

P = precipitation, in acre-feet, that falls on the net vegetated area and open-water surfaces in the reach, and

T_t = tributary inflow, in acre-feet, in the reach

Precipitation can be expressed as

$$P = \left(\frac{p}{12}\right)(A_v + A_w), \quad (3)$$

where

p = annual precipitation, in inches, at representative weather stations for the reach or subreaches,

A_v = net vegetated area, in acres, in the reach or subreaches, and

A_w = area, in acres, of the open-water surfaces in the reach or subreaches

The net vegetated area (A_v) was calculated from multitemporal, multispectral image classifications of individual subreaches of the river The area of open water (A_w) was calculated from single-image classifications of individual subreaches of the river

Total outflow other than CU_{cr} from the reach can be expressed as

$$OF = Q_{ds} + Q_{rf}, \quad (4)$$

where

Q_{ds} = flow in the Colorado River, in acre-feet, below or at the downstream boundary, and

Q_{rf} = quantity, in acre-feet, of water from a diversion in the reach that returns to the river below the downstream boundary or flows into Mexico

Consumptive use of Colorado River water (equation 1) includes individual components and can be expressed as

$$CU_{cr} = Q_{ex} + CU_v + E + CU_d, \quad (5)$$

where

Q_{ex} = quantity, in acre-feet, of water diverted from the river and exported out of the study area,

CU_v = consumptive use by vegetation, in acre-feet, of Colorado River water,

E = evaporation, in acre-feet, from the open-water surfaces in the reach, and

CU_d = domestic, municipal, and industrial consumptive use, in acre-feet, of the reach

It is important to separate the consumptive use of Colorado River water into its component parts for accounting purposes as stated in the Decree because not all the water lost from the river is charged to water users Q_{ex}, CU_v, and CU_d are apportioned to water users E is considered an instream loss CU_v is the most complex component because it includes consumptive use by crops and consumptive use by phreatophytes Consumptive use by crops is apportioned to agricultural water users, whereas consumptive use by phreatophytes, like evaporation, is considered an instream loss Separating consumptive use by vegetation into its component parts is accomplished in the second part of the LCRAS method

Evaporation from the river, reservoirs, lakes, marshes, and flooded areas can be expressed as

$$E = A_w \times e, \quad (6)$$

where

e = evaporation rate, in feet, for that reach of the river

The value of e was determined for the individual reaches as described in a subsequent section entitled "Evaporation Rates "

The water budget used to compute consumptive use by vegetation of Colorado River water in terms of the independent flow components (see figs 9 and 10) defined in equations 2, 4, and 5 is

$$CU_v = Q_{us} + P + T_r - Q_{ds} - Q_{ex} - Q_{rf} - E - CU_d - \Delta S_t - \Delta S_a \quad (7)$$

Equation 7 is the completion of the water-budget analysis as shown in figure 9 The remote-sensing technique of LCRAS is used to separate CU_v into its two component parts, crops and phreatophytes, and to distribute consumptive use by crops to agricultural water users

Distribution of Consumptive Use by Vegetation

Estimates of evapotranspiration are used to distribute the computed consumptive use by vegetation to water users LCRAS uses estimates of annual water-use rates by vegetation types to estimate annual evapotranspiration To incorporate the spatial variations in precipitation, temperature, and evaporation between Hoover Dam and Mexico in LCRAS, the river was divided into four subreaches The four subreaches for which individual calculations of evapotranspiration were made are (1) Hoover Dam to Davis Dam, (2) Davis Dam to Parker Dam, (3) Parker Dam to Imperial Dam, and (4) Imperial Dam to Morelos Dam These four subreaches were also used to estimate precipitation (equation 3) and open-water evaporation (equation 6) as components of the water budget for the total reach to incorporate spatial variations in precipitation and evaporation along the Colorado River

Evapotranspiration is the loss of water from a land area through transpiration by vegetation and evaporation from the soil surface under the vegetation Evapotranspiration estimated for specific users of Colorado River water can be expressed as

$$ET_u = \sum_{i=1}^{n} (A_i \times U_i), \qquad (8)$$

where

ET_u = estimated evapotranspiration, in acre-feet, for a user u of Colorado River water,

A_i = the area, in acres, for vegetation type i,

U_i = water-use rate, in feet per year, for vegetation type i,

n = number of types of vegetation in a user's area, and

$\sum_{i=1}^{n} A$ = the total vegetated area

The areas for each vegetation type A_i were calculated from multitemporal, multispectral image classifications of individual reaches of the river The values of U_i were calculated for each vegetation type by using the Blaney-Criddle formula (Blaney and Criddle, 1950) as discussed in the subsequent section entitled "Water Use by Vegetation "

For each diverter, the number of acres of each crop A_i was multiplied by the respective water-use rate U_i to obtain the amount of evapotranspiration by that crop Total evapotranspiration by diverter was obtained by summing the computed evapotranspiration for each crop in the area served by each diversion Evapotranspiration by phreatophytes was summed separately by State for each subreach and for the total reach Total evapotranspiration by crops and phreatophytes for any specified reach is

$$ET_r = \sum_{u=1}^{x} ET_u , \qquad (9)$$

where

ET_r = estimated evapotranspiration, in acre-feet, for a reach r of the Colorado River, and

x = number of users in reach r

Total evapotranspiration for the reach from Hoover Dam to Morelos Dam (ET) is

$$ET = \sum_{r=1}^{4} ET_r \qquad (10)$$

The ratio of evapotranspiration by each user (ET_u) to total evapotranspiration (ET) multiplied by consumptive use by vegetation for the Hoover Dam to Morelos Dam reach (CU_v) results in adjusted estimates of consumptive use by vegetation for each diverter (CU_{vu}) Consumptive use by phreatophytes is not assigned to a particular water user For the purpose of providing information, consumptive use by phreatophytes is summed and listed separately by State The adjusted consumptive use by crops for a user (u) is

$$CU_{vu} = CU_v\left(\frac{ET_u}{ET}\right) \qquad (11)$$

In summary, consumptive use by vegetation for the lower Colorado River is computed using a water budget and is distributed among users using an apportionment technique based on the relative amount of evapotranspiration computed for each water user This apportionment technique allows the effects of errors in the estimate of CU_v to be distributed equitably to all users LCRAS is reliable only if the major independent components of the water budget are accurately measured and computed, the minor independent components are accurately measured or estimated, and the apportionment is based on accurate measurements or estimates of water-use rates and areas for the various vegetation types Before LCRAS is applied, the complex system to distribute flow in the study area is defined

DISTRIBUTION OF COLORADO RIVER WATER

Depletion of streamflow occurs as the Colorado River flows southward from Hoover Dam to Mexico (fig 11) The principal components of streamflow depletion, listed in order of magnitude, are (1) diversions exported to areas outside the study area, (2) consumptive use by crops irrigated with river water, (3) consumptive use by phreatophytes on the flood plain, (4) evaporation from open-water surfaces, mainly the reservoirs and the river, and (5) domestic, municipal, and industrial consumptive use (fig 10) Below Davis Dam, river water is diverted to crops on the flood plain in Arizona and California and is exported to interior regions of California and Arizona LCRAS is applied to the flood plain of the Colorado River (fig 2) and other adjacent areas on terraces where crops are grown

A shallow alluvial aquifer underlies the river and flood plain and is in hydraulic connection with the Colorado River (fig 10) Water levels in the aquifer change in response to changes in river stage In Parker Valley, Palo Verde Valley, and the Yuma area where ground-water levels are near the land surface, drainage ditches are used to remove excess water and thereby promote crop growth When releases from the reservoirs satisfy downstream water requirements, most reaches of the river adjacent to the croplands drained by drainage ditches gain water from the aquifer The river loses water to the aquifer through seepage, and ground water moves away from the river in areas where the flood plain is narrow and covered with phreatophytes and in Mohave and Cibola Valleys, which do not have drainage ditches River water that enters the ground is transpired by phreatophytes and, in places, flows out of the flood plain into bordering areas beneath the older alluvial terraces In years of high flow when the annual average river stage rises, some of the river reaches that normally gain flow from the aquifer become losing reaches

Most of the agricultural areas are on the younger alluvium of the flood plain but, in a few areas, land on the older alluvial terraces has been cultivated Croplands on the terraces are (1) east and south of the town of Parker, (2) in Vidal Valley, where less than 10 acres of citrus are grown, (3) on Palo Verde Mesa, and (4) on Yuma Mesa (pl 2) On Palo Verde and Yuma Mesas, crops are irrigated with water diverted from the Colorado River and water pumped from wells In some places, the ground-water gradient is toward the terraces from the river, indicating that river water is flowing to the terraces Water pumped from beneath the terraces is a mixture of river water and tributary water Pumpage of these mixed waters is assumed to be Colorado River water for Decree accounting purposes (U S Supreme Court, 1960, p 317)

Along the lower Colorado River, the extensive network of streamflow-gaging stations at regulatory structures, diversions, and drainage ditches (figs 7 and 8) provides streamflow data for Decree accounting and the water budget of LCRAS Data also are collected to compute flow from pumps in the river and from wells The complex system of dams, canals, pumps, and drainage ditches used to meet water-use and power demands is described in the following sections Also included are historical information and a description of the streamflow-gaging stations that gives justification for the location of some streamflow-gaging stations where the distribution of flow is complex

Dams and Reservoirs

Flow in the lower Colorado River is regulated by a series of dams Downstream from Hoover Dam, the northernmost and largest dam, are Davis Dam, Parker Dam, Headgate Rock Dam, Palo Verde Dam, Imperial Dam, Laguna Dam, and Morelos Dam (pl 1) Flow is gaged below Hoover, Davis, Parker, Imperial, and Laguna Dams and 1 1 mi above Morelos Dam at the NIB Flow decreases downstream and follows the same trend from year to year (fig 11)

Several of the dams divide the river into distinct reaches where the dams are located in bedrock outcrops that constrict the river and flood plain

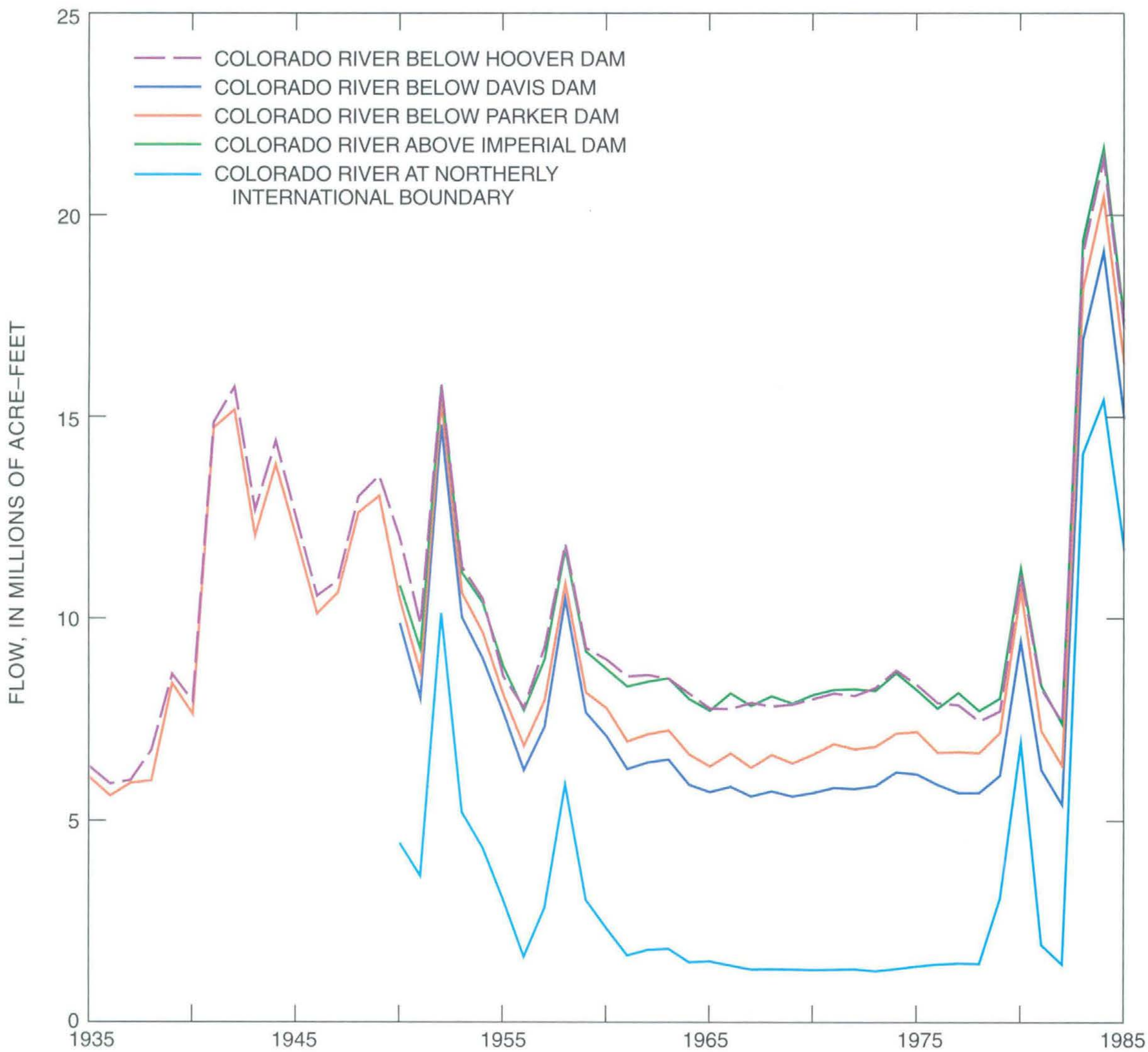


Figure 11. Annual flow in the Colorado River below Hoover Dam, 1935–85, below Davis Dam, 1950–85, below Parker Dam, 1935–85, above Imperial Dam, 1950–85, and at the northerly international boundary, 1950-85.

Consumptive use by vegetation can be conveniently calculated for the reaches between these dams. Flow in the Colorado River near the dams is confined in bedrock-lined channels and underflow through the bedrock is minimal; therefore, the releases of water through the regulatory structures measured at streamflow-gaging stations below the dams represent the flow that enters or leaves a reach.

Water stored in reservoirs behind Hoover, Davis, and Parker Dams (pl. 1) is released to meet downstream water requirements, to make storage available for flood control, and to generate power. Annual change in storage is required for LCRAS and was calculated as the difference between the reservoir contents at midnight on December 31 of one year and that of the previous year.

Hoover Dam (pl. 1) is a concrete arch-gravity structure completed March 1, 1936. Flow has been regulated since storage began February 1, 1935. Water is stored for irrigation, municipal, industrial, and power uses. The municipal water supplies for Boulder City, Henderson, and Las Vegas, Nevada, are pumped from the reservoir, Lake Mead. Lake Mead has a usable capacity of 26,159,000 acre-ft (White and Garrett, 1987, p. 96). Annual change in storage ranged from –6,973,000 to 8,891,000 acre-ft from 1936 to 1984 (fig. 12). The dam provides flood control, river regulation, and hydroelectric-power

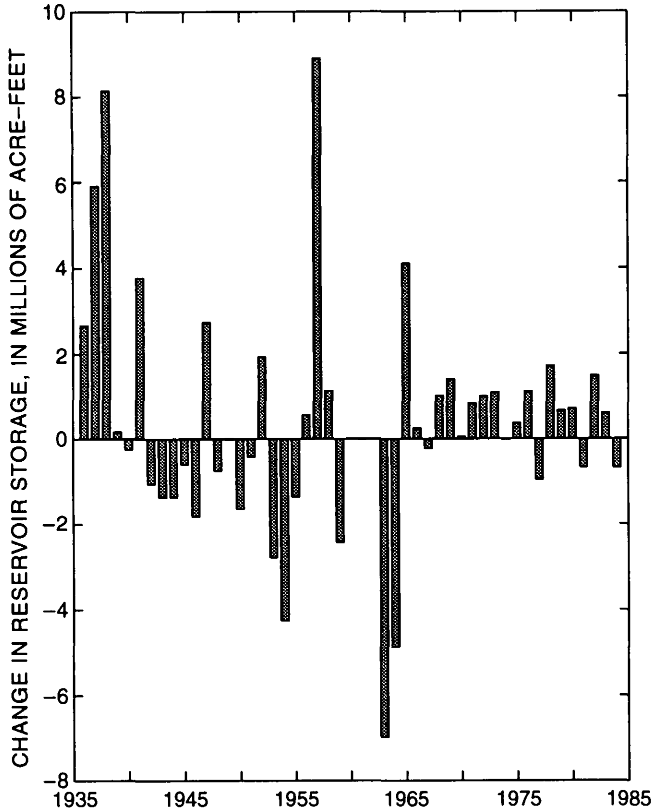


Figure 12. Annual change in reservoir storage for Lake Mead, 1936–84

generation, the reservoir provides recreation and fish and wildlife habitat Hoover Dam is operated and maintained by the USBR

Davis Dam (pl 1), 68 mi downstream from Hoover Dam, is an earth- and rock-fill structure The dam was completed in April 1949 and storage began January 17, 1950 The dam provides for the regulation of flow to meet downstream demands in the United States, to satisfy the requirements of the Treaty of 1944 with Mexico, and to generate power The reservoir, Lake Mohave, has a usable capacity of 1,810,000 acre-ft (White and Garrett, 1987, p 111) Annual change in storage ranged from –566,000 to 174,000 acre-ft from 1951 to 1984 (fig 13) Davis Dam is operated and maintained by the USBR

Parker Dam (pl 1), 83 mi downstream from Davis Dam, is a concrete-arch structure Storage began when the dam was completed on July 1, 1938 The dam provides flood control, power generation, and regulation for irrigation demand Parker Dam is operated and maintained by the USBR The reservoir, Lake Havasu, has a usable capacity of 619,400 acre-ft

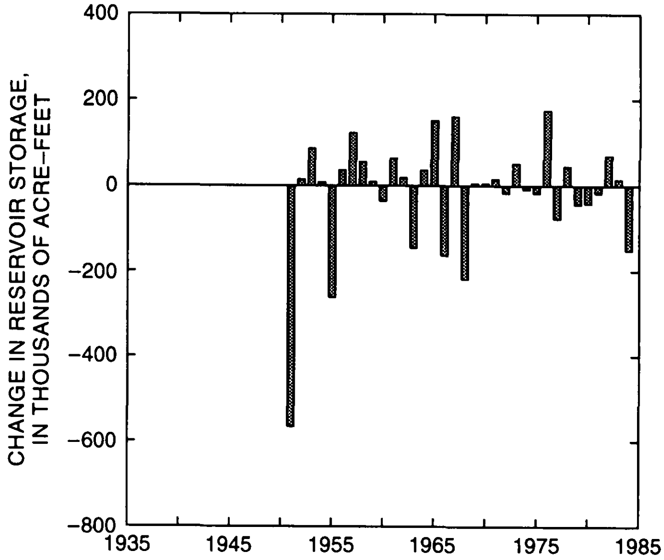


Figure 13. Annual change in reservoir storage for Lake Mohave, 1951–84

(White and Garrett, 1987, p 132) Annual change in storage ranged from –107,200 to 89,800 acre-ft from 1939 to 1984 (fig 14) Water is pumped from Lake Havasu into the Colorado River aqueduct and CAP Canal (pl 1)

Headgate Rock Dam (pl 1), 14 mi downstream from Parker Dam, is a rock- and earth-fill structure used for the diversion of irrigation water to the Colorado River Indian Reservation in Parker Valley, Arizona The dam was completed in 1941 The stable pool behind the dam, known as Moovalya Lake, is used extensively for recreation

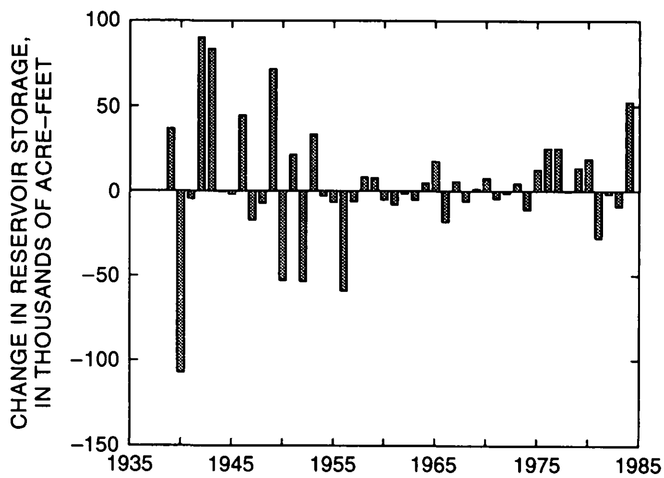


Figure 14. Annual change in reservoir storage for Lake Havasu, 1939–84

Palo Verde Dam (pl. 1), 58 mi downstream from Parker Dam, is a rock- and earth-fill structure used for the diversion of irrigation water to Palo Verde Irrigation District in Palo Verde Valley, California. The dam, completed in 1958, is owned and operated by Palo Verde Irrigation District.

Senator Wash Dam (pl. 1) and its small auxiliary reservoir was built in 1965 about 2 mi upstream from Imperial Dam on Senator Wash—a tributary to the Colorado River (Hely, 1969, p. 9). Water is pumped from the river to the reservoir for subsequent release to help avoid waste or water shortage in meeting deliveries ordered from upstream reservoirs. Senator Wash Reservoir provides 13,840 acre-ft of storage capacity (White and Garrett, 1987, p. 148). Annual change in storage ranged from –5,550 to 5,750 acre-ft between 1966 and 1984 (fig. 15). Senator Wash Dam is owned by the USBR and operated by Imperial Irrigation District.

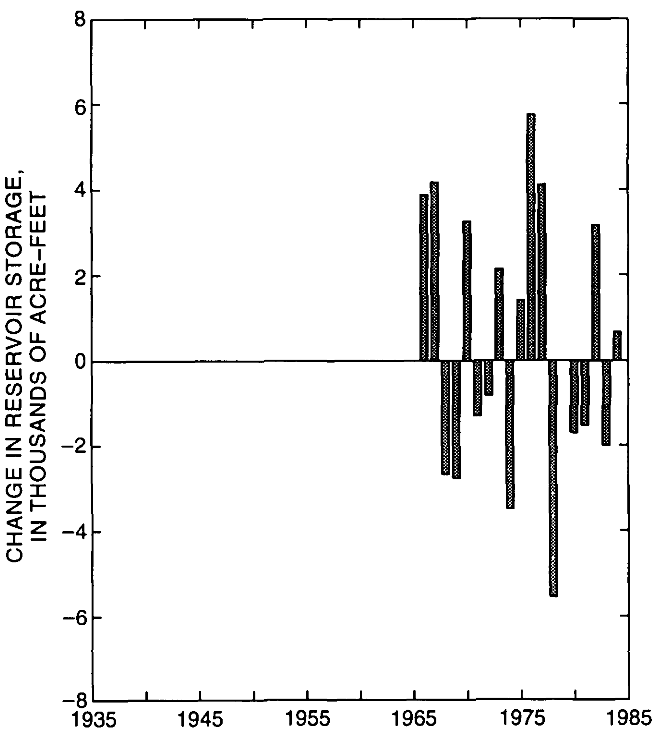


Figure 15. Annual change in reservoir storage for Senator Wash Reservoir, 1966–84.

Imperial Dam (pl. 1), 147 mi downstream from Parker Dam, is a concrete-diversion structure with gates that was completed in 1939. The dam proved to be an effective sediment trap when the reservoir capacity of 85,000 acre-ft was quickly reduced to 1,000 acre-ft soon after its completion (Fradkin, 1984). Dredging allows for minimal storage behind the dam. Imperial Dam is owned by the USBR and operated and maintained by Imperial Irrigation District. The dam is used for the diversion of water into the All-American Canal and the Gila Gravity Main Canal. The All-American Canal intake is at the west end of Imperial Dam. Water is used for power generation and irrigation in Yuma, Coachella, and Imperial Valleys. The Gila Gravity Main Canal intake is at the east end of Imperial Dam. Irrigation water is delivered to North Gila and South Gila Valleys, Yuma Mesa, and the Wellton-Mohawk Canal.

Laguna Dam (pl. 1), 5 mi downstream from Imperial Dam, is a low diversionary structure built in 1909 by the USBR. The dam is operated and maintained by Imperial Irrigation District. The settling basin behind the dam was filled by sediment within weeks of its completion (Fradkin, 1984). Sediment from the All-American Canal desilting basins is discharged back to the river above Laguna Dam. Dredging keeps the channel open and provides for minimal storage. Water diverted at Laguna Dam was delivered to Yuma Valley through the Colorado River siphon (north of site 69, fig. 6) from 1912 to 1945.

Morelos Dam (pl. 1), 27 mi downstream from Imperial Dam, is a concrete-diversion structure with multiple gates and was built by Mexico in 1950. The dam is 1.1 mi south of the northerly international boundary with Mexico and 21.9 mi north of the southerly international boundary. The dam is used to divert water into the Alamo Canal, which supplies water to Mexico's network of canals in the Colorado Irrigation System and to Mexicali Valley.

Records of releases of water through regulatory structures controlled by the United States are required by the Decree. LCRAS requires as input variables the quantity of flow below Hoover Dam and at the NIB and the net change in storage for all reservoirs. A potential refinement of LCRAS requires computed annual flow of the river below Davis Dam, below Parker Dam, and at Imperial Dam. The use of water budgets for four individual reaches defined by the dams is a potential means of refining estimates of consumptive use by vegetation.

The Colorado River above Imperial Dam streamflow-gaging station (site 44, fig. 6) is operated by the USGS as part of the National Stream-Quality Accounting Network (NASQAN) program (White and Garrett, 1988, p. 19). Flow data at this station, needed by LCRAS, are computed from stations that are required by the Decree Records of flow above Imperial Dam are based on the combined daily total flow of the Colorado River below Imperial Dam (site 45), All-American Canal near Imperial Dam (site 60), Gila Gravity Main Canal at Imperial Dam (site 53), and diversions to Mittry Lake (site 52, fig 6)

Records of flow for the Colorado River below several dams commonly are based on the stage-discharge relations defined by current-meter measurements At Hoover Dam, the flow records are based on velocity measurements using acoustic velocity meters (AVM's) in the discharge pipes within the dam Current-meter measurements made at the Colorado River below Hoover Dam streamflow-gaging station (site 1, pl 1) are used to check the discharge determined from the AVM's The AVM's are operated by the USBR and the check measurements are made by the USGS

In 1986, an analysis of flow records at Hoover and Davis Dams (figs 11 and 16) revealed that the AVM's probably were introducing persistent error After correction for storage in Lake Mohave was taken into account, there was a computed gain in annual flow between the gages at Hoover and Davis Dams (sites 1 and 3, pl 1) since the AVM's were installed in 1976 Because losses of river water to evaporation and transpiration commonly exceed tributary inflow for this reach, sources of computational and measurement errors were examined for the reach

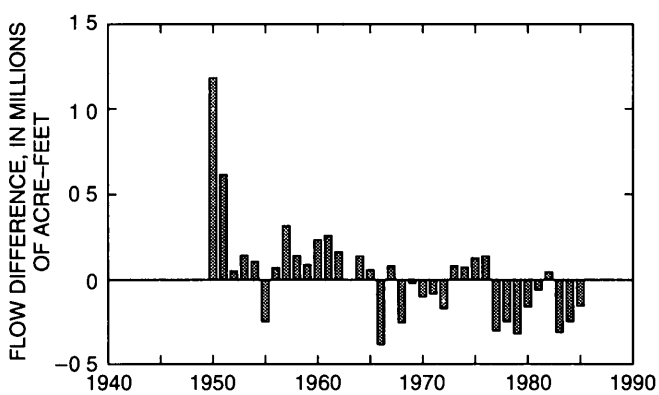


Figure 16 Difference in annual flow between the Colorado River below Hoover Dam and the Colorado River below Davis Dam accounting for the change in reservoir storage in Lake Mohave, 1950–85

Ten current-meter measurements of discharge made between August 12, 1981, and March 12, 1986, showed a persistent difference from the AVM measurements The difference between the AVM and the current-meter measurements was calculated as

$$D = \left(\frac{Q_{AVM} - Q_{cm}}{Q_{cm}}\right)100, \qquad (12)$$

where

D = difference, in percent, between the AVM and the current-meter measurements of discharge,

Q_{AVM} = AVM measurement of discharge, in cubic feet per second, and

Q_{cm} = current-meter measurement of discharge, in cubic feet per second

The AVM measurements of discharge are, on the average, 2 1 percent less than the current-meter measurements, and 9 of the 10 measurement pairs show more discharge for the current-meter measurements

Inflow, reportedly from leakage around Hoover Dam and from springs that flowed before the dam was constructed, occurs in the reach between the dam and the cableway Further analysis was made to determine the quantity of this inflow by using 65 pairs of AVM and vertical-axis current-meter measurements For discharges less than 10,000 ft^3/s, there was no significant difference between the measured discharges at the 99 percent level of significance (table 6) Therefore, the quantity of spring flow and seepage between the dam and the cableway is considered insignificant relative to the quantity of flow in the river On the basis of the available current-meter measurements for flows above 10,000 ft^3/s, the average difference in discharge is 2 6 percent, which is statistically significant The measuring conditions at the cableway for high flows

Table 6. Evaluation of pairs of discharge measurements made by using vertical-axis current meters and acoustic-velocity meters (AVM's) below Hoover Dam

Discharge, in cubic feet per second	Number of measurements	Average difference between AVM and current-meter measurements, in percent
Less than 10,000	15	−0 1
10,000–20,000	26	−1 9
20,000–30,000	33	−3 0
More than 30,000	12	−2 7

are not ideal because of a large eddy on the right bank The eddy and turbulent conditions change with time and the quantity of flow Although the current-meter measurements seldom can be rated better than good (within 5 percent), there is no known bias, therefore, little, if any, of the computed difference is considered a result of possible overregistration by current meters Because the computed difference generally increases with increasing discharge and turbulence, some of the difference could be from overregistration or from the possible inaccurate definition of the boundary for the eddy (H W Hjalmarson, hydrologist, U S Geological Survey, written commun , 1986)

On the basis of a relation between the discharge from current-meter measurements and discharge from the AVM's, the AVM's underregister an average of about 2 percent for medium and high flows At 5,000 ft^3/s, there appears to be no bias, and the underregistration increases linearly about 1 percent for each 10,000 ft^3/s above 5,000 ft^3/s to 35,000 ft^3/s The AVM's underregister by 1 percent at 15,000 ft^3/s and about 2 percent at 25,000 ft^3/s, at about 35,000 ft^3/s, the apparent underregistration appears to reach a maximum of about 3 percent (H W Hjalmarson, written commun , 1986) Upgrades to the AVM's have been installed at Hoover Dam Any necessary corrections to AVM discharge like those shown above will be made and incorporated into LCRAS

Before the AVM's were installed at Hoover Dam in 1976, ratings for the powerplant turbines were used to compute discharge On the average, current-meter measurements made by the USGS closely agreed with the turbine discharges, however, there were large undesirable short-term differences The use of AVM's potentially can result in unbiased records of discharge with less variance between the current-meter measurements and the ratings used to compute discharge at Hoover Dam

Exported Water

Colorado River water is diverted and exported out of the study area Water is exported to California in the Colorado River aqueduct and the All-American Canal Water is exported to Arizona in the CAP Canal The exported water does not return to the river, therefore, exported water is considered to be consumptively used All the exported water is measured at streamflow-gaging stations, and LCRAS utilizes these flow quantities in the water budgets

