A METHOD FOR ESTIMATING GROUND-WATER RETURN FLOW TO THE COLORADO RIVER IN THE PALO VERDE-CIBOLA AREA, CALIFORNIA AND ARIZONA

By Sandra J. Owen-Joyce

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CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

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ABSTRACT

Ground-water return flow to the Colorado River was estimated as the residual in water budgets for the areas that drain in the subsurface to the river in Palo Verde and Cibola Valleys, California and Arizona. Two ground-water drainage areas in each valley were delineated using average annual water-table altitudes in the shallow alluvial aquifer that underlies Palo Verde and Cibola Valleys. Surface-water diversions from and returns to the Colorado River were measured. Consumptive use was estimated using a water budget for the area drained by drainage ditches in Palo Verde Valley and was adjusted for the unequal distribution of vegetation types on either side of the ground-water divide. Cibola Valley had no drainage ditches in 1981, and consumptive use was estimated using vegetation types, empirically determined consumptive use, and acreages. Vegetation data were obtained from crop records, crop mapping, and Landsat satellite imagery. A 1-year period was used because river-surface altitudes, ground-water heads, and irrigation-water deliveries follow a 1-year cycle and changes in ground-water storage are probably negligible at the end of the 1-year period. Estimates of ground-water return flow using data from 1981 were 23,900 acre-feet from Palo Verde Valley and 5,200 acre-feet from Cibola Valley.

INTRODUCTION

In a decree by the U.S. Supreme Court (1964) that apportions consumptive use of water from the lower Colorado River, consumptive use is defined as "* * * diversions from the stream less such return flow thereto as is available for consumptive use * * * ." Subsequently, the U.S. Bureau of Reclamation estimated consumptive use of diverted water from the main stem of the Colorado River below Lees Ferry as diversions from the river less surface-water return flow to the river. In 1969, the State of Arizona protested to the Secretary of the Interior the practice of computing consumptive use as diversions from the stream less surface-water return flow. Arizona argued that the States should also receive credit for ground-water return flow to the river. The U.S. Department of Interior agreed with Arizona, and in 1970 the U.S. Geological Survey and U.S. Bureau of Reclamation began a cooperative investigation to estimate the amount of ground-water return flow along the lower Colorado River. A Task Force on Unmeasured Return Flows to the Colorado River was formed to provide input from interested agencies during the investigation. The task force includes representatives from the States of California, Arizona, and Nevada; Federal Indian Agencies; the U.S. Bureau of Reclamation; and the U.S. Geological Survey.

An earlier investigation of the water resources of the lower Colorado River-Salton Sea area identified three reaches of the lower Colorado River where water diverted from the river for irrigation was returning to the river as ground-water (subsurface) flow (Metzger and others, 1973; Olmsted and others, 1973). The reaches are Parker, Palo Verde-Cibola, and Yuma (fig. 1). The three reaches were studied individually and presented in separate reports. This report presents a study of ground-water return flow in the Palo Verde-Cibola reach.

The Palo Verde-Cibola area is on the California-Arizona border about 150 mi northeast of San Diego and about 140 mi west of Phoenix (fig. 1). The boundaries of the study area are longitudes 114°25'57" and 114°49'15" and latitudes 33°12'51" and 33°45'00".

The Palo Verde-Cibola area includes about 215 mi^2 of Colorado River flood plain, which comprises Palo Verde and Cibola Valleys, and part of the surrounding mesas and terraces. The area occupies 730 mi^2 and includes parts of Imperial and Riverside Counties, California, and La Paz County, Arizona. The main population center is Blythe, California. Mesas and terraces adjacent to the flood plain and part of the flood plain along the river in Parker Valley were included and studied because they are hydraulically connected to the flood plain in Palo Verde and Cibola Valleys and are needed to understand the hydrology of the flood plain. In the Palo Verde-Cibola area, ground-water return flow from the flood-plain aquifer is estimated for the part of the flood plain downstream from the Palo Verde Diversion Dam in Palo Verde Valley on the California side of the river and the part south of Ehrenberg and in Cibola Valley on the Arizona side (fig. 2). The south boundary of the area is at the Colorado River below Cibola Valley gaging station where the flood plain narrows to about 0.5 mi wide.

Purpose and Scope

The purpose of the investigation was to develop a method or methods for estimating the amount of ground-water return flow discharging directly to the Colorado River. The estimates are for use by the Secretary of the Interior in accounting for consumptive use of water from the Colorado River as set forth in Article V of the decree by the

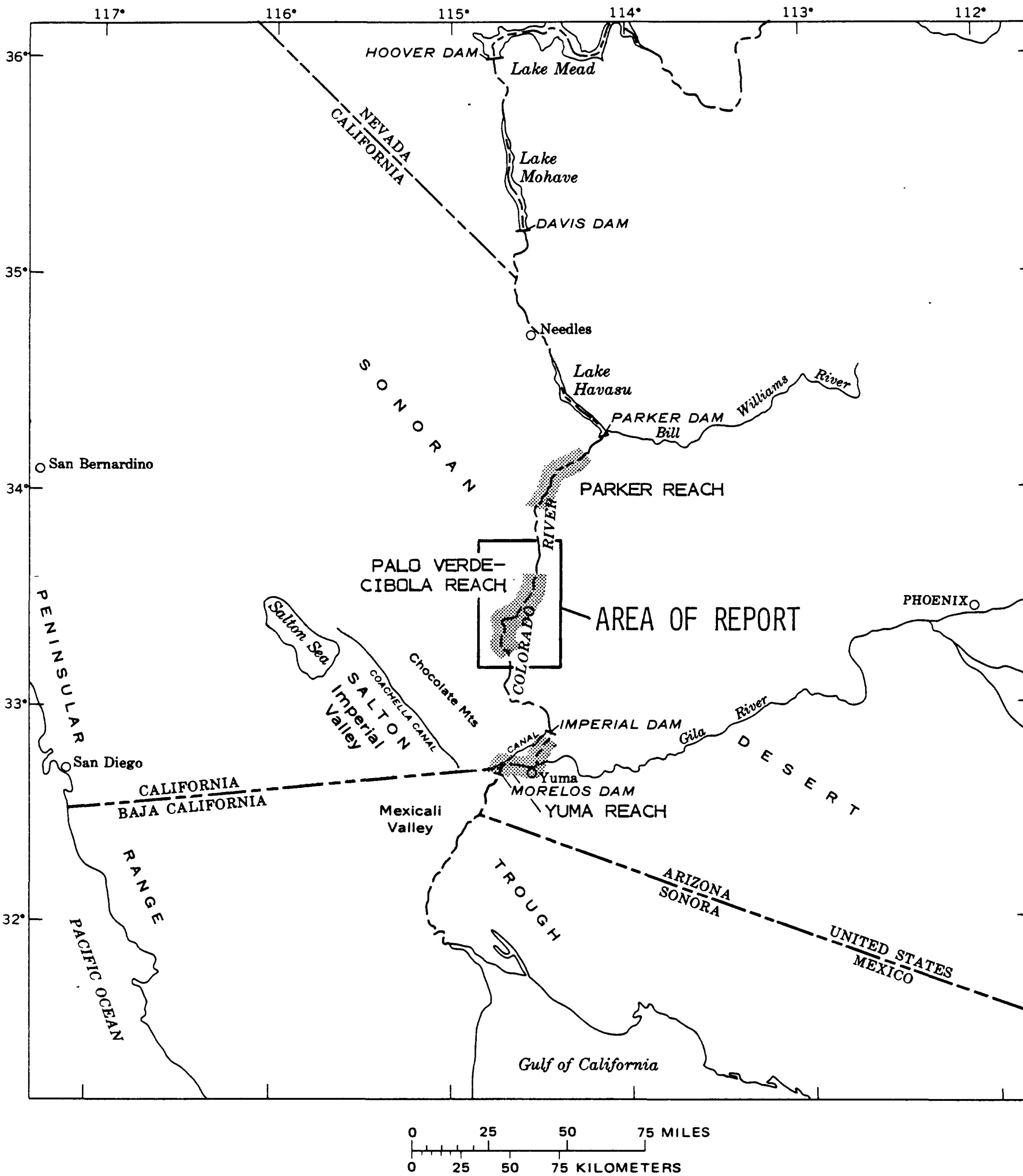

Figure 1.--Area of report. Shaded areas indicate reaches of the Colorado River where diverted water returns to the river as subsurface flow.

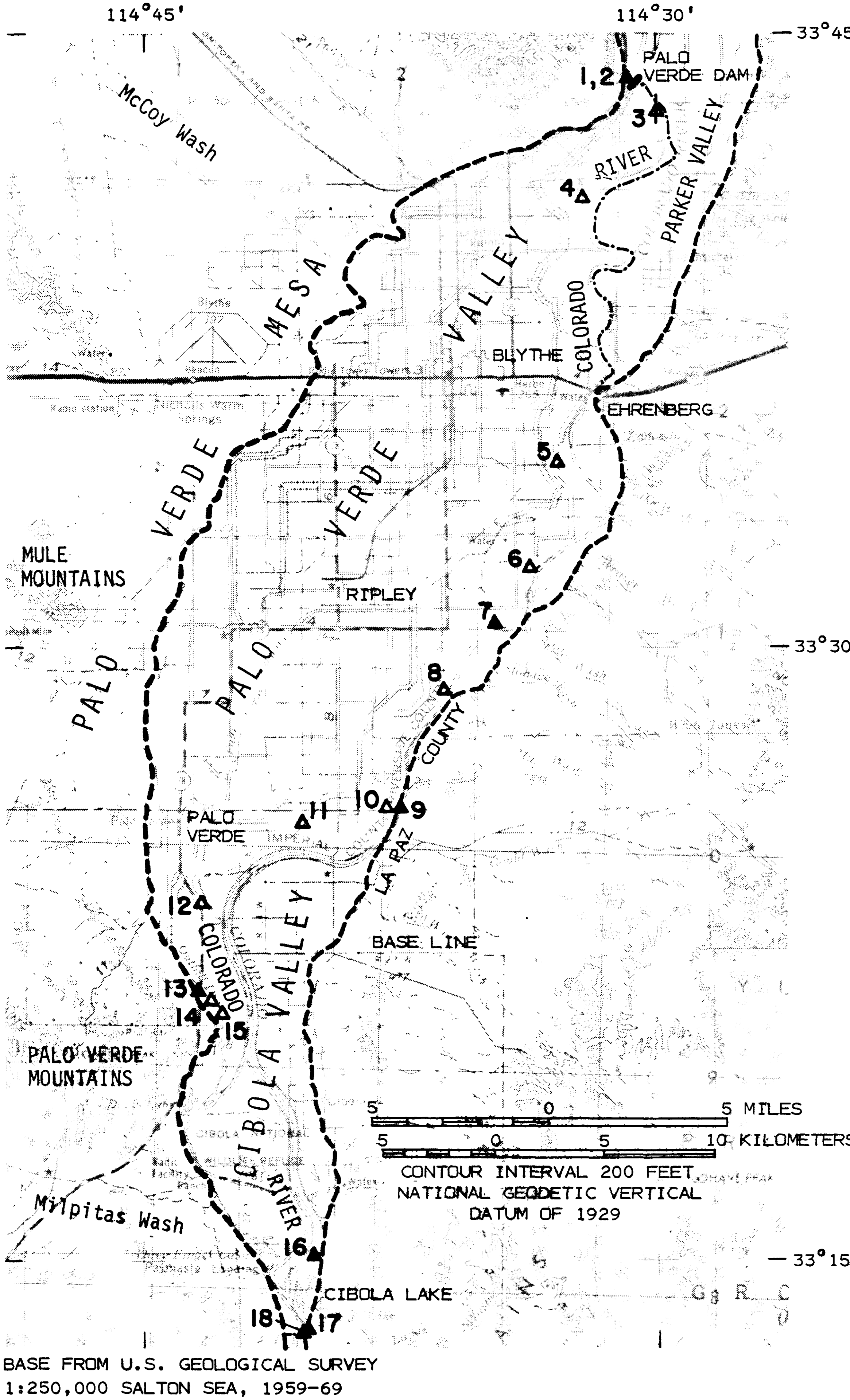

Figure 2.--Palo Verde-Cibola flood-plain area and location of gaging stations and surface-water measurement sites.

EXPLANATION

▲2	CONTINUOUS-RECORD GAGING STATION—Number, 2, correlates to station names listed below
△4	MEASUREMENT SITE—Number, 4, correlates to site names listed below
3	DISCONTINUED GAGING STATION—Number, 3, correlates to station names listed below
- - - - - - - - - - - -	COLORADO RIVER FLOOD-PLAIN BOUNDARY
—·—·—·—·—·—·—	BOUNDARY OF THE FLOOD PLAIN OF THE PALO VERDE-CIBOLA AREA WHERE THE FLOOD-PLAIN AQUIFER IS CONTINUOUS

Index of gaging stations and measurement sites

1. Palo Verde Canal near Blythe.
2. Colorado River at Palo Verde Dam.
3. Colorado River below Palo Verde Dam.
4. Olive Lake drain near Blythe.
5. F-canal spill near Blythe.
6. D-10-11-2 spill near Blythe.
7. D-10-11-5 spill near Blythe.
8. D-23 spill near Blythe.
9. Colorado River at Taylor Ferry near Blythe.
10. D-23-1 spill near Blythe.
11. C-canal spill near Blythe.
12. C-28 upper spill near Blythe.
13. Palo Verde Outfall drain near Palo Verde.
14. Anderson drain near Palo Verde.
15. C-28 lower spill near Blythe.
16. Cibola Lake inlet near Cibola.
17. Cibola Lake outlet near Cibola.
18. Colorado River below Cibola Valley.

