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

By S. A. Leake

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

For readers who prefer to use metric units, the 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)
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

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

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ABSTRACT

A method for estimating unmeasured ground-water return flow from water diverted for irrigation is needed to determine consumptive use of water from the lower Colorado River in the Parker area, Arizona and California. For use of the method, a part of Parker Valley is divided into two subareas. Ground water under one of the subareas drains directly to the river as unmeasured ground-water return flow. Ground water under the other subarea drains to drainage ditches and is a part of the measured surface-water return flow at the point of discharge to the river. The subareas were delineated using average annual water-table altitudes in a shallow aquifer that underlies Parker Valley. For the subarea under which ground water drains directly to the river, ground-water return flow is estimated with a water budget. In the water budget, consumptive use is estimated on the basis of a consumptive-use value computed for irrigated land in the subarea under which ground water drains to drainage ditches. Surface-water diversions are estimated on the basis of measured diversions to Parker Valley and irrigation requirements within the valley. Application of the method using data from 1981 resulted in an estimate of 15,400 acre-feet of ground-water return flow that discharges directly to the Colorado River.

INTRODUCTION

In a decree that apportions consumptive use of water from the lower Colorado River, the U.S. Supreme Court (1964) defined consumptive use as "* * * diversions from the stream less such return flow thereto as is available for consumptive use * * *." The decree 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 of such water. Subsequently, networks of gaging stations for monitoring surface-water diversions and surface-water returns were established to comply with the decree. In 1969 the State of Arizona protested the limitation of return-flow credits to only measured surface-water return flow. Arizona argued that return-flow credits should include water diverted for irrigation that returns to the river as unmeasured ground-water return flow. To estimate the ground-water return-flow quantities, a cooperative study by the U.S. Bureau of Reclamation and the U.S. Geological Survey was initiated. Additionally, an interagency Task Force on Unmeasured Return Flows was formed to solicit input from State and Federal agencies concerned with management of the water resources of the lower Colorado River.

Purpose and Scope

The purpose of this report is to present a method for estimating ground-water return flow that discharges directly to the Colorado River from the irrigated land adjacent to the Parker reach of the Colorado River (fig. 1). Ground-water return flow is water diverted from the Colorado River that returns to the river directly as ground-water seepage into the river channel. For this study, ground water that seeps into drainage ditches and subsequently discharges to the river as surface water is considered to be surface-water return flow. In the Parker area, surface-water return flow is measured. Ground-water return flow, which cannot be measured, originates from irrigated land adjacent to the river. The return-flow estimates made by the method presented in this report may be used in accounting for consumptive use of water from the Colorado River as outlined in Article V of the decree by the U.S. Supreme Court (1964). The method involves estimating ground-water return flow on the basis of a water budget that accounts for consumptive use by crops and native vegetation and for irrigation diversions. The results of the method as applied to the Parker reach in 1981 are presented. The sensitivity of the results to uncertainties in hydrologic data is discussed.

The method was developed to estimate the ground-water return flow from land that is irrigated with the surface-water diversion from the Colorado River at Headgate Rock Dam (fig. 2). The irrigated land is in Parker Valley on the Arizona side of the river above Palo Verde Dam. The method may be used to estimate ground-water return flow from other land in Arizona and California irrigated with water from the Colorado River where ground water under the land drains toward the river.

Relation to Other Reports

A method for estimating ground-water return flow in the Yuma reach (fig. 1) was presented by Loeltz and Leake (1983). Several previous reports discuss the geohydrology in the Parker area. A report by Metzger and others (1973) presents results of a geohydrologic study of the area made in the 1960's. A report by Boyle Engineering Corp. (1976) for the U.S. Bureau of Reclamation details the results of a study to analyze the irrigation system and recommend salinity-control measures for the irrigated land on the Colorado River Indian Reservation in Parker Valley. A report by Tucci (1982) discusses the development of a ground-water flow model for evaluating the present knowledge and