The Colorado River aqueduct (pl 1) was completed by the Metropolitan Water District (MWD) of Southern California in 1941 Pumping to reservoirs in southern California began January 7, 1939 Water is pumped into the aqueduct from Lake Havasu (site 11, pl 1) and delivered to the metropolitan areas on the coastal plain of southern California from north of Los Angeles to San Diego The quantity of water exported in the aqueduct annually ranged from 30,700 to 1,273,537 acre-ft between 1939 and 1985 (fig 17)

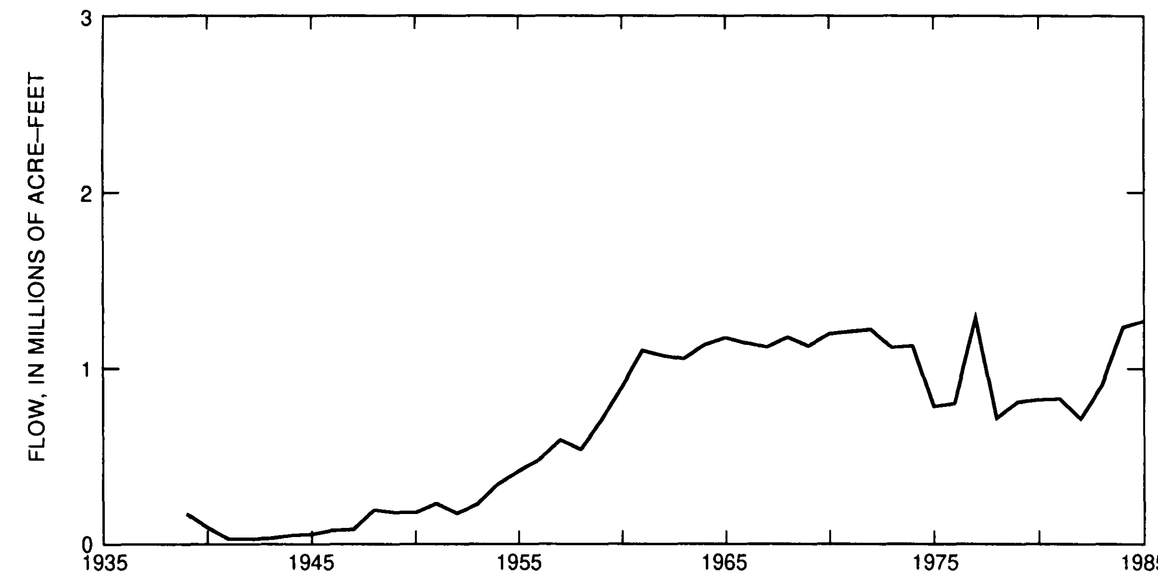


Figure 17. Annual flow diverted from the Colorado River and exported to California in the Colorado River aqueduct, 1939–85

On March 8, 1985, the USBR began pumping water from Lake Havasu into the CAP Canal (site 14, pl 1) to test the pumps The exportation of water to Arizona in the CAP Canal totaled 33,500 acre-ft in 1985 Water was delivered as far east as the city of Phoenix Water delivery to the city of Tucson is scheduled for 1991 After the canal is completed to Tucson, the pumps and canal will be operated and maintained by the Central Arizona Water Conservation District (CAWCD)

Water was first diverted to the All-American Canal in October 1938 From October 1938 to October 1940, diverted water was used to prime the canal Water deliveries began in 1940 and full flow occurred in 1942, when Imperial Valley no longer used the Alamo Canal The All-American Canal supplies water to areas in California and Arizona along the Colorado River Water also is exported to Imperial and Coachella Valleys in California Annual diversions near Imperial Dam (site 60, figs 6 and 8) ranged from 793 to 8,368,000 acre-ft between 1938 and 1985 (fig 18) Annual diversions below Pilot Knob wasteway (site 72, figs 6 and 8), exported to Imperial and Coachella Valleys, ranged from 2,865,000 to 3,699,000 acre-ft between 1960 and 1985 (fig 18) Part of the flow diverted to the All-American Canal returns to the river as seepage between Imperial Dam and Pilot Knob and through the Pilot Knob Powerplant and wasteway The quantity of water returning to the river annually through the powerplant and wasteway (site 71, figs 6 and 8) ranged from 0 to 4,865,000 acre-ft between 1939 and 1985 (fig 18)

Diversions

Water from the Colorado River is diverted at dams for use in the study area Streamflow-gaging stations are located to measure the quantity of water diverted at the dams as required by the Decree Water diverted at the dams is delivered to many individual users (see table 7 for the quantity of water pumped by water users in 1984) Diversions to individual users, although required by the Decree, are internal to the surface-water budgets as delineated by the boundaries selected for LCRAS

Water is pumped from the Colorado River for use in Mohave Valley, Parker Valley, and the Bard area in California and in Mohave Valley, Cibola Valley, and Yuma Valley in Arizona Water is pumped from wells on the flood plain for use in Mohave Valley and on the California side of the river in the Yuma area The quantity of water pumped is computed from power records, sites are visited biannually and discharge is measured when the pumps are in operation

Most of the water diverted or pumped from the river is used for irrigation of croplands Water diverted at Headgate Rock Dam into the CRIR Main

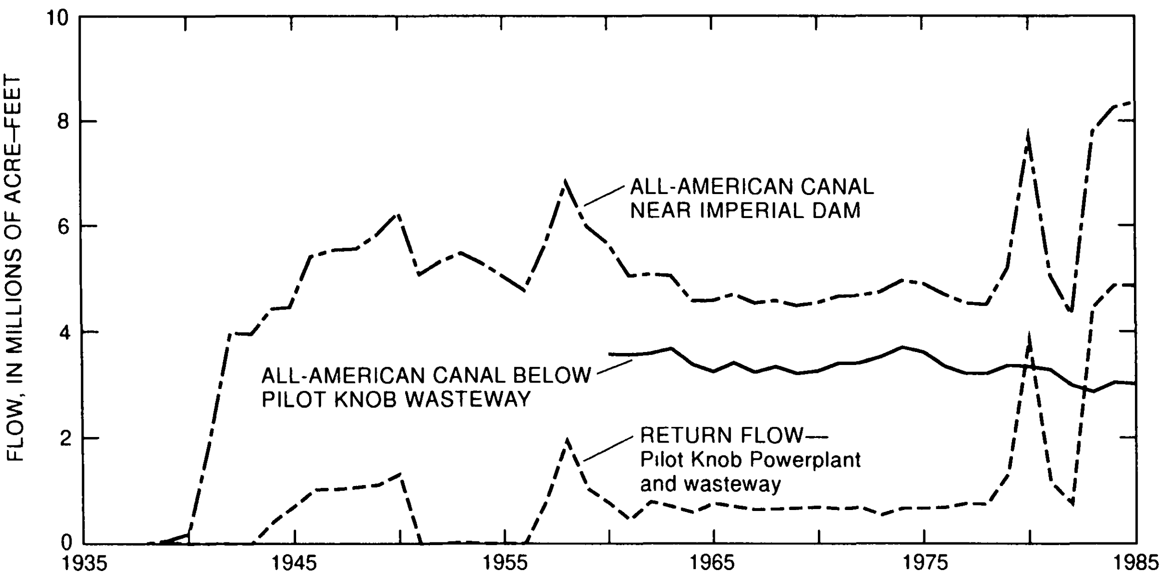


Figure 18 Annual flow diverted from the Colorado River into the All-American Canal near Imperial Dam, 1938–85, flow diverted to Imperial and Coachella Valleys in the All-American Canal below Pilot Knob wasteway, 1960–85, and flow returning to the river through the Pilot Knob Powerplant and wasteway, 1939–85

Table 7 Diversions and pumpage from the Colorado River and pumpage from wells on the flood plain between Hoover Dam and Mexico, 1984

[State AZ, Arizona, CA, California, NV, Nevada Type P, pump in the river, W, well on flood plain or mesa, D, diversion at the dam, X, unknown Water use A, agricultural, M, municipal, I, irrigation other than agriculture, S, steam plant, X, unknown]

Water user	State	Type	Water use	Quantity, in acre-feet[1]
Hoover Dam				
Willow Beach	AZ	W	M	90
Cottonwood Cove	NV	W	M	439
Katherine	AZ	W	M	370
Davis Dam Government Camp	AZ	X	M	142
Davis Dam L C R D Project	AZ	X	M	60
Total (rounded)				1,100
Davis Dam				
Southern California Edison Company	NV	X	S	14,198
Clark County Parks and Recreation Department	NV	P	X	6
Big Bend Water District	NV	P	M	31
Wiebke, Armin T	NV	P	X	8
Portenier, Warren W	NV	P	M	42
Welles, John C	NV	P	A	8
Knight, John B	NV	P	A	5
Boy Scouts of America	NV	P	A	10
Mohave Water Conservation District	AZ	W	M	108
Soto Brothers	CA	W	A	1,512
Deason, Richard (Tri-State)	CA	W	A	1,200
Deason, Richard (Tri-State)	CA	W	A	960
Deason, Richard (Tri-State)	CA	W	A	960
Mohave Valley Irrigation and Drainage District	AZ	P,W	A	23,496
Fort Mohave Indian Reservation	AZ	P,W	A	41,377
Fort Mohave Indian Reservation	CA	P,W	A	20,760
City of Needles	CA	W	M	3,334
San Bernardino County	CA	W	M	15
Lake Havasu Irrigation and Drainage District	AZ	W	M	9,085
Consolidated Water Utilities Ltd	AZ	P	M	291
BLM Permittees	CA	X	M	206
Total (rounded)				117,600
Parker Dam				
Parker Dam Government Camp	CA	D	M	171
Lye, R L	CA	W	A	60
Town of Parker	AZ	W	M	851
Colorado River Indian Reservation	AZ	W	M	7
Colorado River Indian Reservation	CA	P,W	A	3,670
Colorado River Indian Reservation—Big River	CA	W	M	890
Colorado River Indian Reservation—South Farm	AZ	P	A	8,954
Rayner, Jack, Jr	AZ	P	A	936
Rayner, Jack, Jr	AZ	W	A	231
Ehrenberg Improvement Association	AZ	P	M	145
Arakelian Farms	AZ	P	A	2,520
Cibola Valley Irrigation and Drainage District	AZ	P	A	15,580

Table 7 Diversions and pumpage from the Colorado River and pumpage from wells on the flood plain between Hoover Dam and Mexico, 1984—*Continued*

Water user	State	Type	Water use	Quantity, in acre-feet[1]
Parker Dam—Continued				
Sprawl (Towery, A)	AZ	P	A	3,600
Cibola National Wildlife Refuge	AZ	P	A	5,434
Total (rounded)				43,000
Imperial Dam				
Yuma Project Reservation Division—Indian Unit	CA	D	A	26,751
Yuma Project Reservation Division—Bard Unit	CA	D	A	40,452
Yuma Proving Ground	AZ	D	M	9
Warren Act Contractors	AZ	D	A	4,848
City of Yuma	AZ	D	M	17,527
City of Winterhaven	CA	W	M	80
Marine Corps Air Station	AZ	D	M	1,775
Southern Pacific Company	AZ	D	M	48
County of Yuma	AZ	D	M	12
Yuma Mesa Fruit Growers Association	AZ	D	M	12
University of Arizona Test Station	AZ	D	A	697
Yuma Union High School	AZ	D	M	200
Camille, Alec, Jr	AZ	D	X	26
Desert Lawn Memorial	AZ	D	I	150
North Gila Valley Irrigation District	AZ	D	A	40,551
Yuma Irrigation District	AZ	D	A	55,917
Yuma Irrigation District	AZ	W	A	8,787
Yuma Mesa Irrigation and Drainage District	AZ	D	A	213,157
Unit B Irrigation and Drainage District	AZ	D	A	34,526
Yuma County Water Users Association	AZ	D	A	274,299
Yuma County Water Users Association	AZ	W	A	11,144
Cocopah Indian Reservation	AZ	D	A	627
Cocopah Indian Reservation	AZ	W	A	3,666
Fort Yuma Indian Reservation	AZ	W	A	1,779
Dulin, Arlin	AZ	W	A	219
Dulin, Arlin	AZ	W	A	930
Sturges, Steve	AZ	W	A	12,098
Yowelman, R	AZ	W	A	720
Auza, Pete	AZ	P	A	1,590
Auza, Pete	AZ	W	A	1,590
Ott, Judd T	AZ	W	A	195
Ott, Judd T	AZ	W	A	345
Cameron Brothers	AZ	W	A	29
Harp, R	AZ	W	A	1,458
Vukasovich	AZ	W	A	3
Vukasovich	AZ	W	A	424
Sunkist of Yuma	AZ	W	A	484
Nunnaley	AZ	W	A	73
Curtis, A (Jennings, A)	AZ	P	A	81
Power, Bill	AZ	P	A	1,980
Power, R E (P Power)	AZ	P	A	1,920
Hall, Ansil	AZ	P	A	480
Burrell	AZ	W	A	192
Cole (R Land)	CA	W	A	461
Perez, F (Slade)	CA	W	A	819
Barrett (R Harp)	CA	W	A	858
Spencer, M	CA	W	A	630

Table 7. Diversions and pumpage from the Colorado River and pumpage from wells on the flood plain between Hoover Dam and Mexico, 1984—*Continued*

Water user	State	Type	Water use	Quantity, in acre-feet[1]
Imperial Dam—Continued				
Martin, M (A Dees)	CA	W	A	350
Schaffer, F (R Harp)	CA	W	A	631
Wilson (R Harp)	CA	W	A	449
Easterday, A	CA	W	A	425
Evans, E (R Harp)	CA	W	A	480
Harp, R	CA	W	A	882
Easterday, Kenneth	CA	W	A	1,377
Smith, R (P Power)	CA	W	A	2,026
Musgrave (Barkley Company)	CA	W	A	55
Total (rounded)				771,300
GRAND TOTAL				933,000

[1]Most of the pumpage quantities were reported by the U S Bureau of Reclamation (1986a, 1987) except for a few additional water users identified during this study

Canal (site 17, fig 4) is used for irrigation of reservation croplands on the flood plain on the Arizona side of the river Annual diversions ranged from 7,290 to 663,200 acre-ft between 1915 and 1984 (fig 19) Water diverted at Palo Verde Dam into Palo Verde Canal (site 24, fig 5) is used for irrigation of croplands in Palo Verde Valley by Palo Verde Irrigation District Annual diversions ranged from 131,100 to 1,006,000 acre-ft between 1922 and 1984 (fig 19)

Water is diverted from the All-American Canal to the Reservation Main Canal (site 61), Titsink Canal (site 62), Yaqui Canal (site 63), Pontiac Canal (site 64), and Walapai Canal (site 65, figs 6 and 8) for the irrigation of croplands in the Reservation Division of the California part of the USBR Yuma Project Water also is diverted from the Yuma Main Canal to the Reservation Division (site 67, figs 6 and 8) Annual diversions to the Reservation Division ranged from

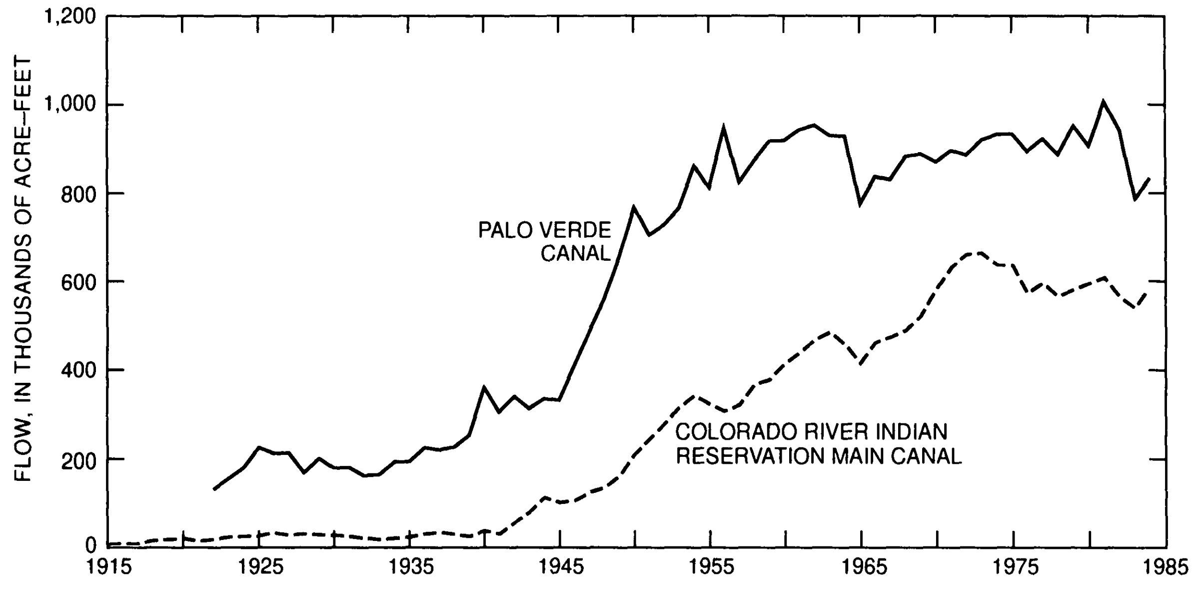


Figure 19 Annual flow diverted for irrigation in Parker Valley in the Colorado River Indian Reservation Main Canal, 1915–84, and for Irrigation in Palo Verde Valley in the Palo Verde Canal, 1922–84

62,700 to 95,300 acre-ft between 1966 and 1985 (fig 20) The Yuma Main Canal turnout is 13.7 mi downstream from the All-American Canal intake at Imperial Dam Water is delivered to Yuma Valley on the Arizona side of the river through the Colorado River siphon, which was completed in 1912 Annual diversions of water from the All-American Canal into the Yuma Main Canal are monitored at the Siphon-Drop Powerplant (site 66, figs 6 and 8) and ranged from 280,000 to 1,443,000 acre-ft between 1939 and 1985 (fig 21) Water in the Yuma Main Canal is delivered to the Reservation Division and Yuma Valley Division for irrigation and the City of Yuma for municipal use The Yuma Valley Division and the

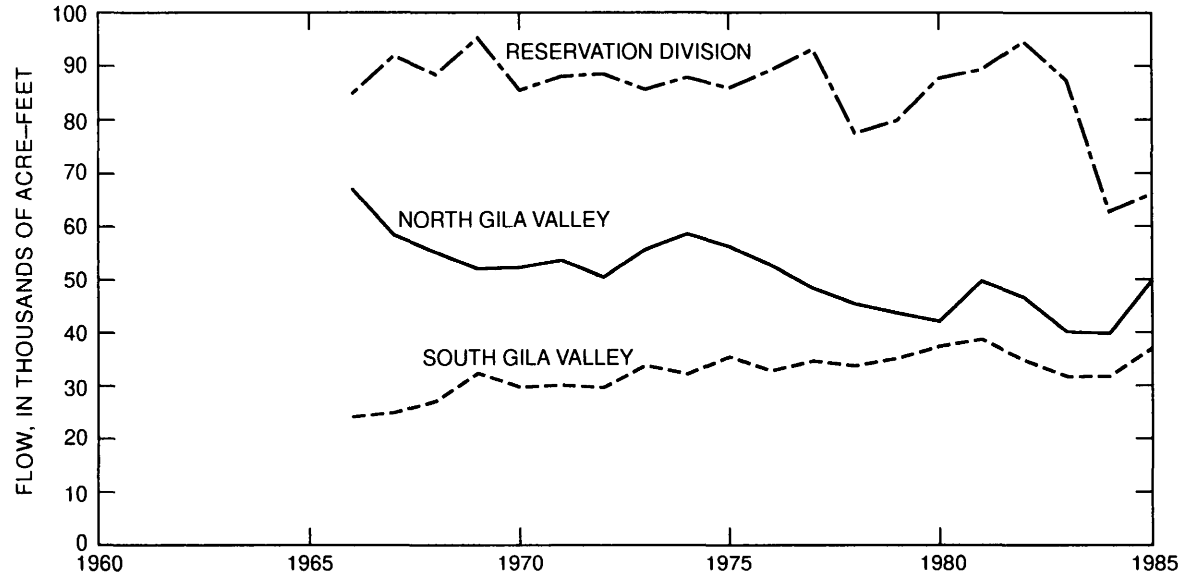


Figure 20 Annual flow diverted from the Gila Gravity Main Canal to North Gila Valley, 1966–85, and to South Gila Valley, 1966–85, and from the All-American Canal to the Reservation Division of the California part of the Bureau of Reclamation Yuma Project, 1966–85

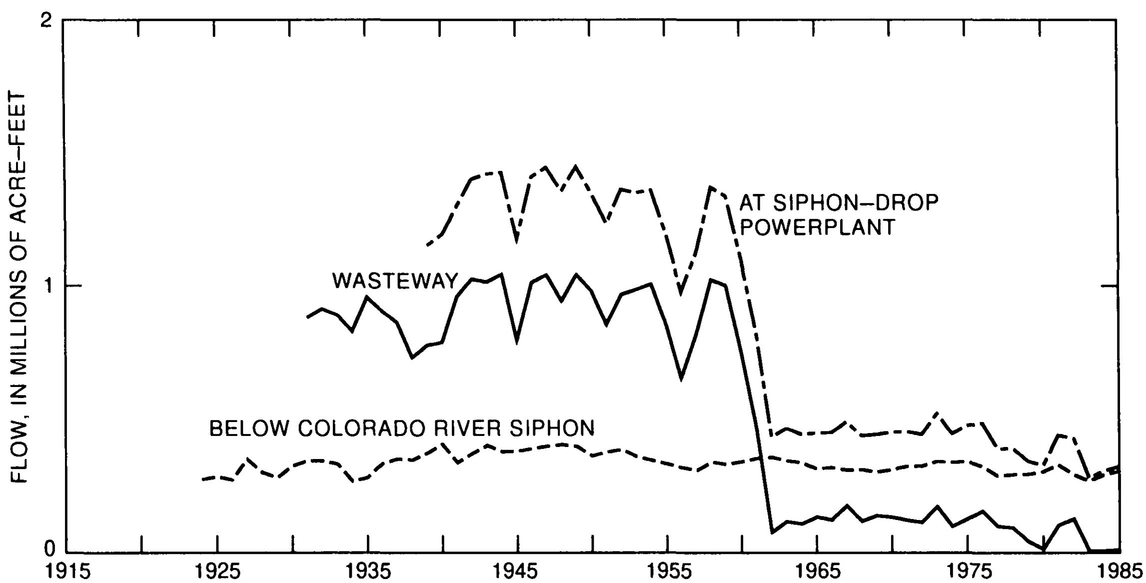


Figure 21. Annual flow in the Yuma Main Canal at the Siphon–Drop Powerplant, 1939–85, Yuma Main Canal below the Colorado River siphon, 1924–85, and flow released back to the river at the Yuma Main Canal wasteway, 1931–85

City of Yuma are on the Arizona side of the river and the quantity of water actually delivered across the river is computed in the Yuma Main Canal below the Colorado River siphon (site 69, figs 6 and 8) Annual flow through the siphon ranged from 265,800 to 405,000 acre-ft between 1924 and 1985 (fig 21) Another station monitors the diversion from Yuma Main Canal for the City of Yuma (site 70, figs 6 and 8), annual diversions ranged from 5,410 to 16,510 acre-ft between 1965 and 1985 (fig 22)

Water has been diverted into the Gila Gravity Main Canal at the east end of Imperial Dam since 1944 (site 53, figs 6 and 8) Annual diversions at Imperial Dam ranged from 60,910 to 938,700 acre-ft between 1944 and 1985 (fig 23) The Gila Gravity Main Canal supplies water to areas in Arizona along the Colorado River and to the lower Gila Valley The Wellton-Mohawk Canal, a major branch off the Gila Gravity Main Canal, has delivered water from the Colorado River into the lower Gila Valley since

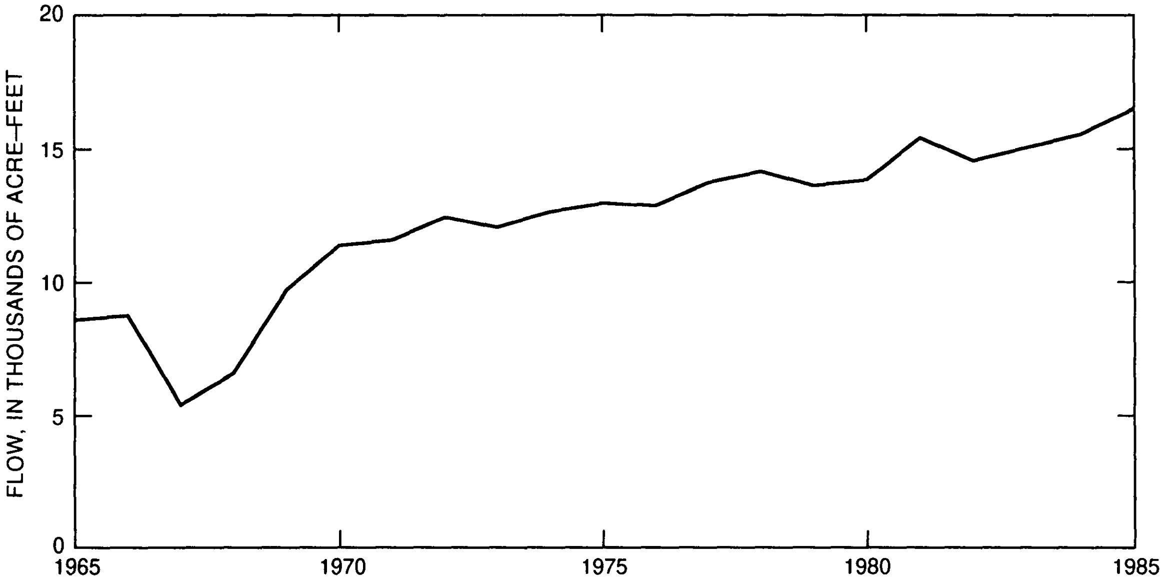


Figure 22. Annual flow diverted from Yuma Main Canal for the City of Yuma, 1965–85

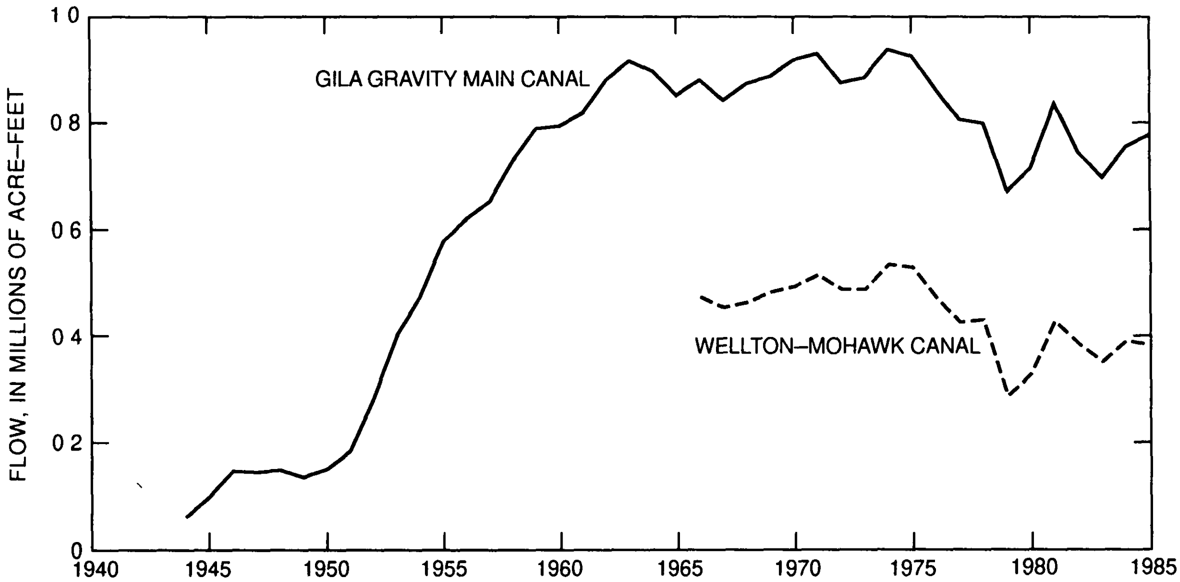


Figure 23. Annual flow diverted from the Colorado River into the Gila Gravity Main Canal, 1944–85, and from the Gila Gravity Main Canal into the Wellton–Mohawk Canal, 1966–85

1952 Water diverted into the Wellton-Mohawk Canal (site 56, figs 6 and 8) is used for irrigation in the Dome, Wellton, and Mohawk areas of the lower Gila Valley The quantity of water diverted into the Wellton-Mohawk Canal has been measured since October 1965 and ranged from 286,900 to 533,500 acre-ft/yr between 1966 and 1985 (fig 23)

Water is diverted out of the Gila Gravity Main Canal into the North Gila Main Canal (site 54) and North Gila Main Canal No 2 (site 55, figs 6 and 8) for delivery to croplands in the North Gila Valley Division of the USBR Gila Project in Arizona Annual diversions ranged from 39,790 to 67,160 acre-ft between 1966 and 1985 (fig 20) Water is also diverted into the South Gila Main Canal (site 57, figs 6 and 8) for the irrigation of croplands in the South Gila Valley Division of the Gila Project Annual diversions ranged from 24,130 to 38,600 acre-ft between 1966 and 1985 (fig 20) Water is pumped from the Gila Gravity Main Canal at a pumping plant (site 58, figs 6 and 8) and delivered to Yuma Mesa for the irrigation of croplands in the Yuma Mesa Division of the Gila Project and Yuma Auxiliary Division Unit B of the Yuma Project The quantity of water pumped annually to Yuma Mesa ranged from 221,600 to 286,900 acre-ft between 1966 and 1985 (fig 24) The quantity of water diverted to the Yuma Auxiliary Division Unit B is monitored at the Unit B Main Canal streamflow-gaging station (site 59, figs 6 and 8) and ranged from 28,860 to 39,110 acre-ft/yr between 1966 and 1985 (fig 24)

Some of the water pumped from the river is used to support the wildlife habitat in the marshes along the river Water is diverted into Topock Marsh inlet (site 7, figs 3 and 7) for delivery to Topock Marsh in Havasu National Wildlife Refuge, which is operated by the U S Fish and Wildlife Service Two pumps in the inlet deliver water for the irrigation of adjacent croplands The elevation of the water in Topock Marsh is influenced by river stage, water flowing back and forth between the river and the marsh through the levees, and return flows from irrigation that drain to the marsh

Cibola Lake inlet (site 41, figs 5 and 7) is in the Cibola National Wildlife Refuge, which is operated by the U S Fish and Wildlife Service Pumps at the inlet are used occasionally to pump water from the river into the lake The streamflow-gaging stations at Cibola Lake inlet and outlet (sites 41 and 42, figs 5 and 7) originally were operated for 6 years to determine an estimate of consumptive use for the lake The water-surface elevation of the lake is influenced by the elevation of the river The data collected at the inlet and outlet are not representative of inflow and outflow quantities of the lake because water flowing back and forth between the river and lake through the levees is not included and cannot be monitored accurately As a consequence, the USBR, USGS, and U S Fish and