Figure 2

U.S. Supreme Court (1964). This report presents a method for estimating ground-water return flow from irrigated land adjacent to the Colorado River along the Palo Verde-Cibola reach.

The method used in the Palo Verde-Cibola area is a slightly modified version of the method proposed for the Parker area (Leake, 1984) and involves estimating ground-water return flow as the residual quantity solved for in a water budget that accounts for consumptive use by crops and native vegetation, irrigation diversions, and surface-water return flow. In this study, surface-water return flow includes ground-water seepage into drainage ditches that discharges to the river as surface-water flow. The report includes a brief discussion of the hydrologic system in the Palo Verde-Cibola area and a detailed description of how the method is applied using hydrologic data and irrigation information for the 1981 calendar year.

Relation to Other Reports and Investigations

Two methods of estimating ground-water return flow along reaches of the lower Colorado River are presented in previous reports associated with the investigation. The hydraulic-analysis method using steady-state cross-sectional models at 18 sections normal to the river was used to estimate ground-water return flow in the Yuma area (Loeltz and Leake, 1983). A water budget for the subarea under which ground water drains to the river was used to estimate ground-water return flow in the Parker area (Leake, 1984).

Other studies and investigations provided information relating to the geohydrology of the area. Comprehensive studies of the Parker-Blythe-Cibola area included geology, ground-water resources, water quality, and paleohydrology of the lower Colorado River (Metzger and others, 1973; Metzger, 1965). Ground-water basic data for Palo Verde Valley are presented in Moyle and Mermod (1978). Bookman-Edmonston Engineering, Inc. (1976), under a contract with the U.S. Bureau of Reclamation, studied the effect of irrigation distribution system rehabilitation on incremental salt loading to the Colorado River from the Palo Verde Irrigation District. This study of the irrigation and drainage system in Palo Verde Valley provided information on the history, distribution of irrigation and drainage water in the valley, water losses from seepage and evaporation, consumptive use, and water quality. The application of excess irrigation water was tested as a means of reducing ground-water and soil salinity in Palo Verde Valley (Anthony Buono, U.S. Geological Survey, oral commun., 1983). Multitemporal analysis of Landsat satellite imagery to identify crops is being studied as a method for estimating consumptive use along the lower Colorado River (L. H. Raymond, U.S. Geological Survey, oral commun., 1983).

Acknowledgments

Roger E. Henning and Terry Wolford, Jr., of Palo Verde Irrigation District and Wayne Sprawls of Cibola Irrigation and Drainage District provided irrigation and agricultural information. Wes Martin of Cibola National Wildlife Refuge and Ron Swan provided information and gave permission to install an observation-well network on and near the wildlife refuge. H. H. Carver of the U.S. Bureau of Reclamation furnished estimates of river-surface altitudes from a step-backwater computer model. W. E. Moffitt, formerly of the U.S. Bureau of Reclamation, and E. E. Burnett and D. E. Watt of the U.S. Bureau of Reclamation developed methods for the installation of piezometers. The assistance of these geologists as well as drilling crews and other employees of the U.S. Bureau of Reclamation provided support needed to complete this study. Steve Quesenberry of the U.S. Soil Conservation Service provided consumptive-use values for Palo Verde Valley. H. C. Millsaps of the U.S. Soil Conservation Service provided consumptive-use values for alfalfa, cotton, and grains determined from soil-moisture depletion studies in Parker Valley. L. H. Raymond of the U.S. Geological Survey provided crop types for 1981 as identified from Landsat satellite imagery and field acreages in Palo Verde and Cibola Valleys. D. M. Clay, D. J. Bivens, and G. R. Scarbrough of the U.S. Geological Survey collected and processed many of the water-level data used for this study.

HYDROLOGY

In the Palo Verde-Cibola area, the hydrologic system includes the highly regulated Colorado River, a shallow alluvial aquifer that underlies the flood plain, river water diverted or pumped into a system of canals for application to fields on the flood plain, and ground water discharged to a network of drainage ditches or the river. Agricultural development and its associated irrigation have a significant effect on the amount and movement of surface water and ground water in the area. Palo Verde and Cibola Valleys are treated separately because of different points of diversion from the river and different hydrologic conditions present in each valley.

In Palo Verde Valley, agricultural development has caused changes in the ground-water flow pattern in the flood-plain aquifer. Irrigation and the associated network of drainage ditches has a significant effect on the saturated thickness of the aquifer and on the direction of ground-water movement through the aquifer. Water diverted from the Colorado River into Palo Verde Canal at Palo Verde Dam is distributed in Palo Verde Valley in a system of canals. Some water in the canals spills back to the river or into the network of drainage ditches as regulatory waste, some is pumped for use on Palo Verde Mesa, some evaporates, and the rest is applied to fields where it is consumptively used by crops. Water diverted for irrigation is the main source of recharge to the aquifer because of deep percolation of canal seepage and applied irrigation water. The deep percolation of irrigation water causes mounding of the water table under the fields and creates shallow ground-water divides between drainage ditches and between drainage ditches and the river. Other sources of recharge are ground-water inflow from areas that border the flood plain and infiltration of runoff from tributary areas. Water that infiltrates to the water table moves downgradient toward the drainage ditches and returns to the river as surface water via the Outfall drain or moves downgradient directly to the Colorado River between the ground-water divide and the river (fig. 3). Some water is intercepted and consumed by phreatophytes—mainly saltcedar, arrowweed, and mesquite—and some is pumped for municipal and domestic use. In places, ground water flows from the flood plain to Palo Verde Mesa. In 1981, the depth to water ranged from 3.65 to 23.70 ft below the land surface in 272 observation wells that were measured monthly by the Palo Verde Irrigation District (R. E. Henning, written commun., 1982).

In Cibola Valley, agricultural development also has an effect on the saturated thickness of the aquifer and the direction of ground-water movement in the flood-plain aquifer. Water from the Colorado River is the main source of recharge in Cibola Valley. Deep percolation of applied irrigation water recharges the aquifer in the cultivated areas in the northern part of the valley. Ground water moves toward the river between the ground-water divide and the river. Ground water on the other side of the divide moves away from the divide into areas of phreatophytes and possibly out of the flood-plain aquifer. In the southern part of the valley, the river loses water directly to the aquifer through infiltration and ground water moves away from the river. From February to May 1983, the depth to water ranged from 1.12 to 24.99 ft below the land surface in 33 observation wells that were measured monthly.

The Colorado River and the drainage ditches are hydraulically connected to the shallow alluvial aquifer. During normal flow in the river, most of the reaches adjacent to the irrigated areas gain water from the aquifer. Some of the reaches adjacent to areas of phreatophytes lose water to the aquifer. When the average annual stage in the river rises, some of the gaining reaches of the river can become losing reaches particularly where the ground-water divide is close to the river. Gaining and losing reaches of the river have to be identified on a yearly basis in the estimation of annual ground-water return flows to the river because of changes in river stage from year to year.

Estimating ground-water return flow requires an evaluation of the flow components that affect the hydrologic system of the flood plain and how these components interrelate. Each flow component is discussed and the quantity is estimated for input into the water budgets, which are used to estimate the ground-water return-flow component to the river.

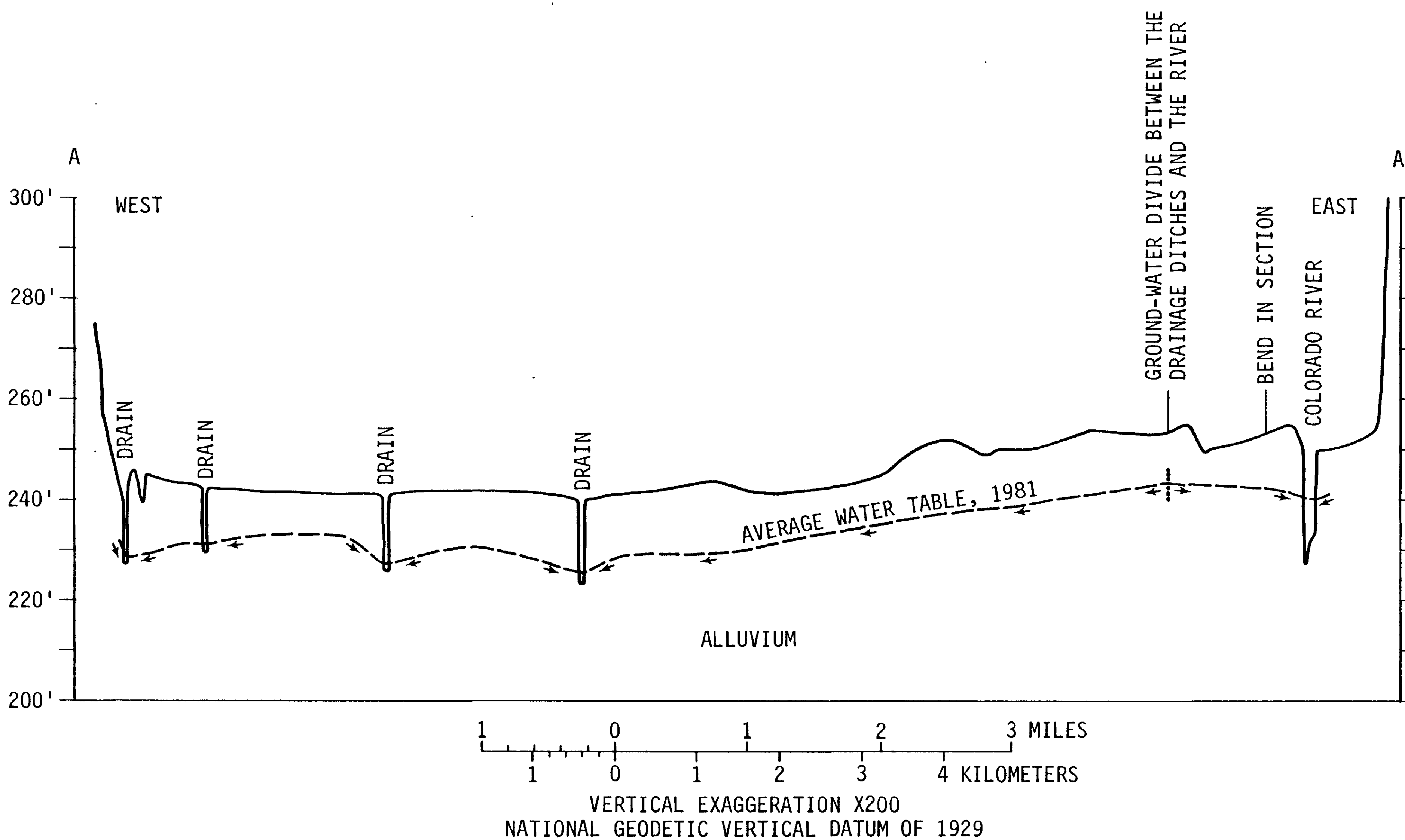

Figure 3.--Geohydrologic section A-A' in Palo Verde Valley. Arrows indicate direction of ground-water movement. (Location of section A-A' is shown on figure 9.)

Surface Water

Flow in the Colorado River is controlled by a series of dams upstream from the study area. Palo Verde Dam, at the northern end of the study area, is used to divert water for irrigation in Palo Verde Valley. The annual diversion of water from the Colorado River at Palo Verde Dam ranged from 775,300 to 1,008,000 acre-ft between 1960 and 1982. From 1960 to 1982, annual flow in the Colorado River downstream from Palo Verde Dam ranged from 5.0 to 6.5 million acre-ft except in 1980; the flow in 1980 was 8.9 million acre-ft because of flood-control releases (fig. 4). Annual flow in the Colorado River leaving the Palo Verde-Cibola area ranged from 5.5 to 7.0 million acre-ft from 1960 to 1982 and was 9.6 million acre-ft in 1980 (fig. 4). The increase in flow between the two gaging stations indicates a gaining reach of the river; most of the gain can be accounted for as surface-water and ground-water return flows, including some return flows from Parker Valley on the Arizona side of the river north of Ehrenberg.