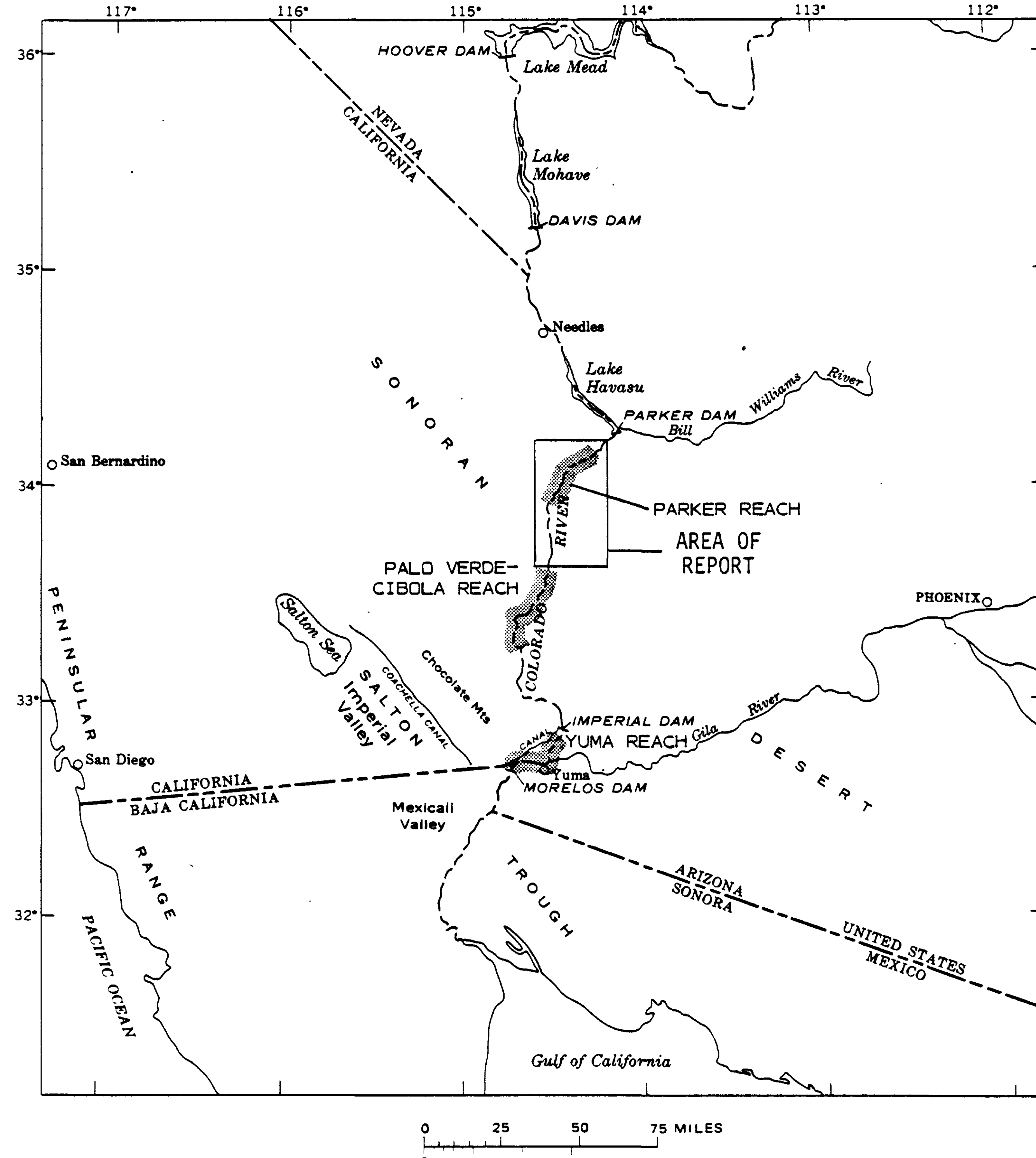

Figure 1.--Area of report. Shaded areas indicate reaches of the Colorado River where diverted water returns to the river as subsurface flow.