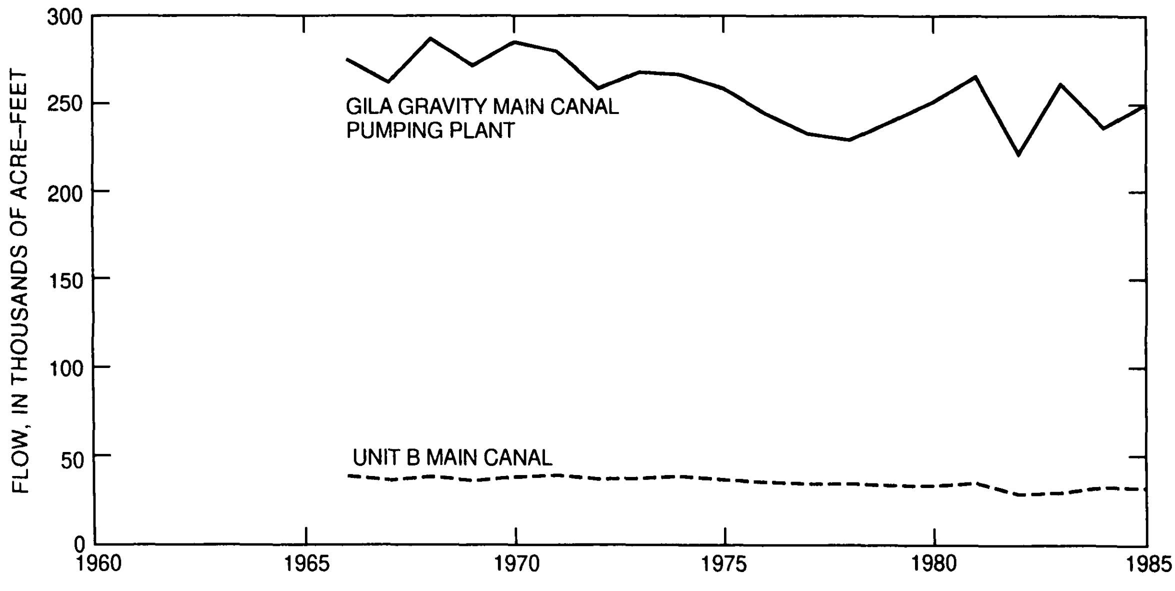


Figure 24. Annual flow diverted to Yuma Mesa at the Gila Gravity Main Canal pumping plant, 1966–85, and into Unit B Main Canal, 1966–85

Wildlife Service agreed to assign a consumptive use of 5,000 acre-ft/yr for the lake

Water is diverted from the river at Imperial Dam (site 52, figs 6 and 8) to maintain the water-surface elevation in Mittry Lake, which is on the flood plain adjacent to the river in the Mittry Lake Wildlife Area (pl 2) The elevation of the lake is influenced by the elevation of the river surface because water flows back and forth between the river and the lake as the river level rises and falls Mittry Lake inlet and outlet streamflow-gaging stations (sites 52 and 73, figs 6 and 8) were established to monitor the total inflow and outflow of the lake to compute consumptive use Because the water-surface elevation of the lake is influenced by the elevation of the river, total inflow and outflow are not monitored

Return Flows

Some of the water diverted from the Colorado River returns to the river in the study area and is available for use downstream Records of the return flows available for use downstream are required by the Decree Surface-water return flows are monitored in an attempt to determine credit for water being returned to the river In Parker Valley, Palo Verde Valley, and the Yuma area, drainage ditches are used to lower the water table and prevent crop damage Water in the drainage ditches flows into the river Some of the diverted water returns directly to the river from canal spillways or in wasteways Streamflow-gaging stations are positioned to measure the quantity of water that returns to the river as surface-water flow in the study area (see table 8 for return flows measured in 1984) Most of the return flows are internal to the LCRAS surface-water budget because they return to the river in the same reach in which the diversion occurs and, therefore, are not required by LCRAS This criterion is met by all the returns except those that return to the river downstream from Morelos Dam and the NIB, where Q_{ds} of the water budget is determined The quantities of water that originated from water diverted upstream from Morelos Dam and return to the river south of Morelos Dam or flow across the border into Mexico are required water-budget components (Q_{if}, figs. 9 and 10)

Diverted water returns to the river from Parker Valley and Palo Verde Valley In Parker Valley, water returns through the Gardner Lateral spill (site 19), Poston wasteway (site 21, includes drainage from Upper Main drain and spills from Main Canal), Palo Verde drain (site 26), and Lower Main drain (site 27, figs 4 and 7) Annual surface-water return flows from Parker Valley ranged from 13,700 to 407,600 acre-ft between 1946 and 1984 (fig 25) In Palo Verde Valley, water returns through Olive Lake drain (site 28), F Canal spill (site 29), D-10-11-2 spill (site 30), D-10-11-5 spill (site 31), D-23 spill (site 32), D-23-1 spill (site 34), C Canal spill (site 35), C-28 upper spill (site 36), Outfall drain (site 37), Anderson drain (site 38), and C-28 lower spill (site 39, figs 5 and 7) Annual surface-water return flow from Palo Verde Valley ranged from 424,600 to 580,400 acre-ft between 1961 and 1984 (fig 25) The flow data for these sites in Palo Verde Valley are furnished by Palo Verde Irrigation District

Flow measured in the Palo Verde drain (site 26, figs 4 and 7), Lower Main drain (site 27, figs 4 and 7), and Outfall drain (site 37, figs 5 and 7) is not an accurate representation of drainage return flows from applied irrigation water that was diverted at the dams The streamflow-gaging stations on the Lower Main drain and Outfall drain are upstream from the mouths of the drains because of backwater problems during high flow in the river Drainage water entering these drains between the stations and the mouths is not measured During high flows in the river, the flow measured at the Palo Verde drain and Outfall drain streamflow-gaging stations does not represent total drainage water from the diversions because river seepage flows into the drains and is measured as drainage water (Owen-Joyce and Kimsey, 1987, Owen-Joyce, 1988)

Diverted water returns to the river in the Yuma area through wasteways, drainage ditches, and drainage wells Return flow from the North Gila Valley Irrigation District is monitored at Laguna Canal wasteway (site 74), Levee Canal wasteway (site 75), North Gila Main Canal wasteway (site 79), Bruce Church wasteway (site 83), North Gila drain No 1 (site 76), and Bruce Church drain (site 81, figs 6 and 8) Annual surface-water return flows from North Gila Valley ranged from 5,340 to 52,510 acre-ft between 1961 and 1985 (fig 26)

Six gates along the Gila Gravity Main Canal open automatically when the water surface in the canal exceeds a set elevation Flow through these gates rarely reaches the Gila or Colorado Rivers because the flow infiltrates into the soils downstream from the gates Only the gate on Fortuna wasteway (site 78,

Table 8 Surface-water return flow computed at streamflow-gaging stations along the lower Colorado River between Hoover Dam and Mexico, 1984

[Station name CRIR, Colorado River Indian Reservation, PVID, Palo Verde Irrigation District, NIB, northerly international boundary, SIB, southerly international boundary Method of determination C, calculated, M, measured or computed, R, reported, dashes, not determined]

Site number[1]	Station name	Flow, in acre-feet	Method of determination
Colorado River below Hoover Dam		([2])	--
Colorado River below Davis Dam		([2])	--
Colorado River below Parker Dam			
19	Gardner lateral spill near Parker	1,760	M
21	CRIR Poston wasteway near Poston[3]	79,920	C
22	Poston wasteway spill gates	38,880	M
26	Palo Verde drain near Parker	48,200	M
27	CRIR Lower Main drain near Parker	143,700	M
28	PVID Olive Lake drain near Blythe	7,710	R
29	PVID F-canal spill near Blythe	12,240	R
30	PVID D-10-11-2 spill near Blythe	1,370	R
31	PVID D-10-11-5 spill near Blythe	5,510	R
32	PVID D-23 spill near Blythe	14,620	R
34	PVID D-23-1 spill near Blythe	6,090	R
35	PVID C-canal spill near Blythe	19,070	R
36	PVID C-28 upper spill near Blythe	187	R
37	PVID Outfall drain near Palo Verde	426,200	M
38	PVID Anderson drain near Palo Verde	152	R
39	PVID C-28 lower spill near Blythe	9,900	R
42	Cibola Lake outlet near Cibola	0	M
	Total (rounded)	815,500	
Colorado River above Imperial Dam			
73	Mittry Lake outlet channel near Yuma	([4])	M
74	Laguna Canal wasteway	0 5	M
75	Levee Canal wasteway	2,060	M
76	North Gila drain No 1	7,720	M
	Gila River		
77	North Gila drain No 3 near Yuma	0	M
78	Fortuna wasteway near Yuma	595	M
79	North Gila Main Canal wasteway	1,860	M
80	South Gila Pump Outlet Channel No 3 near Yuma	14,550	M
81	Bruce Church drain	1,050	M
82	South Gila Pump Outlet Channel No 2 near Yuma	17,650	M
83	Bruce Church wasteway	1,310	M
85	South Gila Pump Outlet Channel No 1 near Yuma	22,940	M
86	South Gila drain No 2 near Yuma	762	M
87	South Gila terminal wasteway	750	M
88	South Gila Pump Outlet Channel No 4	8,940	M
93	Reservation Main drain No 4	43,390	M
68	Yuma Main Canal wasteway at Yuma	6,810	M
94	Yuma Mesa outlet drain at Yuma	22,390	M
96	Drain 8-B near Yuma	7,360	M
71	Pilot Knob Powerplant and wasteway near Pilot Knob	4,865,000	M
97	Main Outlet Drain Extension above Morelos Dam (MODE 2)	1,490	M
	Total (rounded)	5,026,600	
Colorado River at NIB			
99	Main Outlet Drain Extension below Morelos Dam (MODE 3)	370	M
100	Eleven Mile wasteway[4]	1,530	M
101	Twenty-one Mile wasteway[4]	0	M
	Total (rounded)	1,900	

Table 8. Surface-water return flow computed at streamflow-gaging stations along the lower Colorado River between Hoover Dam and Mexico, 1984—*Continued*

Site number[1]	Station name	Flow, in acre-feet	Method of determination
Colorado River at SIB			
Water to Mexico not in river.			
98	Cooper wasteway[5]	721	M
102	Wellton-Mohawk Bypass drain at Arizona-Sonora boundary	71 4	M
103	Main drain at SIB near San Luis[5]	99,380	M
104	West Main Canal wasteway[5]	0	M
105	East Main Canal wasteway[5]	4,090	M
106	Two-Forty-Two well field lateral near San Luis	3,020	M
	Total (rounded)	107,300	
	GRAND TOTAL	5,951,300	

[1]Locations shown on figures 4–8

[2]No surface-water return flows in this reach

[3]Equal to Colorado River Indian Reservation Poston wasteway near Poston minus Poston wasteway spill gates

[4]No discharge record Gage inundated by Colorado River, October 1, 1984, to March 31, 1985 (White and Garrett, 1988, p 282)

[5]Surface-water return flows from irrigation water diverted from the Colorado River at Imperial Dam and applied to fields in Yuma Valley These return flows enter the river south of Morelos Dam or flow into Mexico without entering the river Total flow in 1984 was about 105,700 acre-feet

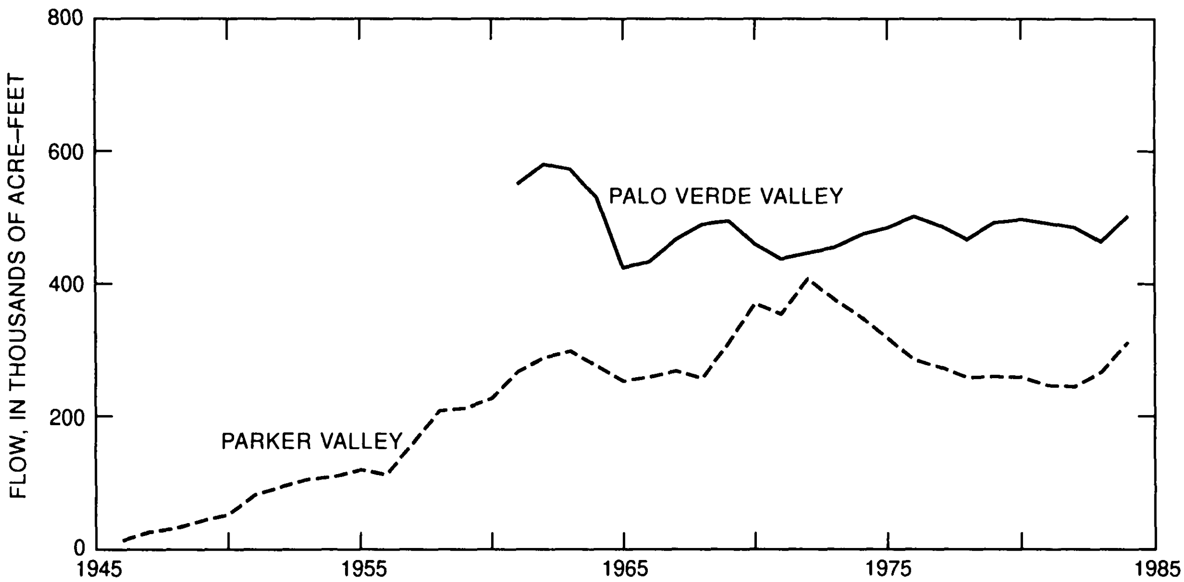


Figure 25. Annual surface-water return flows from Parker Valley, 1946–84, and Palo Verde Valley, 1961–84

figs 6 and 8) is gaged to monitor emergency releases of water in case of floods or canal maintenance

The Wellton-Mohawk Main Outlet drain is a conveyance channel into which water is pumped from drainage wells to lower the water table in the Wellton-Mohawk Irrigation and Drainage District These wells are outside the Colorado River flood plain The water is saline and is not discharged into the Colorado River but flows through the Wellton-Mohawk Bypass drain into Mexico and is discharged into the Santa Clara Slough Water can be released from the drain through five outlets into the Gila River or Colorado River With the completion of the Bypass drain in 1977, all the discharge from the Main Outlet drain, with the exception of releases during repair work or flooding, has flowed into Mexico During 1984, some water was discharged into the Gila River Flow in the drain is monitored so that the USBR can give credit to the

Wellton-Mohawk Irrigation and Drainage District for irrigation return flows One of the outlets from the Bypass drain to the Colorado River is Main Outlet Drain Extension (MODE) 2 (site 97, figs 6 and 8) at the north end of the Bypass drain, which will be used to monitor releases from the Yuma Desalting Plant The plant will reportedly desalt most of the water in the drain before it is discharged to the Colorado River for use by Mexico

Drainage wells are used in South Gila Valley Four sites monitor the return flow from the drainage wells South Gila Pump Outlet Channels No 1, No 2, No 3, and No 4 (sites 85, 82, 80, and 88, respectively, figs 6 and 8) Spills from canals are monitored at the South Gila Terminal wasteway (site 87, figs 6 and 8) Drainage water is monitored at the South Gila drain No 2 (site 86, figs 6 and 8), which is a buried 2-foot-diameter concrete pipe that intercepts excess water The outlet for the drain is subject to backwater from the river and filling by sand and silt when the river is high During the 1983 high flows in the Colorado and Gila Rivers, the outlet and 0 5 mi of the drain pipe were inundated and exposed by the high flow and completely filled in with silt and sand Annual surface-water return flows from South Gila Valley ranged from 941 to 67,220 acre-ft between 1961 and 1985 (fig 26)

Return flow to the river from drainage wells along the edge of Yuma Mesa is monitored in Yuma Mesa Outlet drain (site 94, figs 6 and 8) The purpose of the wells is to intercept the excess water from the Yuma Mesa Division and prevent bank erosion along the mesa The water pumped from the wells is conveyed by underground conduit to the river Annual discharges from Yuma Mesa Outlet drain ranged from 1,230 to 58,670 acre-ft between 1970 and 1985 (fig 27)

Excess water diverted into the All-American Canal is returned to the river at the Pilot Knob Powerplant and wasteway (site 71, figs 6 and 18) and is used to generate power Excess water also is returned to the river from the Yuma Main Canal through the Yuma Main Canal wasteway (site 68, figs 6 and 21), the control at this site is not sensitive at low flows

Five sites were established within the Reservation Division to determine leakage from the All-American Canal Reservation drain No 2 (site 91), drain No 3 (site 92), Main drain No 6 (site 90), drain No 7 (site 89), and drain No 11 (site 95, figs 6 and 8) As the elevation of the water in the canal changed, the flow at these sites did not change These sites are used by the USBR in an interim method of accounting for unmeasured return flows from the All-American Canal These drains do not enter the river directly but enter or are part of two main drains—Main drain No 4 (site 93) and Drain 8-B (site 96, figs 6 and 8)—that are monitored where they enter the river The streamflow-gaging station on Main drain No 4 monitors the return of water to the river from drain No 2, drain No 3, Main drain No 6, and

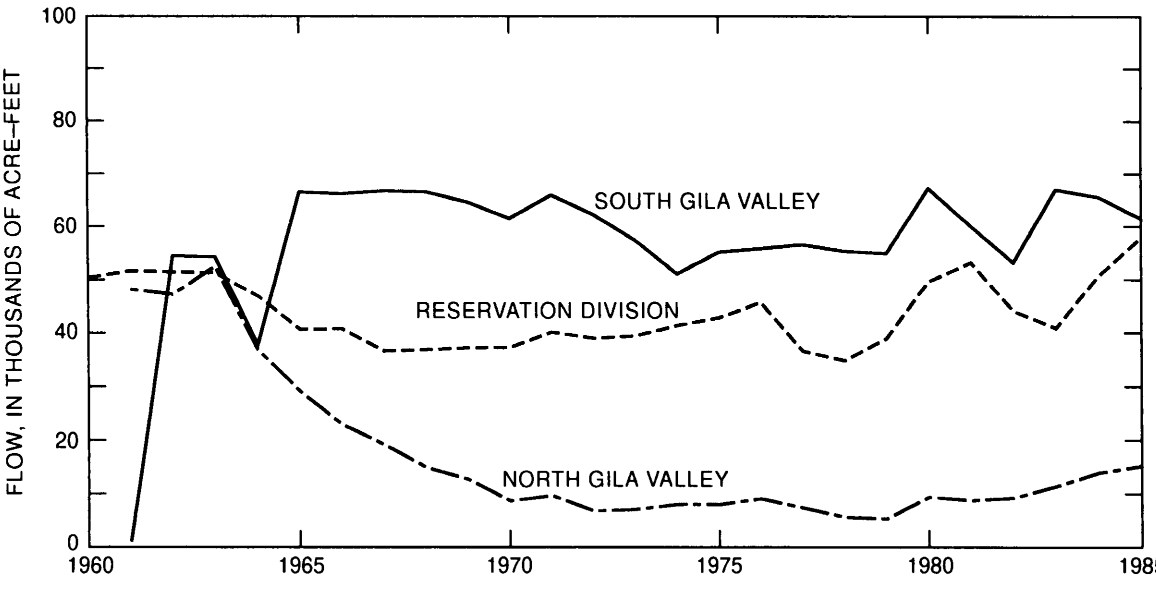


Figure 26 Annual surface-water return flows from North Gila Valley, 1961–85, South Gila Valley, 1961–85, and the Reservation Division, 1960–85

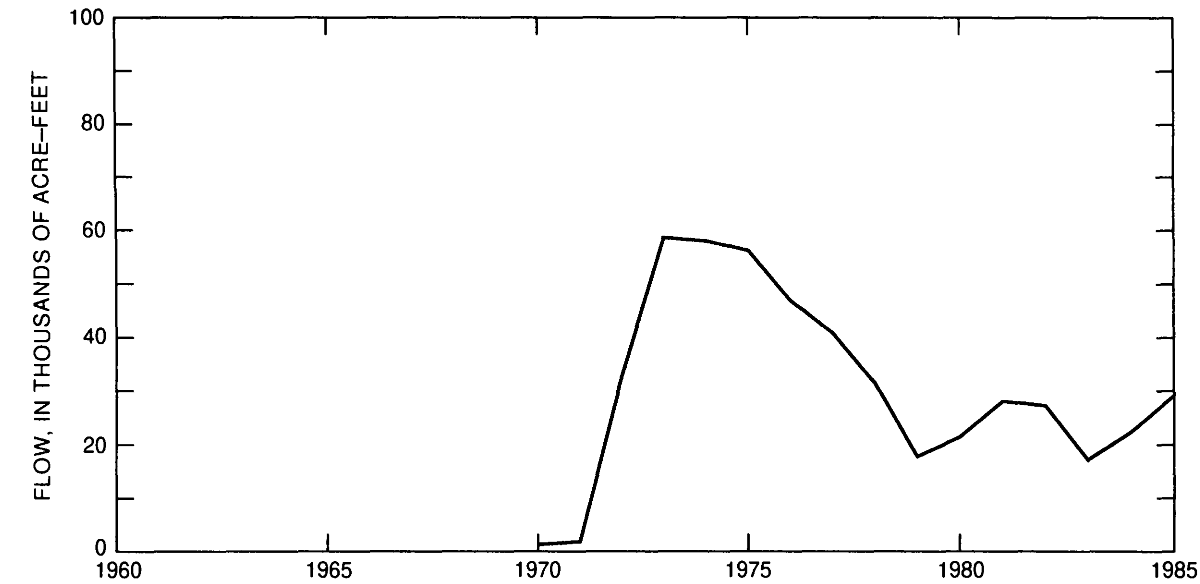


Figure 27. Annual flow in Yuma Mesa Outlet drain, 1970–85

drain No 7 The streamflow-gaging station on Drain 8-B monitors the return of water to the river that includes the flow from drain No 11 Annual surface-water return flows from the Reservation Division in Main drain No 4 and Drain 8-B ranged from 34,810 to 57,850 acre-ft between 1960 and 1985 (fig 26)

For 1983–85, high flows in the Colorado River in the Yuma area raised the water table above the land surface in some areas The USBR installed eight drainage wells near the Colorado and Gila Rivers that pumped water from the aquifer into the Bypass Canal and the river to alleviate problems from the rise of the water table caused by river seepage into the aquifer Pumping began April 24, 1984, and continued until July 1985 In 1984, about 7,800 acre-ft of water was pumped from the drainage wells (U S Bureau of Reclamation, 1985b, p A21)

In Parker, Palo Verde, and Cibola Valleys and the Yuma area, ground water drains directly into the river from beneath some cropped areas adjacent to the river Methods to estimate the quantity of ground water that returns to the river have been developed and documented in previous reports (Loeltz and Leake, 1983a, b, Leake, 1984, Owen-Joyce, 1984, 1988, 1990, Owen-Joyce and Kimsey, 1987)

The distribution of water through the network of dams, diversions, drainage ditches, and pumps is complex, and it is difficult to precisely meet the gaging requirements of the Decree The quantity of flow in the Colorado River below Hoover Dam plays a major role in the interaction of flow between the river and the alluvial aquifer, which is under and adjacent to the river throughout much of the study reach During the high flow of 1984, for example, an unusually large quantity of flow passed through the system to Mexico and river water entered the alluvial aquifer throughout much of the study reach The unusually high flow also scoured the bed and banks of the river channel, and the ratings used to compute discharge of the river were less precise than normal Thus, the application of LCRAS for years with abnormal quantities of flow in the river is further complicated

APPLICATION OF THE LOWER COLORADO RIVER ACCOUNTING SYSTEM

The application of LCRAS to the lower Colorado River is illustrated using calendar year 1984 To aid future users of LCRAS, the description of the application follows the step-by-step process used to estimate and distribute consumptive use by vegetation to water users The process occurs in four major steps First, the compilation and estimation of the independent water-budget components are discussed, which include the general method of estimation, any adjustments required for conditions during the year being evaluated, and the estimated quantity of the components for 1984 Second, consumptive use by vegetation is estimated as the residual in a water budget Third, the estimation of evapotranspiration is described, which includes the identification of vegetation types and calculation of total acreage for each type by diverter, estimation of water-use rates for each vegetation type, and calculation of evapotranspiration by reach Fourth, consumptive use by vegetation is apportioned to water users using the estimates of evapotranspiration determined for each user

To meet the requirements of the Decree on an annual basis, LCRAS should provide reliable results under all conditions that affect the lower Colorado River Calendar year 1984 was preselected for study during project planning, prior to the high flows that began in 1983 Although 1984 was a year of unusually high flow in the river, the high flow did not prevent collection of the data required for LCRAS A year that contained anomalous conditions also provided an added test of the reliability of LCRAS

Water-Budget Components

All the major water-budget components for LCRAS are measured, and some of the minor components are estimated Measured components include flow in the mainstream, major tributaries, diversions, return flows, and change in reservoir storage Flow below Hoover Dam requires an adjustment, and inflow from the Bill Williams River is estimated Other independent water-budget components that have to be estimated are unmeasured tributary inflows, precipitation, evaporation from open-water surfaces, domestic, municipal, and industrial consumptive use, and change in storage in the alluvial aquifer The collection and estimation of these water-budget components are described, and any adjustments required for 1984 are documented

Flow Components

Annual flow data for each of the sites required by LCRAS are compiled and entered into a data file (table 9) Annual flow data for calendar year 1984 are published by the USGS (White and Garrett, 1988) and IBWC (International Boundary and Water Commission United States and Mexico, 1984)

For use in LCRAS, the flow reported below Hoover Dam for 1984 was increased by 2 1 percent (see analysis of flow data described in the section entitled "Dams and Reservoirs") In 1984, daily flow below Hoover Dam was reported to range from 15,600 to 37,500 ft^3/s and the mean was 29,490 ft^3/s (White and Garrett, 1988) In 1984, Q_{us} and Q_{ds} were exceptionally large because inflow from the upper basin in 1983 filled the major reservoirs and flowed over the spillways Releases from the dams continued through 1984 and maintained the high flows in the river throughout the year Flow below Hoover Dam in 1984 was 2 9 times the flow in 1982, and flow at Morelos Dam in 1984 was 10 7 times the flow in 1982

Tributary Inflow

Tributaries are defined in the Decree as the waters of all stream systems that naturally drain into the mainstream of the Colorado River, including reservoirs thereon The Bill Williams and Gila Rivers and surface-water and ground-water flow in the Colorado River valley and from adjacent basins provide tributary water to the Colorado River The Decree does not affect the rights or priorities of the States to the water in the tributaries except for that in the Gila River Tributary waters are accountable under the Decree upon entry into the mainstream of the Colorado River Estimates and areal distribution of tributary inflow to the lower Colorado River were summarized (Owen-Joyce, 1987) and provided to the States for their allocation of tributary inflow Methods of estimating captured and uncaptured tributary inflow need to be developed and incorporated into LCRAS Tributary water that is captured by the States and does not reach the Colorado River is not an inflow component in a water budget for the river

Bill Williams River

Flow in the Bill Williams River is measured below Alamo Dam, about 36 mi upstream from Lake Havasu (site 12, pl 1 and fig 7) The streamflow-gaging station was established by the USGS to monitor releases from Alamo Dam for the U S Army Corps of Engineers The Corps of Engineers uses the data to operate the dam for flood control, for storage, and to maintain a base flow of 10 ft^3/s to meet a downstream water right The accuracy of the data collected is good (95 percent of the data are within 10 percent of the true values) The average annual flow below Alamo Dam between 1940 and 1983 was 84,770 acre-ft (White and Garrett, 1986, p 122) Flow in 1984 was 111,800 acre-ft

Below Alamo Dam, tributary inflow to the Bill Williams River is unmeasured Between the streamflow-gaging station and the mouth, average annual runoff was estimated to be 4,000 acre-ft (Metzger and Loeltz, 1973, p 35), average annual

Table 9. Flow computed at streamflow-gaging stations and change in reservoir storage along the lower Colorado River between Hoover Dam and Mexico, 1984, compiled for input into the Lower Colorado River Accounting System computer program[1]

[Station name NIB, northerly international boundary, SIB, southerly international boundary]

Site number[2]	Station number	Station name	Flow or change in storage, in acre-feet
1	09421500	Colorado River below Hoover Dam	[3]21,861,000
2	09422500	Change in storage Lake Mohave	−150,000
3	09423000	Colorado River below Davis Dam	21,658,000
11	09424150	Colorado River aqueduct	1,237,230
12	09426000	Bill Williams River below Alamo Dam	111,800
14	09426650	Central Arizona Project Canal	0
15	09427500	Change in storage Lake Havasu	53,100
16	09427520	Colorado River below Parker Dam	20,464,000
---	([4])	Change in storage Senator Wash	652
44	09429490	Colorado River above Imperial Dam	19,106,000
52	09522400	Diversion to Mittry Lake	9,790
53	09522500	Gila Gravity Main Canal	754,800
56	09522700	Wellton-Mohawk Canal	391,400
60	09523000	All-American Canal	8,269,000
72	09527500	All-American Canal below Pilot Knob	3,046,000
45	09429500	Colorado River below Imperial Dam	10,080,000
47	09520500	Gila River near Dome	266,000
50	09522000	Colorado River at NIB	15,431,000
98	09531850	Cooper wasteway	721
100	09532500	Eleven Mile wasteway	1,530
101	09533000	Twenty-one Mile wasteway	0
103	09534000	Main drain at SIB	99,380
104	09534300	West Main Canal wasteway	0
105	09534500	East Main Canal wasteway	4,090

[1]Lower Colorado River Accounting System computer program is documented by von Allworden and others (1991)

[2]Locations shown on figures 4–6 and plate 1

[3]Adjusted flow value, measured flow of 21,411,000 acre-feet was increased by 2 1 percent

[4]Quantity published with the data for the Colorado River above Imperial Dam gaging station in the annual U S Geological Survey Water-Data Report for Arizona (White and Garrett, 1988)

ground-water discharge was estimated to be 4,000 acre-ft (Metzger and Loeltz, 1973, p 36)

A water budget similar to that used by Owen-Joyce (1987) to estimate the average annual flow can be used to estimate the annual quantity of water that reaches Lake Havasu, which was 75,600 acre-ft in 1984 (table 10) Components in an annual budget include annual flow measured below Alamo Dam, precipitation that falls on vegetation and open-water surfaces, estimates of evapotranspiration by vegetation, evaporation from the open-water surface, and estimates of average annual runoff and ground-water discharge Evapotranspiration can be estimated on an annual basis if the types and acreages of the vegetation growing on the flood plain are known The types and acreages were compiled for this study from image classifications of satellite digital-image data (table 11) In 1984, evapotranspiration was estimated to be 46,670 acre-ft Evapotranspiration for the Bill Williams River was calculated according to the general procedure described in the subsequent section entitled "Calculation of Evapotranspiration by Reach "

Surface water was not diverted for irrigation along the Bill Williams River below Alamo Dam Ground water pumped for irrigation was partially replaced by recharge from the river Evaporation from the open-water surface was estimated to be 2,880 acre-ft by using the length and an average width of the river from topographic maps The surface area could not be calculated from an open-water classification of digital-image data because the river is too narrow for the resolution of the satellite images and the water surface is obscured by vegetation

Table 10. Water budget for the Bill Williams River below Alamo Dam, 1984

Component	Quantity, in acre-feet
Inflow.	
Flow below Alamo Dam	111,800
Precipitation	5,340
Unmeasured average annual runoff	4,000
Ground-water discharge	4,000
Total (rounded)	125,100
Outflow:	
Evapotranspiration by crops and phreatophytes	46,670
Evaporation from water surface	2,880
Total (rounded)	49,500
Flow reaching the Colorado River[1]	75,600

[1]Computed residual of the water-budget method

Table 11. Areas by vegetation types and evapotranspiration along the Bill Williams River below Alamo Dam, 1984

Vegetation type	Area, in acres[1]	Water-use, in feet	Evapotranspiration, in acre-feet
Crops.			
Cotton	642	[2]3 43	2,202
Alfalfa	1,180	[2]6 50	7,670
Total (rounded)	1,822		9,870
Phreatophytes·			
Dense	1,724	[3]6 48	11,172
Medium	1,451	[3]5 38	7,806
Sparse	4,144	[3]4 30	17,819
Total (rounded)	7,319		36,800
GRAND TOTAL	9,141		46,670

[1]Types and areas of vegetation were compiled from image classifications of satellite digital-image data

[2]Calculated using equation 13 and weather data for Parker, Arizona (table 18)

[3]Calculated using equation 14 and weather data for Parker, Arizona (table 18)

Gila River

Flow in the Gila River is measured near Dome, about 12 mi upstream from the confluence with the Colorado River (site 47, pl 1 and fig 8) The streamflow-gaging station was established by the USGS for the USBR to monitor the tributary inflow from the Gila River basin where it enters the Colorado River valley The accuracy of the data is good (95 percent of the data are within 10 percent of the true value) Flow is highly variable because of regulation by reservoirs and many diversions for irrigation above the streamflow-gaging station Annual flow ranged from 0 to 4,665,000 acre-ft between 1903 and 1984 Flow in 1984 was 266,000 acre-ft (White and Garrett, 1988) Flow measured near Dome consists of two components—Gila River water (tributary inflow) and return flow from upstream irrigation with Colorado River water in the Wellton-Mohawk area During low-flow years, flows near Dome are solely irrigation return flow

Flow measured in the Gila River near Mohawk, upstream from Dome and the area irrigated with water from the Wellton-Mohawk Canal, was 233,900 acre-ft in 1984 (White and Garrett, 1988, p 258) The difference in flow between the Mohawk and Dome gages is influenced by seepage from the river into the alluvium when flows are high, subsequent returns from bank storage when high flows recede, runoff from the intervening 2,420 mi^2 of drainage area, and irrigation return flows All flow measured near Mohawk is considered tributary inflow In 1984, flow near Mohawk was reduced to 0 by mid-June and remained at 0 for most days through December except for runoff from three small local storms In contrast, there was flow all year near Dome More runoff events occurred between June and December near Dome than near Mohawk Estimating the quantity of irrigation return flow from diverted Colorado River water mixed with the flow from runoff events and bank-storage returns from runoff events near Dome is not possible using only streamflow records Flow records will have to be analyzed each year to determine if the source of the flow near Dome can be identified or divided into components For the 1984 computation, the total flow near Dome is assumed to be tributary inflow because tributary inflow makes up most of that flow.