Flow in the Colorado River varies seasonally, daily, and from place to place along the river. Seasonal variations occur because releases from the dams upstream are highest in summer when the irrigation needs

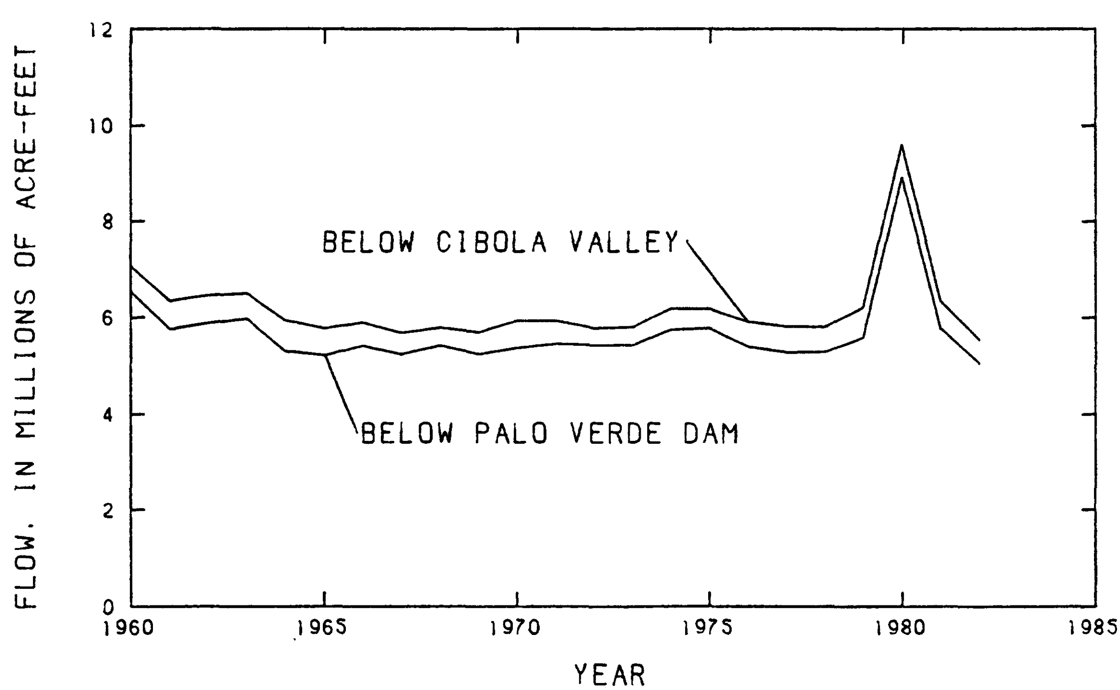

Figure 4.--Flow in the Colorado River below Palo Verde Dam and below Cibola Valley, 1960-82. Colorado River below Palo Verde Dam includes the return flow from two Parker Valley drains.

are greatest (fig. 5). Releases of water for irrigation and power generation, evapotranspiration, spillage from canals, and returns to the river all contribute to the daily fluctuations in flow. The pattern of flow variations is the same at the gaging stations at the upstream and downstream ends of the study reach; however, the quantity of flow is larger at the downstream station. A traveltime of about 1 day offsets the quantities recorded at the two sites and the magnitude of the fluctuation is decreased at the downstream station (fig. 5).

In 1981, 1,008,000 acre-ft of water was diverted from the Colorado River at Palo Verde Dam on the California side of the river. The amount of water diverted is measured at the Palo Verde Canal near Blythe gaging station (fig. 2, site 1). About 253 mi of canals distribute water throughout the valley.

In 1981, 491,500 acre-ft of water returned to the river as surface water from Palo Verde Valley. About 152 mi of open-channel drainage ditches drain the valley and maintain an average depth to water of 10 ft. Surface-water return flow includes water that spills from canals, laterals, and wasteways and ground water that returns to the river by surfacing in the open-channel drainage system. In 1981, surface-water return flow was measured or computed at the following sites:

Site number[1]	Site name	Quantity, in acre-feet
5	F-canal spill	9,880
6	D-10-11-2 spill	946
7	D-10-11-5 spill	6,130
8	D-23 spill	10,020
10	D-23-1 spill	3,290
11	C-canal spill	25,910
12	C-28 upper spill	1,900
15	C-28 lower spill	7,480
	Subtotal of surface-water return flows that spill from canals (rounded)	65,600
4	Olive Lake drain[2]	6,370
13	Palo Verde Outfall drain[3]	419,400
14	Anderson drain[3]	110
	Subtotal of surface-water return flows from the drainage system (rounded)	425,900
	Total surface-water return flows (rounded)	491,500

[1]Site number corresponds to locations shown on figure 2.
[2]Located in the area drained by the river.
[3]Located in the area drained by drainage ditches.

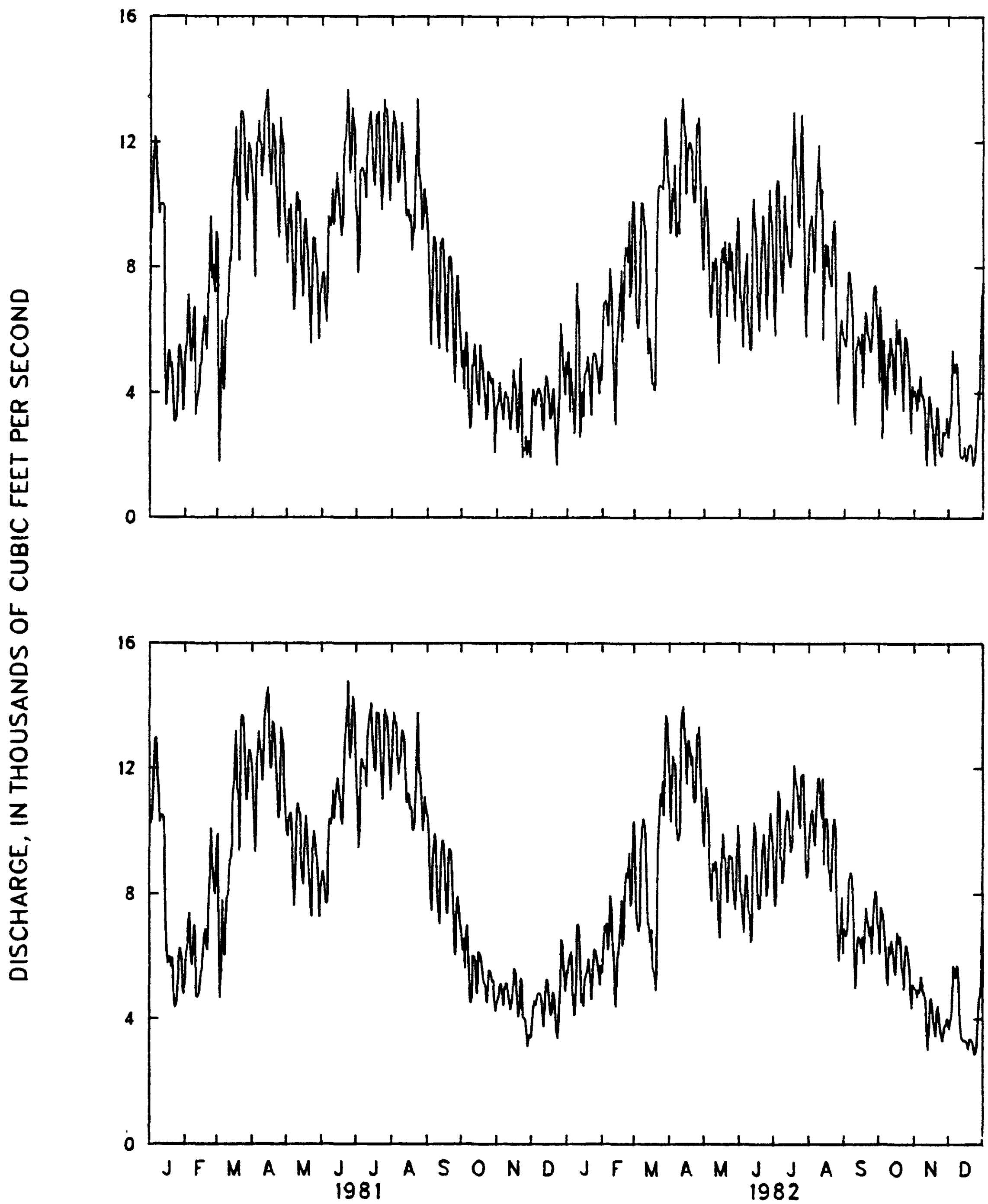

Figure 5.--Flow in the Colorado River for 1981 and 1982. A, Daily mean discharges for the Colorado River at Palo Verde Dam. B, Daily mean discharges for the Colorado River below Cibola Valley.

Flow in Palo Verde Canal fluctuates seasonally and daily according to irrigation requirements. Flow in the Outfall drain shows a small seasonal variation and smaller daily fluctuations than flow in the canal. In 1981, daily mean discharges ranged from 0 to 2,360 ft^3/s in Palo Verde Canal and from 348 to 757 ft^3/s in the Outfall drain (fig. 6). Monthly totals of flow in Palo Verde Canal illustrate the seasonal nature of the input to the hydrologic system (fig. 7). Total surface-water return flow, which includes flow in the drains and canal spillage, follows a seasonal pattern, although the month-to-month variations in flow quantities are smaller. The maximum flow in the drain occurred during September 1981, which was 2 months after the maximum flow in the canal (fig. 7).

On the Arizona side of the river, water is pumped or diverted directly from the river at different sites by water users. Cibola Lake is at the south end of the valley; water flows to the lake through a controlled inlet from the river (fig. 2, site 16). In 1981, a total of 47,100 acre-ft of water was pumped or diverted by the following water users (U.S. Bureau of Reclamation, 1982, p. 8 and 12):

Water user	Quantity, in acre-feet
South of Ehrenberg:	
Arakelian Farms	2,646
Cibola Valley:	
Cibola Valley Irrigation and Drainage District	[1]3,180
	[2]21,122
Swan, Ron	240
Bishop, Louis	960
Cibola National Wildlife Refuge	8,922
Cibola Lake inlet	8,046
Arizona Fish and Game	1,980
Total (rounded)	47,100

[1]One pump in T. 1 N., R. 23 W., sec. 20.
[2]Three pumps in T. 1 N., R. 23 W., sec. 21.

Cibola Lake outlet is the only gaged surface-water return from the Arizona side of the river (fig. 2, site 17); in 1981, 4,736 acre-ft of surface water returned to the river. No drains were in use in 1981. In the Cibola National Wildlife Refuge, a drainage ditch about 0.5 mi from and parallel to the east flood-plain boundary is partially installed but was not operational in May 1983.

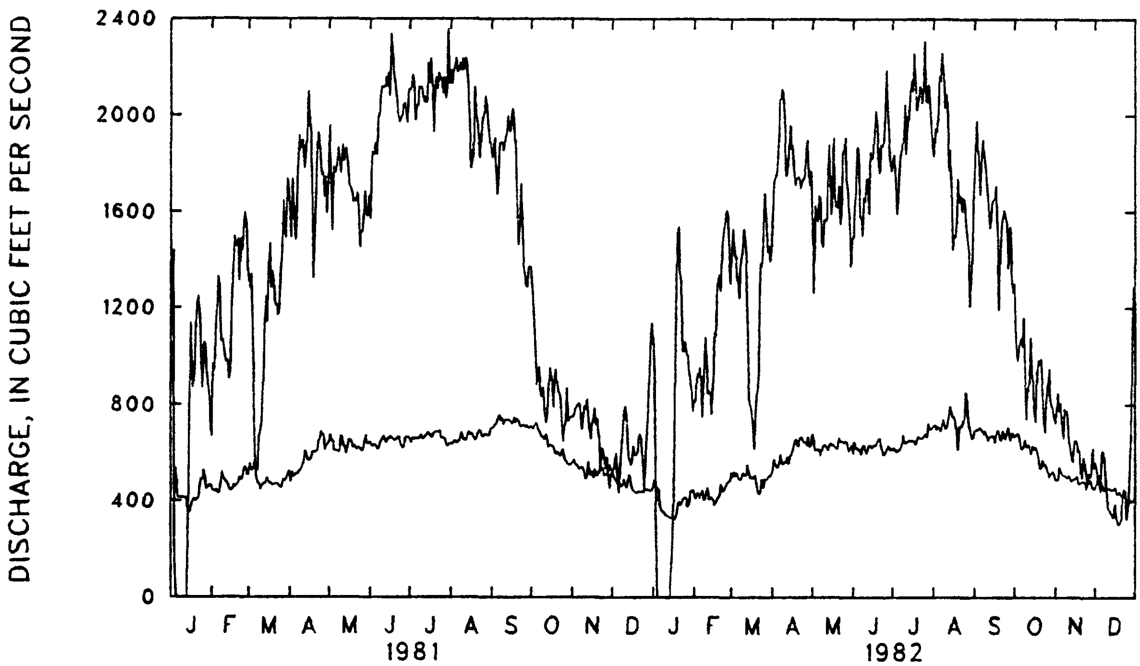

Figure 6.--Flow in Palo Verde Canal near Blythe and Palo Verde Outfall drain near Palo Verde, California, 1981 and 1982.

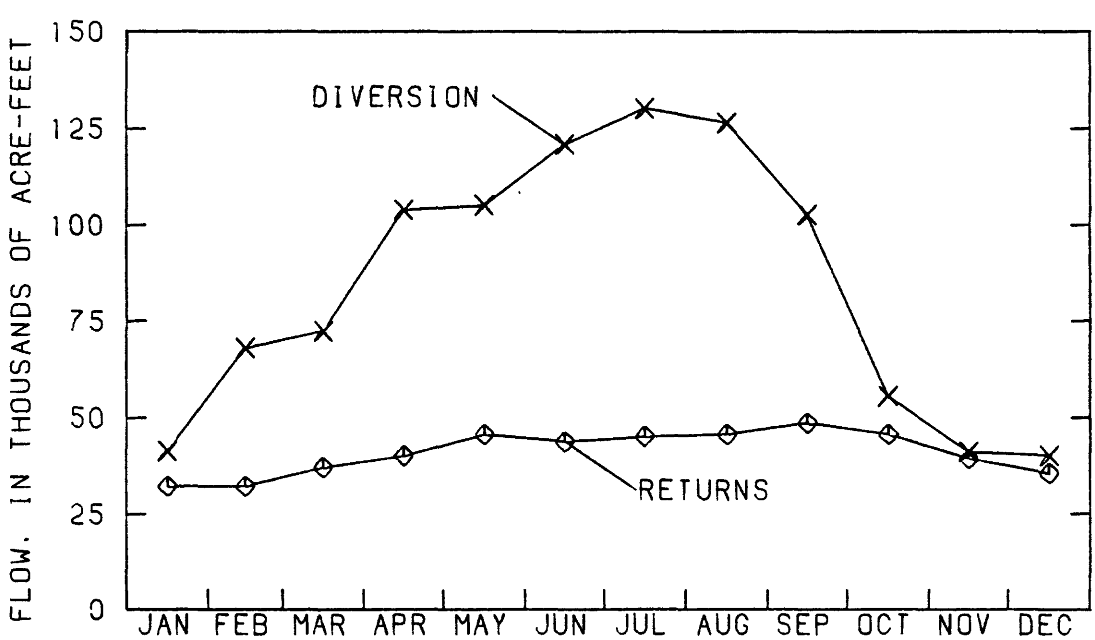

Figure 7.--Monthly flow in Palo Verde Canal near Blythe and total surface-water return flow from 11 sites in Palo Verde Valley, California, 1981.