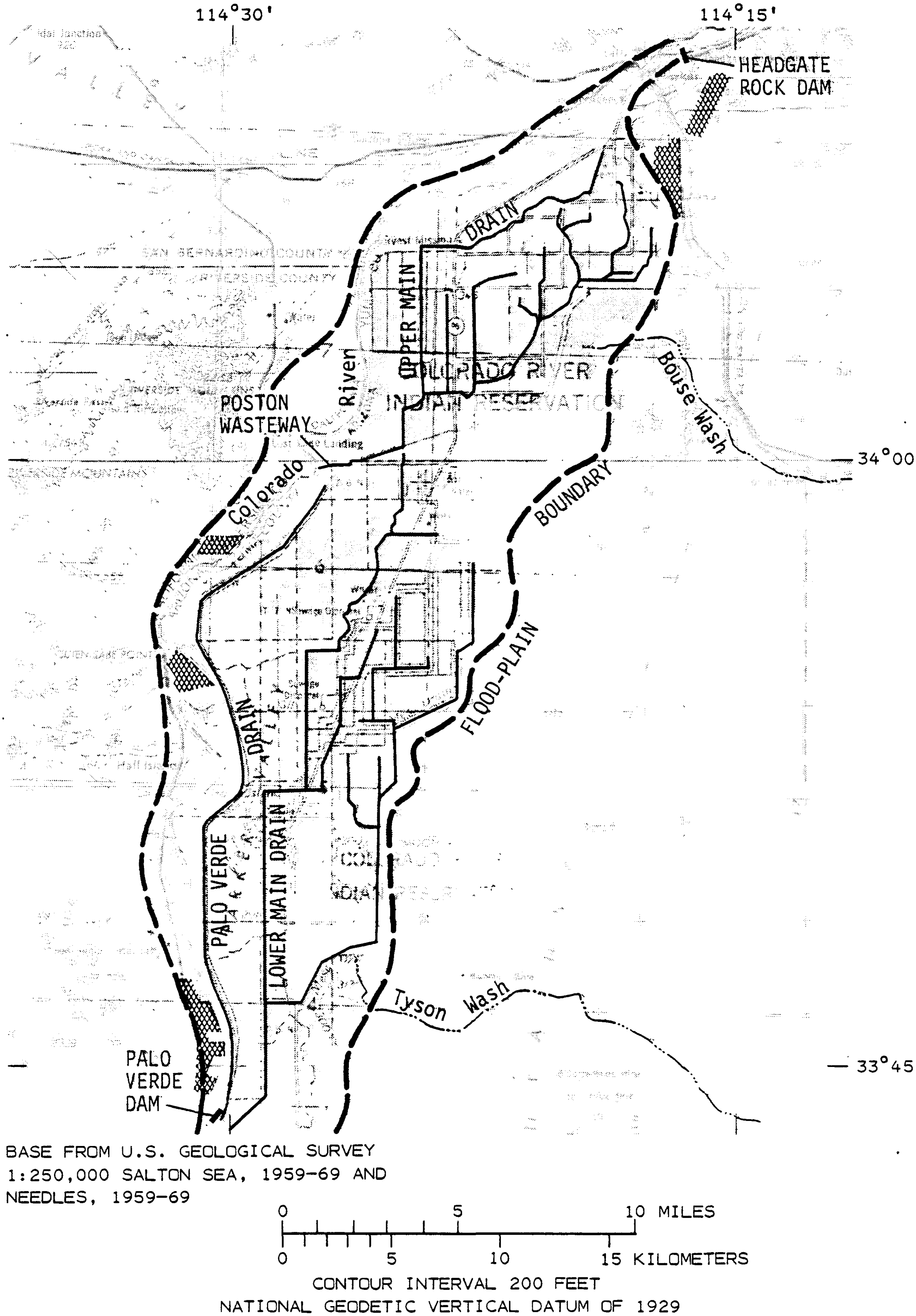

Figure 2.--Location of irrigated land and drainage ditches in the Parker area, Arizona and California, 1981.

EXPLANATION

LAND IRRIGATED WITH SURFACE-WATER DIVERSION AT HEADGATE ROCK DAM

LAND IRRIGATED WITH GROUND-WATER PUMPAGE OR SURFACE-WATER DIVERSION OTHER THAN HEADGATE ROCK DAM

DRAINAGE DITCH

Figure 2

existing concepts of the hydrologic system in Parker Valley. Tucci (1982) used geohydrologic information given by Metzger and others (1973) as the primary basis for developing the ground-water flow model.

Acknowledgments

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 and obtained geologists' and geophysical logs that were used in the analysis of the hydrology of the Parker area. The assistance of these geologists, the drilling crews, and other employees of the U.S. Bureau of Reclamation provided support needed to complete this study. 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

The Colorado River, a shallow unconfined alluvial aquifer that underlies the river and adjacent flood plain, and a system of canals and drainage ditches are the major features of the hydrologic system in Parker Valley. The canals distribute water from the Colorado River at Headgate Rock Dam to irrigated land in the valley. Some water in the canals is not applied to irrigated land but is discharged directly to the drainage ditches and wasteways. Part of the applied irrigation water percolates to the water table in the alluvium and eventually discharges to the system of drainage ditches (drains) over most of the area. The drains lower the water table beneath cropland to sufficient depths to reduce waterlogging and damage to the crops. Water in the drains discharges to the Colorado River at Poston wasteway and below Palo Verde Dam (fig. 2). The Colorado River and the drains are in direct hydraulic connection with the ground water in the alluvial aquifer.

The Colorado River

Flow in the Colorado River is controlled by several dams upstream from the Parker area. Releases from Parker Dam, which is about 15 mi upstream from Parker, satisfy most downstream water and flood-control requirements. The annual releases from 1960 to 1981 were from 6.3 to 7.8 million acre-ft except in 1980 (fig. 3A); the releases in 1980 were 10.7 million acre-ft. The hydrograph of daily mean discharges for the river below Parker Dam for 1981-82 illustrates the seasonal variations in the releases (fig. 3B). The largest quantities of water are released in the spring and summer months when irrigation demands are the greatest.