Flow in the Gila River between Dome and the confluence with the Colorado River consists of flow that originates upstream from Dome and return flow from irrigation with Colorado River water on the adjacent flood plain. During low-flow years, flow near the mouth (site 48, fig 6) is higher than that near Dome because irrigation return flow enters the reach between the sites During high-flow years, flow near the mouth is lower than near Dome because water from the Gila River infiltrates and recharges the aquifer

Unmeasured Tributary Inflow

Unmeasured tributary inflow consists of surface-water and ground-water inflow to the flood plain of the Colorado River or to the river and reservoirs from various tributary areas In previous studies, average annual quantities of unmeasured tributary inflow were estimated as a function of mean annual precipitation for 1931—60 These estimates were determined to be valid for use in 1984 because mean annual precipitation for 1951—80 did not differ significantly from that of 1931—60 (Owen-Joyce, 1987) Although 1984 was a wet year and inflows from tributary washes were reported by the USBR (Carl Mayrose, oral commun , 1986) in Piute Wash, Sacramento Wash, and Mineral Wash (a tributary to the Bill Williams River), inflow quantities could not be defined At times, storm runoff from tributaries can be observed on hydrographs of mainstream gages, but none could be seen for 1984 Estimates of average annual tributary inflows were compiled and itemized by State and reach (Owen-Joyce, 1987, table 3) These estimates are used in LCRAS (table 12)

Unmeasured tributary inflow to the Colorado River between Hoover Dam and Mexico is a small component in the water budget Estimated average annual unmeasured tributary inflow to the Colorado River is 96,400 acre-ft, or about 1 percent of the 7 5 million acre-ft/yr of consumptive use of Colorado River water apportioned to the lower-basin States About 62 percent of the tributary inflow originates in Arizona, 30 percent in California, and 8 percent in Nevada (Owen-Joyce, 1987)

The dynamic nature of the hydrologic system makes the quantification of unmeasured tributary inflows difficult, and the quantity can be estimated only by indirect means as a required component in a water budget Tributary ground-water inflow commingles with water that originated as infiltrated surface water diverted from the Colorado River in the flood-plain aquifer Commingled waters are pumped from wells that tap the flood-plain aquifer for irrigation, such as in Mohave Valley and the Yuma area, and for domestic and municipal use along much of the river Data on the quantities of tributary water used by the States before entry into the Colorado River are not available For the purpose of illustrating LCRAS, it

Table 12. Estimates of unmeasured tributary inflow by reaches of the lower Colorado River compiled for input into the Lower Colorado River Accounting System computer program[1]

River reach and source of tributary inflow	Inflow, in acre-feet per year
Hoover Dam to Davis Dam	
Springs	3,080
Unmeasured runoff	2,100
Ground-water discharge	200
Eldorado Valley	1,100
Total (rounded)	6,500
Davis Dam to Parker Dam	
Unmeasured runoff	
Davis Dam to Topock	12,000
Topock to Parker Dam	15,000
Whipple Mountains	1,150
Unmeasured runoff from tributary streams	
Piute Wash	1,000
Sacramento Wash	2,500
Bill Williams River subarea	4,000
Ground-water discharge	
Davis Dam to Topock	0
Topock to Parker Dam	880
Piute Valley	2,300
Sacramento Valley	10,000
Chemehuevi Valley	260
Bill Williams River subarea	4,000
Total (rounded)	53,100
Parker Dam to Imperial Dam	
Unmeasured runoff	
Whipple Mountains	1,150
Big Maria-Riverside Mountains	2,300
Palo Verde-Mule Mountains	1,200
Dome Rock-Trigo-Chocolate Mountains	16,200
Unmeasured runoff in tributary streams	
Vidal Wash	1,300
Bouse Wash	4,800
Tyson Wash	2,600
McCoy Wash	800
Milpitas Wash	1,200
Ground-water discharge	
Bouse Wash	1,200
Tyson Wash	350
Vidal Wash	250
Chuckwalla Valley	400
Total (rounded)	33,800
Imperial Dam to Morelos Dam	
Ground-water discharge	
Gila River	1,000
Unmeasured runoff in Yuma area	2,000
Total (rounded)	3,000
GRAND TOTAL	96,400

[1]Lower Colorado River Accounting System computer program is documented by von Allworden and others (1991)

was assumed that all the estimated tributary inflow entered the Colorado River

Precipitation

Little or no recharge to the aquifer occurs because a mean annual precipitation of less than 8 in (Metzger and Loeltz, 1973, p 35) throughout most of the study area is much less than the potential evapotranspiration However, precipitation that falls directly on vegetation is available for consumptive use by the vegetation and affects the quantity of Colorado River water lost to evapotranspiration The quantity of precipitation falling on vegetation and on the river surface is one of the input components in the water budgets used to calculate consumptive use by vegetation Precipitation as an inflow component is calculated by using equation 3 A comparison of precipitation in 1984 with the mean annual precipitation for 1951—80 shows that 1984 was a wet year, and that precipitation ranged from about 33 to 128 percent higher than the mean at all stations (table 13) Complete records of monthly precipitation were available for some of the stations in 1984 (table 13)

Precipitation as well as temperature data are required to estimate evapotranspiration, therefore, the data sets are discussed together Weather stations for the individual reaches were selected so that the data represented meteorological conditions in agricultural areas in the reach Stations located on the flood plain in agricultural areas best represent conditions that affect vegetation on the flood plain If data at these stations were incomplete, stations with the least change in meteorological conditions were selected as replacements In some areas, automated weather stations could be used to provide the necessary data Weather stations selected for use in 1984 were

Weather station	*Reach or area*
Willow Beach	Hoover Dam to Davis Dam
Bullhead City	Davis Dam to Parker Dam
Parker	Parker Dam to Poston, Arizona
Parker	Bill Williams River flood plain
Blythe	Poston to Imperial Dam
Yuma Valley	Imperial Dam to Morelos Dam

The Parker Dam to Imperial Dam reach covers approximately 1 1° latitude and includes an elevation change from about 400 ft at Parker Dam to about 300 ft at Imperial Dam A comparison of precipitation and temperature from Parker, Arizona, at the north end of the reach with precipitation and temperature from Blythe, California, in the southern part of the reach shows definite differences in local weather patterns, therefore, the reach was subdivided to calculate evapotranspiration The boundary separating areas that used data from the Parker weather station from areas that used data from the Blythe weather station was placed at latitude 34° N , near Poston, Arizona, which is also the boundary between the north and south Landsat scenes used in the vegetation classifications Parker and Palo Verde Valleys have similar growing conditions and have considerable overlap in latitude near Palo Verde Dam

Evaporation from Open-Water Surfaces

Evaporation Rates

Evaporation rates from open-water surfaces are required by LCRAS to estimate the quantity of water lost by evaporation from the reservoirs, rivers, marshes, and other smaller water surfaces Annual evaporation rates vary throughout the lower Colorado River valley, but only two stations collect pan-evaporation data, one near Lake Mead and the other at Yuma Previous studies have made estimates of mean annual lake evaporation for Lake Mead, Lake Mohave, and Lake Havasu (Harbeck and others, 1958, Meyers, 1962, U S Bureau of Reclamation, 1985c) These studies also estimated a pan-to-lake coefficient for Lake Mead Between Hoover Dam and Mexico, mean annual lake evaporation estimated for 1946—55 ranged from about 6 4 ft near Yuma to more than 7 2 ft in the area extending from Topock to north of Imperial Dam (Meyers, 1962, pl 3) Mean annual lake evaporation for Lake Mead estimated for 1941—53 was 6 56 ft, and the pan-to-lake coefficient was 0 60 (Harbeck and others, 1958, p 59) From a regression analysis that used 1975 data from Boulder City, Nevada, the U S Bureau of Reclamation (1985c) corrected the Boulder City pan evaporation for use at Lake Mead The calculated coefficient between the corrected Boulder City pan evaporation and the Lake Mead mean annual evaporation estimated by Harbeck and others (1958) was 0 57, which compares well with the 0 60 value The 0 57 value was used to estimate lake evaporation for Lake Mohave using data from the Davis Dam No 2 weather station for 1967—76 and for Lake Havasu using data from the Parker Reservoir station for the same period The average annual evaporation rate was 7 31 ft from Lake Mohave

Table 13. Precipitation at selected weather stations along the lower Colorado River, 1984, and mean annual precipitation, 1951–80

[Weather station NV, Nevada, AZ, Arizona, CA, California]

River reach	Weather station[1]	Elevation, in feet above sea level[2]	Monthly (1984) precipitation, in inches[2] Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual precipitation, in inches 1984[2]	Mean annual precipitation, in inches 1951–80
Hoover Dam to Davis Dam	Boulder City, NV	2,525	0.00	0.06	0.03	0.09	0.05	0.00	0.08	5.08	3.12	0.03	1.64	2.46	12.64	5.54
	Searchlight, NV	3,540	0.00	0.00	0.00	0.06	0.00	0.17	4.97	0.66	0.18	0.12	1.60	4.07	11.83	7.28
	Willow Beach, AZ	800	0.00	0.00	0.05	0.00	0.00	0.02	1.83	1.85	0.75	0.27	0.76	2.93	8.46	(3)
Davis Dam to Parker Dam	Bullhead City, AZ	580	0.00	0.00	0.00	0.01	0.00	0.00	3.12	1.28	0.08	0.00	1.62	4.25	10.36	(3)
	Needles Airport, CA	914	0.00	0.00	0.00	0.02	0.00	0.00	0.59	1.60	0.38	0.00	0.64	2.60	5.83	4.39
	Lake Havasu, AZ	482	0.01	0.00	0.00	0.04	0.05	0.00	0.11	0.61	0.91	0.00	0.46	2.41	14.77	(3)
Bill Williams River	Alamo Dam, AZ	1,480	0.00	0.00	0.00	0.00	0.00	0.17	0.94	3.55	0.51	0.00	1.37	3.52	10.06	(3)
Parker Dam to Imperial Dam	Parker Reservoir, CA	738	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.77	0.49	0.00	0.54	4.20	6.98	(3)
	Parker, AZ	425	0.03	0.00	0.00	0.00	0.00	0.00	0.91	0.35	1.06	0.00	0.43	3.79	6.57	4.09
	Blythe, CA	390	0.06	0.00	0.00	0.00	0.03	0.00	1.09	2.28	0.00	0.00	0.56	3.77	6.06	(3)
	Blythe Airport, CA	268	0.06	0.00	0.00	0.00	0.02	0.00	2.44	0.11	0.00	0.00	0.10	3.33	7.79	3.75
	Ehrenberg, AZ	465	0.04	0.00	0.00	0.00	0.02	0.00	1.19	0.72	0.00	0.00	0.54	3.16	5.67	3.93
Imperial Dam to Morelos Dam	Yuma Airport, AZ	324	0.14	0.00	0.00	0.55	0.00	0.00	2.11	1.08	0.21	0.00	0.53	1.57	6.42	(3)
	Yuma Citrus Station, AZ	206	0.26	0.00	0.00	0.43	0.00	0.00	3.12	0.63	0.14	0.00	0.45	1.77	6.19	2.89
	Yuma Proving Ground, AZ	191	0.10	0.00	0.00	0.58	0.00	0.00	1.39	1.76	0.35	0.00	0.52	1.72	6.80	3.07
	Yuma Valley, AZ	120	0.00	0.00	0.00	0.45	0.00	0.01	2.51	1.15	0.04	0.00	0.32	1.62	6.10	(4)

[1]Locations shown on plate 1

[2]National Climatic Data Center (1951–84a, b, c)

[3]Data collection at the site began after 1951

[4]Four years have missing record, therefore, no average calculated

and 7 39 ft from Lake Havasu Average pan evaporation for Yuma Citrus Station for 1931—84 was 9 09 ft (International Boundary and Water Commission, United States and Mexico, 1984), which is equivalent to a lake evaporation of 5 45 ft using the 0 60 coefficient Average pan evaporation was about 156 in or 13 ft at Davis Dam for 1955—76 (International Boundary and Water Commission, United States and Mexico, 1976, p 51) Using a pan-to-lake coefficient of 0 60 (U S Bureau of Reclamation, 1985c, p 4—1) results in an average annual evaporation rate of 7 8 ft, which indicates that the average annual evaporation rates for Lake Mohave and Lake Havasu could be too low Data are not available, however, to assess the area represented by this higher value Also, evaporation rates for large bodies of water can differ from those for the free-flowing river surface, but data were not available to evaluate this hypothesis

Average annual evaporation was selected from the available data for each of the reaches for use in LCRAS (table 14) by comparing the average values with the values observed in 1984 In addition, above-average precipitation in 1984 would cause evaporation to be lower than average Pan evaporation at Yuma Citrus Station in 1984 was 8 38 ft, which corresponds with a lake evaporation of 5 03 ft by using the 0 60 coefficient This value is 23 percent lower than the average annual value selected for the Imperial Dam to Morelos Dam reach of 6 50 ft (table 14) Evaporation from Lake Mead for 1984 was 5 42 ft (White and Garrett, 1988, p 83), which is 17 percent lower than the average annual value of 6 56 ft Therefore, to account for the effect of the wetter year, the average annual evaporation rates were reduced by 20 percent for use in LCRAS in 1984 (table 14)

Open-Water Surface Areas

Landsat satellite images in digital form were obtained for use in identifying and determining the acreages of crop types (see subsequent section entitled "Identification of Vegetation Types and Acreages by Diverter"), however, the images were also used to identify and determine the areas of open-water surfaces in the lower Colorado River flood plain A single-image classification technique was used to determine the areas of open water rather than a multispectral, multitemporal classification, which is used for vegetation identification A multispectral, multitemporal classification gives a poor classification of water because the band ratios reduce and combine the spectral responses of nonvegetation-cover classes The areas of open water obtained from the image classifications were used to estimate evaporation from open-water surfaces as part of the calculation of consumptive use

Interpretation of the single-image classifications to determine areas of open water was made by observing the spectral characteristics of the classes Water absorbs most of the red [0 5—0 6 μm (micrometers)] and near-infrared (0 8—1 1 μm) radiation that falls on it Potential open-water classes were selected on the basis of this reflectance response Calibration of the classifications was made by observing the locations of the potential open-water classes relative to the mapped locations of the river and its reservoirs, which are the only open-water areas in the flood plain Interpretation of the single-image classification resulted in the identification and grouping of open-water classes into clear, moderately turbid, and turbid water for 1984 The sum of the areas of these three groups for

Table 14. Evaporation along the lower Colorado River

River reach	Adjusted 1984 evaporation, in feet[1]	Mean annual evaporation, in feet	Source of mean annual evaporation data
Hoover Dam to Davis Dam	5 85	7 31	U S Bureau of Reclamation (1985c, p 19)
Davis Dam to Parker Dam	5 91	7 39	U S Bureau of Reclamation (1985c, p 29)
Parker Dam to Imperial Dam	5 68	7 10	Meyers (1962, pl 3)
Imperial Dam to Morelos Dam	5 20	6 50	Meyers (1962, pl 3)
Bill Williams River	5 00	6 25	Meyers (1962, pl 3)

[1] Adjusted 1984 evaporation equals 80 percent of the mean annual evaporation

each of the reaches is the open-water surface from which evaporation occurs (table 15).

Table 15. Evaporation from open-water surface areas along the lower Colorado River, 1984

River reach	Open-water surface area, in acres	Evaporation, in acre-feet[1]
Hoover Dam to Davis Dam	25,400	148,700
Davis Dam to Parker Dam	22,000	129,800
Parker Dam to Imperial Dam	10,300	58,300
Imperial Dam to Morelos Dam	1,390	7,200
Bill Williams River	[2]576	2,880
TOTAL (rounded)	59,700	346,900

[1]Evaporation rates used to calculate evaporation from open-water surfaces in the different reaches are listed in table 14.
[2]Calculated for 36 miles of river that averages 132 feet in width.

Calculation of Evaporation from Open-Water Surfaces

Evaporation from open-water-surface areas in each of the reaches was calculated by using equation 6 (table 15). Computed evaporation is the product of the open-water-surface areas (table 15) and the adjusted evaporation rates for 1984 (table 14).

Domestic, Municipal, and Industrial Consumptive Use

In LCRAS, domestic, municipal, and industrial uses are collectively referred to as domestic use, which conforms to the Decree definition. Water used by cities, towns, and individuals along the river that obtain their water supply from the river or shallow alluvial aquifer is considered to be domestic and municipal consumptive use. Domestic and municipal consumptive use was estimated two ways: (1) domestic and municipal consumptive use was assumed equal to pumpage when there were no return flows to the river, and (2) water consumptively used by cities and towns was estimated as the product of the resident population and resident per capita consumptive use when there were unmeasured returns to the river (table 16). In 1984, domestic and municipal consumptive use totaled 40,360 acre-ft between Hoover Dam and Mexico.

Domestic and municipal consumptive use was equal to pumpage in areas such as Willow Beach, Cottonwood Cove, and Katherine within the Lake Mead National Recreation Area. The resident population is small, but the number of annual visitors that use the facilities is large (table 16). Water was pumped from wells, and effluent is treated in lagoons and evaporated. Irrigation is minor and consists of watering ornamental shrubs (Gary Bunney, Assistant Superintendent, Lake Mead National Recreation Area, oral commun., 1988).

Industrial consumptive use was equal to pumpage at the Mohave Steam Plant in Laughlin. Total evaporation results in no return flows to the river (George Blake, Colorado River Commission of Nevada, oral commun., 1988).

In most of the cities and towns along the river, domestic and municipal consumptive use was estimated by using resident population and estimates of per capita consumptive use (table 16) that were supplied by the States (Thomas Perry, Arizona Department of Water Resources, written commum., 1988; Richard E. Angelos, Colorado River Board of California, written commun., 1988). A major problem with estimating the population is that some smaller towns are unincorporated and census population includes those towns within much larger areas. Another problem is that the Colorado River area supports high recreational use year round and has a large number of winter visitors. Winter visitors stay in trailer parks that are not part of any town but are scattered along the river.

Change in Storage in the Alluvial Aquifer

Some of the river water diverted to irrigate crops infiltrates to the underlying alluvial aquifer and returns to the river. In some reaches, water also seeps from the river into the alluvial aquifer. To determine if this water needs to be accounted for in the water budget, change in storage in the alluvial aquifer was investigated under the assumption that any other inflows or outflows to the alluvial aquifer are small compared with infiltration from irrigation and seepage from the river channel.

Change in storage in the alluvial aquifer of the flood plain was shown to be small in relation to consumptive use by vegetation during 1984. Storage increased 1,400 acre-ft in Palo Verde Valley (Owen-Joyce and Kimsey, 1987, p. 44), increased 2,600 acre-ft in Parker Valley (Owen-Joyce, 1988,

Table 16. Data on domestic and municipal consumptive use along the lower Colorado River between Hoover Dam and Mexico

	Resident population (1)	Resident per capita consumptive use, in acre-feet (2)	Number of visitors (3)	Pumpage with no returns, in acre-feet (4)	Resident consumptive use, in acre-feet (1) x (2) (5)
Arizona					
Hoover Dam to Davis Dam					
Willow Beach	25 (1987)	-----	177,604 (1984)	90	---------
Katherine	100 (1987)	-----	1,083,571 (1984)	370	---------
Diversion at Davis Dam	----------------	-----	--------------------	[1]142	---------
L C R D Project	----------------	-----	--------------------	[1]60	---------
Davis Dam to Parker Dam					
Bullhead City-Riviera	15,895 (1984)	0 03	--------------------	---------	477
Bermuda City	500 (1987)	0 03	--------------------	---------	15
Golden Shores	650 (1987)	0 03	--------------------	---------	20
Topock	25 (1987)	0 03	--------------------	---------	0 8
Lake Havasu City	17,645 (1984)	0 03	--------------------	---------	529
Mohave Water Conservation District	----------------	-----	--------------------	[1]108	---------
Lake Havasu Irrigation and Drainage District	----------------	-----	--------------------	[1]9,085	---------
Consolidated Water Utilities Ltd	----------------	-----	--------------------	[1]291	---------
Parker Dam to Imperial Dam					
Town of Parker	2,530 (1984)	0 13	--------------------	---------	329
Poston	260 (1988)	0 03	--------------------	---------	8
Ehrenberg	1,204 (1988)	0 03	--------------------	---------	36
Cibola	293 (1985)	0 03	--------------------	---------	9
Martinez Lake	10 (1980)	0 03	--------------------	---------	0 3
Imperial Dam to Morelos Dam					
Yuma (City)	45,960 (1984)	0 09	--------------------	---------	4,136
Yuma (County)	19,406 (1984)	0 03	19,465 (1984)	---------	582
Yuma Proving Ground	1,100 (1982)	0 03	--------------------	---------	33
Marine Corps Air Station	----------------	-----	--------------------	[1]1,775	---------
Southern Pacific Company	----------------	-----	--------------------	[1]48	---------
Yuma County	----------------	-----	--------------------	[1]12	---------
Yuma Mesa Fruit Growers Assn	----------------	-----	--------------------	[1]12	---------
Yuma Union High School	----------------	-----	--------------------	[1]200	---------
Below Morelos Dam					
Somerton	4,320 (1984)	0 03	--------------------	---------	130
Gadsden	([2])	-----	--------------------	---------	---------
Town of San Luis	2,575 (1984)	0 03	--------------------	---------	77
California					
Davis Dam to Parker Dam					
Needles	5,100 (1984)	[3]0 39	--------------------	---------	1,989
Havasu Lake (Trailers)	([2])	------	--------------------	---------	---------
San Bernardino County	----------------	------	--------------------	[1]15	---------

Table 16. Data on domestic and municipal consumptive use along the lower Colorado River between Hoover Dam and Mexico—*Continued*

	Resident population (1)	Resident per capita consumptive use, in acre-feet (2)	Number of visitors (3)	Pumpage with no returns, in acre-feet (4)	Resident consumptive use, in acre-feet (1) x (2) (5)
California—Continued					
Parker Dam to Imperial Dam					
Earp	[4]1,500	0 75	--------------------	---------	1,125
Parker Dam and Government Camp	[5]136	0 88	--------------------	---------	120
Vidal	[5]36	0 07	--------------------	---------	3
City of Blythe	7,512 (1984)	[3]0 29	--------------------	---------	2,178
East Blythe	[5]1,940	0 25	--------------------	---------	485
Ripley	[5]450	0 16	--------------------	---------	72
Palo Verde	[5]332	0 07	--------------------	---------	23
Big River	----------------	-----	--------------------	[1]890	---------
BLM Permittees	----------------	-----	--------------------	[1]206	---------
Imperial Dam to Morelos Dam					
Bard	1,532 (1986)	0 06	--------------------	---------	92
Winterhaven	896 (1986)	0 09	--------------------	---------	81
Nevada					
Hoover Dam to Davis Dam					
Cottonwood Cove	[5]20	-----	172,001 (1984)	439	---------
Davis Dam to Parker Dam					
Laughlin	95 (1984)	0 30	--------------------	--------	29
Mohave Steam Plant	----------------	-----	--------------------	14,198	---------
Clark County Parks and Recreation	----------------	-----	--------------------	[1]6	---------
Portenier, Warren E	----------------	-----	--------------------	[1]42	---------

[1]U S Bureau of Reclamation (1986a) No returns reported for these diversions (Carl F Mayrose, U S Bureau of Reclamation, oral commun , 1988)
[2]Unincorporated area, population estimates are not available
[3]Includes water use by motels
[4]Earp population is 533 The utility official estimates Earp's population is as much as 2,000 because of year-round recreation, an average population is 1,500 for the year
[5]Estimate

p 57), and increased 4,500 acre-ft in Cibola Valley (Owen-Joyce, 1990, p 33) In the Yuma area, storage decreased by 2,650 acre-ft in 1984 (U S Bureau of Reclamation, 1985b, p 8) Ground-water-level data were not available to make an estimate for Mohave Valley or along any other reaches between the areas listed above For the purpose of this study using 1984 data, change in storage is assumed to be negligible, although further work is needed to assess the validity of this assumption along the entire reach below Hoover Dam and for use with other years

Estimation of Consumptive Use by Vegetation

For 1984, the river between Hoover Dam and Morelos Dam was treated as a single reach to estimate consumptive use by vegetation using equation 7 Computed consumptive use by vegetation was 2,069,800 acre-ft (see table 17 for an itemized listing of the water-budget components and quantities used in 1984) Calculations of precipitation, domestic consumptive use by municipalities, and evaporation from open-water surfaces are estimated separately for

Table 17. Water budget for the Hoover Dam to Morelos Dam reach of the lower Colorado River, 1984

[Component NIB, northerly international boundary, SIB, southerly international boundary]

Component	Quantity, in acre-feet
Inflow:	
Flow below Hoover Dam	[1]21,861,000
Precipitation	
Hoover Dam to Davis Dam	18,500
Davis Dam to Parker Dam	51,900
Parker Dam to Imperial Dam	137,400
Imperial Dam to Morelos Dam	70,600
Bill Williams River	[2]75,600
Flow in Gila River near Dome	266,000
Unmeasured average annual tributary runoff	
Hoover Dam to Davis Dam	2,100
Davis Dam to Topock	12,000
Topock to Parker Dam	15,000
Whipple Mountains	2,300
Big Maria Mountains	2,300
Palo Verde-Mule Mountains	1,200
Dome Rock-Trigo-Chocolate Mountains	16,200
Yuma area	2,000
Unmeasured tributary stream	
Piute Wash	1,000
Sacramento Wash	2,500
Vidal Wash	1,300
Bouse Wash	4,800
Tyson Wash	2,600
McCoy Wash	800
Milpitas Wash	1,200
Tributary ground-water discharge	
Springs below Hoover Dam	3,080
Colorado River valley	200
Eldorado Valley	1,100
Davis Dam to Topock	0
Topock to Parker Dam	880
Piute Valley	2,300
Sacramento Valley	10,000
Chemehuevi Valley	260
Vidal Wash	250
Bouse Wash	1,200
Tyson Wash	350
Chuckwalla Valley	400
Gila River	1,000
Total (rounded)	22,569,300

Component	Quantity, in acre-feet
Outflow other than consumptive use by vegetation:	
Flow at NIB (Morelos Dam)	15,431,000
Colorado River aqueduct	1,237,230
Central Arizona Project Canal	0
All-American Canal below Pilot Knob	3,046,000
Wellton-Mohawk Canal	391,400
Domestic consumptive use by municipalities	
Hoover Dam to Davis Dam	1,101
Davis Dam to Parker Dam	26,805
Parker Dam to Imperial Dam	5,484
Imperial Dam to Morelos Dam	6,971
Evaporation from open-water surfaces	
Hoover Dam to Davis Dam	148,700
Davis Dam to Parker Dam	129,800
Parker Dam to Imperial Dam	58,300
Imperial Dam to Morelos Dam	7,200
Surface-water return flows below Morelos Dam	
Eleven Mile wasteway	1,530
Cooper wasteway	721
Twenty-one Mile wasteway	0
Main drain at SIB	99,380
West Main Canal wasteway	0
East Main Canal wasteway	4,090
Total (rounded)	20,595,700
Change in storage	
Lake Mohave	-150,000
Lake Havasu	53,100
Senator Wash	652
Total (rounded)	-96,200
Consumptive use by vegetation[3]	2,069,800

[1]Adjusted for AVM error

[2]Flow reaching the Colorado River from the Bill Williams River calculated in table 10

[3]Computed residual of the water-budget method

four subreaches of the river, therefore, the individual reach estimates are listed separately in table 17

Yuma Valley and Yuma Mesa are two areas included in the calculation of consumptive use of Colorado River water (fig 6) Although most of Yuma Valley is downstream from Morelos Dam, the water delivered to the valley is diverted from the Colorado River at Imperial Dam For this study, water pumped from wells for irrigation of crops on Yuma Mesa was assumed to be Colorado River water Another factor affecting this reach is the inability to account for underflow to Mexico from water applied to fields south of Morelos Dam or on the mesa (pl 2) For this study, underflow to Mexico was assumed negligible because of pumping from the Two-Forty-Two Well Field—a line of wells east of San Luis that parallels the border with Mexico

Unused water that was diverted for irrigation at Imperial Dam returns to the river above and below Morelos Dam The flow that returns to the river below Morelos Dam is accounted for in the water budget that estimates consumptive use by vegetation to prevent this flow from being counted as consumptive use Surface-water return flows from Yuma Valley below Morelos Dam are from Eleven Mile, Cooper, Twenty-one Mile, West Main Canal, and East Main Canal wasteways and from Main drain Flows at these sites are measured by the IBWC to account for the annual quantity of water that flows into Mexico

Estimating Evapotranspiration Using Remotely Sensed Data

Direct separation of consumptive use by diverter—as specified by the Decree—is difficult in the lower Colorado River flood plain, owing primarily to the problem of correlating subsurface return flows with their points of origin The following method proposed by Raymond and Rezin (1989) and Raymond and Owen-Joyce (1987) was used to calculate evapotranspiration by vegetation in each reach (1) vegetation types and distribution are identified by computer analysis of digital satellite images to produce vegetation maps, referred to in this report as vegetation classifications, (2) water-use rates are estimated for each vegetation type, (3) the boundaries of the subareas served by each diverter are digitized and used to digitally separate the vegetated area of the reach by diverter, (4) the evapotranspiration for each vegetation type in a diverter's subarea is computed as the product of the area and the water-use rate of each vegetation type to calculate the annual volume of water used by each type, and (5) the water used by each vegetation type in each diverter's subarea is summed to give the evapotranspiration by each diverter The following sections describe in detail the technique of calculating evapotranspiration for each reach

Identification of Vegetation Types and Acreages by Diverter

Multispectral, multitemporal classification of Landsat satellite images in digital form was used to classify vegetation types for the lower Colorado River flood plain in 1984 Raymond and Rezin (1989) showed that multispectral, multitemporal vegetation classifications using three images collected at different times during the growing season correctly identified 80 to 90 percent of the area covered by the major crops in Parker and Palo Verde Valleys Other sources of data from which vegetation types can be identified, separated, and quantified are available and could be used in the future The use of field reconnaissance, aerial photography, and satellite images in digital and photographic form to classify vegetation is discussed by Raymond and Rezin (1989)