Ground Water in the Flood-Plain Aquifer

Ground water occurs under water-table conditions in the alluvium, which is hydraulically connected to the river. The alluvium in Palo Verde and Cibola Valleys has been divided into the younger alluvium and the older alluviums. The younger alluvium forms the flood plain of the Colorado River; the older alluviums form the terraces and alluvial slopes that bound the flood plain (Metzger and others, 1973). The younger and older alluviums are hydraulically connected. In Palo Verde Valley, the younger and older alluviums are difficult to separate in the subsurface and their combined thickness is as much as 600 ft. Between Palo Verde Valley and Cibola Valley, the younger and older alluviums are 200 ft thick. Near Cibola, the older alluviums are not present in the subsurface and the younger alluvium is 128 ft thick in a well in T. 1 S., R. 24 W., sec. 36 (Metzger and others, 1973, p. 28).

Inflow components from areas that border the flood plain have been estimated. The components include ground-water inflow across the west boundary from Palo Verde Mesa and infiltration of surface-water runoff from the west side of the valley. Ground-water gradients and transmissivity of the aquifer were used to estimate the amount of ground-water inflow across the west flood-plain boundary. Average water-table contours for 1981 parallel the westernmost drainage ditch and indicate a component of ground-water inflow from the west that is intercepted by the drainage ditch (fig. 9). About 22 mi of the west boundary has a ground-water flow component toward the flood plain from Palo Verde Mesa. Ground-water head gradients were estimated from water levels measured in 1971, which are the most recent available data (Moyle and Mermod, 1978); the average gradient across the boundary was 2.25 ft/mi. Using a transmissivity value of 23,000 ft^2/d for the older alluviums (Metzger and others, 1973, p. 68), the inflow was estimated to be 9,500 acre-ft/yr. Sources and amounts of surface-water runoff from tributary areas were identified and estimated by Metzger and others (1973).

Sources of surface-water runoff	Amount, in acre-feet per year
McCoy Wash	800
Milpitas Wash	1,200
Palo Verde Mountains-Mule Mountains	1,200
Total	3,200

Some of the runoff recharges the flood-plain aquifer and some is consumed by vegetation on the flood plain.

Seepage from the Colorado River to the aquifer occurred along a reach of the river north of Ehrenberg in 1981 and was estimated to be

3,100 acre-ft. A ground-water gradient of 11.75 ft/mi between two piezometers along the river and a transmissivity of 53,000 ft^2/d (Metzger and others, 1973, p. 68) were used to estimate the seepage along a 0.6-mile distance perpendicular to the flow direction.

Ground-water outflow components that have been estimated are consumptive use by phreatophytes, flow across the flood-plain boundary, and pumpage. Within the flood-plain area, phreatophytes consume an average 3.4 ft of water annually (Boyle Engineering Corporation, 1976, p. II-7; L. H. Raymond, U.S. Geological Survey, oral commun., 1983). Therefore, 24,200 acres of phreatophytes consume about 82,300 acre-ft of water annually. Average water-table contours for 1981 indicate that outflow occurs along 3.5 mi of the boundary between the flood plain and Palo Verde Mesa. Outflow was estimated to be 4,700 acre-ft/yr in 1981 using a transmissivity of 40,000 ft^2/d (Metzger and others, 1973, p. 68) and a ground-water gradient of 4 ft/mi. Annual ground-water pumpage, which was consumptively used for domestic, municipal, and industrial purposes, was estimated to be 2,000 acre-ft (Bookman-Edmonston Engineering, Inc., 1976, p. 37). Ground-water outflow below Cibola Valley is negligible because ground water discharges from the alluvium to the Colorado River owing to the constriction of the valley (Metzger and others, 1973, p. 46).

METHOD FOR ESTIMATING GROUND-WATER RETURN FLOW

The water-budget method for estimating ground-water return flow to the Colorado River requires that the flood plain be subdivided into two ground-water drainage areas—one area where ground water drains to drainage ditches and another area where ground water drains directly to the river. Surface-water diversions to the study area and surface-water return flows need to be measured. Consumptive use of water by crops and phreatophytes, which includes evaporation from bare-soil and open-water surfaces, can be reliably estimated for the area drained by drainage ditches. Ground-water return flow can be estimated as the residual in a water budget for the area in which ground water drains to the river.

The method for estimating ground-water return flow to the Colorado River from an area with drainage ditches is a slightly modified version of the method used in the Parker area (Leake, 1984) and is outlined in the following steps:

1. Delineate the area under which ground water drains to the river and the area under which ground water drains to the drainage ditches.

2. Estimate diversions to irrigated land in each area by either (a) assuming the diversion is distributed uniformly on the irrigated acreage or (b) when crop data are available, the distribution of

applied water is proportioned according to the irrigation requirements by crop type.

3. Estimate consumptive use per unit area in the area drained by the drainage ditches and assume the consumptive use per unit area is the same for the area drained by the river. When crop data are available, adjust consumptive use per unit area for unequal distribution of vegetation types in the two drainage areas.

4. Compute ground-water return flow to the river with a water budget that uses the diversions to the area drained by the river estimated in step 2 and the consumptive use per unit area estimated in step 3.

The following estimation of ground-water return flow from Palo Verde Valley includes a comparison of the alternate ways of estimating diversions to irrigated land in step 2. The use of option (b) is dependent on the availability of crop data.

The water-budget method can also be used to estimate ground-water return flow from a study area that does not have drainage ditches by modifying step 3. In an area without drainage ditches, total consumptive use can be estimated using information on the types of vegetation, empirically determined consumptive use for each vegetation type, and acreage of each vegetation type for the individual ground-water drainage areas.

The modified method for estimating ground-water return flow to the Colorado River from an area without drainage ditches is outlined in the following steps:

1. Delineate the area under which ground water drains to the river.

2. Estimate diversions to irrigated land in the area delineated in step 1 by either (a) assuming the diversion is distributed uniformly on the irrigated acreage or (b) when crop data are available, the distribution of applied water is proportioned according to the irrigation requirements by crop type.

3. Estimate consumptive use by crops and phreatophytes in the area delineated in step 1 using types of vegetation, empirically determined consumptive use for each vegetation type, and

acreage of each vegetation type. To obtain total consumptive use, estimates of evaporation from water and soil surfaces must be added to that computed for vegetation.

4. Compute ground-water return flow to the river with a water budget that uses the diversions to the area drained by the river estimated in step 2 and the consumptive use estimated in step 3.

The steps of the method to estimate ground-water return flow to the Colorado River as applied to Palo Verde and Cibola Valleys for 1981 are described in the following sections. Annual flow quantities are rounded to the nearest 100 acre-ft. Areas of crops and phreatophytes are rounded to the nearest 100 acres. Consumptive use, irrigation requirements, and application rates given on the basis of volume per unit area are rounded to the nearest 0.1 ft. These rounding criteria are used for the convenience of presenting the quantities and do not necessarily imply accuracies of the quantities.

Shallow ground-water divides as indicated by contours of water-table altitude are used to delineate areas under which ground water flows in different directions. In the Palo Verde-Cibola area, ground-water flow varies with time in response to seasonal variations in river stage, evapotranspiration, and recharge from irrigation. For an analysis of ground-water return flow in the Yuma area, Loeltz and Leake (1983, p. 23) determined that transient ground-water flow can be treated as steady-state flow by taking time averages of flow components over a 1-year period. This treatment of transient flow was determined to be valid because (1) head changes within a 1-year period do not significantly change the transmissive properties of the aquifer and (2) the net change in ground-water storage over a 1-year period generally is small. Similar reasoning can be used to show that in the Palo Verde-Cibola area the average position of a ground-water divide over a 1-year period is appropriate for delineating areas of ground-water drainage. Contours of average annual water-table altitude can be used to determine the location of the divide.

Precipitation provides a small quantity of water, which is available for consumptive use by plants and is therefore included in the water budgets, although it probably is not a significant source of recharge to the aquifer. The average annual precipitation, which was based on an estimated average annual effective precipitation of 2.01 in., was estimated to be 18,500 acre-ft on 173 mi^2 of flood plain in Palo Verde Valley and 3,000 acre-ft on 28 mi^2 of flood plain in Cibola Valley. The average annual effective precipitation was computed using 12 years of weather records for Blythe, California (L. H. Raymond, U.S. Geological Survey, oral commun., 1983). The effective precipitation estimate was made by summing annual rainfall exceeding 0.25 in. per storm and averaging the annual values.

Palo Verde Valley

The data needed to use the method of calculating ground-water return flow to the river from an area with drainage ditches are available for Palo Verde Valley. All the irrigation water is obtained from the Colorado River, and there is one point of diversion at the head of the valley at Palo Verde Dam. A network of ditches drains ground water from the aquifer to lower the water table for crop protection. Ground water drains to the river in a narrow area along most of the river. Information on irrigated acreages and crop types as well as records on quantities of surface water distributed throughout the valley are available for development of water-budget quantities. The amount of irrigated land in Palo Verde Valley has been stable since 1969 (fig. 8).

Step 1—Delineate areas of ground-water drainage.--In Palo Verde Valley the area that drains in the subsurface to the river can be delineated by locating the ground-water divide between the river and the adjacent drainage ditches. Deep percolation of canal-seepage water and irrigation water applied to the cropland between the ground-water divide and the river infiltrates to the water table, moves downgradient through the aquifer, and discharges to the river. Deep percolation of canal-seepage water and irrigation water from cropland between the ground-water divide and the drainage ditches moves downgradient through the aquifer to discharge into the network of drainage ditches, which channels the flow to the Outfall drain.

Two ground-water drainage areas were delineated using average water-table contours for 1981 (fig. 9). Land on the east side of the divide is drained in the subsurface by the river, and land on the west side of the divide is drained in the subsurface by the network of drainage ditches. Average water-table altitudes were determined by averaging monthly water levels in wells and monthly stage measurements in the drainage ditches measured by Palo Verde Irrigation District (R. E. Henning, written commun., 1983) and by averaging monthly water levels in piezometers installed along the river and river-stage data from continuous-record gages of the U.S. Geological Survey. A step-backwater computer model developed and operated by the U.S. Bureau of Reclamation provided estimates of river-surface altitudes for reaches where river-stage data were not available (H. H. Carver, written commun., 1983). The water-table contours indicate that in 1981 the river gained ground-water inflow from Palo Verde Valley on the west except for a short reach of the river north of Ehrenberg, which was a losing reach (fig. 9).

Olive Lake drain is in the area that drains to the river and intercepts some ground-water return flow (fig. 2, site 4). Insufficient data exists to determine what area is effectively drained by Olive Lake drain. To address this problem, the entire area in question is assumed to drain to the river and the measured flow in Olive Lake drain is subtracted from the computed ground-water return flow from this area and is included in the budget as a surface-water return-flow component.