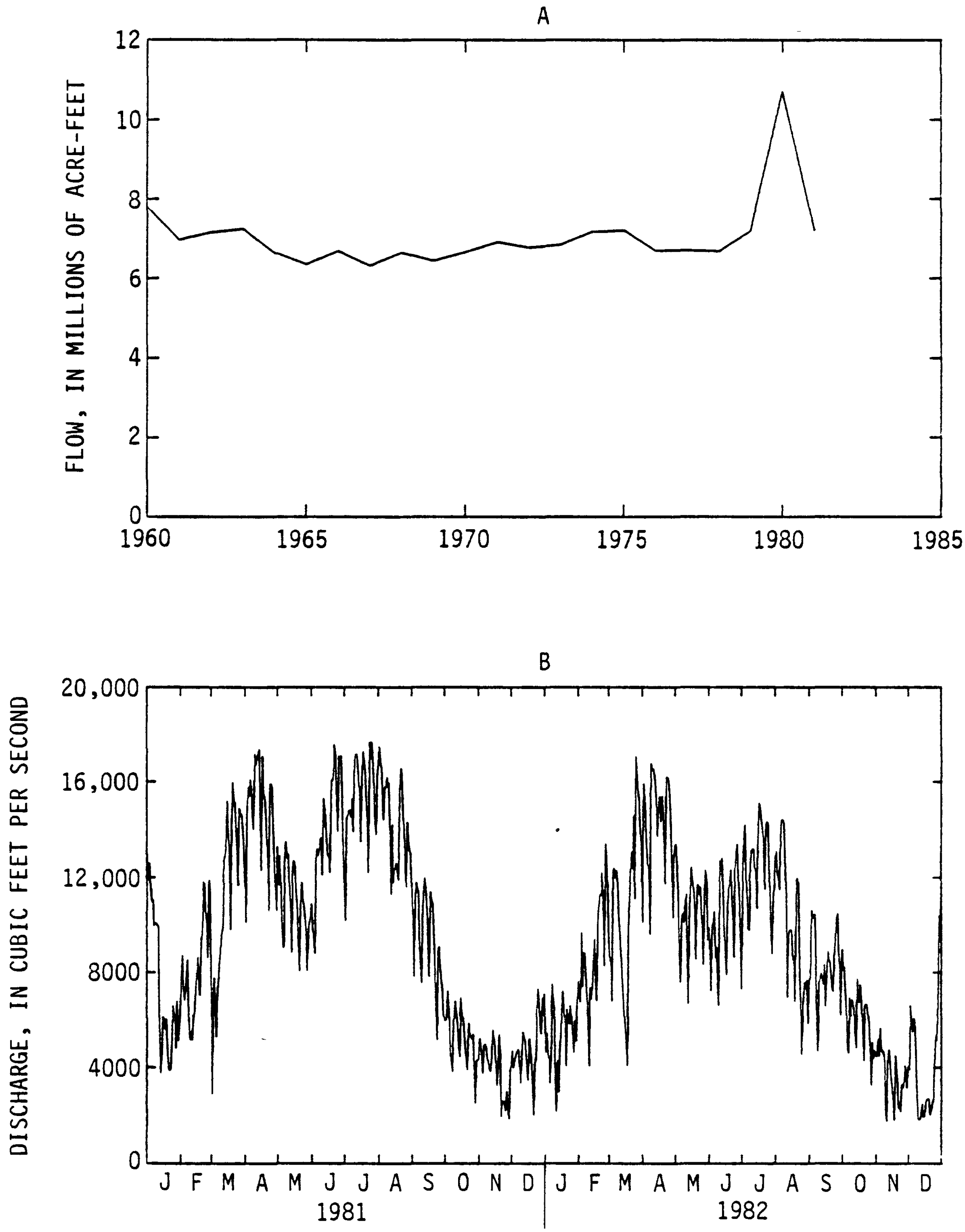

Figure 3.--Flow in the Colorado River below Parker Dam. A, Annual releases from the dam, 1960-81. B, Daily mean discharges for 1981 and 1982.

The Flood Plain and Underlying Alluvial Aquifer

Water that is diverted for irrigation from the Colorado River at Headgate Rock Dam (fig. 2) is the major source of inflow to the flood plain and recharge to the alluvial aquifer. Diversions and irrigated area for 1960-81 are shown in figure 4. In 1981 the amount of water diverted for irrigation in Parker Valley on the Arizona side was 609,700 acre-ft. Of that amount, 608,100 acre-ft was diverted at Headgate Rock Dam and 1,600 acre-ft was diverted by pumps in the river about 1 mi upstream from Palo Verde Dam.

Water that is discharged directly from canals to wasteways and drains is referred to as regulatory waste. About 28,600 acre-ft of the diverted water was estimated to be discharged from canals to wasteways in the valley in 1981 (J. B. Townsend, Supervisory Irrigation System Operator, U.S. Bureau of Indian Affairs, oral commun., 1983). Some of the diverted water discharged into drainage ditches from 30 spillways in the valley. The amount of water discharged through spillways was not measured in 1981; however, in 1982 the measured discharge was about 21,600 acre-ft (H. C. Millsaps, hydraulic engineer, U.S. Soil Conservation Service, oral commun., 1983). If this amount is representative of discharge through spillways in 1981, the total amount of regulatory waste in the valley in 1981 was estimated to be 50,200 acre-ft. The rest of the diverted water, 559,500 acre-ft, was consumed by plants, evaporated from water and soil surfaces, discharged to drains as runoff from fields, or recharged to the aquifer as deep percolation of the applied irrigation or the canal seepage.

The aquifer is also recharged directly by the river over most of the reach between Poston wasteway and Palo Verde Dam. The recharge is indicated by average annual water-surface altitudes in the river that generally are equal to or higher than those in the adjacent Palo Verde drain. Recharge from the river is either consumed by the phreatophytes or intercepted by the Palo Verde drain. The amount of recharge from the river to the aquifer therefore can be computed as the sum of the quantity consumed by phreatophytes and the quantity intercepted by the Palo Verde drain.

The quantity consumed by phreatophytes can be estimated as follows: About 7,000 acres of phreatophytes between the river and the Palo Verde drain consume ground water. Using an estimate of phreatophyte consumptive use of 2.3 ft annually (Metzger and others, 1973, p. 51), the annual consumptive use by the phreatophytes is computed to be about 16,000 acre-ft.

The quantity of river recharge intercepted by the Palo Verde drain cannot be precisely determined; however, a probable upper limit of the quantity may be estimated as follows: The only sources of water in the drain are Colorado River recharge from the west side of the drain and irrigation drainage from about 10,000 acres of cropland on the east side. Ground-water discharge to the entire drainage system in Parker