The vegetation-classification techniques described in the following sections have been developed for Landsat satellite images in digital form but could be modified for other data sources, including digital and analog video-imaging techniques Data for the 1984 vegetation classifications were collected by the multispectral scanner (MSS) aboard the Landsat 5 satellite The number of potentially available images was limited by (1) this satellite passing over a given area of the Earth's surface at a given time once every 16 days, (2) occasional cloud cover, and (3) conflicting uses of communication satellites or ground stations that prevent collection of data from the Landsat satellite on some overpass dates

The multispectral, multitemporal classification technique was used for all classifications except to calculate the (1) areas of phreatophytes for the Hoover Dam to Davis Dam reach and (2) areas of vegetation types along the Bill Williams River below Alamo Dam, where the single-image classification technique was used Phreatophyte classification was by density class only, this technique works faster and easier than the multispectral, multitemporal technique Field reconnaissance of the Bill Williams River flood plain showed that small amounts of alfalfa and cotton were planted in some areas of the flood plain Dense, medium, and sparse phreatophytes were the dominant vegetation types, however, the single-image classification was selected to give the best classification of these types

Landsat images obtained on August 28 were used to determine areas of phreatophytes and open water for all areas described above except the Hoover Dam to Davis Dam reach That reach, which is in a Landsat-orbital path different from that of the rest of the flood plain, was classified by using an image obtained on March 20 A file containing values of the four raw-data bands of each image was classified by using the maximum-likelihood classification algorithm (Graham and others, 1985, p A14—A17) Georeferencing was not required because no diverter boundaries needed to be digitized from maps The boundaries of the Colorado River flood plain were digitized directly on the video-displayed images by using the technique described in Graham and others (1985, p POLY 1—3) to obtain the areas of phreatophytes that used Colorado River water and the areas of open-water surfaces The boundaries of the Bill Williams River flood plain were digitized directly on the video-displayed image to determine the areas of phreatophytes that used tributary water that would otherwise flow into Lake Havasu Phreatophyte classes were identified and separated as described in the section "General Interpretation of the Classification "

Field Reconnaissance

Previous studies of the lower Colorado River flood plain (Raymond and Owen-Joyce, 1987, Raymond and Rezin, 1989) have shown that correct identification of vegetation types by the image-analysis method requires detailed knowledge of representative sites for calibration purposes The digital images only contain information about the spectral characteristics of the electromagnetic radiation sensed by the satellite Ground-truth data are required to establish the relation between the remotely sensed data in the images and the vegetation types on the ground Crop type for every field in the calibration site is required to provide a block of data for correct interpretation of the vegetation classifications Phreatophyte species, distribution, and stand density also are required Variations in planting and harvesting times for each major crop are considered in the selection of data-collection dates during the growing seasons Methods and scheduling of irrigation, occurrence and distribution of volunteer vegetation in the fields, and mowing schedules for hay crops are some important factors that influence the correct calculation of evapotranspiration Much of this information can be acquired from the literature, local records, or conversations with personnel in the area, but experience has shown that field reconnaissance is essential for understanding the study area

A general field reconnaissance of the entire lower Colorado River flood plain and the adjacent terraces was made before beginning the 1984 calculation of evapotranspiration The field reconnaissance consisted of field trips in 1984 and use of a complete set of aerial photographs taken in August 1985 at an approximate scale of 1 32,000 Field reconnaissance of the Hoover Dam to Davis Dam reach was accomplished entirely by using aerial photographs Specific objectives were (1) delineation of the total area for which evapotranspiration would be calculated, (2) selection of one or more calibration sites that were representative of each reach, and (3) selection of approximate dates for mapping the vegetation to get the necessary information with the fewest trips to the sites The reconnaissance included a survey of crop and phreatophyte types, irrigation practices, distribution of diverters, and hydrology and geomorphology of the flood plain Potential problem areas were noted as well as places where special care in interpretation might be necessary in the analyses

Delineation of the Total Vegetated Area

To calculate evapotranspiration, all areas to which water diverted from the river or pumped from the flood plain was applied were included in the analysis Crops are grown in Mohave Valley in the Davis Dam to Parker Dam reach, in Parker, Palo Verde, and Cibola Valleys in the Parker Dam to Imperial Dam reach, and in the Yuma area in the Imperial Dam to Morelos Dam and Morelos Dam to the SIB reaches (fig 2)

Identification of the species, stand mix, and stand density of phreatophytes also was made for each reach to calibrate the vegetation classifications Many phreatophyte areas located between and in cropped fields complicated the interpretation of the subsequent classifications The flood releases of 1983 and 1984 changed the areas of phreatophyte distribution, areas covered by phreatophytes in 1984 were not always the same as those shown in earlier photographs and maps

The Bill Williams River flows into Lake Havasu (pl 1) just upstream from Parker Dam Reconnaissance showed that dense phreatophytes were transpiring water in the reach between the gage below Alamo Dam and the confluence with the Colorado River The Bill Williams River therefore had to be included in the area for which evapotranspiration was calculated to determine the quantity of discharge to the Colorado River

The boundaries of the areas used to calculate evapotranspiration were mapped (pl 2) All areas that used water from the Colorado River or pumped water on the adjacent terraces are included for consistency in the calculations

Selection of Calibration Sites

Vegetation classifications require interpretation and calibration in at least one area in each valley where the vegetation types are known. The statistical characteristics of different vegetation types at various times during a year generally are not sufficiently distinct to positively identify each type without calibration. Therefore, detailed vegetation maps were made for one or more calibration sites on the flood plain for each reach.

Calibration sites were selected in each of the five agricultural areas of the flood plain: Mohave (fig. 3), Parker (fig. 4), Palo Verde, and Cibola (fig. 5) Valleys and the Yuma area (fig. 6). Calibration sites were not selected for nonagricultural areas containing only phreatophytes. These areas were calibrated by vegetation-type maps published by Anderson and Ohmart (1976). Each of the agricultural areas in the flood plain and each of the phreatophyte areas between them are referred to as subreaches of their respective reach.

Calibration sites were selected according to four criteria:

(1) Crop mix—A calibration site should have a crop mix that is representative of the area being classified. The correct crop mix in all growing seasons is the most important characteristic to accurately classify the crop types. All crops, except minor crops planted in only a few fields, should be represented.

(2) Proportion of crops—The proportion of crops in the calibration site should approximate the proportion found in the total area. On the lower Colorado River flood plain, major crops such as alfalfa tend to form two or more classes in the vegetation classifications. Some of these classes can be misinterpreted if the calibration site contains too few alfalfa fields to represent all the classes.

(3) Physical characteristics of the site—Unbroken areas of each cover type should be as large as possible to distinguish among the cover types and to determine characteristics of each type. Otherwise, border pixels covering part of the field and part of an adjacent area could dominate and obscure the classification of a small field. Either the site should be easily accessible by road if ground transportation is used for reconnaissance, or permission for low-flying aircraft must be obtainable.

(4) Cost of revisiting the site—Finally, the site should not be too large to survey in about a day on the ground or an hour by plane or helicopter to keep the cost of revisiting as low as possible.

Calibration sites selected for the lower Colorado River are shown in figures 3–6. One calibration site was selected for Mohave Valley because the crop mix was fairly uniform over the area and no double cropping occurred. Two calibration sites were used for Parker Valley in order to include all the double cropping and diversity of crop mixes. One calibration site was selected for Palo Verde Valley because crop data by fields are compiled annually for the entire valley by Palo Verde Irrigation District and are available to augment field reconnaissance if required. Cibola Valley Irrigation and Drainage District was mapped entirely because it is relatively small and because the area planted with crops changed in each of the 3 years prior to 1984. A few fields in the southern part of the Yuma area were not included in the 1984 Landsat images of the area (fig. 6). Crops were identified in these fields by field reconnaissance. Areas of the fields were digitized from maps and areas by crop types were subsequently added to the crop areas from the Yuma classification. The single Yuma calibration site selected to calibrate the image classification is adjacent to these fields (fig. 6).

Selection of Calibration Dates

Selection of the best times to map vegetation in an area depends on the growing seasons of the crops in that area. In Mohave and Cibola Valleys, only alfalfa, cotton, wheat, and bermuda grass were found during the field reconnaissance; therefore, one trip in May when all these crops were growing and could be identified in the fields was sufficient to map the vegetation in 1984. Field reconnaissance of the flood plain of the Bill Williams River below Alamo Dam showed that only phreatophytes and small amounts of alfalfa and cotton grew on the flood plain.

Parker Valley, Palo Verde Valley, and the Yuma area have a complex mix of vegetation types and many multiple-cropped fields. In 1984, lettuce was the only winter vegetable crop mapped in Parker and Palo Verde Valleys. Several additional winter vegetable crops—including cauliflower, broccoli, and cabbage—were mapped in the Yuma area. Melons, tomatoes, and onions were grown in the spring and early summer in all three areas; therefore, three crop-mapping trips were required—winter (January) for spring lettuce, cauliflower, broccoli, cabbage, and wheat, late spring (May) for cotton, melons, tomatoes, and onions, and fall (October) for fall lettuce Alfalfa, bermuda grass, and other perennials were mapped on all trips In the Yuma area, late summer crops, such as milo and peanuts, necessitated an additional reconnaissance trip in August The dates are somewhat flexible in each growing season and depend not only on the crop mix each year but also on variations in local weather conditions that could delay or advance crop planting, development, or harvesting times

Preparation of Crop Maps

Base maps were prepared at a scale of 1 48,000 for the agricultural areas from USGS 1 24,000-scale topographic maps Boundaries of the fields were drafted onto the base maps from the aerial photographs During each crop-mapping trip, fields were coded with their crop types At the end of the year, a unique color or pattern was selected for each crop type or multiple-crop mix found during the trips A master map was then made for each calibration site, using the color-pattern codes, to calibrate the vegetation classifications (pl 3)

Selection of Image Dates

Growing seasons of the major vegetation types were used to identify image dates for the 1984 vegetation classifications from the images available Image dates were selected to correspond to the maximum ground cover of the vegetation types to be classified Another important temporal feature was the absence or dormancy of a crop on one or more of the image dates The identification of major crop types, such as cotton (summer) and wheat (winter), was aided significantly by the presence or absence of these crops at key times of the year

The path of the Landsat satellite is from northeast to southwest over the Earth's surface Although the path is continuous, the data are separated into images of approximately 115 mi in length for processing by Goddard Space Flight Center Two Landsat 5 images, which overlapped approximately at Poston, Arizona, were required to cover all the Colorado River flood plain from Davis Dam to the southern part of the Yuma area The same overpass dates were selected for both the north and south images to minimize variability caused by differences in atmospheric haze, sun angle, and percentage of ground cover within a growing season

The image dates selected for the 1984 classification were February 17, May 24, and August 28 Major vegetation types in the February 17 image were lettuce, cauliflower, and early wheat Vegetation types in the May 24 image were senescent wheat, melons, safflower, and spring phreatophytes Cotton and summer phreatophytes were the principal vegetation types included in the August 28 image Many fields prepared and irrigated for fall crops also were evident on the August image Perennial crops, such as citrus, alfalfa, and bermuda, were present on all image dates

Georeferencing

Georeferencing is the process of establishing the geographic location of each pixel in an image and coding that information as an attribute of the pixel Georeferencing is required when images are combined with other spatial-data layers, such as the boundaries of the areas served by diversions from the river, by matching map coordinates The coordinate system used for the 1984 classification was the Universal Transverse Mercator (UTM) projection The UTM projection is divided into zones 1,000,000 m wide The lower Colorado River flood plain is near the east edge of zone 11 Because the UTM projection is flat and the Earth's surface is curved, the projection becomes increasingly distorted near the edges of each zone

Four steps were required to georeference the 1984 images (1) ground-control points, such as road intersections and field corners, were identified on the images, and the row and column numbers of the corresponding pixels were determined, (2) the UTM coordinates for these points were digitized from USGS 1 24,000-scale topographic maps, (3) a georeferencing program (Graham and others, 1985, p PMGE 1) matched the row and column numbers to the UTM coordinates and mapped the images by generating UTM coordinates for each pixel, and (4) the pixels were resampled to 50 m × 50 m (0 62 acres) georeferenced pixels As much as possible of the area outside the flood plain was trimmed from the georeferenced images before the analysis in order to increase processing efficiency and to minimize the amount of misleading or extraneous information to be processed

Band Ratios

The band-ratio technique (Taranik, 1978) was used to enhance the reflectance characteristics of the vegetated areas The Landsat MSS records the reflectance of the ground cover in four bands of the spectrum green, 0 4–0 5 μm, red, 0 5–0 6 μm, and two near-infrared bands, 0 7–0 8 and 0 8–1 1 μm Healthy vegetation reflects a high percentage of near-infrared radiation and absorbs a high percentage of red radiation, whereas nonvegetated areas tend to reflect or absorb about the same amount of radiation in both the near-infrared and red spectral bands This characteristic reflectance response allows vegetated areas to be separated from nonvegetated areas The reflectance values of pixels in the near-infrared (0 8–1 1 μm) band were divided by their corresponding values in the red band to obtain infrared/red band ratios

Image Classification

The purpose of image classification is to group together those pixels that have similar reflectance characteristics on the image dates selected The assumption is made that all the pixels in each class represent the same type of ground cover In an "ideal" classification, the number of classes generated would be equal to the number of different kinds of ground cover in the image In reality, the number of classes generally is greater or less than the number of cover types because of one of the following conditions (1) border pixels that contain more than one ground-cover type, (2) different ground-cover types, such as crops and volunteer vegetation or phreatophytes, that have similar spectral characteristics through time, and (3) single ground-cover types, such as mowed and unmowed alfalfa, that differ in appearance over the area classified

The band ratios for each of the three image dates were combined into a single data file for each classification Each file was then classified by using the maximum-likelihood classification algorithm (Graham and others, 1985, p A13–A17) The output from each image classification was a table containing the sequential number of each ground-cover class, the number of pixels in the class, and the mean value of the pixels in each of the three band ratios in the combined-image file

General Interpretation of the Classification

The number of classes resulting from an image classification varies with the number of cover types having different reflectance characteristics in the area covered by the images For the 1984 classifications, the number of classes ranged from 28 in Mohave Valley to 45 in the Yuma area Interpretation of classes for the flood-plain area was made by using the output tables and the crop maps prepared for each calibration site

Most of the classes in each classification represented vegetation ground-cover types because the band ratios enhanced the vegetation-reflectance characteristics The reflectance characteristics of nonvegetated types of ground cover in the images were minimized, which caused them to be compressed into only a few ground-cover classes The output tables were used to separate vegetation classes, which had high band-ratio values, from nonvegetation classes, which had low values The dates on which high or low band-ratio values occurred were indicative of the growing seasons of specific vegetation types

In most areas, the crop mix was too complex to be separated using only spectral and temporal characteristics, crop maps prepared for the calibration sites also were required to separate vegetation types Vegetation classes were identified throughout each classification as the vegetation type they represented in the calibration site Some classes were so small or discontinuous that they were not represented in the calibration site The vegetation types were then determined by spectral and temporal characteristics alone In cases where two or more vegetation types had the same characteristics and were combined in the same class, the type covering the largest area in the calibration site was selected because it had the highest probability of being correct Some minor vegetation types therefore might not have been correctly identified with this approach

Different criteria were used to identify and separate phreatophytes Crops usually are grown in fields that have regular geometric shapes in the lower Colorado River flood plain on the United States side of the border The distribution of phreatophytes generally follows that of the old river meanders because of the phreatophytes' dependency on soil moisture (and therefore soil type) Some phreatophytes, however, grow in and between cropped fields Crop types and density generally are uniform in a field, whereas phreatophytes grow in mixed stands of variable density, these characteristics provide a basis for separating crops from phreatophytes Landsat MSS resolution proved insufficient for separating phreatophyte species from each other in these mixed stands Phreatophyte classes were identified and separated by density by using spectral and temporal characteristics in the output tables and by using vegetation-type maps for the lower Colorado River flood plain compiled by Anderson and Ohmart (1976)

Photographs, maps, and Landsat false-color composites showing the general occurrence and distribution of ground-cover types outside the flood plain were used to interpret classes in those areas In most cases, a few pixels from each of these classes also occurred in the flood plain and had to be identified to complete the classification All nonvegetation classes and parts of vegetation classes that occurred outside the flood plain were then ignored for the rest of the analyses

Separation of the Classification by Diverter Boundaries

To calculate evapotranspiration by diverter and point of diversion, the vegetated areas in the flood plain are separated into the subareas served by each diversion Evapotranspiration can then be calculated for each vegetation type in the subarea and summed to obtain evapotranspiration by diverter

Identification of Boundaries

The boundaries of each subarea are established first In this context, the term "diverters" includes all users of water from the river—whether that water is diverted or pumped, transpired directly from the flood-plain aquifer by the vegetation, or used to maintain wildlife habitat Many of the diverters specifically named in the Decree have subareas with well-established and mapped boundaries, such as Indian reservations, military reservations, national wildlife refuges, and Federal, State, and local parks and recreation areas These boundaries, intersected by the boundaries of the flood plain, were used for separating the 1984 vegetation classification Subareas in which all the water used is transpired by phreatophytes, such as in the wildlife refuges, had to be included because phreatophyte transpiration is part of total consumptive use by vegetation and therefore also is a part of the estimated total evapotranspiration

Irrigation-district boundaries were well established in most cases and were obtained from the USBR or from the records of the irrigation districts The boundaries were not as obvious between subareas that used water diverted from the river or pumped from wells on the flood plain and those that used water pumped from wells on the adjacent terraces Irrigation-district and USBR records were used to establish these boundaries wherever possible, but a few areas require further clarification for the operational accounting system

The boundaries of subareas served by non-contract diverters and those of subareas pumping water that might be defined as tributary inflow are not complete in the 1984 calculations The boundaries of subareas from which subsurface flows do not return to the lower Colorado River or are not available for reuse in the United States also have not been firmly established in all areas Boundaries of subareas served by each diverter (pl 2) are the most accurate that could be determined at the time of the study

Mapping the Boundaries

Boundaries of all the subareas established for the lower Colorado River flood plain were drafted onto USGS 1 24,000-scale topographic maps The polygons formed by the subarea boundaries, intersected by the map boundaries where applicable, were each digitized from the separate maps (Graham and others, 1985, p DGTZ 1—2) The UTM coordinates were generated by the software for each digitized point to georeference the polygons

Separation by Diverter

Digitized polygons were mapped to the classified images for each reach by matching the corresponding UTM coordinates The polygons served as the boundaries for those subareas of the classified images within them The classified images were separated by the polygons into the subareas or parts of subareas belonging to each diverter (Graham and others, 1985, p PLYX 1) Each of these parts of the classified image then became a separate file

The number of acres covered by each vegetation type in each subarea of the classified images was determined as follows (1) the number of pixels in each class was summed, (2) the sums were multiplied by 0 62 acres per georeferenced pixel, and (3) a table was generated showing the class numbers, number of pixels for that class in the subarea, percentage of the subarea covered by that class, and the number of acres in the polygon covered by the class A technical description of these three steps is found in a report by Graham and others (1985, p PLYA 1—4) The number of acres of each vegetation type in the polygons was obtained by summing the number of acres of each class identified as that vegetation type The number of acres of each vegetation type in each subarea was then generated by summing the polygons within that subarea Final output from the image classification was a table for each reach of the river that contains a description of each class, a description of each subarea, and a list showing the classes grouped into each cover type

Water Use by Vegetation

Vegetation, which consists of crops and phreatophytes, uses water from the lower Colorado River In 1984, the major crops were alfalfa, cotton, wheat, lettuce, melons, bermuda grass, citrus, and safflower The rest of the vegetation consists of phreatophytes, which include saltcedar, mesquite, arrowweed, saltbush, cottonwood, and willow, in stands of various compositions and densities Consumptive use of Colorado River water by crops is charged to users by point of diversion, diverter, and State as specified in the Decree Consumptive use by phreatophytes, which is part of the consumptive use by vegetation calculated in the water budget of the river, is separated from consumptive use by crops in LCRAS so that it is not charged to agricultural water users

Weather data, used in LCRAS to estimate evapotranspiration, are available from the National Climatic Data Center for a number of stations throughout the study area (pl 1) An adequate number of weather stations are in or near the Colorado River valley, where temperature and precipitation data are collected Availability of weather data for stations in each of the river reaches allows local weather conditions to be incorporated into the calculations of evapotranspiration and consumptive use by vegetation The data are not complete for some years, therefore, the stations used to calculate the amount of precipitation falling on vegetation (see section of report entitled "Precipitation") and the precipitation and temperature data used to estimate water-use rates need to be evaluated on an annual basis prior to input into LCRAS

To calculate water-use rates, complete records of both temperature and precipitation have to be available for the station selected to represent the reach Stations with complete monthly records used for each reach in 1984 were selected from those listed in tables 13 and 18, stations with incomplete data were not included in tables 13 and 18 In 1984, availability of complete records of temperature and precipitation at the same weather stations on the flood plain resulted in the same stations being used to calculate precipitation that falls on the vegetated area and water-use rates

Average water-use rates by vegetation type are required to calculate evapotranspiration These rates vary with local weather conditions—particularly temperature, precipitation, solar radiation, and wind speed Temperature and precipitation data are

Table 18. Monthly mean temperatures at selected weather stations along the lower Colorado River, 1984

[Data from National Climatic Data Center (1951–84a, b, c)]

River reach	Weather station[1]	Monthly mean temperature, in degrees Fahrenheit											
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Hoover Dam to Davis Dam	Boulder City	49 9	52 3	59 7	64 1	81 3	83 0	87 6	85 6	81 8	64 4	55 1	45 3
	Willow Beach	51 6	54 6	62 9	67 5	83 7	87 6	92 5	89 8	87 1	69 0	58 6	49 0
Davis Dam to Parker Dam	Bullhead City	57 1	58 5	66 4	71 7	87 2	89 6	96 2	93 7	89 3	70 8	59 4	51 3
	Needles Airport	55 3	58 4	65 3	70 5	86 2	89 1	94 1	92 5	88 8	70 3	59 8	51 3
	Lake Havasu	54 8	57 4	65 7	70 5	86 6	90 2	95 1	94 2	89 9	72 0	61 0	51 7
Parker Dam to Imperial Dam	Parker Reservoir	55 6	58 2	66 3	70 7	87 1	89 0	93 2	92 2	88 8	69 9	59 8	50 8
	Parker	55 9	58 0	66 2	71 1	85 2	87 7	93 0	92 5	88 0	69 8	59 0	51 9
	Blythe	55 0	56 8	65 0	69 1	84 3	85 5	91 9	91 0	86 7	69 3	58 5	52 1
	Blythe Airport	56 7	58 3	67 0	70 6	85 5	87 5	93 2	92 2	89 4	71 9	60 5	53 1
	Ehrenberg	58 0	60 1	65 5	71 6	86 3	89 0	93 1	92 6	90 0	71 9	61 4	53 8
Imperial Dam to Morelos Dam	Yuma Airport	60 0	61 5	67 8	70 8	85 9	87 7	92 6	92 4	90 6	73 5	63 2	56 0
	Yuma Citrus Station	55 7	56 7	64 0	67 2	81 2	83 9	90 4	89 2	87 2	69 6	58 8	52 8
	Yuma Proving Ground	58 6	59 6	66 5	69 7	84 4	86 8	91 1	91 4	89 1	71 8	61 5	54 3
	Yuma Valley	56 9	58 8	64 8	67 2	80 6	83 0	89 1	88 4	86 8	70 4	59 8	53 9

[1]Locations shown on plate 1

available at most of the weather stations in the study area, but solar-radiation and wind-speed data are not The availability of only temperature and precipitation data limits the choice of formulas available to estimate water-use rates Wind-speed and solar-radiation data would allow use of other formulas, which include the effects from changes in local conditions on the estimation of evapotranspiration

The Blaney-Criddle formula (Blaney and Criddle, 1950) can be used to calculate water-use rates by vegetation type provided that empirical water-use coefficients have been computed The Blaney-Criddle formula was modified to adjust water-use rates for crops for precipitation variations throughout the flood plain Empirical water-use coefficients are not available for mixed stands of phreatophytes, therefore, annual (K factors) and monthly (k factors) water-use coefficients were estimated during this study for phreatophyte mixtures along the lower Colorado River for use in LCRAS

Water-Use Rates for Crops

Water-use rates for a particular crop type vary with (1) local weather conditions, (2) density distribution, and (3) farm-management practices, such as planting and harvesting dates, crop variety, and amount and scheduling of irrigation Differences in weather conditions owing to temperature and precipitation variations were accounted for by adjusting the water-use rates for these variables Data were insufficient to adjust the water-use rates for the effects of solar radiation and wind speed Variations in evapotranspiration owing to density distributions were accounted for by the vegetation classifications, from which only the areas of actual ground cover for each vegetation type were calculated Accounting for variations within and between individual fields that resulted from differences in management practices was beyond the scope of this study

Water-use rates were calculated by modifying the formula developed by Blaney and Criddle (1950) to include precipitation The modified formula is expressed as

$$U = \sum_{m=1}^{12} \left[k_m \left(\frac{t_m d_m}{100} \right) - \frac{p_m}{12} \right], \qquad (13)$$

where

U = crop irrigation water-use rate, in acre-feet per acre per year, during the growth of the crop,

k_m = monthly empirical water-use coefficient that is dependent on the type and location of the crop,

t_m = monthly mean temperature, in degrees Fahrenheit,

d_m = percentage of daylight hours of the year that occur during a particular month, and

p_m = monthly precipitation, in inches

Monthly precipitation was included in the formula used to estimate evapotranspiration by crop types because crops are shallow-rooted plants compared with phreatophytes, and precipitation that falls on irrigated soil can be used by the plants Crop use of precipitation reduces the use of irrigation water Empirical water-use coefficients for the crops (table 19) were obtained from field tests conducted by the U S Department of Agriculture near Phoenix, Arizona (Erie and others, 1965, 1982) Monthly mean temperatures and monthly precipitation were used for the various agricultural areas as follows (1) Bullhead City, Arizona, for Mohave Valley, (2) Parker, Arizona, for Parker Valley north of latitude 34° N and for the Bill Williams River area below Alamo Dam, (3) Blythe, California, for the part of Parker Valley south of latitude 34° N and for Palo Verde and Cibola Valleys, and (4) Yuma Valley, Arizona, for the Yuma area (pl 1) The monthly percentage of daylight hours (table 20) was interpolated from Cruff and Thompson (1967, p M17)

Water-use rates were calculated for each of the crop types identified in each of the reaches for 1984 by using LCRAS (table 21) Water-use rates for crop types calculated by using weather data from Parker are slightly higher than those calculated by using weather data from Bullhead City because average monthly temperatures are higher and precipitation is lower during the summer in Parker than in Bullhead City Wheat, a winter-spring crop, has about the same water-use rate in both areas Water-use rates calculated by using weather data from Blythe are slightly lower than those for the same crop types calculated by using Parker data, with the exception of fall lettuce The differences could be attributed to slightly higher precipitation and lower temperatures in Blythe during the winter-spring-summer months than in Parker Water-use rates were calculated for crops in Cibola Valley by using weather data from Blythe because continuous weather records were not available from

Table 19. Empirical water-use coefficients for crops in the lower Colorado River valley

[Data from Erie and others (1965, table 1)]

Vegetation type	Monthly empirical water-use coefficient											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Cotton	0 00	0 00	0 00	0 09	0 27	0 60	1 20	1 40	1 11	0 60	0 27	0 00
Alfalfa	00	92	1 21	1 25	1 36	1 36	1 22	1 10	1 33	95	80	00
Bermuda	00	00	00	66	79	1 06	1 17	1 10	89	71	00	00
Sorghum	00	00	00	00	00	00	44	1 48	1 05	35	00	00
Wheat	43	80	1 63	1 63	42	00	00	00	00	00	04	30
Citrus	39	48	41	46	47	55	58	63	64	63	59	40
Broccoli	1 02	54	00	00	00	00	00	00	20	74	1 19	99
Melons	00	00	00	12	51	1 42	63	00	00	00	00	00
Cauliflower	96	00	00	00	00	00	00	00	20	66	1 33	78
Fall lettuce	00	00	00	00	00	00	00	00	04	35	67	94
Safflower	14	33	80	1 92	1 49	1 56	34	00	00	00	00	00
Spring lettuce	04	35	67	94	00	00	00	00	00	00	00	00
Dry onions	34	56	1 23	1 72	43	00	00	00	00	00	00	00
Milo	00	00	00	00	00	00	44	1 48	1 10	34	00	00
Corn	07	44	1 50	1 49	00	00	00	00	00	00	00	00
Dates	5 17	00	00	00	00	00	00	00	00	00	00	00
Tomatoes	2 00	00	00	00	00	00	00	00	00	00	00	00

Table 20 Monthly percentage of total daylight hours of the year

[Data from Cruff and Thompson (1967, p M17)]

Latitude, °N.	Monthly percentage of daylight hours of the year											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
24	7 58	7 17	8 40	8 60	9 30	9 20	9 41	9 05	8 31	8 09	7 43	7 46
26	7 49	7 12	8 40	8 64	9 38	9 30	9 49	9 10	8 31	8 06	7 36	7 35
28	7 40	7 07	8 39	8 68	9 46	9 38	9 58	9 16	8 32	8 02	7 27	7 27
30	7 30	7 03	8 38	8 72	9 53	9 49	9 67	9 22	8 34	7 99	7 19	7 14
32	7 20	6 97	8 37	8 75	9 63	9 60	9 77	9 28	8 34	7 93	7 11	7 05
34	7 10	6 91	8 36	8 80	9 72	9 70	9 88	9 33	8 36	7 90	7 02	6 92
36	6 99	6 86	8 35	8 85	9 81	9 83	9 99	9 40	8 36	7 85	6 92	6 79
38	6 87	6 79	8 34	8 90	9 92	9 95	10 10	9 47	8 38	7 80	6 82	6 66
40	6 76	6 73	8 33	8 95	10 02	10 08	10 22	9 54	8 38	7 75	6 72	6 52
42	6 62	6 65	8 31	9 00	10 14	10 21	10 35	9 62	8 40	7 70	6 62	6 38
44	6 49	6 58	8 30	9 05	10 26	10 38	10 49	9 70	8 41	7 63	6 49	6 22
46	6 33	6 50	8 29	9 12	10 39	10 54	10 64	9 79	8 42	7 58	6 36	6 04
48	6 17	6 42	8 27	9 18	10 53	10 71	10 80	9 89	8 44	7 51	6 22	5 86
50	5 98	6 32	8 25	9 25	10 69	10 93	10 99	10 00	8 44	7 43	6 07	5 65

a weather station closer to the agricultural areas of Cibola Valley

Water-use rates for crop types calculated by using weather data from Yuma Valley are lower than those calculated by using data from the stations north of Imperial Dam for all crops except fall lettuce The Yuma Valley weather station is in the middle of a large agricultural area where temperatures are not as extreme as those recorded by weather stations north of Imperial Dam Occasional records of wind speed and evaporation also indicate that the evaporation in the Yuma area could be the lowest or among the lowest measured on the flood plain between Hoover Dam and Mexico, although it is the most southerly reach with the lowest average elevation

Alfalfa consistently used almost twice as much water per unit area as cotton and almost three times as much as wheat throughout the flood plain (table 21) This relation between water-use rates for the three

Table 21. Water-use rates for vegetation types and densities along the lower Colorado River, 1984, calculated by the Lower Colorado River Accounting System