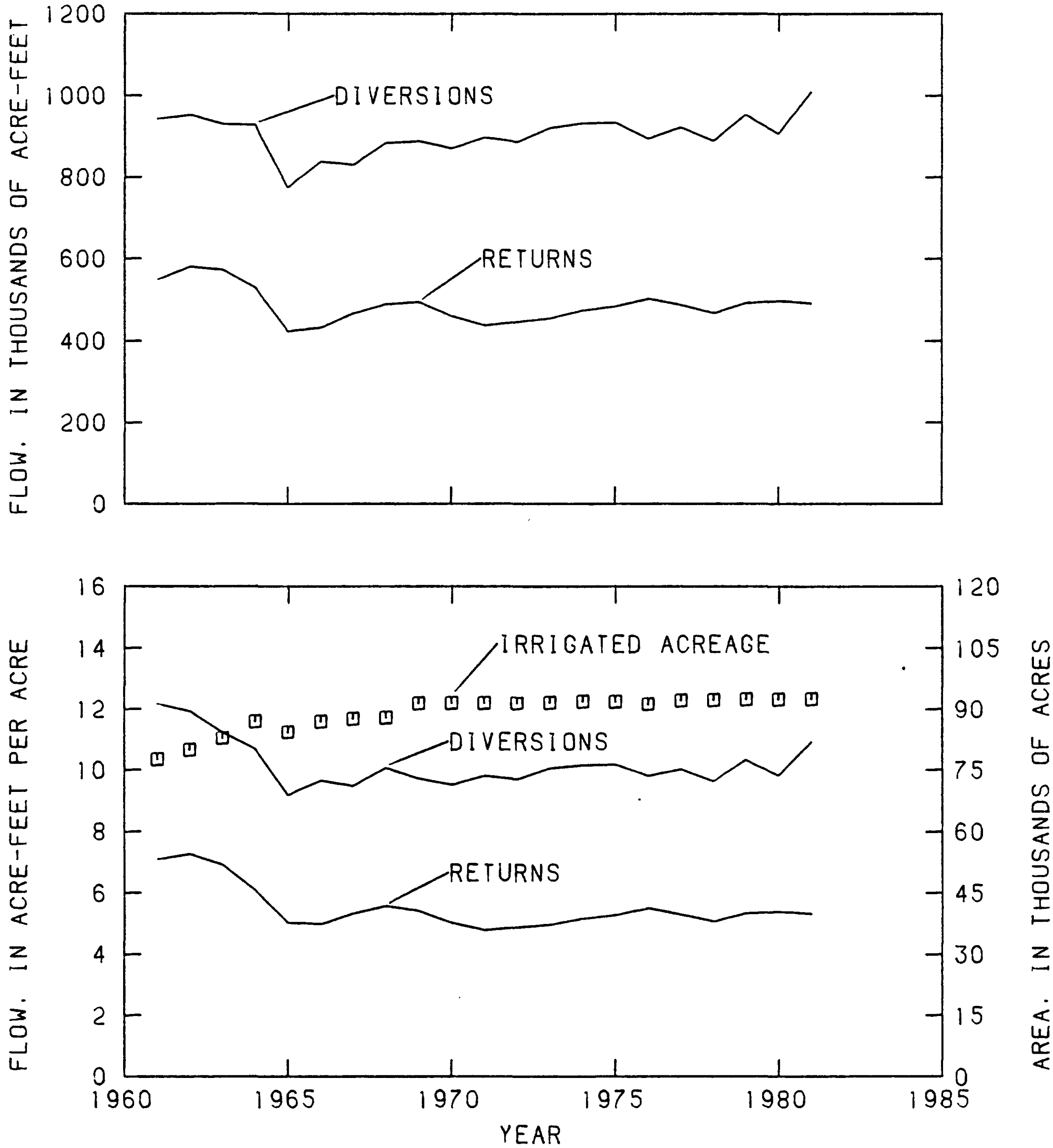

Figure 8.--Diversions, surface-water returns, and irrigated area in Palo Verde Valley, California, 1961-81.

The location of the irrigated land was determined from crop mapping by Palo Verde Irrigation District (Jerry Wolford, Jr., written commun., 1983) and aerial photographs. Phreatophytes were mapped from aerial photographs and from a study by Anderson and Ohmart (1976). The ground-water divide was superimposed on the irrigated-land map in order to determine the amount of irrigated land that drains in the subsurface to the river (fig. 10). The areal distribution of double-cropped acreage was taken into consideration when calculating the total cultivated area on each side of the divide as shown in the following table.

	Area, in acres		
	West of divide	East of divide	Palo Verde Valley
Irrigated area	82,900	8,300	[1]91,200
Double-cropped area	29,000	1,400	[1]30,400
Total cultivated acreage........	111,900	9,700	121,600
Phreatophytes	4,200	2,700	6,900
Total vegetated acreage	116,100	12,400	128,500

[1]Rounded from Palo Verde Irrigation District totals.

Step 2—Estimate diversions to irrigated land.--The approach to estimating the amount of water diverted to the two ground-water drainage areas is dependent on the amount of agricultural data available in the study area. Two approaches are discussed—one where agricultural data are not available and one where agricultural data are available. The amount of diverted water applied to the fields in Palo Verde Valley was estimated to be 773,100 acre-ft or 6.4 ft per cultivated acre in 1981. The amount of water applied to fields was calculated using the amount of water diverted from the river at Palo Verde Dam minus the amount of water that leaves the canals as seepage, spills to the river, spills as regulatory waste into drainage ditches, is diverted out of the flood plain to Palo Verde Mesa, and evaporates from canals (table 1). The resultant quantity of water is used for irrigation of cropland. Applied irrigation water, canal seepage, regulatory waste to drainage ditches, and evaporation from canals are not equally distributed in Palo Verde Valley. To estimate the surface-water diversion to the two ground-water drainage areas, it was necessary to determine the distributions of the individual quantities so that the total diversion to each area reflects any differences.

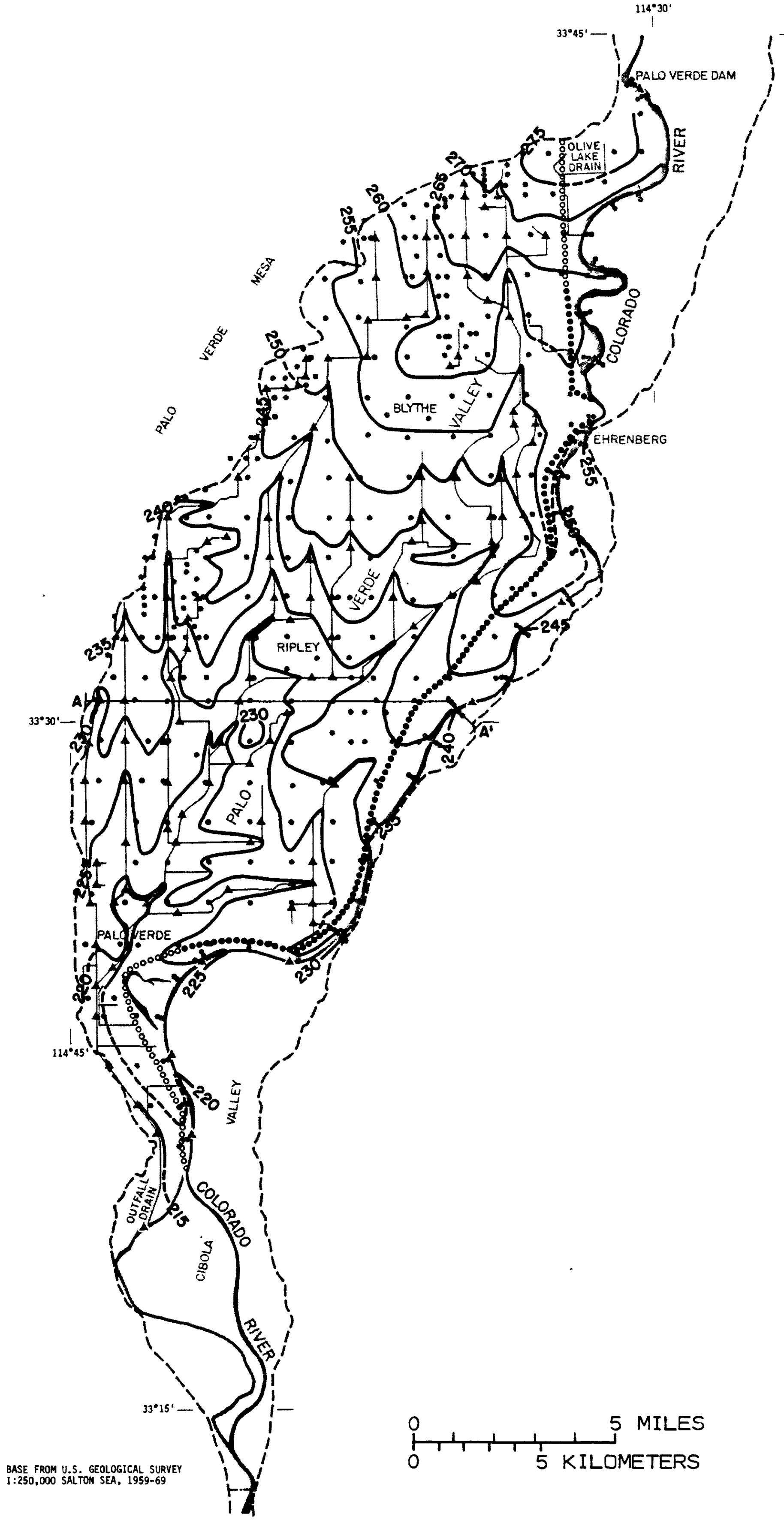

Figure 9.--Average water-table altitude in Palo Verde Valley, California, 1981.

EXPLANATION

——— 250 - - - - - -	WATER-TABLE CONTOUR—Shows average altitude of water table, 1981. Dashed where approximately located. Contour interval 5 feet. National Geodetic Vertical Datum of 1929
•	SHALLOW OBSERVATION WELL OR PIEZOMETER
▲	STAFF GAGE
———————	DRAINAGE DITCH
••••••••••••••oooooooooooooo	GROUND-WATER DIVIDE BETWEEN THE COLORADO RIVER AND DRAINAGE DITCHES—Open symbol where approximately located
- - - - - - - - - - - - - - -	COLORADO RIVER FLOOD-PLAIN BOUNDARY
—·—·—·—·—·—·—·—	BOUNDARY OF THE FLOOD PLAIN OF THE PALO VERDE-CIBOLA AREA WHERE THE FLOOD-PLAIN AQUIFER IS CONTINUOUS
A ├———————┤ A'	LINE OF SECTION DEPICTED IN FIGURE 7

Figure 9

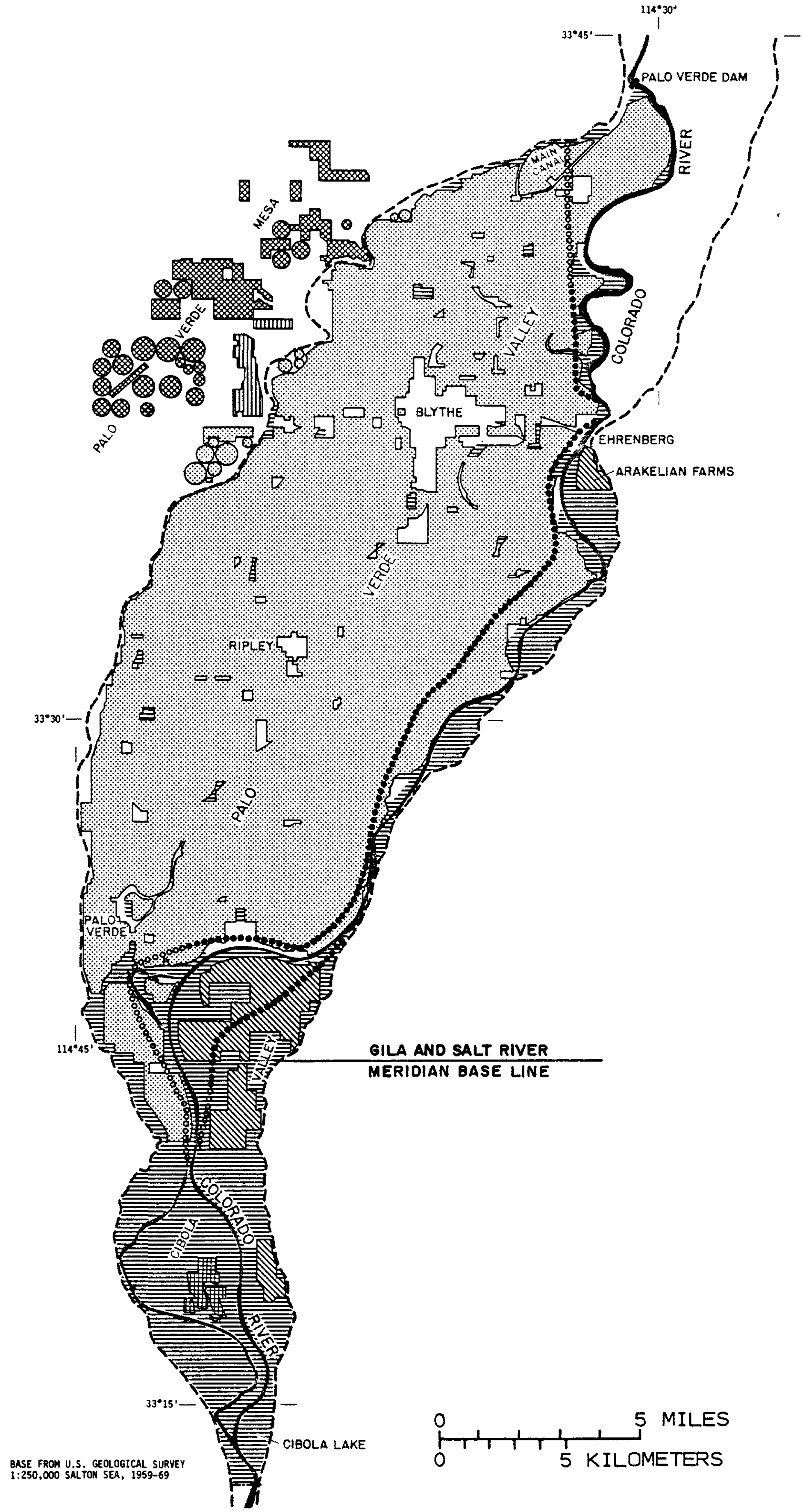

Figure 10.--Irrigated land in Palo Verde and Cibola Valleys, California and Arizona.