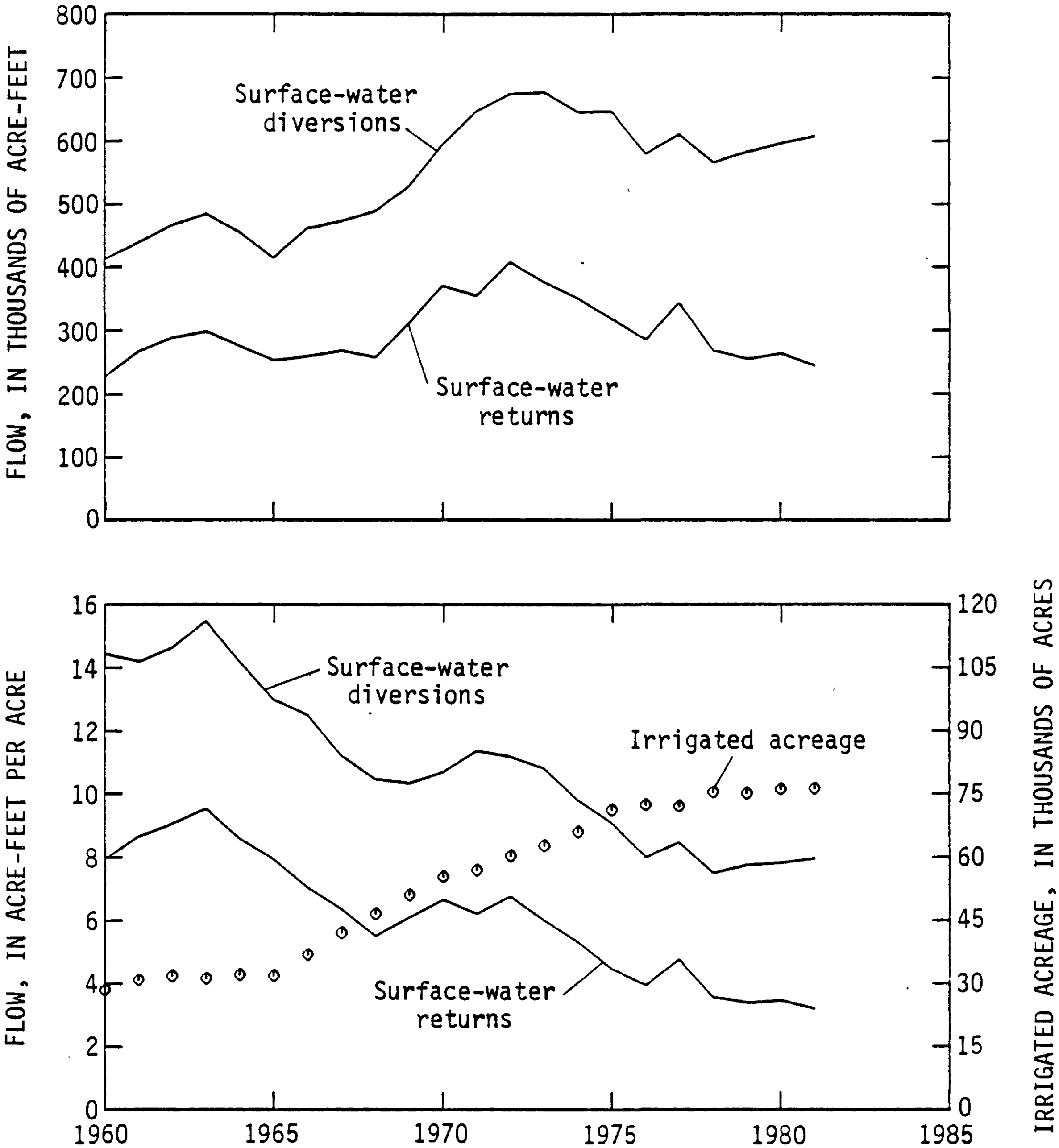

Figure 4.--Diversions, returns, and irrigated acreage in Parker Valley, Arizona. Irrigated acreage from crop reports furnished by U.S. Bureau of Indian Affairs.

Valley in 1981 was estimated to be about 2.7 ft per irrigated acre. The intercepted drainage to the Palo Verde drain from cropland in 1981 therefore was estimated to be about 27,000 acre-ft; the drain discharged about 27,100 acre-ft of water to the river in 1981. The amount of intercepted river recharge therefore is small. Allowing for uncertainties in the quantities used to estimate ground-water drainage to the Palo Verde drain, the intercepted river recharge probably is on the order of several thousand acre-feet or less.

The amount of river recharge from the reach between Poston wasteway and Palo Verde Dam in 1981 was estimated to be 20,000 acre-ft. This value was used in water-budget analyses in Parker Valley.

Metzger and others (1973, p. 51-52) identified the sources of ground-water inflow to the east side of the valley. This ground-water inflow is either consumptively used by plants or infiltrated to the aquifer. The sources and estimated amounts of inflow are:

Sources of ground-water inflow	Annual amount, in acre-feet
From Bouse Wash	1,200
From Tyson Wash	350
Across northeast boundary	3,400
Unmeasured surface runoff infiltrated to aquifer	7,400
Total (rounded)	12,400

Infiltration from precipitation is not a significant source of recharge to the alluvial aquifer. Some of the precipitation, however, is available for consumptive use by crops and phreatophytes. L. H. Raymond (hydrologist, U.S. Geological Survey, oral commun., 1983) estimated an annual average effective precipitation of 2.12 in. that probably can be consumed directly by crops and phreatophytes. The effective-precipitation estimate was made by summing annual rainfall at Parker from storms that exceeded 0.25 in. and averaging the annual values for a 23-year period. Using this estimate of effective precipitation and an area of crops and phreatophytes of about 99,400 acres, the average annual precipitation available for plant consumption is 17,600 acre-ft.

Most of the diverted water that is not consumptively used is returned to the river by the drains, which discharge at Poston wasteway and below Palo Verde Dam. In 1981, 246,800 acre-ft of water discharged to the river from the drainage system (fig. 4). Using the estimate of 50,200 acre-ft for regulatory waste and assuming that the surface runoff from fields is negligible, the annual ground-water seepage to the drainage system is estimated to be 196,600 acre-ft.