River reach and vegetation type	Monthly water-use rate, in feet												
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Hoover Dam to Davis Dam—Willow Beach, Arizona[1]													
Phreatophytes													
Medium	0 00	0 22	0 41	0 48	0 72	0 75	0 81	0 73	0 62	0 33	0 21	0 00	5 28
Sparse	00	18	32	38	57	60	65	58	50	26	17	00	4 21
Mohave Valley—Bullhead City, Arizona[1]													
Alfalfa	00	31	56	66	97	1 00	72	70	82	44	14	00	6 32
Cotton	00	00	00	05	19	44	70	92	68	28	00	00	3 26
Wheat	14	27	75	86	30	00	00	00	00	00	00	00	2 32
Phreatophytes													
Dense	00	28	52	61	90	92	1 01	92	77	41	25	00	6 59
Medium	00	24	43	51	75	77	84	76	63	34	21	00	5 48
Sparse	00	19	34	41	60	62	67	61	51	27	17	00	4 39
Bill Williams River—Parker, Arizona[1]													
Alfalfa	00	31	56	66	95	98	87	77	73	43	24	00	6 50
Cotton	00	00	00	05	19	43	85	99	59	27	06	00	3 43
Phreatophytes													
Dense	00	28	52	60	88	91	98	91	75	40	25	00	6 48
Medium	00	24	43	50	73	75	81	75	63	33	21	00	5 38
Sparse	00	19	34	40	59	60	65	60	50	26	17	00	4 30
Parker Valley north of latitude 34° N —Parker, Arizona[1]													
Alfalfa	00	31	56	65	94	96	86	76	73	44	24	00	6 45
Citrus	13	16	19	24	32	39	37	42	30	29	17	00	2 98
Cotton	00	00	00	05	19	43	84	98	59	28	06	00	3 42
Fall lettuce	00	00	00	00	00	00	00	00	00	16	20	00	36
Melons	00	00	00	06	35	1 01	41	00	00	00	00	00	1 83
Spring lettuce	01	12	31	49	00	00	00	00	00	00	00	00	93
Wheat	14	27	75	85	29	00	00	00	00	00	00	00	2 30
Phreatophytes													
Dense	00	28	52	60	87	89	96	90	75	40	26	00	6 43
Medium	00	24	43	50	72	74	80	75	63	34	21	00	5 36
Sparse	00	19	34	40	58	60	64	60	50	27	17	00	4 29
Parker Valley south of latitude 34° N , Palo Verde and Cibola Valleys—Blythe, California[1]													
Alfalfa	00	30	55	63	93	94	83	59	80	43	23	00	6 23
Citrus	12	16	19	23	32	38	35	26	39	29	16	00	2 85
Cotton	00	00	00	05	18	41	82	80	67	27	05	00	3 25
Fall lettuce	00	00	00	00	00	00	00	00	02	16	18	00	36
Melons	0 00	0 00	0 00	0 06	0 35	0 98	0 39	0 00	0 00	0 00	0 00	0 00	1 78

Table 21 Water-use rates for vegetation types and densities along the lower Colorado River, 1984, calculated by the Lower Colorado River Accounting System—*Continued*

River reach and vegetation type	Monthly water-use rate, in feet												
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Parker Valley south of latitude 34° N , Palo Verde and Cibola Valleys—Blythe, California[1]—Continued													
Spring lettuce	01	11	30	48	00	00	00	00	00	00	00	00	90
Wheat	13	26	74	83	28	00	00	00	00	00	00	00	2 24
Phreatophytes													
Dense	00	28	51	58	86	87	95	88	74	40	25	00	6 32
Medium	00	23	42	49	72	73	79	74	62	33	21	00	5 28
Sparse	00	19	34	39	57	58	64	59	50	26	17	00	4 23
Yuma Area—Yuma Valley, Arizona[1]													
Bermuda	00	00	00	29	51	70	64	66	53	33	00	00	3 66
Citrus	13	16	19	19	30	36	21	33	38	29	18	00	2 72
Cotton	00	00	00	01	17	40	66	86	67	28	07	00	3 12
Fall lettuce	00	00	00	00	00	00	00	00	02	16	21	16	55
Safflower	05	11	36	90	96	1 04	04	00	00	00	00	00	3 46
Spring lettuce	01	12	30	42	00	00	00	00	00	00	00	00	85
Wheat	15	27	74	76	27	00	00	00	00	00	00	00	2 19
Phreatophytes													
Dense	00	29	51	56	81	84	91	85	74	41	26	00	6 18
Medium	00	24	42	47	68	70	76	71	62	34	22	00	5 16
Sparse	00	19	33	38	54	56	61	57	49	27	17	00	4 11

[1]Weather station used to calculate water-use rates for each of the areas noted

crops has remained relatively constant in similar studies done previously along the lower Colorado River flood plain (Raymond and Owen-Joyce, 1987, Owen-Joyce, 1988, Raymond and Rezin, 1989), although the actual values of the rates fluctuated from area to area and from year to year

Water-Use Rates for Phreatophytes

Water use by phreatophytes is an important part of the total evapotranspiration and has to be included in the calculations, even though consumptive use by phreatophytes is not charged to the diverters Water-use rates have not been well established for phreatophytes growing in mixed stands of variable density Culler and others (1982) determined water-use rates for mixed phreatophytes of different densities in south-central Arizona 3 50 ft for dense phreatophytes, 2 50 ft for medium phreatophytes, and 1 50 ft for sparse phreatophytes Investigations by McDonald and Hughes (1968), Rantz (1968), Boyle Engineering Corporation (1976), and L W Gay (School of Renewable Natural Resources, University of Arizona, oral commun , 1985) indicate that the Culler rates are not unrealistic for a mesquite-saltcedar-arrowweed mix that is mostly mesquite By 1984, most phreatophyte communities along the lower Colorado River were dominated by saltcedar, which is a change from mesquite-dominated communities in the past Saltcedar has a higher water-use rate than mesquite (U S Bureau of Reclamation, 1963, p 30)

Empirical coefficients are available for some phreatophyte species from studies done by the U S Bureau of Reclamation (1963, 1973) to estimate annual water use by phreatophytes along the lower Colorado River The annual water-use rates and empirical coefficients estimated by the USBR are for growth at 100-percent-volume density and include only ground-water use (U S Bureau of Reclamation, 1963, p 30) Additional work by the USBR on estimating water use by phreatophytes defined a relation between evapotranspiration and the density of vegetative cover (U S Bureau of Reclamation, 1973, p 3) The most recent maps of phreatophyte community types were compiled for 1986 (Younker and Andersen, 1986) Using the data and the methods developed in these studies, the USGS and USBR developed the following method to estimate empirical coefficients for mixed stands of phreatophytes of variable density These coefficients are used in LCRAS to estimate evapotranspiration by phreatophytes with the Blaney-Criddle formula (Blaney and Criddle, 1950)

The lower Colorado River flood plain was separated into divisions, and the areas of phreatophyte community types were compiled for each division (Younker and Andersen, 1986) To use these data, the divisions were grouped to correlate with the reaches used in LCRAS The Davis Dam to Parker Dam reach contains the Mohave, Topock Gorge, and Havasu divisions The Parker Dam to Imperial Dam reach contains the Parker, Palo Verde, Cibola, and Imperial divisions The Imperial Dam to Morelos Dam (near NIB) reach contains the Laguna and Yuma divisions The Limitrophe division is the reach between Morelos Dam and the SIB The Davis Dam to Morelos Dam reach contains all the divisions except the Limitrophe division and is used to represent the reach from Hoover Dam to Morelos Dam in LCRAS

Annual evapotranspiration rates and *K* factors were selected from Younker and Andersen (1986) to match the phreatophyte species or community types mapped along the lower Colorado River in 1986 (table 22) For community types, a rate or factor was calculated by using the percentages by species within the community Computational details are given in the footnotes of table 22

Evapotranspiration by phreatophytes (table 23) was calculated by multiplying the area of each community type (table 22) by the evapotranspiration rate for that community type (table 23) Average evapotranspiration rates by reach were computed by dividing the total evapotranspiration summed for the divisions in each reach (table 23) by the total area summed for the divisions in the reach (table 22) The average evapotranspiration rates by reach are shown in table 23

Weighted average annual *K* factors (table 24) for mixed stands of phreatophytes of 100-percent density were computed by multiplying the annual *K* factors for the community types (table 24) by the areas of each community type (table 22) Weighted average annual *K* factors by reach (table 24) were computed by dividing the total product of *K* factor times the area, summed for the divisions in the reach (table 24), by the total area summed for the divisions in the reach (table 22)

The average evapotranspiration rate (table 23) and weighted annual *K* factor (table 24) calculated for the Davis Dam to NIB reach were used as the evapotranspiration rate and weighted annual *K* factor for a mixed stand of lower Colorado River phreatophyte types of 100-percent density Evapotranspiration rates (table 23) and weighted annual *K* factors (table 24) for medium and sparse densities were calculated by using the density factors, 85 and 70 percent, respectively, developed by the U S Bureau of Reclamation (1973)

The weighted annual *K* factors calculated for dense, medium, and sparse phreatophytes were then used to develop monthly *k* factors so that the estimation of phreatophyte evapotranspiration calculated in LCRAS could use the Blaney-Criddle formula and be similar to that used for crops The development of monthly *k* factors from annual *K* factors is shown and explained in table 25 The monthly *k* factors for phreatophytes were developed by prorating the annual *K* factor value over the months of the year, assuming the same growing season as alfalfa

Water-use rates were calculated for the three density types classified by image analysis in each of the reaches (table 21) by using the formula developed by Blaney and Criddle (1950), which can be expressed as

$$U = \sum_{m=1}^{12} \left[k_m \left(\frac{t_m d_m}{100} \right) \right] \qquad (14)$$

The same mean monthly temperatures used for estimating water-use rates for crops for the different reaches were used to estimate water-use rates for phreatophytes Monthly precipitation was not included in equation 14 to estimate water-use rates for phreatophytes because phreatophytes are deep-rooted plants that use ground water from the alluvial aquifer Little or no penetration of the small quantities of precipitation occurs below the soil zone in the study area Moisture measurements made during a previous study showed that the materials between the top few feet and the water table are nearly dry outside the irrigated areas (Olmsted and others, 1973, p 72)

Table 22 Areas by community type of phreatophytes along the lower Colorado River, 1986

Vegetation community type[2]	Evapo-transpiration, in feet	K^3	Community type area by division[1], in acres									
			Mohave	Topock Gorge	Havasu	Parker	Palo Verde	Cibola	Imperial	Laguna	Yuma	Limitrophe
Saltcedar	[4]8 5	[4]1 4	14,455	272	671	7,562	2,221	9,966	3,047	3,096	2,153	1,594
Cottonwood-Willow	[4]7 0	[4]1 2	1,090	10	681	1,003	804	185	240	207	260	1,274
Honey mesquite	[4]3 9	[4]0 7	4,567	0	147	573	5,444	758	166	26	0	0
Saltcedar-Screwbean mesquite	[5]7 6	[5]1 3	6,246	0	20	5,237	2,411	1,336	84	78	80	0
Saltcedar-Honey mesquite	[5]7 6	[5]1 3	2,802	45	52	205	1,593	2,554	534	95	0	0
Arrowweed	[4]5 5	[4]0 9	2,389	0	77	3,194	424	91	57	1,062	117	67
Atriplex	[6]5 5	[6]0 9	623	0	16	320	11	7	0	0	254	0
Inkweed	[7]3 9	[7]0 7	221	0	0	0	0	0	0	0	0	0
Marsh[8]												
Marsh 1	[9]8 5	[9]1 4	1,211	511	537	93	75	60	2,302	799	69	0
Marsh 2–7	[10]7 2	[10]1 2	927	502	0	566	78	48	2,621	66	853	1,231
Creosote	[7]3 9	[7]0 7	0	0	0	0	0	0	0	0	426	0
TOTAL			34,531	1,340	2,201	18,753	13,061	15,005	9,051	5,429	4,212	4,166

[1]Data from Younker and Andersen (1986, p 18)
[2]Vegetative community types are defined in Younker and Andersen (1986, p 4)
[3]Annual empirical consumptive-use coefficient that is dependent on the type and location of vegetation used in the Blaney-Criddle formula (Blaney and Criddle, 1950)
[4]U S Bureau of Reclamation (1963, p 30)
[5]Calculated for 20-percent mesquite and 80-percent saltcedar by definition in Younker and Andersen (1986, p 4) using the evapotranspiration and *K* factors from U S Bureau of Reclamation (1963, p 30)
[6]Assumed same as arrowweed
[7]Assumed same as mesquite
[8]Marsh types are designated by numbers 1–7 and defined in Younker and Andersen (1986, p 5)
[9]Used evapotranspiration and *K* factors for tules (U S Bureau of Reclamation, 1963, p 30)
[10]Calculated as 75-percent tules (U S Bureau of Reclamation, 1963, p 30) and 25-percent bermuda grass (U S Bureau of Reclamation, 1973, table 9)

Calculation of Evapotranspiration by Reach

Hoover Dam to Davis Dam

Evapotranspiration by phreatophytes in the Hoover Dam to Davis Dam reach was calculated by using equation 14 The classification included areas of medium and sparse phreatophytes (table 26) but no areas of dense phreatophytes greater than or equal to 0 62 acres, which is the maximum resolution of a resampled Landsat pixel About 2,980 acre-ft of water was transpired by phreatophytes in 1984 (table 27)

Davis Dam to Parker Dam

The reach from Davis Dam to Parker Dam was subdivided into three subreaches on the basis of the morphology of the flood plain and the vegetation distribution (1) Davis Dam to Big Bend near the north end of Mohave Valley, (2) Big Bend to Topock, which includes Mohave Valley and Topock Marsh, and (3) Topock to Parker Dam, which includes Lake Havasu Subreach 2 contains all the agricultural areas and most of the phreatophytes and is discussed first Subreaches 1 and 3 contain most of the open water and

Table 23. Evapotranspiration by phreatophytes along the lower Colorado River assuming 100-percent density

[NIB, northerly international boundary, SIB, southerly international boundary]

Vegetation community type[2]	Evapo-trans-piration, in feet[3]	Evapotranspiration[1] by area, in acre-feet									
		Mohave	Topock Gorge	Havasu	Parker	Palo Verde	Cibola	Imperial	Laguna	Yuma	Limi-trophe
Saltcedar	8 5	122,869	2,313	5,704	64,278	18,879	84,711	25,900	26,317	18,301	13,549
Cottonwood-Willow	7 0	7,630	70	4,767	7,021	5,628	1,295	1,680	1,449	1,820	8,918
Honey mesquite	3 9	17,811	0	573	2,235	21,232	2,957	648	101	0	0
Saltcedar-Screwbean mesquite	7 6	47,469	0	152	39,802	18,323	10,154	638	593	608	0
Saltcedar-Honey mesquite	7 6	21,295	342	395	1,558	12,106	19,410	4,058	722	0	0
Arrowweed	5 5	13,140	0	424	17,567	2,332	501	314	5,841	644	369
Atriplex	5 5	3,427	0	88	1,760	61	39	0	0	1,397	0
Inkweed	3 9	862	0	0	0	0	0	0	0	0	0
Marsh											
Marsh 1	8 5	10,294	4,344	4,565	791	638	510	19,567	6,792	587	0
Marsh 2–7	7 2	6,674	3,614	0	4,076	561	346	18,872	476	6,141	8,863
Creosote	3 9	0	0	0	0	0	0	0	0	1,661	0
TOTAL		251,471	10,683	16,668	139,088	79,760	119,923	71,677	42,291	31,159	31,699
Average evapotranspiration by division, in feet		7 3	8 0	7 6	7 4	6 1	8 0	7 9	7 8	7 4	7 6

Average evapotranspiration by reach

Davis Dam to Parker Dam	7 3	Davis Dam to NIB	[4]7 4 Dense phreatophytes
Parker Dam to Imperial Dam	7 3		[5]6 3 Medium phreatophytes
Imperial Dam to NIB	7 6		[6]5 2 Sparse phreatophytes
NIB to SIB	7 6		

[1]Evapotranspiration (column 2) times the area from table 22
[2]Vegetative community types are defined in Younker and Andersen (1986 p 4)
[3]See table 22 for source
[4]Assumed a density factor of 100 percent for dense phreatophytes (U S Bureau of Reclamation, 1973, p 3)
[5]Assumed a density factor of 85 percent for medium phreatophytes (U S Bureau of Reclamation, 1973, p 3)
[6]Assumed a density factor of 70 percent for light or sparse phreatophytes (U S Bureau of Reclamation, 1973, p 3)

minor amounts of phreatophytes and are discussed together

Big Bend to Topock

Field reconnaissance showed that many of the cropped fields, particularly alfalfa, in Mohave Valley contained sufficient areas of volunteer vegetation and bare soil to be classified as mixed stands of variable density This type of vegetation distribution resulted in a "salt and pepper" mix of ground-cover classes in the image classification Interpretation of these classes was often difficult Alfalfa and wheat were the

Table 24. Estimation of annual empirical consumptive-use coefficients (*K*) for the mixed stands of phreatophytes of variable density along the lower Colorado River

[NIB, northerly international boundary, SIB, southerly international boundary]

Vegetation community type[2]	K^3	*K* × area[1]									
		Mohave	Topock Gorge	Havasu	Parker	Palo Verde	Cibola	Imperial	Laguna	Yuma	Limitrophe
Saltcedar	1 4	20,238	381	939	10,588	3,109	13,952	4,266	4,335	3,014	2,233
Cottonwood-Willow	1 2	1,308	12	816	1,203	965	222	288	249	312	1,529
Honey mesquite	0 7	3,197	0	103	401	3,811	531	116	18	0	0
Saltcedar-Screwbean mesquite	1 3	8,120	0	26	6,808	3,135	1,737	109	101	104	0
Saltcedar-Honey mesquite	1 3	3,642	59	66	267	2,071	3,321	694	124	0	0
Arrowweed	0 9	2,150	0	69	2,875	382	82	51	956	105	60
Atriplex	0 9	561	0	14	288	10	6	0	0	229	0
Inkweed	0 7	155	0	0	0	0	0	0	0	0	0
Marsh											
Marsh 1	1 4	1,695	715	752	130	105	84	3,223	1,119	97	0
Marsh 2–7	1 2	1,112	602	0	680	93	58	3,146	80	1,023	1,477
Creosote	0 7	0	0	0	0	0	0	0	0	298	0
TOTAL		42,178	1,769	2,785	23,240	13,681	19,993	11,893	6,982	5,182	5,299
Weighted average annual *K*		1 2	1 3	1 3	1 2	1 0	1 3	1 3	1 3	1 2	1 3

Weighted average annual *K* by reach

Davis Dam to Parker Dam	1 2	Davis Dam to NIB	[4]1 2 Dense phreatophytes
Parker Dam to Imperial Dam	1 2		[5]1 0 Medium phreatophytes
Imperial Dam to NIB	1 3		[6]0 8 Sparse phreatophytes
NIB to SIB	1 3		

[1]Area from table 22

[2]Vegetative community types are defined in Younker and Andersen (1986, p 4)

[3]Annual empirical consumptive-use coefficient that is dependent on the type and location of vegetation used in the Blaney-Criddle formula (Blaney and Criddle, 1950) See table 22 for source

[4]Assumed a density factor of 100 percent for dense phreatophytes (U S Bureau of Reclamation, 1973, p 3)

[5]Assumed a density factor of 85 percent for medium phreatophytes (U S Bureau of Reclamation, 1973, p 3)

[6]Assumed a density factor of 70 percent for light or sparse phreatophytes (U S Bureau of Reclamation, 1973, p 3)

vegetation types most frequently confused because areas of volunteer vegetation in the poorly distributed alfalfa died or became dormant during the hot summer months, their spectral and temporal characteristics therefore resembled those of winter wheat The classes were coded according to the dominant vegetation type on the crop map for the area covered by each type

Table 25. Calculated monthly empirical water-use coefficients (*k*) for dense, medium, and sparse phreatophytes of mixed species along the lower Colorado River

[NIB, northerly international boundary]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
				ALFALFA *k* FACTORS (with dormancy period) Annual = 1 20								
Monthly[1]	0 00	0 92	1 21	1 25	1 36	1 36	1 22	1 10	1 33	0 95	0 80	0 00
Distribution[2]	0 00	0 77	1 01	1 04	1 13	1 13	1 02	0 92	1 11	0 79	0 67	0 00
				ALFALFA *k* FACTORS (without dormancy period) Annual = 1 29[3]								
Monthly	0 00	0 92	1 21	1 25	1 36	1 36	[4]1 36	[4]1 35	1 33	0 95	0 80	0 00
Distribution[2]	0 00	0 71	0 94	0 97	1 05	1 05	1 05	1 05	1 03	0 74	0 62	0 00
				PHREATOPHYTE *k* FACTORS FOR DAVIS DAM TO NIB (Based on alfalfa without dormancy period)								
Dense[5]	0 00	0 85	1 12	1 15	1 26	1 26	1 26	1 25	1 23	0 88	0 74	0 00
Medium[6]	0 00	0 71	0 96	0 96	1 05	1 05	1 05	1 04	1 02	0 73	0 62	0 00
Sparse[7]	0 00	0 57	0 77	0 77	0 84	0 84	0 84	0 83	0 82	0 58	0 49	0 00

[1]Erie and others (1982, table 2)

[2]Calculated as the ratio of monthly *k* factor to annual *K* factor

[3]Estimated as the ratio of annual consumptive use, 80 0 in , of alfalfa without a dormancy period and the annual consumptive use, 74 3 in , with a dormancy period times the annual *k* factor of alfalfa with a dormancy period (80 0/74 3 × 1 20 = 1 29, data from Erie and others, 1982, p 11)

[4]Monthly *k* factors for July and August were extrapolated by smoothing a plot of monthly consumptive use vs month of year (Erie and others, 1982, p 11)

[5]Assumed a density factor of 100 percent for dense phreatophytes (U S Bureau of Reclamation, 1973, p 3)

[6]Assumed a density factor of 85 percent for medium phreatophytes (U S Bureau of Reclamation, 1973, p 3)

[7]Assumed a density factor of 70 percent for light or sparse phreatophytes (U S Bureau of Reclamation, 1973, p 3)

Table 26. Areas of phreatophytes, Hoover Dam to Davis Dam, 1984

[Types and areas of vegetation were compiled from image classifications of satellite digital-image data]

Diverter[1]	Phreatophytes, in acres: Medium	Sparse	Total
Lake Mead National Recreation Area	10	696	706
Total	10	696	706
Total vegetated area			706
Net vegetated area			706

[1]Boundaries of the areas served by each diverter are plotted on plate 2

Table 27 Estimates of evapotranspiration by vegetation by diverter, Hoover Dam to Davis Dam, 1984

Diverter[1]	Evapotranspiration, in acre-feet	Percentage[2]
Federal lands:		
Lake Mead National Recreation Area	2,983	100 00
Total (rounded)	2,980	100 00
Reach total	2,980	100 00

[1]Areas plotted on plate 2

[2]Percentage of total evapotranspiration calculated for the Hoover Dam to Davis Dam subreach

Vegetation classes showing winter and spring growth, but not summer growth, included both alfalfa and wheat, according to the image classification (pl 3*A*) when compared with the crop map (pl 3*B*) of the calibration area Fields containing these mixed classes were most apparent in the northwestern part of the calibration site Fields coded as abandoned on the crop map were classified as alfalfa, wheat, cotton, or nonvegetated, depending on the spectral and temporal characteristics of the volunteer vegetation, if any, growing in them Boundaries between fields of different crops were often indistinct and fuzzy in the image classification of the calibration site in Mohave Valley compared with those from calibration sites in other parts of the flood plain (pl 3), indicating that the fields were not cultivated and (or) not irrigated uniformly from the centers to the edges This pattern of crop distribution in fields was confirmed by the field reconnaissance

All the fields with bermuda grass were classified as alfalfa Bermuda and alfalfa are perennial crops with similar spectral characteristics and are harvested by periodic mowing The image class containing alfalfa and bermuda was coded as alfalfa because alfalfa covers a much larger total area in Mohave Valley The bias in image interpretation of mixed classes is always toward the major crop The cotton class, as shown in the calibration site, corresponded quite closely to the areas mapped as cotton, except for one field coded as weeds in the crop map Cotton is the only crop mapped in Mohave Valley that has a summer growing season but no apparent growth on the winter or spring images, which contributed to its correct classification

The distribution of vegetated areas by diverter and point of diversion is particularly complex in Mohave Valley (pl 2) On the Arizona side of the river, ownership is by sections and alternates between the Fort Mohave Indian Reservation and the State of Arizona in a checkerboard pattern Most of the flood plain on the west side of the river, with the exception of part of the Fort Mohave Indian Reservation in California, is covered by phreatophytes or by irrigated landscaping, including lawns and gardens in the city of Needles The boundaries of urban areas were digitized separately wherever possible to prevent misclassification of landscaping as irrigated crops Water use in urban areas is a separate category of consumptive use and is discussed in the section "Domestic, Municipal, and Industrial Consumptive Use "

Topock Marsh in the southern part of Mohave Valley contains large areas of phreatophytes, and some of the phreatophytes have the same density, spectral, and temporal characteristics as the crops in the valley In a few cases, these phreatophytes were included in classes that also contained crops The digitized ownership boundaries were used to make major separations between crops and phreatophytes for these classes Field reconnaissance had shown that crops were not grown in the Havasu National Wildlife Refuge, which includes most of Topock Marsh (pl 2) Classes containing both crops and phreatophytes in the refuge were coded as dense, medium, or sparse phreatophytes according to their spectral characteristics in the statistical tables The same vegetation classes were coded as crops in areas belonging to the Fort Mohave Indian Reservation or the States of Arizona, California, or Nevada Some phreatophytes, therefore, were misclassified as crops in areas outside the refuge, but the misclassification was minimized by this approach

Davis Dam to Big Bend and Topock to Parker Dam

These subreaches are similar in morphology and vegetation distribution to the Hoover Dam to Davis Dam reach Field reconnaissance showed that crops were not present in these subreaches Areas of phreatophytes around Lake Havasu were small and generally confined to the mouths of tributaries Land-ownership boundaries were determined only to the level of State or Federal reserves Areas of phreatophytes by State are combined with those of the Big Bend to Topock subreach

Evapotranspiration

Areas of each vegetation type that resulted from the image classification of the Davis Dam to Parker Dam reach were summed by diverter (table 28) The Fort Mohave Indian Reservation had the largest agricultural area in production, followed by the States of Arizona and California, respectively Alfalfa was more common than cotton, although the classification problem between alfalfa and wheat, discussed previously, might have resulted in areas of alfalfa that are classified as too large or too small Phreatophytes accounted for 45 percent of all the vegetation in the Davis Dam to Parker Dam reach About 35 percent of the phreatophytes were in Havasu National Wildlife Refuge The rest were distributed in and between the cropped fields and probably included areas mapped as crops

Evapotranspiration was estimated by using equation 9 for each diverter in the Davis Dam to Parker Dam reach (table 29) Most of the evapotranspiration, about 58 percent, was in Arizona The largest single diverter in the reach was the Fort Mohave Indian Reservation (in all three States), which used 57 percent of all the water transpired by crops and 32 percent of all the water used in the reach Phreatophytes transpired about 43 percent of the total evapotranspiration and covered 45 percent of the vegetated area More than half the total phreatophyte area, however, was classified as sparse

Table 28 Areas of each vegetation type by diverter, in acres, Davis Dam to Parker Dam, 1984

[Types and areas of vegetation were compiled from image classifications of satellite digital-image data]

Diverter[1]	Alfalfa	Cotton	Wheat	Phreatophytes Dense	Phreatophytes Medium	Phreatophytes Sparse	Total
Arizona:							
Bullhead City	0	0	0	0	0	4	4
Fort Mojave Indian Reservation	5,873	3,829	222	0	0	3,557	13,481
Lake Havasu Airport	0	0	0	0	0	0	0
State of Arizona	4,256	1,114	157	92	9	3,585	9,213
California:							
Chemehuevi Indian Reservation	0	0	0	1	0	2	3
City of Needles	0	0	0	137	146	365	648
Fort Mojave Indian Reservation	1,749	19	346	0	0	268	2,382
Park Moab	0	0	0	1	5	12	18
State of California	1,993	271	557	105	19	1,151	4,096
Nevada							
Fort Mojave Indian Reservation	0	0	0	[2]151	[2]26	487	664
State of Nevada	0	0	0	[2]418	468	883	1,769
Federal lands							
Havasu National Wildlife Refuge	0	0	0	1,860	1,450	2,768	6,078
Lake Mead National Recreation Area	0	0	0	4	6	31	41
TOTAL	13,871	5,233	1,282	2,769	2,129	13,113	38,397
Total vegetated area	38,397						
Net vegetated area	38,397						

[1] Boundaries of the areas served by each diverter are plotted on plate 2

[2] No crops were grown in Nevada in 1984 Misclassification of phreatophytes as crops was minimized but could not be eliminated within some of the water-user boundaries (see subsection "Davis Dam to Parker Dam" in the section "Calculation of Evapotranspiration by Reach") In Nevada, vegetation classified as alfalfa was actually dense phreatophytes, and that classified as cotton was actually medium phreatophytes

The importance of correct alfalfa classification can be seen by comparing evapotranspiration for the Fort Mohave Indian Reservation and for State land, both in Arizona, with their respective areas of alfalfa and cotton Although the reservation had 1 8 times as many acres planted to crops as did the State land, evapotranspiration calculated for the reservation was only 1 6 times as high as that calculated for the State land owing primarily to the difference in water-use rates for alfalfa and cotton

Parker Dam to Imperial Dam

The Parker Dam to Imperial Dam reach covers about half the total length of the flood plain between Hoover Dam and the SIB (pl 1) and includes more than half the irrigated acreage The subreaches from Parker Dam to Headgate Rock Dam near the north end of Parker Valley and from the streamflow-gaging station below Cibola Valley to Imperial Dam are similar in morphology and vegetation distribution to the Hoover Dam to Davis Dam reach, however, the

Table 29. Estimates of evapotranspiration by vegetation by diverter, Davis Dam to Parker Dam, 1984

Diverter[1]	Evapo-trans-piration, in acre-feet	Per-cent-age[2]
Arizona:		
Bullhead City	0	0 00
Fort Mojave Indian Reservation	50,115	25 70
Lake Havasu Airport	0	00
State of Arizona	30,894	15 85
Phreatophytes	32,026	16 43
Total (rounded)	113,000	58 00
California:		
Chemehuevi Indian Reservation	0	00
City of Needles	0	00
Fort Mojave Indian Reservation	11,918	6 11
Park Moabi	0	00
State of California	14,771	7 58
Phreatophytes	10,434	5 35
Total (rounded)	37,100	19 00
Nevada:		
Fort Mojave Indian Reservation	[3]0	00
State of Nevada	[3]0	00
Phreatophytes	12,260	6 29
Total (rounded)	12,300	6 00
Federal lands:		
Havasu National Wildlife Refuge	32,355	16 60
Lake Mead National Recreation Area	195	10
Total (rounded)	32,600	17 00
Reach totals	195,000	100 00

[1]Boundaries of the areas served by each diverter are plotted on plate 2

[2]Percentage of total evapotranspiration calculated for the Davis Dam to Parker Dam subreach

[3]Misclassification within the image classification process of phreatophytes as crops resulted in 1,039 and 2,642 acre-feet of evapotranspiration calculated for the Fort Mojave Indian Reservation and State of Nevada, respectively, which have been added to evapotranspiration by phreatophytes in Nevada

flood plain is slightly wider with more phreatophytes in the subreach between the gage below Cibola Valley and Imperial Dam