E X P L A N A T I O N

LAND IRRIGATED WITH WATER DIVERTED FROM THE COLORADO RIVER AT PALO VERDE DAM

LAND ON PALO VERDE MESA PARTIALLY IRRIGATED WITH WATER DIVERTED FROM THE COLORADO RIVER AT PALO VERDE DAM

LAND ON PALO VERDE MESA IRRIGATED WITH GROUND-WATER PUMPAGE

LAND IRRIGATED WITH WATER PUMPED FROM THE COLORADO RIVER AT VARIOUS SITES

LAND NOT IRRIGATED IN 1981 WHERE CROPS ACT AS PHREATOPHYTES IN OBTAINING GROUND WATER

AREA OF PHREATOPHYTES

GROUND-WATER DIVIDE BETWEEN THE COLORADO RIVER AND DRAINAGE DITCHES—Open symbol where approximately located

COLORADO RIVER FLOOD-PLAIN BOUNDARY

BOUNDARY OF THE FLOOD PLAIN OF THE PALO VERDE-CIBOLA AREA WHERE THE FLOOD-PLAIN AQUIFER IS CONTINUOUS

Figure 10

Table 1.--Estimates of surface-water diversions to irrigated land in Palo Verde Valley, California, 1981, in acre-feet per year

Surface-water diversion at Palo Verde Dam		[1]1,008,000
Canal seepage	[2]125,000	
Spills to river	[3]65,500	
Regulatory waste to drainage ditches	[4]22,300	
Diversion to Palo Verde Mesa	[4]17,100	
Evaporation from canals	[5]5,000	
Subtotal		234,900
Net water applied to irrigated land		773,100

	Diversion to area west of divide	Diversion to area east of divide
Surface water applied to irrigated land	706,600	66,500
Regulatory waste to drainage ditches	22,300	0
Canal seepage	112,500	12,500
Evaporation from canals	4,500	500
Total diversion	845,900	79,500

[1]Gaged by the U.S. Geological Survey, Palo Verde Canal near Blythe.

[2]Estimated by Bookman-Edmonston Engineering, Inc. (1976, p. 35).

[3]Measured and computed by the U.S. Geological Survey (see section entitled "Hydrology" of this report).

[4]Measured by Palo Verde Irrigation District (R. E. Henning, written commun., 1983).

[5]Estimated by Bookman-Edmonston Engineering, Inc. (1976, p. 36).

One approach to estimating the amount of water applied to irrigated land on each side of the ground-water divide when the distribution of crop types is unknown is to assume that water is applied uniformly to cropland. The percentage of the resultant quantity applied to cultivated land on each side of the ground-water divide (fig. 10) can be estimated using a ratio between the cultivated acreage on each side of the divide and the total cultivated acreage in the valley as determined in step 1. If the assumption is valid, the diversion to the area west of the divide would include 92 percent of the applied water or 711,300 acre-ft; the diversion to the area east of the divide would include 8 percent of the applied water or 61,800 acre-ft.

Another approach to estimating the amount of water applied to the two ground-water drainage areas is to assume the amount of water applied is proportional to the irrigation requirements—the volume of water per unit area required to grow a crop. This approach requires data on the type of crops grown and their distribution in the area. The irrigation requirements by crop type were obtained from a study by the U.S. Department of Agriculture in Parker Valley and used in the water-budget method for estimating ground-water return flow along the Parker reach of the Colorado River (Leake, 1984, table 1); the irrigation requirements from Parker Valley can be transferred to Palo Verde and Cibola Valleys. Irrigation requirements are dependent on soil texture; therefore, soil textures were determined from soil surveys by the U.S. Department of Agriculture, Soil Conservation Service (1974; 1980).

The relative distribution of applied water to the two ground-water drainage areas that was estimated using the percentages determined from irrigation requirements is probably better than the distribution estimated using cultivated area because areal variations in cropping patterns are likely to have an effect on the areal distribution of the applied water. Data on crop types, the distribution of crop types, and the distribution of double cropping are known in Palo Verde Valley; therefore, the approach, where the diversions are estimated assuming the diversions are proportional to the irrigation requirements, is used to determine the amount of water diverted to each drainage area. The area east of the divide requires 8.6 percent of the total irrigation requirement and the area west of the divide requires 91.4 percent (table 2). The irrigation requirement per unit cultivated area for the area drained by the river is higher than the percentage calculated assuming uniform application because this area has proportionally more alfalfa, which has a high irrigation requirement. Using the percentages determined from irrigation requirements, the amount of water applied to the area west of the divide is estimated to be 706,600 acre-ft; the amount of water applied to the area east of the divide is estimated to be 66,500 acre-ft (table 1).

The total surface-water diversion was estimated to be 845,900 acre-ft to the area west of the divide and 79,500 acre-ft to the area east of the divide (table 1). Canal seepage and evaporation were distributed between the two ground-water drainage areas by assuming that the amount of seepage in each area is proportional to the total length of

Table 2.--Estimates of irrigation requirements and consumptive use by vegetation in Palo Verde Valley, California, 1981

Vegetation type	Consumptive use, in feet	Area, in acres			Irrigation requirement, in acre-feet			Consumptive use, in acre-feet		
		West of divide	East of divide	Total	West of divide	East of divide	Total	West of divide	East of divide	Total
Crops										
Alfalfa	[1]5.3	39,100	4,600	43,700	371,500	43,700	415,200	207,200	24,400	231,600
Cotton	[1]3.2	32,200	2,100	34,300	183,500	12,000	195,500	103,000	6,700	109,700
Grain	[1]1.9	18,700	1,600	20,300	61,700	5,300	67,000	35,500	3,000	38,500
Other	[2]2.0	21,900	1,400	23,300	87,600	5,600	93,200	43,800	2,800	46,600
Subtotal		111,900	9,700	121,600	704,300	66,600	770,900	389,500	36,900	426,600
Phreatophytes	[3]3.4	4,200	2,700	6,900	-------	------	-------	14,300	9,200	23,500
Total		116,100	12,400	128,500	704,300	66,600	770,900	403,800	46,100	449,900

[1]Determined by U.S. Soil Conservation Service on the basis of soil-moisture depletion studies in Parker Valley (H. C. Millsaps, oral commun., 1983).

[2]Calculated as area-weighted average of empirically determined consumptive use for other crops.

[3]Boyle Engineering Corp. (1976, p. II-7).

canals on each side of the divide. The amounts of seepage and evaporation were estimated using the percentage of canals by length multiplied by the total canal seepage or evaporation from canals in Palo Verde Valley given in table 1. The area west of the divide contains 90 percent of the canals and the area east of the divide contains 10 percent. There was no regulatory waste to Olive Lake drain in 1981 (Roger E. Henning, Palo Verde Irrigation District, oral commun., 1983).

Step 3—Estimate consumptive use.--A water budget for the area of Palo Verde Valley drained by the drainage ditches was used to estimate 451,900 acre-ft of consumptive use in 1981 (table 3). Consumptive use includes transpiration by crops, phreatophytes, and other plants and evaporation from open-water and bare-soil surfaces. The average consumptive-use value of 3.9 ft for the area drained by drainage ditches can be used to estimate consumptive use in the area drained by the river if the assumption is made that the average consumptive use per unit area is the same on both sides of the ground-water divide. Consumptive use for a total of 12,400 acres of crops and phreatophytes in the area of Palo Verde Valley drained by the river would be 48,400 acre-ft in 1981. The effective precipitation in each ground-water drainage area was estimated using an annual effective precipitation of 2.01 in. multiplied by the total area of the flood plain on each side of the divide. The area west of the divide is 153 mi^2 and the area east of the divide is 20 mi^2. Surface-water diversions and returns were based on measurements of flow as discussed in the section entitled "Surface Water." Other quantities were estimated as explained in the section entitled "Ground Water in the Flood-Plain Aquifer."

River-surface altitudes, ground-water heads, and irrigation-water deliveries generally follow a 1-year cycle; therefore, the change in ground-water storage for the 1-year period studied is probably negligible. The amount of ground-water in storage and the position of the ground-water divide from year to year could change because of year-to-year variations in river-surface altitudes and changes in irrigation practices or crop types. The effects of the changes in storage are probably insignificant within the 1-year period in the computation of consumptive use.

Consumptive use by vegetation types was estimated for the two ground-water drainage areas in Palo Verde Valley using vegetation type, empirically determined consumptive use per vegetation type, and total acreage for each vegetation type (table 2). Consumptive use by vegetation types in the area drained by drainage ditches is about 12 percent less than the value computed in the water budget (table 3). The difference in the two values may be attributed to evaporation from water and soil surfaces, which is included in consumptive use from the water budget but not in consumptive use by vegetation types. Consumptive use was 3.5 ft in the area west of the divide and 3.7 ft in the area east of the divide. The higher value in the area that drains to the river is caused by a larger percentage of the cultivated area planted with alfalfa and more phreatophytes per total area. Alfalfa and phreatophytes use more

Table 3.--Water budget for the area of Palo Verde Valley, California, drained by the drainage ditches, 1981, in acre-feet per year

Inflow:	
Surface-water diversion	845,900
Effective precipitation	16,400
Ground-water inflow from west bordering area	9,500
Tributary runoff	3,200
Seepage from the Colorado River	3,100
Total	878,100
Outflow:	
Surface-water discharge to Colorado River from drainage ditches	419,500
Outflow to west bordering area	4,700
Pumpage	2,000
Evaporation from canals	4,500
Total	430,700
Consumptive use other than evaporation from canals:	
Inflow minus outflow	447,400
Total consumptive use: (447,400 + 4,500)	451,900

water than other vegetation types in the study area. The analysis of consumptive use by vegetation types indicates that consumptive use per unit area by crops and phreatophytes is about 6 percent higher in the area drained by the river than in the area drained by drainage ditches. The difference is assumed to apply to overall consumptive use; therefore, the previously determined consumptive-use value of 48,400 acre-ft for the area drained by the river, adjusted for the 6-percent increase, results in an adjusted consumptive-use value of 51,300 acre-ft. Because the distribution of vegetation types was different on each side of the divide and the adjusted consumptive-use value incorporates the areal variation in consumptive use, the adjusted consumptive-use value of 51,300 acre-ft was used in the water budget (table 4) for the area east of the divide in order to compensate for the unequal distribution of vegetation types in the estimation of ground-water return flow.

Table 4.--Water budget for the area of Palo Verde Valley, California, drained by the river, 1981, in acre-feet per year

Inflow:	
Surface-water diversion	79,500
Effective precipitation	2,100
Total	81,600
Outflow (other than ground-water return flow to river):	
Consumptive use	51,300
Surface-water discharge to Colorado River from Olive Lake drain (measured)	6,400
Total	57,700
Unmeasured ground-water return flow to river:	
Inflow minus outflow	23,900

Step 4—Compute ground-water return flow.--A water budget was used to compute 23,900 acre-ft of ground-water return flow to the river in 1981 (table 4). Diversions were estimated in step 2 to be 79,500 acre-ft. Consumptive use was estimated in step 3 to be 51,300 acre-ft.

Sensitivity analysis.--The method presented in this report combines measured and unmeasured quantities to obtain estimates of ground-water return flow. Values given previously for each of the 40 primary variables used in the estimation of ground-water return flow are shown in table 5. For each measured or estimated quantity, there is some uncertainty as to the degree to which the value is representative of the "true" or "actual" value. A quantitative analysis of how these uncertainties affect the uncertainty in the final result is referred to as an error analysis. Objective error analyses require knowledge of errors or uncertainties in individual quantities. Because of the judgment involved in estimating many of the quantities in table 5, objective error analyses cannot be performed.

A basic sensitivity analysis however can be done by determining the change in computed ground-water return flow for a specified change in the value of a primary variable. The sensitivity values in table 5 indicate that ground-water return flow is most sensitive to diversions at Palo Verde Dam, to various irrigation requirements and crops areas, and to discharge from drains to the river.

Table 5.--Primary variables used in the computation of ground-water return flow in Palo Verde Valley, California, and sensitivity of results to a change in specified value

[Source: M, measured; E, estimated. East area is drained by the Colorado River, west area is drained by drainage ditches. Sensitivity: Percentage change in computed ground-water return flow for a +10 percent change in value of the primary variable]

Variable	Source	Value	Sensitivity
Diversions at Palo Verde Dam	M	1,008,000 acre-ft	7.9
Canal seepage	E	125,000 acre-ft	-0.8
Spills to the river	M	65,500 acre-ft	-0.5
Regulatory waste to ditches	E	22,300 acre-ft	0.9
Diversion to Palo Verde Mesa	E	17,100 acre-ft	-0.1
Evaporation from canals	E	5,000 acre-ft	-0.0
Length of canals in east area	M	25.8 miles	-6.2
Length of canals in west area	M	226.9 miles	6.2
Areas of vegetation in east area:			
Alfalfa	M	4,600 acres	12.4
Cotton	M	2,100 acres	3.7
Grain	M	1,600 acres	0.8
Other crops	M	1,400 acres	0.4
Phreatophytes	M	2,700 acres	4.8
Areas of vegetation in west area:			
Alfalfa	M	39,100 acres	-11.1
Cotton	M	32,200 acres	-5.9
Grain	M	18,700 acres	-1.5
Other crops	M	21,900 acres	-2.0
Phreatophytes	M	4,200 acres	-0.8
Irrigation requirement in east area:			
Alfalfa	E	43,700 acre-ft	-22.0
Cotton	E	12,000 acre-ft	-7.3
Grain	E	5,300 acre-ft	-3.7
Other crops	E	5,600 acre-ft	-3.7
Irrigation requirement in west area:			
Alfalfa	E	371,500 acre-ft	14.6
Cotton	E	183,500 acre-ft	7.3
Grain	E	61,700 acre-ft	0.0
Other crops	E	87,600 acre-ft	3.7
Average consumptive use:			
Alfalfa	E	5.3 feet	0.0
Cotton	E	3.2 feet	-2.1
Grain	E	1.9 feet	0.0
Other crops	E	2.0 feet	-2.1
Phreatophytes	E	3.4 feet	4.1
Effective precipitation in:			
West area	E	16,400 acre-ft	0.8
East area	E	2,100 acre-ft	-0.9
Inflow from west side of valley	E	9,500 acre-ft	0.5
Tributary runoff from west side of valley	E	3,200 acre-ft	0.2
Inflow from river seepage	E	3,100 acre-ft	0.2
Discharge from drains to river from:			
West area	M	419,500 acre-ft	-20.4
East area	M	6,400 acre-ft	2.7
Outflow to west from valley	E	4,700 acre-ft	-0.2
Pumpage	E	2,000 acre-ft	-0.1

A more involved sensitivity analysis considers how uncertainty in all the primary variables affects the uncertainty in the ground-water return flow. For this analysis, the error or uncertainty in a quantity is most conveniently expressed in terms of the variance of the quantity. Variance is the mean squared deviation of individual estimates of the quantity from the mean or "true" value. A measure of error expressed in terms of the original units of the variable is the standard deviation, which is the positive square root of the variance. A measure of error expressed as a fraction of a quantity is the coefficient of variation, which is the ratio of the standard deviation to the mean value.