Water also discharges from the aquifer and flood plain as evapotranspiration by crops and phreatophytes. For 1981, L. H. Raymond (written commun., 1983) estimated that crops in Parker Valley on the Arizona side consumed more than 260,000 acre-ft of water and that about 28,000 acres of phreatophytes—mostly mesquite, arrowweed, and saltcedar—consumed water from the alluvial aquifer. On the basis of an average annual consumptive use of 2.3 ft (Metzger and others, 1973, p. 51) about 64,000 acre-ft of water is consumed annually by phreatophytes. Water is also removed from the flood plain by evaporation from water and soil surfaces and transpiration by plants other than crops and phreatophytes.

From Parker to about 1 mi south of Poston wasteway, contours of average annual water-table altitudes indicate that water in the aquifer discharges to the river (fig. 5). Prior to agricultural development in the area, the river generally recharged the aquifer (Metzger and others, 1973, p. 46-48). Water that flows from the aquifer to the river therefore is return flow.

The alluvial aquifer extends beyond the study area to the area south of Palo Verde Dam on the Arizona side of the river. Some of the ground water flows to this part of the aquifer. On the basis of an analysis of hydrologic conditions for 1959-65, Metzger and others (1973, table 3) estimated that the annual underflow to the south was 3,000 acre-ft. The amount of underflow in 1981 is not known. The amount probably is not much greater than it was during 1959-65 because drains north and east of Palo Verde Dam intercept most of the additional drainage water from agricultural land in the southern part of the valley put into production since 1965.

The following table summarizes the previously discussed flow components that were measured or estimated for 1981:

Flow component	Amount, in acre-feet	Remarks
1. Diversion at Headgate Rock Dam	608,100	Measured
2. Diversion by pumps in river 1 mi upstream from Palo Verde Dam	1,600	Measured
3. Total diversion	609,700	Item 1 + item 2
4. Regulatory waste	50,200	Estimated; water was discharged directly into wasteways and drains from irrigation system
5. Recharge to the aquifer from the Colorado River	20,000	Estimated; occurred between Poston wasteway and Palo Verde Dam; probably consumed by phreatophytes
6. Effective precipitation available for consumption by plants	17,600	Estimated
7. Ground-water inflow to east side of valley	12,400	Estimated
8. Water discharged into Colorado River from drainage system	246,800	Measured

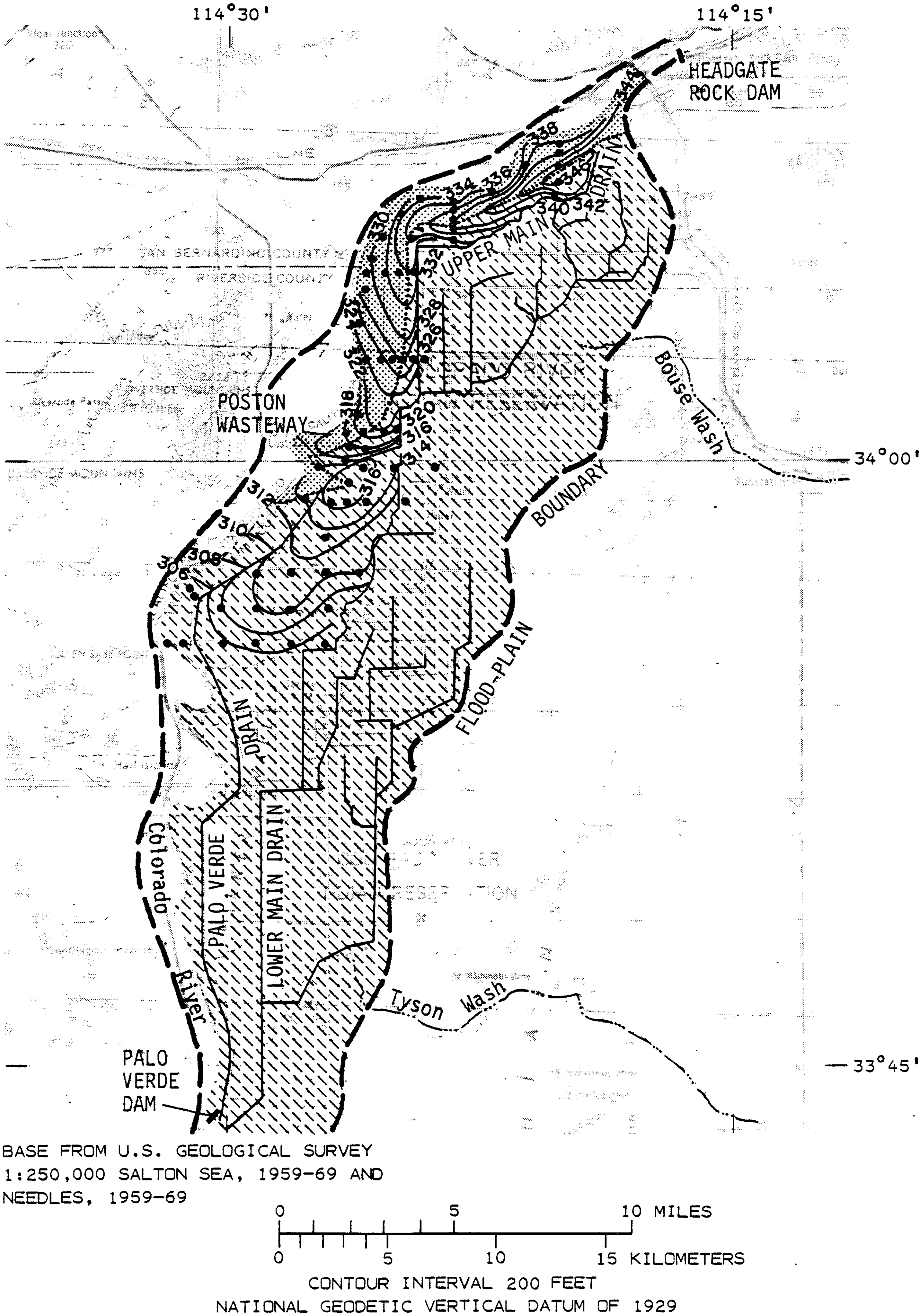

Figure 5.--Average water-table altitude and location of ground-water divide between the Colorado River and adjacent drainage ditches in Parker Valley, Arizona, July 1981-June 1982.