Two image classifications were required because of a boundary between Landsat scenes in Parker Valley near Poston, Arizona (pl 2) The same interpretation was used for both classifications in Parker Valley Image interpretations for Parker, Palo Verde, and Cibola Valleys and for the nonagricultural subreaches are discussed separately The calculation of areas of vegetation and separation of evapotranspiration by diverter are discussed for the entire reach as a unit

Parker Valley

Principal crops by acreage for Parker Valley were cotton, alfalfa, wheat, melons, grasses (hay, pasture, and bermuda seed), and miscellaneous vegetables, according to crop reports available from the BIA This crop mix was confirmed by field reconnaissance of the calibration sites (pl 3*D*, *F*) Crop types were determined by image classification (pl 3*C*, *E*)

Most of the area classified as cotton corresponded to areas mapped as cotton The two exceptions, cotton followed by wheat and cotton followed by alfalfa, were classified as cotton because the second crops were planted in the late fall after the summer Landsat images were obtained The alfalfa classification corresponded closely to the areas mapped as alfalfa in the calibration sites Two exceptions included a small area of bermuda grass, as in Mohave Valley, and some fields where the alfalfa was replanted with onions in the fall (pl 3*E*, *F*) Most of the wheat was correctly classified A few wheat fields in the northern parts of both calibration sites were misclassified as alfalfa that had been mowed in the summer, therefore, both crops appeared as winter-spring vegetation in the classification Several blocks of fields were mapped as fall lettuce from the previous year followed by spring wheat These fields were classified as wheat

The most common multiple-cropping pattern was lettuce followed by cotton Four blocks of fields of this crop mix can be identified near the center of the calibration sites (pl 3*D*, *C*) A fifth block near the upper center of one calibration site did not have sufficient ground cover (pl 3*C*) to be classified as an unbroken vegetated area Fewer types of multiple cropping were identified by image classification than were mapped in the calibration sites The tendency for crops that cover small areas to be included in the same classes as crops that cover large areas is discussed in the section entitled "General Interpretation of the Classification " Some crops were not present in the fields during any of the overpass dates selected for classification Fall lettuce, which is usually planted in August and harvested by the end of November, cannot be identified directly by a multitemporal classification when February is the earliest image date of the year and August is the latest The presence of fall lettuce was indicated, however, by the spectral characteristics in the August image of the cultivated, generally wet fields in which the lettuce had been or was about to be planted In some cases, multiple-cropped fields were also misclassified as perennial crops—usually as alfalfa because of its large acreage—owing to the interpretation bias

The maximum resolution of the images (0 62 acres) precluded fine distinctions between vegetation types that differ primarily in their distribution patterns within the fields, such as the difference between the distribution of melon and tomato plants (north-central part of pl 3*F*, *E*) The class containing both melons and tomatoes was coded as melons because this crop had the larger acreage in the calibration sites and in the BIA crop reports

Minimal overlap occurred between crop and phreatophyte classes in Parker Valley except for a few areas of spring-summer phreatophytes in the melons and tomatoes class Neither digitized boundaries nor separate interpretations were used to improve the identification of the phreatophyte classes Some phreatophyte classes were located in and between fields These corresponded to areas of natural or volunteer vegetation observed during field reconnaissance

Boundaries of the areas served by each diversion in Parker Valley (pl 2) were determined according to the procedure described in the section "Separation of the Classification by Diverter Boundaries " Additional boundaries were digitized to separate areas that were hydrologically discrete so that the evapotranspiration calculated for these areas could be used to help calculate total consumptive use for the test site, as described in the subsequent section "Comparison of Methods in the Parker Dam to Imperial Dam Reach " These areas included four individual farms (North Lyn-de Farm, South Lyn-de Farm, Bernal Farm, and Clark Farm) on the flood plain on the California side of the Colorado River near the middle of the valley, two farms (CRIR South Farm and Ehrenberg Farm) on the flood plain on the Arizona side of the river at the south end of the valley, and Lower Quail Mesa in the southern part of the Colorado River Indian Reservation on the Arizona side (pl 2) Arizona and California lands were not subdivided further into private and State ownership

Palo Verde Valley

The distribution of crop types in Palo Verde Valley was similar to that in Parker Valley, according to crop reports and maps supplied by the PVID The distribution was confirmed by field reconnaissance and is shown in the crop map for the calibration site (pl 3*H*) Field reconnaissance of the calibration site was incomplete in March Spring-crop information for some fields was obtained from the crop data supplied by PVID

A comparison of the image classification and the crop map of the calibration site (pl 3*G*, *H*) gave similar results to those obtained for Parker Valley and shows that most areas of the major crops—cotton, alfalfa, wheat, and lettuce followed by cotton—were correctly identified by the image classification Fields of melons or tomatoes were classified as a single ground-cover type, which was coded as melons A few fields of alfalfa in the northwestern part of the calibration site were misclassified as wheat Fields identified as fall cotton (1983 crop) and spring wheat (1984 crop) were classified as wheat

Misclassifications among perennial crops are a common problem in multitemporal-image classification, particularly when one or more of the crops cover a small area In the Palo Verde classification, the perennial crops misclassified as alfalfa were bermuda grass and citrus orchards The orchards were identified by their distinctive ground-cover pattern on the aerial photographs This information was added into the image classification by digitizing the boundaries of the orchards and creating a new ground-cover class for the areas within the digitized boundaries The recoding technique could not be applied to other minor crops, such as bermuda grass, that did not have a distinctive appearance on the aerial photographs

Separate interpretation of phreatophyte classes was not required because phreatophytes are only a minor part of the vegetation in Palo Verde Valley These phreatophyte classes corresponded to areas of natural or volunteer vegetation observed during field reconnaissance, as in Parker Valley

Some of the established boundaries of the areas served by each diversion (pl 2) do not appear to coincide with the boundaries of the agricultural fields as shown by the image classification, particularly in the area just north of Palo Verde Dam on the California side of the river and on Palo Verde Mesa Other established boundaries separate areas that are legally but not hydrologically distinct, such as areas where the river channel was relocated by the USBR for management purposes One example is Cibola Island (pl 2) just west of Cibola Valley Irrigation and Drainage District, where channelization of the river isolated land in Arizona on the California side of the main channel

Cibola Valley

Cibola Valley includes the Cibola Valley Irrigation and Drainage District (CIDD), which is primarily covered by irrigated agriculture, and the Cibola National Wildlife Refuge (CNWR) (pl 2), which consists mainly of phreatophytes, although some fields are cultivated and irrigated to grow alfalfa and forage crops for wildlife The crop map for Cibola Valley was obtained entirely by field reconnaissance (pl 3*J*) The crop mix was simpler in CIDD than in Parker or Palo Verde Valleys and multiple cropping did not occur Cotton, alfalfa, milo, and bermuda grass were the only crops grown in CIDD in 1984 Small areas of alfalfa, small grains (including wheat, barley, and rye), and milo were grown in CNWR

Separate interpretations of the image classification were required for the two areas of Cibola Valley because the dense phreatophytes in CNWR and the alfalfa in CIDD had similar spectral and temporal characteristics and were included in some of the same vegetation classes (see plate 3*I* for interpretation results) Cotton fields were correctly identified A small area of alfalfa near the center of CIDD (pl 3*I*, *J*) was classified as cotton, presumably because the mowing patterns for those fields showed apparent vegetation only on the summer image The rest of the alfalfa and the bermuda and milo were classified as alfalfa Some overlap between crop and phreatophyte classes can be observed because phreatophytes were growing in some cropped fields, as in Mohave Valley The mixed classes of crops and phreatophytes in CNWR were coded as phreatophytes because phreatophytes dominated the area and because water use by cropped fields in the wildlife refuges is included in the refuge allocations

Parker Dam to Headgate Rock Dam and Cibola Gage to Imperial Dam

Separate image classifications were not made for the subreaches from Parker Dam to Headgate Rock Dam and from the Colorado River below Cibola Valley streamflow-gaging station (site 43, pl 1) to Imperial Dam Phreatophytes were separated by density classes dense, medium, or sparse Established boundaries for Federal and State parks and recreation areas were digitized The rest of the areas were separated by the boundaries of the flood plain and the State line into Arizona and California lands (pl 2)

Areas of Vegetation by Diverter

The number of acres classified as each vegetation type for the Parker Dam to Imperial Dam reach were summed by diverter (table 30) In Parker Valley, most of the cultivated land is on the Colorado River Indian Reservation Alfalfa and cotton covered the largest acreages—about 27,400 and 25,600 acres, respectively Wheat covered the third largest with about 11,700 acres Lettuce and melons were the only other crops identified from the calibration site for Parker Valley Other diverters in Parker Valley specialized in particular vegetation types, such as alfalfa and wheat for CRIR South Farm and cotton for Ehrenberg Farm The large areas of phreatophytes (22,900 acres) are primarily along the Colorado River west of Poston and along the edge of the flood plain southeast of Poston

Palo Verde Irrigation District had the greatest number of acres under cultivation in the entire reach The areas of alfalfa and cotton were smaller than those of the Colorado River Indian Reservation, but the areas of wheat, lettuce, and melons were much larger Included in these major crop areas were sudan and bermuda (in the alfalfa class), tomatoes (in the melons class), and onions (observed during field reconnaissance but not mapped in the calibration site) Field reconnaissance also showed that the areas classified as fall lettuce included fields cultivated and irrigated in preparation for planting a fall crop other than lettuce (usually cauliflower) On Palo Verde Mesa, areas classified as melons probably included jojoba because, according to crop reports and field reconnaissance, jojoba was more common than melons on the mesa Areas classified as lettuce or melons in CIDD appeared in parts of the valley mapped as phreatophytes because some phreatophytes have spectral and temporal characteristics similar to those crops

Cotton and alfalfa were the major crops in the Parker Dam to Imperial Dam reach, with nearly equal areas, followed in order by wheat, lettuce, melons, and citrus Cotton and alfalfa accounted for 66 percent of the net cropped area in the reach, compared with 94 percent of the net cropped area in the Davis Dam

Table 30. Areas of each vegetation type by diverter, in acres, Parker Dam to Imperial Dam, 1984

[Types and areas of vegetation were compiled from image classifications of satellite digital-image data]

Diverter[1]	Alfalfa	Citrus	Cotton	Fall lettuce	Melons	Spring lettuce	Wheat	Phreatophytes Dense	Phreatophytes Medium	Phreatophytes Sparse	Total
Arizona:											
Arkelian Farms	265	15	0	26	49	0	57	7	9	5	433
Cibola Valley Irrigation and Drainage District	430	99	2,077	11	65	13	60	301	302	296	3,654
Cibola Island	18	12	26	3	1	6	16	4	0	0	86
Colorado River Indian Reservation	27,434	1,601	25,594	4,634	4,128	1,727	11,698	4,339	5,265	5,805	92,225
Colorado River Indian Reservation—Mesa	62	0	3	0	6	0	0	12	10	44	137
Colorado River Indian Reservation—South Farm	553	94	1	88	8	0	286	233	323	155	1,741
Ehrenberg Farm	2	12	468	3	31	20	47	36	88	73	780
Lower Quail Mesa	447	104	192	0	11	7	44	161	64	40	1,070
State of Arizona	28	14	487	14	142	20	58	479	1,114	1,045	3,401
California:											
Bernal Farm	5	0	336	7	45	0	7	68	75	72	615
Clark Farm	553	106	469	82	9	20	184	269	403	204	2,299
Colorado River Indian Reservation	864	4	202	6	100	0	11	1,168	1,256	2,030	5,641
North Lyn-De Farm	40	1	120	2	95	0	2	432	166	48	906
Picacho State Recreation Area	0	0	0	0	0	0	0	30	472	180	682
Palo Verde Mesa	175	225	574	19	500	27	156	103	36	32	1,847
Palo Verde Irrigation District	22,486	5,169	23,505	9,493	11,972	3,672	20,963	2,969	2,541	1,391	104,161
South Lyn-De Farm	0	0	105	9	83	0	9	25	41	34	306
State of California	92	12	518	159	596	1	285	814	809	741	4,027
Federal lands:											
Cibola National Wildlife Refuge	0	0	0	0	0	0	0	2,322	794	3,937	7,053
Havasu National Wildlife Refuge	0	0	0	0	0	0	0	10	75	43	128
Imperial National Wildlife Refuge	0	0	0	0	0	0	0	527	4,692	2,381	7,600
TOTAL	53,454	7,468	54,677	14,556	17,841	5,513	33,883	14,309	18,535	18,556	238,792
Total vegetated area	238,792										
Net vegetated area	214,956										

[1]Boundaries of the areas served by each diverter are plotted on plate 2

to Parker Dam reach. Phreatophytes decreased from 45 percent of the net vegetated area in the Davis Dam to Parker Dam reach to 24 percent of the net vegetated area in the Parker Dam to Imperial Dam reach. A trend toward lower water-use crops and more speculative cropping practices is apparent from north to south along the flood plain.

Evapotranspiration

Evapotranspiration was estimated by using equation 9 for each diverter in the Parker Dam to Imperial Dam reach (table 31). Results were combined by State for the entire reach (table 31). Arizona had more evapotranspiration than California, about 430,000 acre-ft for Arizona and 418,000 acre-ft for California; however, California had about 17,000 more acres of vegetation mainly because of multiple cropping. The two major water users, PVID and CRIR, used about 66 percent of the total evapotranspiration by vegetation and about 93 percent of the total evapotranspiration by crops. Evapotranspiration by phreatophytes was about 29 percent of the total evapotranspiration in the Parker Dam to Imperial Dam reach compared with about 43 percent in the Davis Dam to Parker Dam reach.

Imperial Dam to Morelos Dam

In the reach from Imperial Dam to Morelos Dam, no division was made between agricultural areas that receive water diverted from the Colorado River at Imperial Dam from those that are irrigated with water pumped from beneath Yuma Mesa. The reach was divided into two subreaches—a short subreach, which is covered with phreatophytes, between Imperial Dam and Laguna Dam and a broad subreach between Laguna Dam and the SIB that includes the agricultural areas in Yuma Valley south of Morelos Dam (fig. 6). Separate image interpretations were made for the Imperial Dam to Laguna Dam subreach and for the Laguna Dam to SIB subreach because of similar spectral and temporal characteristics of some of the crops and phreatophytes in the classification.

Imperial Dam to Laguna Dam

This subreach consists of open water surrounded by dense phreatophytes and, along with Topock Marsh and Cibola Marsh, is an important waterfowl-nesting habitat. The phreatophytes were separated by density classes into dense, medium, and sparse. Land-ownership boundaries in this subreach (pl. 2) were difficult to establish because some jurisdictions appeared to overlap. This problem does not affect the amount of consumptive use charged to the States because crops were not present in the subreach.

Table 31. Estimates of evapotranspiration by vegetation by diverter, Parker Dam to Imperial Dam, 1984

Diverter[1]	Evapo-trans-piration, in acre-feet	Per-cent-age[2]
Arizona:		
Arkelian Farms	1,918	0.21
Cibola Valley Irrigation and Drainage District	9,977	1.08
Cibola Island	275	.03
Colorado River Indian Reservation	300,291	32.56
Colorado River Indian Reservation—Mesa	421	.05
Colorado River Indian Reservation—South Farm	4,403	.48
Ehrenberg Farm	1,747	.19
Lower Quail Mesa	3,830	.42
State of Arizona	2,208	.24
Phreatophytes	105,014	11.39
Total (rounded)	430,100	47.00
California:		
Bernal Farm	1,221	.13
Clark Farm	5,747	.62
Colorado River Indian Reservation	6,458	.70
North Lyn-De Farm	816	.09
Picacho State Recreation Area	0	.00
Palo Verde Mesa	4,868	.53
Palo Verde Irrigation District	306,200	33.20
South Lyn-De Farm	512	.06
State of California	4,056	.44
Phreatophytes	88,015	9.54
Total (rounded)	417,900	45.00
Federal lands:		
Cibola National Wildlife Refuge	35,521	3.85
Havasu National Wildlife Refuge	650	.07
Imperial National Wildlife Refuge	38,177	4.14
Total (rounded)	74,300	8.00
Reach total	922,300	100.00

[1]Boundaries of the areas served by each diverter are plotted on plate 2.

[2]Percentage of total evapotranspiration calculated for the Parker Dam to Imperial Dam subreach.

Laguna Dam to the Southerly International Boundary

The crop mix in this subreach is the most complex of the entire lower Colorado River flood plain Multiple cropping is the rule, with the following 2-year-rotation pattern being the most common winter vegetables (primarily fall and spring lettuce or cauliflower), followed by cotton, followed by wheat Other winter crops include cabbage and broccoli Spring-summer crops, in addition to cotton, are safflower, peanuts, onions, and milo Perennial crops include citrus and date orchards, bermuda grass, asparagus, and some alfalfa, which is not as common around Yuma as it is in the rest of the flood plain Calibration-area crop maps for the Yuma area were made entirely from field reconnaissance (pl 3*L*)

A comparison of the calibration-area crop map (pl 3*L*) with the coded-image classification (pl 3*K*) indicates that most major crops are correctly classified in the calibration site Some overlap was evident between fields classified as a single major crop and fields classified as that crop rotated with lettuce Examples are wheat followed by fall lettuce, spring lettuce followed by cotton, and spring lettuce followed by safflower Classification of the major crop (wheat, cotton, or safflower) was usually correct, but the presence or absence of lettuce was not accurately determined by the classification algorithm Citrus was a major crop type in the Yuma area The citrus class was mostly separate from the bermuda and alfalfa class despite similar spectral and temporal characteristics Spring lettuce grown as a single crop did not have sufficient ground cover to be classified as vegetation

Interpretation of the image classification for the entire Yuma area was difficult because of the complex cropping practices General field reconnaissance showed that perennial crops, including date orchards and asparagus, and some multiple crops had been combined in the largest perennial crop class—citrus The small alfalfa acreage was included in the much larger bermuda class, and cauliflower, broccoli, and cabbage (the cauliflower group) tended to show up in the lettuce classes Lettuce and the cauliflower group had similar spectral characteristics and distribution patterns within the fields on the date that the winter image was obtained, and their cultivated and irrigated fields appeared the same on the summer image

Boundaries of the area served by each diverter corresponded to those of established irrigation districts in most cases (pl 2) Some discrepancies were noted on Yuma Mesa, particularly between those areas irrigated by water diverted from Imperial Dam and those areas irrigated by water pumped from beneath the mesa A few of the boundary discrepancies have not yet been resolved Hillander "C" does not use river water, therefore, it is not carried into the calculations to distribute consumptive use to diverters Crop areas for Hillander "C" are included in table 32 for information only

The number of acres classified as each vegetation type in the Imperial Dam to Morelos Dam reach were summed by diverter (table 32) Yuma Valley had the largest area under cultivation Wheat, lettuce (including the cauliflower group), and cotton were the major crops in Yuma Valley as well as in the whole Yuma area, which would be expected for the most common crop-rotation pattern Citrus was the fourth largest crop for the whole Yuma area Most of the citrus classified was located in the Yuma Mesa Irrigation District, which was confirmed by field reconnaissance and aerial photographs The large area classified as citrus in the Bard Water District was primarily date palms

During field reconnaissance, winter vegetables were not observed in all the areas where fall lettuce was classified, such as the fields irrigated by center pivots at the south end of Yuma Mesa Many of the fields in these areas had been abandoned in 1983, owing to the Payment-In-Kind (PIK) program, and grew a cover of volunteer vegetation in the winter of 1983–84 in response to higher than normal precipitation Evidence of this winter vegetation was noted during field reconnaissance in many fields around the Yuma area A detailed description of the effect of the PIK program on vegetation classification from satellite images is found in Raymond and Owen-Joyce (1987)

Vegetation was not classified in the area called the Five Mile Zone (pl 2) nor was any observed there during field reconnaissance Ground-water pumping is prohibited in that area by treaty with Mexico, and the area is not supplied with surface water from the river The purpose of including the Five Mile Zone as a diverter area is to monitor the land use and to ensure that no agriculture appears there in violation of the treaty

Dense phreatophytes were included in several of the crop classes but were not separated into classes of their own Field reconnaissance showed that few dense phreatophytes grew in the Yuma area The mixed classes of crops and phreatophytes therefore

Table 32. Areas of each vegetation type by diverter, in acres, Imperial Dam to Morelos Dam, 1984

[Types and areas of vegetation were compiled from image classifications of satellite digital-image data]

								Phreatophytes			
Diverter[1]	Bermuda	Citrus	Cotton	Fall lettuce	Safflower	Spring lettuce	Wheat	Dense	Medium	Sparse	Total
Arizona:											
City of Yuma	0	0	0	0	0	0	0	67	387	573	1,027
Cocopah Indian Reservation	64	7	148	17	0	61	58	0	133	50	538
Five Mile Zone	0	0	0	0	0	0	0	0	0	0	0
Fort Yuma Indian Reservation— Reservation Division	107	24	28	161	0	1	176	0	319	145	961
Hillander "C"	401	663	0	307	0	0	307	0	1,064	0	2,742
North Gila Valley	769	753	1,303	3,187	597	413	3,959	0	1,283	376	12,640
South Gila Valley	381	384	907	2,137	161	384	2,687	0	690	154	7,885
State of Arizona	1,240	453	1,716	1,664	20	411	1,885	0	4,298	2,437	14,124
Unit B Irrigation District	109	133	226	473	50	61	583	0	332	145	2,112
Yuma Desert	201	26	532	313	12	143	476	0	395	89	2,187
Yuma Mesa Irrigation District	4,727	13,066	5,954	3,844	1,289	2,694	5,732	0	8,951	1,147	47,404
Yuma Valley	6,417	5,214	14,207	16,994	2,172	4,738	20,717	0	11,216	2,680	84,355
California:											
Bard Water District	738	2,103	1,166	1,800	141	400	2,337	0	2,262	560	11,507
Fort Yuma Indian Reservation— Reservation Division	501	385	2,128	2,326	325	557	2,795	0	2,205	1,437	12,659
Picacho Recreation Land	0	0	0	0	0	0	0	0	53	48	101
State of California	529	182	1,005	446	1	21	486	0	1,837	1,263	5,770
Federal lands.											
Luke Air Force Range	0	0	0	0	0	0	0	4	11	3	18
TOTAL	16,184	23,393	29,320	33,669	4,768	9,884	42,198	71	35,436	11,107	206,030
Total vegetated area	206,030										
Net vegetated area	137,108										

[1]Boundaries of the areas served by each diverter are plotted on plate 2

were interpreted as their respective crop types The mixed classes were interpreted as dense phreatophytes for the city of Yuma and Luke Air Force Range because agriculture was not observed in these areas during field reconnaissance Picacho Recreation Land and Five Mile Zone had no mixed classes of dense phreatophytes

Evapotranspiration

Evapotranspiration was estimated by using equation 9 for each diverter in the Imperial Dam to Morelos Dam reach (table 33) Arizona used about 84 percent of the total evapotranspiration in the reach Yuma Valley used about 26 percent of the total evapotranspiration but had 41 percent of the vegetation

Table 33. Estimates of evapotranspiration by vegetation by diverter, Imperial Dam to Morelos Dam, 1984

Diverter[1]	Evapo-trans-piration, in acre-feet	Per-cent-age[2]
Arizona·		
City of Yuma	0	0 00
Cocopah Indian Reservation	903	16
Five Mile Zone	0	00
Fort Yuma Indian Reservation—Reservation Division	1,019	18
North Gila Valley	21,768	3 82
South Gila Valley	13,212	2 32
State of Arizona	16,586	2 91
Unit B Irrigation District	3,228	57
Yuma Desert	3,844	67
Yuma Mesa Irrigation District	92,834	16 30
Yuma Valley	148,254	26 03
Phreatophytes	176,955	31 07
Total (rounded)	478,600	84 00
California·		
Bard Water District	18,995	3 34
Fort Yuma Indian Reservation—Reservation Division	18,519	3 25
Picacho Recreation Land	0	00
State of California	6,898	1 21
Phreatophytes	46,398	8 15
Total (rounded)	90,800	16 00
Federal lands.		
Luke Air Force Range	94	02
Total (rounded)	100	00
Reach totals	569,500	100 00

[1]Boundaries of the areas served by each diverter are plotted on plate 2

[2]Percentage of total evapotranspiration calculated for the Parker Dam to Imperial Dam subreach

Large amounts of low-water-use crops, such as wheat and fall lettuce, accounted for the difference Other diverters in the reach accounted for relatively small amounts of evapotranspiration Phreatophytes used about 39 percent of the total evapotranspiration

Hoover Dam to Morelos Dam

The reach from Hoover Dam to Morelos Dam includes all the agricultural areas delineated and described previously in the calculation of evapotranspiration by reach The estimates of evapotranspiration by diverters calculated using equation 9 in each of the four reaches are summed to estimate total evapotranspiration for the Hoover Dam to Morelos Dam reach (table 34) Arizona used about 60 percent of the total evapotranspiration computed from Hoover Dam to Morelos Dam, California used 32 percent, and Nevada used 1 percent Federal lands, which contain mostly phreatophytes, used 7 percent of the total evapotranspiration

Distribution of Consumptive Use by Diverter

Consumptive use by vegetation computed with the water budget for the reach from Hoover Dam to Morelos Dam is distributed to users by using the estimates of evapotranspiration calculated for each user and equation 11 The amount of consumptive use subsequently totaled by State (table 34) Consumptive use by crops totals about 1,358,100 acre-ft, and 711,800 acre-ft is used by phreatophytes Water use by crops in Arizona totals about 866,800 acre-ft and 491,300 acre-ft in California Additional information on the distribution of consumptive use by vegetation along the reach is provided in a discussion of the distribution of consumptive use by vegetation in each individual subreach

Open-water evaporation is the largest single source of consumptive use in the Hoover Dam to Davis Dam reach because of Lake Mohave (table 17) Phreatophyte transpiration is only a minor (less than 1 percent) part of the total consumptive use and is not significant for this reach Consumptive use by phreatophytes was 3,700 acre-ft for the Hoover Dam to Davis Dam reach

Open-water evaporation is a significant consumptive use in the Davis Dam to Parker Dam reach because of Lake Havasu (table 17) Consumptive use by vegetation in this reach was 238,900 acre-ft, or about 12 percent of the total calculated for the Hoover Dam to Morelos Dam reach Consumptive use by crops was about 99,200 acre-ft for Arizona and 32,700 acre-ft for California Crops were not grown in Nevada in 1984 Consumptive use by crops on the Fort Mojave Indian Reservation was 76,000 acre-ft Phreatophytes used 107,000 acre-ft

Consumptive use by vegetation for the Parker Dam to Imperial Dam reach was 1,129,800 acre-ft, or about 55 percent of the total calculated for the

Table 34. Estimates of evapotranspiration and consumptive use by vegetation by diverter, Hoover Dam to Morelos Dam, 1984

Diverter[1]	Evapotranspiration, in acre-feet	Percentage[2]	Consumptive use, in acre-feet
Arizona:			
Arkelian Farms	1,918	0 11	2,349
Bullhead City	0	00	0
Cibola Valley Irrigation and Drainage District	9,977	59	12,221
Cibola Island	275	02	336
City of Yuma	0	00	0
Cocopah Indian Reservation	903	05	1,106
Colorado River Indian Reservation	300,291	17 77	367,847
Colorado River Indian Reservation—Mesa	421	02	515
Colorado River Indian Reservation—South Farm	4,403	26	5,393
Ehrenberg Farm	1,747	10	2,140
Five Mile Zone	0	00	0
Fort Mojave Indian Reservation	50,115	2 97	61,389
Fort Yuma Indian Reservation—Reservation Division	1,019	06	1,248
Lake Havasu Airport	0	00	0
Lower Quail Mesa	3,830	23	4,691
North Gila Valley	21,768	1 29	26,665
South Gila Valley	13,212	78	16,184
State of Arizona	49,688	2 94	60,866
Unit B Irrigation District	3,228	19	3,954
Yuma Desert	3,844	23	4,708
Yuma Mesa Irrigation District	92,834	5 49	113,718
Yuma Valley	148,254	8 77	181,606
Phreatophytes	313,995	18 58	384,634
Total (rounded)	1,021,700	60 00	1,251,600
California			
Bard Water District	18,995	1 12	23,268
Bernal Farm	1,221	07	1,495
Chemehuevi Indian Reservation	0	00	0
City of Needles	0	00	0
Clark Farm	5,747	34	7,039
Colorado River Indian Reservation	6,458	38	7,910
Fort Mojave Indian Reservation	11,918	71	14,599
Fort Yuma Indian Reservation—Reservation Division	18,519	1 10	22,685
North Lyn-De Farm	816	05	999
Palo Verde Mesa	4,868	29	5,963
Palo Verde Irrigation District	306,200	18 12	375,085
Park Moabi	0	00	0
Picacho Recreation Land	0	00	0
Picacho State Recreation Area	0	00	0
South Lyn-De Farm	512	03	627
State of California	25,725	1 52	31,512
Phreatophytes	144,847	8 57	177,433
Total rounded)	545,800	32 00	668,600
Nevada:			
Fort Mojave Indian Reservation	[3]0	00	0
State of Nevada	[3]0	0 00	0

Table 34. Estimates of evapotranspiration and consumptive use by vegetation by diverter, Hoover Dam to Morelos Dam, 1984—Continued

Diverter[1]	Evapotranspiration, in acre-feet	Percentage[2]	Consumptive use, in acre-feet
Nevada—Continued:			
Phreatophytes	12,260	.73	15,017
Total (rounded)	12,300	1.00	15,000
Federal lands			
Cibola National Wildlife Refuge	35,521	2.10	43,512
Havasu National Wildlife Refuge	33,005	1.95	40,430
Imperial National Wildlife Refuge	38,177	2.26	46,765
Lake Mead National Recreation Area	3,178	.19	3,892
Luke Air Force Range	94	.01	115
Total (rounded)	110,000	7.00	134,700
Reach totals	1,689,800	100.00	2,069,900

[1]Boundaries of the areas served by each diverter are plotted on plate 2.

[2]Percentage of total evapotranspiration applied to total consumptive use from the water budget to estimate consumptive use by diverter.

[3]Misclassification of phreatophytes as crops within the image classification process resulted in 1,039 and 2,642 acre-feet of evapotranspiration calculated for the Fort Mojave Indian Reservation and State of Nevada, respectively, which have been added to evapotranspiration by phreatophytes in Nevada.

Hoover Dam to Morelos Dam reach. Consumptive use by crops was about 397,900 acre-ft for Arizona and 404,300 acre-ft for California. The Colorado River Indian Reservation used 95 percent of the consumptive use for Arizona, and Palo Verde Irrigation District used 93 percent of the consumptive for California in this subreach. Phreatophytes used 327,600 acre-ft.

Consumptive use by vegetation for the Imperial Dam to Morelos Dam reach was 697,600 acre-ft, or about 34 percent of the total calculated for the Hoover Dam to Morelos Dam reach. Consumptive use by crops was about 369,800 acre-ft for Arizona and about 54,300 acre-ft for California. About 88 percent of consumptive use by crops for Arizona comes from fields in Yuma Valley and on Yuma Mesa. Phreatophytes used 273,400 acre-ft.

Total consumptive use of river water (CU_{ci}) was about 7,129,100 acre-ft, which is higher than normal, because California applied for and received permission to divert some of the excess flow into the Colorado River aqueduct. The components of total consumptive use of river water are summarized by State for 1984 (table 35).