To evaluate errors in ground-water return flow, 500 additional sets of the 40 primary variables in table 5 were obtained by introducing random error terms as follows:

$$x_i' = x_i \times (1 + r_i \times e_i)$$

where

x_i' is a new value of the i^{th} primary variable,

x_i is the value of the i^{th} primary variable in table 5,

r_i is a normally distributed random number with mean of 0.0 and variance of 1.0, and

e_i is the error expressed as the coefficient of variation.

Values of e_i were selected as follows:

1. Diversions at Palo Verde Dam and discharge from drains to the river were assumed to have coefficient of variation of 0.05. Other measured surface-water quantities are computed and were assumed to have a coefficient of variation of 0.10.

2. Measured areas were assumed to have a coefficient of variation of 0.10.

3. Estimated values were assumed to have a coefficient of variation equal to an arbitrarily selected error, e'.

To preclude the possibility of generating physically unreasonable values of primary variables, recomputations were done for any value that was computed to be less than zero.

From the additional data sets, 500 values of ground-water return flow were computed. Using standard formulas for sample statistics, the coefficient of variation and the standard deviation of ground-water return flow for e' = 0.10, 0.20, and 0.30 were computed to be:

e'	Coefficient of variation	Standard deviation, in acre-feet
0.10	0.35	8,600
0.20	0.57	14,800
0.30	0.82	20,800

This analysis shows that the level of uncertainty in the ground-water return flow is substantially greater than an assumed level of uncertainty in the estimated values. High levels of uncertainty in ground-water return flow, however, have a minor effect on the level of uncertainty in the total return flow from the diversion at Palo Verde Dam because ground-water return flow is a small fraction of the total.

Cibola Valley

The method used to calculate ground-water return flow to the river in Cibola Valley was the modified water-budget method for an area without drainage ditches. The data needed to estimate return flow from Cibola Valley in 1981 was incomplete; therefore, the magnitude of ground-water return flow from Cibola Valley was estimated for 1981 using partial data available for 1983 and assuming that hydrologic conditions in the valley were similar in 1981 and the first part of 1983. Cibola Valley had no drainage ditches in 1981 and water was pumped or diverted from the river at eight different sites. Records of crop types were not available for 1981. Crop types for 1981 were identified using Landsat satellite imagery from a study in progress by the U.S. Geological Survey (L. H. Raymond, written commun., 1983). The observation wells were not installed until February 1983. The location of the ground-water divide is related to river stage and the river stage was higher in 1983 than in 1981 because of flood-control releases from the dams upstream.

Modifications to the method were made mainly because of the lack of drainage ditches in Cibola Valley. The modified method includes only one water budget; a water budget that solves for ground-water return flow from the area that drains in the subsurface to the river. Consumptive use could not be estimated with a water budget because of the lack of drainage ditches; therefore, consumptive use was estimated using vegetation types, acreages, and consumptive use for each vegetation type that was empirically determined in nearby areas.

Cibola Valley was divided into three areas because of the location of the ground-water divide, multiple points of pumping from the Colorado River, and different usage for diverted water. The three areas are: (1) Cibola Irrigation and Drainage District, which is north of the Gila and Salt River Meridian base line; (2) Cibola National Wildlife Refuge and other land south of the Gila and Salt River Meridian base line; and (3) west of the Colorado River (fig. 10). Cibola Irrigation and Drainage District contains all the irrigated land that drains in the subsurface to the river. In Cibola National Wildlife Refuge, some of the pumped river water is used to irrigate crops and some is used to flood fields during the winter for use as water fowl habitat. West of the Colorado River, some land has been cultivated but not irrigated since 1979. The area west of the river is not considered in the study of ground-water return flow because no water was diverted to the area in 1981 and therefore no ground water returned to the river.

Step 1—Delineate areas of ground-water drainage.--In Cibola Valley the area that drains in the subsurface to the river was delineated using the average water-table contours from monthly water-level measurements from February to May 1983 to approximate the location of the ground-water divide (fig. 11). Water-level data for the area adjacent to the river in 1981 indicated ground-water inflow to the river from Cibola Valley (fig. 9). The position of the ground-water divide from February to May 1983 remained essentially unchanged from month to month and was not affected by the rise in river stage as of the May measurements; therefore, the position of the divide delineated from the average water-table contours from February to May is assumed to be the best estimation of the position of the divide in 1981 during normal flow conditions in the river. Northwest of the divide, ground water drains to the river. Southeast of the divide, ground water flows southward and southeastward out of the flood plain or into areas where the direction of ground-water movement is unknown; therefore, it is not known if the water eventually discharges to the river. Flood-control releases from the dams in 1983 occurred in January, April, and May, and piezometer data along the reach of the river that bounds Cibola Valley indicate inflow to the aquifer from the river. Monthly water-level measurements indicate increases in bank storage near the river but show little effect on the location of the ground-water divide, which is mostly controlled by recharge from irrigation.

The potential for ground-water return flow to the river results from the irrigation of crops in Cibola Irrigation and Drainage District and the northern part of Cibola National Wildlife Refuge. The reach of the river in the southern part of the wildlife refuge loses water to the aquifer. In 1981 and 1983, cropland between the new river channel and the old river channel was not irrigated, but some of the alfalfa acts as a phreatophyte in obtaining ground water (fig. 10).

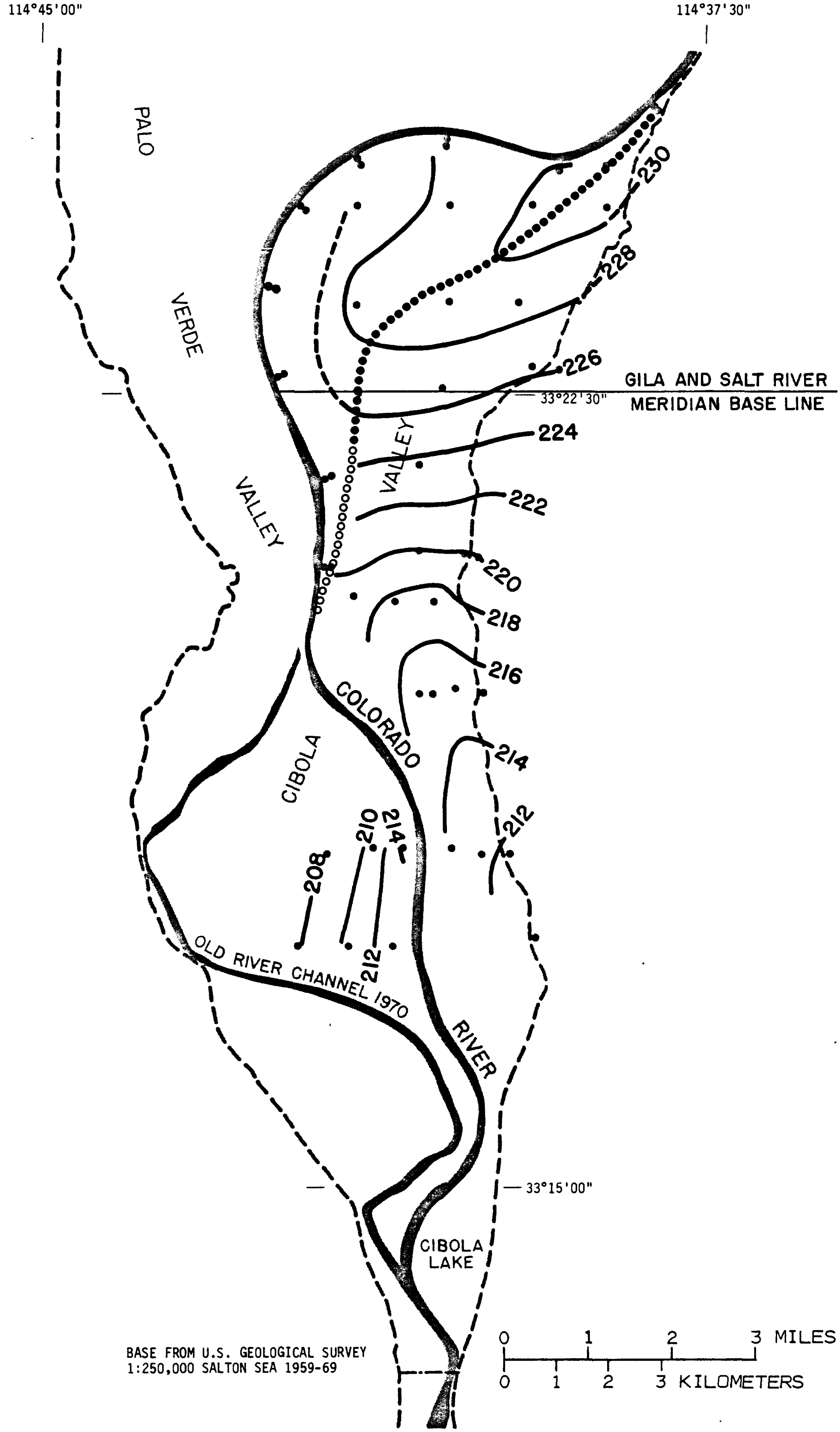

Figure 11.--Average water-table altitude in Cibola Valley, Arizona, February to May 1983.

E X P L A N A T I O N

—— 220 - - - -	WATER-TABLE CONTOUR—Shows average altitude of water table, February to May 1983. Dashed where approximately located. Contour interval 2 feet. National Geodetic Vertical Datum of 1929
•	SHALLOW OBSERVATION WELL OR PIEZOMETER
●●●●●●●●●●●○○○○○○○○○○○	GROUND-WATER DIVIDE—Open symbol where approximately located
— — — — — — — —	COLORADO RIVER FLOOD-PLAIN BOUNDARY
—·—·—·—·—·—·—	BOUNDARY OF THE FLOOD PLAIN OF THE PALO VERDE-CIBOLA AREA WHERE THE FLOOD-PLAIN AQUIFER IS CONTINUOUS

Figure 11

The location of irrigated land was determined from 1982 aerial photographs and crop mapping (L. H. Raymond, U.S. Geological Survey, written commun., 1983). Phreatophyte acreages were determined from a study by Anderson and Ohmart (1976) and aerial photographs. The ground-water divide was superimposed on the irrigated-land map in order to determine the amount of irrigated land that drains in the subsurface to the river (fig. 10). Some double cropping has occurred, but information on which fields were doubled cropped and on what the second crop was each year was not recorded (Wayne Sprawls, Cibola Irrigation and Drainage District, oral commun., 1983).

	Area, in acres			
	Northwest of divide[1]	Southeast of divide[1]	West of river	Total
Irrigated area:				
Cibola Irrigation and Drainage District........	1,900	1,000	--	2,900
South of Cibola Irrigation and Drainage District ...	0	1,100	--	1,100
Subtotal	1,900	2,100	--	4,000
Pheatophytes:				
Cibola Irrigation and Drainage District........	600	800	--	1,400
South of Cibola Irrigation and Drainage District and east of river........	500	4,300	--	4,800
South of Cibola Irrigation and Drainage District and west of river	-----	-----	4,500	4,500
Non-irrigated cropland	-----	-----	600	600
Subtotal	1,100	5,100	5,100	11,300
Total	3,000	7,200	5,100	15,300

[1]East of river.

Step 2—Estimate diversions to irrigated land.--The total amount of water diverted and applied to fields in Cibola Valley in 1981 was 34,400 acre-ft (table 6). Seepage from concrete-lined main canals was negligible and no regulatory waste occurred. Evaporation from 9 mi of main canals in Cibola Irrigation and Drainage District was probably less than 30 acre-ft/yr and was ignored because of the rounding criteria. The percentage of the water applied to the irrigated land on each side of the ground-water divide was determined from a ratio between irrigated acreage on each side of the divide and the total irrigated acreage from step 1 (table 6). The area northwest of the divide in the Cibola Irrigation and Drainage District contained 66 percent of the irrigated acreage and the area southeast of the divide contained 34 percent.