E X P L A N A T I O N

SUBAREA UNDER WHICH GROUND WATER DRAINS TO THE COLORADO RIVER

SUBAREA UNDER WHICH GROUND WATER DRAINS TO DRAINAGE DITCHES

312 — WATER-TABLE CONTOUR—Shows average altitude of water table. Contour interval 2 feet. National Geodetic Vertical Datum of 1929

DRAINAGE DITCH

GROUND-WATER DIVIDE BETWEEN THE COLORADO RIVER AND DRAINAGE DITCHES

SHALLOW OBSERVATION WELL OR PIEZOMETER

Figure 5

METHOD

The method for estimating ground-water return flow in the Parker area involves dividing a part of the flood plain into two subareas. Ground water under one of the subareas drains to the river and ground water under the other subarea drains to drains. Ground-water return flow to the Colorado River may be estimated with a water budget of the subarea under which ground water drains to the river. Surface-water diversions, consumptive use of water by crops and phreatophytes, and ground-water return flow to the river are the major components of the water budget. Ground-water return flow is the residual in the water budget.

The method for estimating ground-water return flow to the Colorado River in the Parker area is outlined in the following steps:

1. Delineate the subarea under which ground water drains to the river and the subarea under which ground water drains to drains.

2. Estimate diversions to irrigated land in each subarea.

3. Estimate consumptive use by crops and phreatophytes.

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

In addition to the ground-water return flow in Parker Valley, canal seepage returns to the river from a 2.4-mile reach of the main canal between Headgate Rock Dam and the north end of the valley. The return flow computed by the method therefore is increased by the estimated seepage losses from this reach of the main canal.

For the following discussion, annual flow quantities are rounded to the nearest 100 acre-ft. Areas of crops and phreatophytes are rounded to the nearest 100 acres. Water 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.

Step 1—Delineate Subareas of Ground-Water Drainage

Ground-water return flow to the river is water from irrigation and canal seepage that percolates to the water table, moves through the aquifer, and discharges to the river. A goal of this step is to delineate the subarea in the valley under which water that percolates to the water table flows toward the river. In the other subarea of the valley, ground water flows toward the drainage ditches, which discharge to the river.

Shallow ground-water divides as indicated by contours of water-table altitude are commonly used by hydrologists to delineate areas under which ground water flows in different directions. If ground water in deeper permeable gravel at the base of the younger alluvium flows under drains and shallow ground-water divides and then discharges to the river, shallow ground-water divides cannot be used to delineate subareas of different ground-water drainage. This condition could exist if restrictive layers in the aquifer prevent water from moving upward into the drain or if the water-surface altitude in the drain is significantly higher than that in the river.

The possibility of water flowing under a drain and toward the river was evaluated using a two-dimensional numerical model. The model simulated steady-state flow in a cross section normal to a river (fig. 6). The model simulated a river at the top of the aquifer near one side of the cross section and two drains at the top of the aquifer near the other side. The differences in the water-surface altitudes and the spacing between the river and the drains were similar to those in Parker Valley several miles north of Poston wasteway. Annual recharge of 3 ft was applied to the water table between the river and the right edge of the cross section. These conditions resulted in a ground-water divide between the river and the adjacent drain and a ground-water divide between the two drains. The aquifer was modeled as being 100 ft thick with a 20-foot-thick permeable zone representing a gravel unit at the bottom of the aquifer overlain by an 80-foot-thick zone representing a sand unit.

The hydraulic-conductivity values for each unit and the overall ratio of horizontal to vertical hydraulic conductivity were varied in simulations to gain insight into conditions that would cause water to flow under a drain. The ranges of values that were tested are given in the following table.

Parameter	Minimum value	Maximum value
Hydraulic conductivity of the sand unit ...	36 ft/d	360 ft/d
Hydraulic conductivity of the gravel unit ..	360 ft/d	3,600 ft/d
Ratio of horizontal to vertical hydraulic conductivity	1/1	100/1

The ranges in hydraulic conductivity result in a range in overall transmissivity of 10,000 to 100,000 ft^2/d. Metzger and others (1973, p. 68) estimated the transmissivity of the alluvial aquifer by analyzing pumping tests. For seven pumping tests in Parker Valley for which the reliability of estimated transmissivity values was rated fair or good, the values