EVALUATION OF THE ACCOUNTING SYSTEM FOR 1984

The lower Colorado River accounting system consists of two parts: (1) the calculation of consumptive use by vegetation with a water budget and (2) the distribution of consumptive use by crops to agricultural water users, which includes the estimation of evapotranspiration for each diverter from digital-image analysis and water-use rates calculated with the Blaney-Criddle formula (Blaney and Criddle, 1950). In each part of the system, the errors associated with the estimation of the individual components, particularly the largest components, have a significant effect on the quantity being calculated and on how the results are interpreted. This evaluation of LCRAS discusses the potential sources of error for the two major parts of LCRAS, compares the computed consumptive use by vegetation in the Parker Dam to Imperial Dam reach with consumptive use by vegetation calculated by using a ground-water budget for the alluvial aquifer that underlies the flood plain, and investigates a potential refinement to LCRAS that would estimate consumptive use by vegetation for four individual subreaches of the Colorado River bounded by Hoover

Table 35 Consumptive use by States of water from the lower Colorado River, 1984

Diverter	Consumptive use, in acre-feet	Percentage of total consumptive use
Arizona:		
Indian reservations	442,189	6 2
State lands	424,747	6 0
Wellton-Mohawk diversion	391,400	5 5
Domestic and municipal	18,575	0 3
Total (rounded)	1,276,900	17 9
California.		
Indian reservations	45,194	0 6
State lands	445,988	6 3
Exported water	4,283,230	60 1
Domestic and municipal	7,278	0 1
Total (rounded)	4,781,700	67 1
Nevada:		
Indian reservations	0	0 0
State lands	0	0 0
Exported water	0	0 0
Domestic and municipal	14,714	0 2
Total (rounded)	14,700	0 2
Phreatophytes[1] (rounded)	711,800	10 0
Open-water surfaces[2]	344,000	4 8
GRAND TOTAL (rounded)	7,129,100	100 0

[1]Includes Federal lands
[2]See table 15

Dam, Davis Dam, Parker Dam, Imperial Dam, and Morelos Dam

Water-Budget Components

In the water budget, the largest components (inflows and outflows) are measured These include the inflow in the river below the upstream dam, outflow in the river below the downstream dam, the diversion of water into canals for export out of the study area, and the inflow of water in the Gila River An estimate of inflow from the Bill Williams River is based on a measurement of flow below Alamo Dam The other components are estimated and are of a smaller magnitude than the measured components During years when releases from the dams are regulated to meet downstream requirements, consumptive use by vegetation is of the same order of magnitude as the measured components of the water budget In 1984, consumptive use by vegetation was an order of magnitude less than the flow below Hoover Dam Errors in annual flows, particularly in reaches where consumptive use by vegetation is small, can have a large affect on the estimate of consumptive use by vegetation For 1984, LCRAS provides a reasonable estimate of consumptive use by vegetation for the Hoover Dam to Morelos Dam reach

Analysis of Annual Streamflow Errors

Flows gaged at or below the dams that are used to divide the river into water-budget reaches have an accuracy rating of excellent or good, with 95 percent of the daily mean values being within 5 or 10 percent of the true value, respectively (table 2) The accuracy for mean annual discharge at these sites was computed using the assigned accuracy, in percent, for each daily discharge Because of the wide variation in daily discharge, the error for each day, in cubic feet per second, will vary greatly The error for the annual mean discharge was determined from the errors of daily discharge (converted to cubic feet per second) using the components-of-variance method by Ostle (1954, p 44)

$$S_{\bar{Q}}^2 = \sum \frac{S_Q^2}{n^2}, \quad (15)$$

where

$S_{\bar{Q}}^2$ = variance of average annual discharge,

S_Q^2 = variance of daily discharge,

n = number of days in the year,

and the errors of daily discharge are assumed to be independent These approximate estimated errors and the actual daily mean discharges for each of the streamflow-gaging stations for 1984 are listed in table 36 The true error might be larger than the computed error because of serial correlation effects, which were not evaluated

Table 36. Standard errors of the annual flow measured at selected streamflow-gaging stations along the lower Colorado River, Hoover Dam to Mexico, 1984

[Accuracy E, about 95 percent of the data are within 5 percent of the true value, G, about 95 percent of the data are within 10 percent of the true value]

Station name	Discharge, in acre-feet	Rating of daily discharge[1]		Approximate standard error of estimated annual discharge,	
		Accuracy	Standard error, in percent	in percent[2]	in acre-feet
Colorado River:					
below Hoover Dam	[3]21,411,000	E	2 5	0 13	27,800
below Davis Dam	21,658,000	G	5 0	0 26	56,300
below Parker Dam	20,464,000	G	5 0	0 26	53,200
below Imperial Dam	10,080,000	G	5 0	0 27	27,200
at NIB	15,431,000	G	5 0	0 26	40,100
Bill Williams River below Alamo Dam	111,800	G	5 0	0 94	1,100
Gila River near Dome	266,000	G	5 0	0 55	1,500
Colorado River aqueduct	1,237,230	G	5 0	0 26	3,200
All-American Canal·					
at Imperial Dam	8,269,000	G	5 0	0 26	21,500
below Pilot Knob	3,046,000	G	5 0	0 28	8,500
Gila Gravity Main Canal	754,800	G	5 0	0 30	2,300
Wellton-Mohawk Canal	391,400	G	5 0	0 30	1,200

[1]From White and Garrett (1987)

[2]Because of the large variability of daily discharge, the error for the annual mean was determined from the errors of daily discharge converted to cubic feet per second using the components-of-variance method by Ostle (1954, p 44)

[3]Measured flow without the adjustment

Annual Changes in Open-Water-Surface Areas

The surface area of the river and reservoirs does not change significantly from year to year as long as releases from the dams are managed to meet downstream water requirements Significant changes in open-water surface area occur when large quantities of water are released from Hoover Dam in response to large inflows from the upper Colorado River basin Large inflows, such as those in 1983, fill the reservoirs and result in overflows at the spillways In response to the high flows in 1983 that filled the reservoirs, releases were still being made in 1984 to adjust the quantity of water stored in the reservoirs, which maintained high flows in the lower Colorado River Because of the high river stage and associated rise above land surface of ground-water levels, many areas along the river were flooded, which caused an increase in the open-water areas

Landsat images were available for the Davis Dam to Morelos Dam reach for 1981, a year in which flow in the river was regulated to meet downstream water requirements To assess the significance of the change in open-water-surface areas between a year of high flow and a year of flow regulated to meet downstream requirements, a single image for 1981 was classified to determine the open-water-surface area In 1984, the open-water-surface area was 33,610 acres for the reach between Davis Dam and Morelos Dam, which includes Lake Havasu The 1984 area was 5,443 acres, or 19 3 percent greater than that in 1981 The percent difference in open-water-surface area is equivalent to the percent difference in the total evaporation calculated for the reach The largest difference in the open-water-surface area within the comparison reach was an increase of 2,355 acres in the reach of the river between Parker Dam and Imperial Dam The open-water-surface area increased by 1,913 acres in the reach between Davis Dam and Parker Dam, which includes Lake Havasu, and 1,175 acres in the reach between Imperial Dam and Morelos Dam. Between Morelos Dam and the SIB, the increase would be most significant because flow measured at the SIB increased from 237,600 acre-ft in 1981 to 12,690,000 acre-ft in 1984. In 1984, water covered most of the flood plain to the levees on the United States side of the river below Morelos Dam, whereas in 1981, flow was confined to a channel and most of the flood plain within the levees was dry. Between Hoover Dam and Davis Dam, the river flows in a bedrock-lined channel until it reaches Lake Mohave; changes in open-water-surface area in this reach are controlled mainly by changes in lake stage.

Evapotranspiration

The calculation of evapotranspiration is dependent on the vegetation classification from digital-image analysis that includes the correct identification of the type of vegetation and area of each vegetation type and the calculation of the water-use rates for each vegetation type. The most difficult and critical part of the calculation is establishing accurate water-use rates that take into account spatial and temporal variability of water use. The calculated water-use rates for phreatophyte stands of mixed species and variable density are different from the water-use rates of crop types. The correct identification of the type of vegetation, especially when multiple crops are grown in the same field during a given year, is also important. For example, some minor crops could be correctly classified but, because they are not represented in the calibration-area crop maps, could be erroneously interpreted as major crops. The misinterpretation is most critical between high- and low-water-use vegetation types. It is important to evaluate the vegetation classifications and adequacy of the type of crops represented and the total area of each crop that is mapped in the crop calibration area for use in improving next year's collection of ground-truth data. Errors, if any, in the estimates of evapotranspiration from misinterpretation between high- and low-water-use vegetation were considered small in the 1984 classification.

Comparison to 1984 Decree Accounting

An annual accounting of consumptive use is published by the USBR in accordance with Decree requirements. Accounting methods used prior to LCRAS resulted in 5,901,000 acre-ft of consumptive use of water from the Colorado River assigned to the States of Arizona, California, and Nevada below Hoover Dam in 1984 (U.S. Bureau of Reclamation, 1986a). This Decree accounting total does not include water lost to phreatophytes and open-water evaporation but does include a credit for return flows from the Wellton-Mohawk area that do not return to the river. Adjusting the total consumptive use of river water calculated by LCRAS for these differences results in 5,949,000 acre-ft, or 0.8 percent more than the Decree accounting method. This test of the reliability of LCRAS shows that LCRAS can provide reliable (less than 1 percent difference from the previous method) results even in a year of anomalously high flow in the river.

Comparison of Methods in the Parker Dam to Imperial Dam Reach

The Parker Dam to Imperial Dam reach was selected as a test reach to compare (1) estimates of consumptive use by vegetation determined using LCRAS and (2) estimates of consumptive use by vegetation determined using ground-water budgets for the alluvial aquifer that underlies the flood plain of Palo Verde Valley (Owen-Joyce and Kimsey, 1987), Parker Valley (Owen-Joyce, 1988), and Cibola Valley (Owen-Joyce, 1990). The ground-water budgets were developed to estimate consumptive use from agricultural areas, primarily for use in estimating ground-water return flows from areas that drain to the river. The diversions at Headgate Rock and Palo Verde Dams and the surface-water return-flow sites (table 8) are measured and ungaged pumpage from the river (table 7) is estimated as required under the Decree. The comparison could be done periodically, possibly every 5 to 10 years, as a means of checking the LCRAS method of calculating consumptive use by vegetation. Data need to be collected at ground-water sites in addition to the surface-water sites for the comparison. To use the methods described by Owen-Joyce and Kimsey (1987) and Owen-Joyce (1988, 1990), monthly water levels need to be measured in 49 observation wells, 30 piezometer wells, and drainage ditches in Parker Valley, 33 observation wells, 18 piezometer wells, and drainage ditches in Cibola Valley, and 52 piezometer wells in Palo Verde Valley. Water levels are measured monthly by PVID in 272 observation wells and at about 150 sites along drainage ditches in Palo Verde Valley. Additional observation wells are needed in Parker Valley as well as a network of sites on the drainage ditches in Parker and Cibola Valleys where stage also can be measured so that consumptive use by vegetation can be estimated in Parker and Cibola Valleys to the same degree of accuracy as it is in Palo Verde Valley.

As part of this study, estimates of consumptive use by vegetation calculated by LCRAS were compared with estimates of consumptive use by vegetation calculated by using ground-water budgets. Before making the comparison between the two methods, the 1984 ground-water budgets for each of the valleys were rerun to incorporate the water-use rates calculated for phreatophytes by LCRAS, which are more realistic than the rates used in the calculations by Owen-Joyce and Kimsey (1987) and Owen-Joyce (1988, 1990). The LCRAS phreatophyte water-use rates were substituted in the ground-water budgets and used to reestimate consumptive use by vegetation as 1,075,500 acre-ft (table 37) for this reach of the river. Reestimated values of annual consumptive use per unit vegetated area were 4.61 ft in Parker Valley and 3.68 ft in Palo Verde Valley in 1984. Annual consumptive use by phreatophytes was calculated by using 5.3 ft, which is the value calculated for mixed stands of medium density in this reach (table 21).

Consumptive use by vegetation calculated by LCRAS throughout this reach in 1984 was 1,129,800 acre-ft, or 55 percent of consumptive use by vegetation from Hoover Dam to Morelos Dam. Consumptive use by vegetation was apportioned to the Parker Dam to Imperial Dam reach by using the percentage of evapotranspiration calculated for the Parker Dam to Imperial Dam reach, which was about 55 percent of evapotranspiration from Hoover Dam to Morelos Dam. Consumptive use by vegetation calculated with the single-reach option is about 5 percent higher than the reestimate from ground-water budgets.

Table 37. Estimates of areas of vegetation and open-water surfaces and consumptive use along the Colorado River between Parker Dam and Imperial Dam, 1984

	Area, in acres	Consumptive use[1], in acre-feet
Parker Dam to Headgate Rock Dam	343	1,600
Parker Valley[2]		
North of Tyson Wash	98,839	438,300
South of Tyson Wash	12,451	49,200
California side of river	11,612	45,800
Islands in river	919	3,600
Subtotal (rounded)	123,800	536,900
Palo Verde Valley[3]		
West of the river	[4]91,609	375,200
East of the river between Ehrenberg and Cibola Valley	3,830	14,100
Diversion to Palo Verde Mesa[5]	---------	12,800
Subtotal (rounded)	95,400	402,100
Cibola Valley[6]		
East of the river	10,274	50,400
Between the old and new channels	4,756	25,200
West of the old channel and north of gaging station	1,745	9,200
Subtotal (rounded)	16,800	84,800
Colorado River below Cibola Valley gaging station to Imperial Dam	9,460	50,100
TOTAL	245,800	1,075,500
Open-water surfaces	10,263	58,300
Domestic use by municipalities	---------	5,484
GRAND TOTAL (rounded)	256,100	1,139,300

[1]Method described by Owen-Joyce (1988, 1990) and Owen-Joyce and Kimsey (1987). Values recalculated using the water-use rates calculated for use in this study for phreatophytes and crops in 1984.
[2]Owen-Joyce (1988, p. 42).
[3]Owen-Joyce and Kimsey (1987, p. 39).
[4]Does not include 26,528 acres of multiple cropping.
[5]Assumed diversion equals consumptive use.
[6]Owen-Joyce (1990).

Potential Refinement of Water Budgets for Four Reaches

The reach of the Colorado River between Hoover Dam and Morelos Dam can be divided into four subreaches bounded by major dams (fig. 2). These subreaches correspond to the subreaches used to determine evapotranspiration as described previously. Water budgets using 1984 data for the subreaches were developed in an attempt to more accurately reflect conditions in the individual subreaches and give LCRAS the capability of providing estimates of consumptive use by vegetation by subreach independent of the total-reach calculations Computed consumptive use by vegetation for the four subreaches is not always reliable, but the results are presented to show how LCRAS can be improved

Hoover Dam to Davis Dam

Consumptive use by vegetation for the reach between Hoover Dam and Davis Dam cannot be reliably calculated for 1984 because the residual amount of the water budget was masked by errors of the Q_{us} and Q_{ds} components The amount of computed error for the Q_{us} and Q_{ds} components was large because these components for 1984 were unusually large Water-budget components and quantities independently estimated for 1984 are itemized in table 38 Until the measurement errors can be reduced, consumptive use by vegetation is computed by using the water budget for the Hoover Dam to Morelos Dam reach

Under the methods currently used to measure flow below Hoover and Davis Dams, this reach cannot be used as a single unit to estimate consumptive use by vegetation with a water budget Flows in the main channel of the river in this reach are more than three orders of magnitude greater than any of the other components The amount of potential errors in Q_{us} and Q_{ds} is much greater than the amount of consumptive use by vegetation in this reach, and the high measurement precision needed to use the water-budget method in this reach is unavailable

Table 38. Water budget for the Hoover Dam to Davis Dam reach of the lower Colorado River, 1984

Component	Quantity, in acre-feet
Inflow	
Flow below Hoover Dam	[1]21,861,000
Precipitation	18,500
Unmeasured average annual tributary runoff	2,100
Tributary ground-water discharge	
Springs	3,080
Colorado River valley	200
Eldorado Valley	1,100
Total (rounded)	21,886,000
Outflow other than consumptive use by vegetation.	
Flow below Davis Dam	21,658,000
Domestic consumptive use by municipalities	1,101
Evaporation from open-water surfaces	148,700
Total (rounded)	21,807,800
Change in storage Lake Mohave	-150,000
Consumptive use by vegetation[2]	[3]228,800

[1]Adjusted for acoustic-velocity-meter error
[2]Computed residual of the water-budget method
[3]Computed residual is considered anomalous

Davis Dam to Parker Dam

For the reach between Davis Dam and Parker Dam, consumptive use by vegetation cannot be calculated for 1984 because computed errors in discharges gaged on the mainstream are of the same magnitude as the estimate of evapotranspiration in this reach Water-budget components and quantities independently estimated for 1984 are itemized in table 39 In this reach, as in the upstream reach, the errors in measurement of flow in the Colorado River are large relative to the computed consumptive use by vegetation A small increase, 1 percent, in the computed flow of the Colorado River below Davis Dam results in an estimate of consumptive use by vegetation in the Hoover Dam to Davis Dam reach of 11,200 acre-ft and 136,700 acre-ft in the Davis Dam to Parker Dam reach Both estimates appear reasonable when compared with estimates of consumptive use by vegetation prorated for the subreaches from the total calculated for the Hoover Dam to Morelos Dam reach (see section of report entitled "Distribution of Consumptive Use by Diverter") Until the measurement errors can be reduced, consumptive use by vegetation is computed by using the water budget for the Hoover Dam to Morelos Dam reach

Throughout the entire reach within Mohave Valley, the river loses water to the alluvial aquifer (pl 1), which makes this reach different from the other agricultural reaches below Davis Dam Mohave Valley does not have drainage ditches as do the valleys to the south of Parker Dam where change in storage within the alluvial aquifer was shown to be small in relation to consumptive use by vegetation during 1984 (Owen-Joyce and Kimsey, 1987, Owen-Joyce, 1988) Change in storage in the alluvial aquifer of the flood plain and the older alluvial terraces needs to be evaluated as to its magnitude in relation to consumptive use by vegetation and as to whether it is large enough to warrant inclusion in the water budget Also during 1984, inflows from tributary

Table 39. Water budget for the Davis Dam to Parker Dam reach of the lower Colorado River, 1984

Component	Quantity, in acre-feet
Inflow:	
Flow below Davis Dam	21,658,000
Precipitation	51,900
Unmeasured average annual tributary runoff	
Davis Dam to Topock	12,000
Topock to Parker Dam	15,000
Whipple Mountains	1,150
Unmeasured tributary stream	
Piute Wash	1,000
Sacramento Wash	2,500
Tributary ground-water discharge	
Davis Dam to Topock	0
Topock to Parker Dam	880
Piute Valley	2,300
Sacramento Valley	10,000
Chemehuevi Valley	260
Bill Williams River	[1]75,600
Total (rounded)	21,830,600
Outflow other than consumptive use by vegetation.	
Flow below Parker Dam	20,464,000
Colorado River aqueduct	1,237,230
Central Arizona Project Canal	0
Domestic consumptive use from municipalities	26,805
Evaporation from open-water surfaces	129,800
Total (rounded)	21,857,800
Change in storage Lake Havasu	53,100
Consumptive use by vegetation[2]	[3]-80,300

[1]Flow reaching the Colorado River from the Bill Williams River calculated in table 10

[2]Computed residual of the water-budget method

[3]Computed residual is considered anomalous

washes were reported but quantities could not be estimated

Parker Dam to Imperial Dam

Consumptive use by vegetation was calculated for the reach between Parker Dam and Imperial Dam by using equation 7 The computed consumptive use by vegetation using the water-budget components and quantities in 1984 (table 40) appears reasonable, of the same magnitude, when compared with the estimates for the subreaches prorated from the total for the Hoover Dam to Morelos Dam reach (see section of report entitled "Distribution of Consumptive Use by Diverter")

Table 40. Water budget for the Parker Dam to Imperial Dam reach of the lower Colorado River, 1984

Component	Quantity, in acre-feet
Inflow.	
Flow below Parker Dam	20,464,000
Precipitation	137,400
Unmeasured average annual tributary runoff	
Whipple Mountains	1,150
Big Maria Mountains	2,300
Palo Verde-Mule Mountains	1,200
Dome Rock-Trigo-Chocolate Mountains	16,200
Unmeasured tributary stream	
Vidal Wash	1,300
Bouse Wash	4,800
Tyson Wash	2,600
McCoy Wash	800
Milpitas Wash	1,200
Tributary ground-water discharge	
Vidal Wash	250
Bouse Wash	1,200
Tyson Wash	350
Chuckwalla Valley	400
Total (rounded)	20,635,100
Outflow other than consumptive use by vegetation:	
Flow above Imperial Dam	19,106,000
Domestic consumptive use by municipalities	5,484
Evaporation from open-water surfaces	58,300
Total (rounded)	19,169,800
Change in storage Senator Wash	652
Consumptive use by vegetation[1]	1,464,700

[1]Computed residual of the water-budget method

As for the upstream reaches, errors in the computed consumptive use by vegetation are mainly related to the errors in the flows of the Colorado River measured below or at dams It is interesting to examine the effect of small changes in the computed flow of the Colorado River below Parker Dam If the computed flow was decreased by 2 percent, the consumptive use by vegetation is 1,055,700 acre-ft in this reach and 328,700 acre-ft in the Davis Dam to Parker Dam reach, amounts that appear reasonable Apparently, the water-budget method can yield reasonable results if more precise computations of flow in the Colorado River can be made

Imperial Dam to Morelos Dam

Consumptive use by vegetation was calculated for the reach between Imperial Dam and Morelos Dam by using equation 7. The computed consumptive use by vegetation using the water-budget components and quantities in 1984 appears reasonable (table 41).

Table 41. Water budget for the Imperial Dam to Morelos Dam reach of the lower Colorado River, 1984

[Component: NIB, northerly international boundary; SIB, southerly international boundary]

Component	Quantity, in acre-feet
Inflow	
Flow above Imperial Dam	19,106,000
Flow in Gila River near Dome	266,000
Precipitation	70,600
Unmeasured average annual tributary runoff	2,000
Tributary ground-water discharge near Dome	1,000
Total (rounded)	19,445,600
Outflow:	
Flow at NIB (Morelos Dam)	15,431,000
All-American Canal below Pilot Knob	3,046,000
Wellton-Mohawk Canal	391,400
Domestic consumptive use by municipalities	6,971
Evaporation from open-water surfaces	7,200
Surface-water return flows below Morelos Dam	
Eleven Mile wasteway	1,530
Cooper wasteway	721
Twenty-one Mile wasteway	0
Main drain at SIB	99,380
West Main Canal wasteway	0
East Main Canal wasteway	4,090
Total (rounded)	18,988,300
Consumptive use by vegetation[1]	457,300

[1]Computed residual of the water-budget method

Evaluation of Water Budgets for Four Reaches

The use of four subreaches in LCRAS potentially could produce more precise estimates of consumptive use by vegetation along the river. In the upper two reaches, small errors in flow measurement of such large discharges at Q_{us} and Q_{ds} can mask the computed consumptive use by vegetation. As shown for the subreach water budgets, if the true amount of flow below either Davis or Parker Dams were increased or decreased 1–2 percent, the computed amounts of consumptive use by vegetation in the subreaches adjacent to those dams appear reasonable. Until such time when the accuracy of flow measurements can be improved at the mainstream stations so that individual budgets can be computed for each subreach separately, consumptive use by vegetation can only be computed for the reach of the river from Hoover Dam to Morelos Dam. Other potential improvements in the overall accuracy of the water budgets for the four individual reaches would include

(1) quantifying streamflow that seeps from the river into the younger alluvium and moves across the flood-plain boundary into the older alluvial terraces,

(2) quantifying annual change in storage in the alluvial aquifer associated with large variations in streamflow during the budget period,

(3) developing methods to improve the vegetation identification in the image classifications,

(4) developing better methods or formulas to calculate water-use rates for crops and phreatophytes, and

(5) incorporating depletion factors for use of unmeasured tributary inflow by States.

MONITORING THE ACCOUNTING SYSTEM

Monitoring of the lower Colorado River accounting system is needed to serve two purposes. First, each potential improvement identified in this study could be evaluated as to the contribution that is made in improving the overall reliability of LCRAS. The major potential improvement to the system could be achieved by increasing the accuracy of the measurements of flow in the Colorado River. Installation of AVM's is a first attempt to improve the accuracy of flows measured at Colorado River dams. Other refinements to improve computation precision include the (1) calculation of water-use rates for vegetation and open-water evaporation that better reflect the variability of water loss under field conditions,

(2) incorporation of spatial and temporal variability in the estimates of precipitation and evapotranspiration, and (3) better recognition and classification of minor crops and multiple cropping Second, as improvements are made to the accounting system, the effects of these improvements could be monitored and, possibly, additional comparisons made between estimates from the accounting system and the ground-water budgets in the test reach from Parker Dam to Imperial Dam (as discussed in the section entitled "Comparison of Methods in the Parker Dam to Imperial Dam Reach")

Evapotranspiration and Evaporation

Water-use rates are an important factor in calculating evapotranspiration Use of the modified formula (equation 13) developed by Blaney and Criddle (1950) allows for local variations in temperature and precipitation to be incorporated into the calculation, but other factors that are not taken into consideration, such as wind speed and solar radiation, are also important Additional weather data collected in each agricultural area along the river could be used in the Jensen-Haise equation (Jensen and Haise, 1963) to estimate water-use rates Automated weather stations, such as the California Irrigation Management Information System (CIMIS) station operated by the California Department of Water Resources in Blythe, could provide the types of weather data needed

Open-water classifications of the digital-image data allow annual changes in the area of open-water surfaces to be incorporated into the accounting system to estimate evaporation from these surfaces The major source of error in estimating evaporation from open-water surfaces is the annual evaporation rates Evaporation data are available at only two stations, one station is in the southern part of the study area, and the other station is near Lake Mead, north of the study area Published evaporation rates along the river differ by greater than 1 ft (see section of report entitled "Evaporation Rates"), which can be significant in reaches with reservoirs Variations probably exist in evaporation rates from reach to reach along the river, but no data are available to document the values for each reach Evaporation data could be collected if automated weather stations were established for each of the agricultural areas or reaches

Vegetation Classification

Accurate classification of the types of vegetation is an important part of calculating evapotranspiration Classification problems encountered in this study include (1) misclassification between crops and phreatophytes, such as dense phreatophytes classified as alfalfa, and (2) the classification of multiple-cropped fields as single-cropped fields Recently developed imaging methods of collecting data for vegetation classifications may be used to improve the classification Remote-sensing methods to collect data for direct calculation of evapotranspiration also are being investigated (Jackson and others, 1987, Moran and others, 1989)

Tributary Inflow

A small amount of the tributary inflow is storm runoff that flows into the Colorado River valley In LCRAS, the average annual runoff is used in the water budgets, however, runoff in wet years can be much larger than the average annual value Storm runoff from major floods in tributary streams needs to be estimated or computed for use in LCRAS, possibly by analysis of hydrographs for streamflow-gaging stations on the Colorado River

In most areas adjacent to the Colorado River valley, ground-water pumpage is small and has not significantly affected the quantity of ground water discharged to the Colorado River valley except in one area Increased pumping in Ranegras Plain has caused a decrease in the ground-water gradient and decreased the ground-water outflow (Owen-Joyce, 1987) Ground-water pumpage and water levels need to be monitored to determine potential areas of water-level declines Pumpage is estimated annually by the USGS, water levels will need to be measured periodically in areas with declining water levels Any changes in the ground-water gradients at the discharge areas would indicate a change in outflow At the discharge areas of basins that drain to the Colorado River valley, periodic measurements of water levels in existing wells or in observation wells installed for this purpose would show when the effects of pumping cause a change in the amount of outflow from the basin

SUMMARY

The lower Colorado River between Hoover Dam and Mexico is the source of water for a large distribution system that is used to export water to agricultural and densely populated areas in adjacent States and for irrigation of agricultural lands along the river. The flow of the river is depleted by (1) diversions exported to areas in interior regions of California and Arizona, (2) consumptive use by irrigated crops along the river, (3) consumptive use by phreatophytes on the flood plain, (4) evaporation from open-water surfaces, mainly the reservoirs and the river, and (5) domestic, municipal, and industrial consumptive use. Precise accounting of the consumptive use of water from the lower Colorado River by diverter of water, point of diversion, and State, required by a U.S. Supreme Court Decree, has increased in importance with the growing demand for water in the United States and Mexico. Implementation of the Decree is complex because consumptive use is the standard of measure and identification of the quantity used by each diverter is required.

The Lower Colorado River Accounting System was developed for the reach between Hoover Dam and Mexico for use in estimating and distributing consumptive use of water by vegetation to water users in an equitable manner and to function in association with the complex system of dams, canals, pumps, wells, and drainage ditches that have been constructed to meet water use and power demands. An extensive network of streamflow-gaging stations at regulatory structures, points of diversion, and drainage ditches provides flow data required for Decree accounting and to calculate the water budget of the accounting system. Data also are collected to compute pumpage from the river and from wells.

Algorithms in the accounting system provide estimates of consumptive use by vegetation as the residual in a water budget for the river reach between Hoover Dam and Morelos Dam and apportion that use to diverters on the basis of estimates of evapotranspiration computed from types and acreages of vegetation determined from digital-image analysis of remotely sensed satellite data and water-use rates. The river was divided into four reaches at the major dams—Hoover Dam, Davis Dam, Parker Dam, Imperial Dam, and Morelos Dam—to improve the estimates of evapotranspiration by diverter by considering the spatial variations in temperature and precipitation.

The water budget that computes consumptive use by vegetation along the lower Colorado River includes the compilation and estimation of the independent water-budget components and description of the general methods of estimation and any adjustments required for conditions during the year being evaluated. Consumptive use by vegetation is distributed among users using an apportionment technique based on the relative amount of evapotranspiration computed for each water user as described in the following steps:

(1) Areas of each vegetation type in each reach are calculated from digital-image analysis of data from the Landsat satellite,
(2) Average annual water-use rates, adjusted for monthly variations in temperature and precipitation, are calculated for each vegetation type,
(3) Areas of each vegetation type are multiplied by their respective water-use rates and summed to estimate evapotranspiration in the reach,
(4) Boundaries of the areas for each diverter of water are digitized from maps and registered to the satellite images to calculate evapotranspiration by diverter, and
(5) The percentage of evapotranspiration in the reach estimated for each diverter is multiplied by the total consumptive use in the reach to calculate consumptive use by diverter.

Although calendar year 1984 was a year of unusually high flow in the river, the high flow did not prevent collection of the data required for the accounting system. The use of a year that contained anomalous conditions also provided an added test of the reliability of the accounting system and showed that it could provide reliable (less than 1 percent difference from the previous method) results under all conditions that affect the lower Colorado River. Consumptive use by vegetation was estimated to be 2,069,900 acre-ft in 1984. A total of 7,129,100 acre-ft of water was consumed in the lower Colorado River basin. California used about 67 percent of the total, 60 percent of the total was exported through the Colorado River aqueduct and the All-American Canal. Nevada used less than 1 percent of the total, most of it for municipal and industrial uses. Arizona used about

18 percent of the total, primarily for agriculture The remaining 15 percent was used by phreatophytes or was lost to open-water evaporation

The Lower Colorado River Accounting System is effective in calculating and distributing total consumptive use among the diverters of Colorado River water, as required by the Supreme Court Decree The principal areas where refinements need to be made to improve the reliability of the accounting system, in order of importance, are to improve the (1) precision of annual flow computation at the main-stream stations, particularly Hoover, Davis, and Parker Dams, (2) accuracy of estimates of open-water evaporation, (3) estimates of precipitation that falls on vegetated areas and open-water surfaces, and (4) estimates of phreatophyte evapotranspiration To use a possible refinement to the accounting system that has the capability to estimate consumptive use by vegetation for four individual reaches and thereby improve the estimate of consumptive use of each diverter, it is most important to maintain and improve the precision of streamflow records at all the main-stream boundary sites for the individual reaches

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