Step 3—Estimate consumptive use.--Consumptive use by crops and phreatophytes east of the river in Cibola Valley in 1981 was estimated to be 35,900 acre-ft. Consumptive use was estimated using the types of crops as identified from Landsat multispectral scanner imagery (L. H. Raymond, U.S. Geological Survey, written commun., 1983), acreages mapped and digitized from aerial photographs, and empirically determined consumptive use per vegetation type (table 7). Phreatophyte acreages

Table 6.--Estimates of applied surface water on irrigated land in Cibola Valley, Arizona, 1981, in acre-feet per year

	Applied irrigation water		
	Northwest of divide	Southeast of divide	Total in Cibola Valley
Surface-water pumpage:			
Cibola Irrigation and Drainage District	[1]16,000	[1]8,300	[2]24,300
Cropland south of Cibola Irrigation and Drainage District	[1]0	[1]10,100	[2]10,100
Total	16,000	18,400	34,400

[1]Prorated from pumpage record totals on the basis of the amount of irrigated land on each side of the divide.

[2]Determined from pumpage records.

Table 7.--Estimates of consumptive use by vegetation on the east side of the Colorado River in Cibola Valley, Arizona, 1981

Vegetation type	Consumptive use, in feet	North of baseline[1]				South of baseline			
		Northwest of divide		Southeast of divide		Northwest of divide		Southeast of divide	
		Area, in acres	Consumptive use, in acre-feet	Area, in acres	Consumptive use, in acre-feet	Area, in acres	Consumptive use, in acre-feet	Area, in acres	Consumptive use, in acre-feet
Crops									
Alfalfa	[2]5.3	500	2,700	400	2,100	0	-----	700	3,700
Cotton	[2]3.2	900	2,900	400	1,300	0	-----	0	------
Grain	[2]1.9	200	400	100	200	0	-----	20	40
Other	[3]2.0	300	600	100	200	0	-----	400	800
Subtotal		1,900	6,600	1,000	3,800	0	-----	1,100	4,500
Phreatophytes	[4]3.4	600	2,000	800	2,700	500	1,700	4,300	14,600
Total (rounded)		2,500	8,600	1,800	6,500	500	1,700	5,400	19,100

[1]Cibola Irrigation and Drainage District.

[2]Determined by U.S. Soil Conservation Service on the basis of soil-moisture depletion studies in Parker Valley (H. C. Millsaps, oral commun., 1983).

[3]Calculated as an area-weighted average of empirically determined consumptive use for other crops.

[4]Boyle Engineering Corp. (1976, p. II-7).

were digitized from aerial photographs and from a study by Anderson and Ohmart (1976). The amount of water consumed by crops and phreatophytes for the area northwest of the divide and drained by the river was estimated to be 10,300 acre-ft. In the area southeast of the divide, the consumptive use by vegetation was 25,600 acre-ft, which is 2.5 times more water than the amount applied to irrigated land.

To incorporate consumptive use into the water budget (table 8), consumptive use by crops and phreatophytes needs to be adjusted to include evaporation by water and soil surfaces. If it is assumed that the difference between the two values of consumptive use is 12 percent in both Palo Verde and Cibola Valleys in 1981, then the overall consumptive use for the area in Cibola Valley that drains to the river is 11,500 acre-ft.

Step 4—Compute ground-water return flow.--The ground-water return flow to the Colorado River was computed using water-level data for part of 1983 and estimates of consumptive use for 1981 to demonstrate that the method can be applied in Cibola Valley. The result may not be accurate for 1981 but represents an estimate of the magnitude of return flow from Cibola Valley. The amount of surface water pumped to irrigate land in the 6.5-square-mile area of Cibola Valley that is drained by the river was estimated in step 2 to be 16,000 acre-ft. This amount, combined with 700 acre-ft of effective precipitation, constituted the inflow. Consumptive use by vegetation was estimated in step 3 to be 11,500 acre-ft, leaving a residual of 5,200 acre-ft of ground water that returned to the river through the subsurface in 1981 (table 8).

Table 8.--Water budget for the area of Cibola Valley, Arizona, drained by the river, 1981, in acre-feet per year

Inflow:	
Surface water applied to irrigated land	16,000
Effective precipitation	700
Total	16,700
Outflow:	
Consumptive use	11,500
Total	11,500
Ground-water flow to river	
Inflow minus outflow	5,200

Sensitivity analysis.--The method presented in this report combines measured and unmeasured quantities to obtain estimates of ground-water return flow. Values given previously for each of the 18 primary variables used in the estimation of ground-water return flow are shown in table 9 for Cibola Valley. The same sensitivitiy analysis used for Palo Verde Valley was used for the data set for Cibola Valley. The sensitivity values in table 9 indicate that ground-water return flow is most sensitive to the diversion to Cibola Irrigation and Drainage District and to the factor used to obtain total consumptive use from consumptive use by vegetation.

A more involved sensitivity analysis considers how uncertainty in all the primary variables affects the uncertainty in the ground-water return flow. To evaluate errors in ground-water return flow, 500 additional sets of the 18 primary variables in table 9 were obtained by introducing random error terms in the equation. Values of error expressed as the coefficient of variation were selected as follows:

1. Measured values were assumed to have a coefficient of variation of 0.10.

2. Estimated values were assumed to have a coefficient of variation equal to an arbitrarily selected error, e'.

From the additional data sets, 500 values of ground-water return flow were computed. Using standard formulas for sample statistics, the coefficient of variation and the standard deviation of ground-water return flow of $e' = 0.10$, 0.20, and 0.30 were computed to be:

e'	Coefficient of variation	Standard deviation, in acre-feet
0.10	0.39	2,100
0.20	0.57	3,000
0.30	0.79	4,200

This analysis shows that the level of uncertainty in the ground-water return flow is substantially greater than an assumed level of uncertainty in the estimated values. High levels of uncertainty in ground-water return flow, however, have a major effect on the level of uncertainty in the total return flow from the diversion because ground-water return flow from Cibola Valley equals total return flow from the diversion. There was no surface-water return flow from Cibola Valley in 1981.

Table 9.--Primary variables used in the computation of ground-water return flow in Cibola Valley, Arizona, and sensitivity of results to a change in specified value

[Source: M, measured; E, estimated. Northwest area is drained by the Colorado River. Sensitivity: Percentage change in computed ground-water return flow for a +10 percent change in value of the primary variable]

Variable	Source	Value	Sensitivity
Diversion by pumps in river to Cibola Irrigation and Drainage District	M	24,300 acre-ft	-31.0
Areas of vegetation in northwest area:			
Alfalfa	M	500 acres	3.0
Cotton	M	900 acres	1.4
Grain	M	200 acres	-0.3
Other crops	M	300 acres	-0.4
Phreatophytes	M	1,100 acres	8.1
Areas of vegetation in southeast area:			
Alfalfa	M	400 acres	4.2
Cotton	M	400 acres	4.2
Grain	M	100 acres	1.1
Other crops	M	100 acres	1.1
Phreatophytes	M	800 acres	0.0
Average consumptive use:			
Alfalfa	E	5.3 feet	5.8
Cotton	E	3.2 feet	6.3
Grain	E	1.9 feet	0.8
Other crops	E	2.0 feet	1.3
Phreatophytes	E	3.4 feet	8.1
Effective precipitation in northwest area	E	700 acre-ft	-1.4
Factor to obtain total consumptive use	E	1.12	22.3

Other Areas

River water is used to irrigate crops on the flood plain adjacent to the river south of Ehrenberg on the Arizona side and on Palo Verde Mesa in California (fig. 10). Along the river, areas of phreatophytes also use water. These areas need to be considered when accounting for ground-water return flow from irrigated areas by the States.

The potential exists in the Arakelian Farms area for ground-water return flow to the river. The following table itemizes consumptive use by vegetation type:

	Consumptive use, in feet	Area, in acres	Consumptive use, in acre-feet
Arakelian Farms area			
Cotton	3.2	100	300
Grain	1.9	200	400
Phreatophytes	3.4	1,100	3,700
Total		1,400	4,400

Arakelian Farms pumped 2,646 acre-ft of river water for irrigation of about 300 acres of crops in 1981 (U.S. Bureau of Reclamation, 1982, p. 12). Crops used 700 acre-ft of irrigation water. Some of the excess irrigation water returns to the river as ground-water outflow from the flood-plain aquifer and some is used by phreatophytes. Piezometers along the river indicate that ground water flowed to the river in 1981, but data are not available to locate a ground-water divide and estimate the quantity of ground-water return flow to the river.

Some of the water diverted at Palo Verde Dam for irrigation is pumped for use on Palo Verde Mesa. The diversion to Palo Verde Mesa was 17,100 acre-ft in 1981 (table 1); this water supplements ground-water pumpage for irrigation. The assumption was made that none of the surface water applied to fields on the mesa returns to the river because the direction of ground-water movement beneath the area is away from the flood plain.

CONCLUSIONS AND DATA NEEDS

Ground-water return flow was estimated to be about 29,100 acre-ft along the Palo Verde-Cibola reach of the Colorado River in 1981. Water diverted from the river and surface-water return flow are measured. The following quantities of diversions, return flows, and consumptive use for 1981 are itemized for Palo Verde and Cibola Valleys:

	Quantity, in acre-feet			
	Palo Verde Valley		Cibola Valley	
Surface water diverted		1,008,000		34,400
Surface-water return flow	491,400		-----	
Ground-water return flow	23,900		5,200	
Total return flow		515,300		5,200
Consumptive use (Diversion minus returns)		492,700		29,200

The U.S. Supreme Court decree (1964) stipulates that the United States shall keep complete, detailed, and accurate records of diversions of water from the mainstream, return flow of such water, and consumptive use by each point of diversion. Total return flow, 515,300 acre-ft, is the sum of the surface-water return flow and ground-water return flow for the point of diversion at Palo Verde Dam. Ground-water return flow, 5,200 acre-ft, is equal to total return flow from the Cibola Valley Irrigation and Drainage District's pumps or point of diversion. Consumptive use, as defined by the decree, is diversions minus return flow.

Ground-water return flow is small in relation to the amount of water diverted and the consumptive use. The estimation of ground-water return flow is dependent on these two quantities in the method; therefore, small errors in the estimated diversions and consumptive use can result in large errors in the estimated ground-water return flow. In Palo Verde Valley, ground-water return flow is small in relation to the diversion and surface-water return flow; whereas, in Cibola Valley, it is a larger percentage of the diversion because there are no drainage ditches and no surface-water return flow. Data in Cibola Valley are incomplete; therefore, the computed ground-water return flow is an estimate of the magnitude of the quantity of ground-water return flow. The computation of ground-water return flow from Cibola Valley was presented to illustrate how the method could be applied when sufficient data are available.

The method presented for estimation of ground-water return flow in Palo Verde and Cibola Valleys requires consideration be given to the following data needs:

1. The position of the ground-water divide depends on the stage of the river and the areal distribution of applied irrigation water. The effects of changing conditions on the position of the divide need to be evaluated. The position of the ground-water divide in Palo Verde Valley is approximated in two places: (1) at the north end

of the valley near Main Canal and Olive Lake drain and (2) at the south end of the valley south of the oxbow lake. The altitudes of the water levels in Olive Lake drain and three drainage ditches in the south are not measured and therefore the effects of the drainage ditches on the water table are not known. The installation of staff gages and monthly monitoring in conjunction with the other drainage ditches in the valley will help to determine the effects of the unmonitored drainage ditches on the direction of ground-water flow in the flood-plain aquifer.

2. About 2.5 mi southeast of the town of Palo Verde at the northwest corner of Cibola Valley (fig. 9), an area of irrigated land is between the old river channel, now an oxbow lake, and the new river channel under which the direction of ground-water movement is not known. The assumption was made that under normal flow conditions in the river the irrigated land drains either (1) to the lake and the lake drains to the river or (2) to the river directly. Irrigation water is obtained from Palo Verde Irrigation District diversion, but the water rights for this irrigated area are divided between California and Arizona. The direction of ground-water movement close to the lake on the California side is unknown. The installation and monthly monitoring of staff gages on the oxbow lake and observation wells in the area of irrigated land surrounded by the oxbow lake and in Palo Verde Valley west of the lake would permit an analysis of ground-water movement to insure that ground-water return-flow credits are assigned to the appropriate state.

3. To apply the method for Cibola Valley, data for a 1-year period during normal flow conditions in the river is needed to locate the ground-water divide and determine the area that drains in the subsurface to the river. Hydrologic conditions in Cibola Valley are changing; proposed drainage ditches are to be installed in the Cibola Irrigation and Drainage District, and a drainage ditch will be completed in the Cibola National Wildlife Refuge. Subsurface drainage in Cibola Valley needs to be reevaluated after the new drainage ditches are operational and a full year of data is available under normal flow conditions in the river.

4. The ground-water hydrology is unknown in the Arakelian Farms area south of Ehrenberg and at the south end of Cibola Valley. Some ground water flows toward Cibola Lake where it evaporates, is used by phreatophytes, or returns to the river. Whether or not any ground water returns to the river is unknown. The installation and monitoring of observation wells for both areas are needed to determine the direction of ground-water movement.

5. Irrigation of crops on Palo Verde Mesa is accomplished mainly by ground-water pumpage. Current water-level data are needed to evaluate the declines in the water table under the mesa and the effect of the declines on the flood-plain aquifer. Outflow to the mesa will increase as water levels decline under the mesa.

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