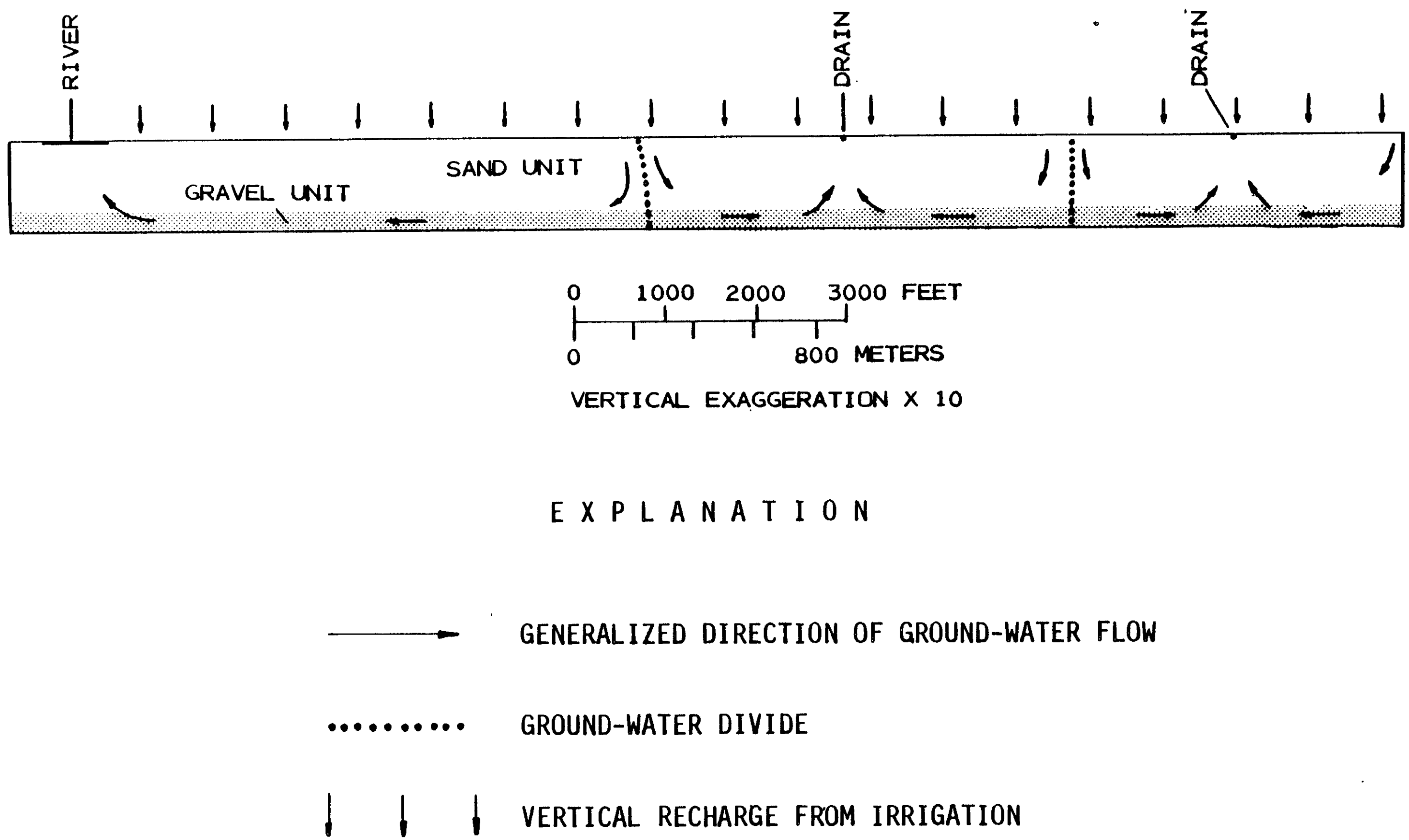

Figure 6.--Flow in a cross section normal to a river.

ranged from about 5,000 ft^2/d to about 94,000 ft^2/d and averaged 40,000 ft^2/d.

Simulations indicated that water flows under the drain and toward the river if the overall transmissivity of the system approaches the upper limit of the range tested. In simulations using a transmissivity value of about 100,000 ft^2/d and ratios of horizontal to vertical hydraulic conductivity in the range of 1/1 to 100/1, some water flows under the drain and discharges to the river. The ground-water divide at the water table between the river and the adjacent drain was 750 to 1,500 ft from the drain. The height of the divide was about 0.1 to 0.7 ft above the water level in the drain. In Parker Valley, the water-table divide generally is more than 2,000 ft from the drain and the height is 2 ft or more above the water level in the drain. The differences between the simulated and the actual conditions indicate that the transmissivity value probably is lower than 100,000 ft^2/d. In simulations using transmissivity values near the average value of 40,000 ft^2/d from Metzger and others (1973), the model more closely approximates the height and position of the ground-water divide in Parker Valley and the ground-water divide extends from the water table to the base of the gravel unit (fig. 6). On the basis of this analysis, the conclusion was that the subareas drained by the river and by drains can be determined from contours of water-table altitude.

The foregoing analysis considered ground-water flow under steady-state conditions. In the Parker 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 Parker 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.

The contours and the location of the ground-water divide between the river and adjacent drains for July 1981 to June 1982 are shown in figure 5. Land on the west side of the divide is drained in the subsurface by the river, and land on the east side is drained in the subsurface by drains. The primary basis for drawing the contours and locating the ground-water divide are average water-table altitudes from 49 shallow piezometers and the water-surface altitudes in the river and drains. Average annual river-surface altitudes were determined by gage-height records from several river-stage gages in the area. A step-backwater computer model developed and run by the U.S. Bureau of Reclamation (H. H. Carver, hydrologic technician, written commun., 1983) provided estimates of river-surface altitudes that were useful for extending the contours to the river over reaches where other river-stage data were not available. The water-surface altitudes in the drains were estimated primarily from design elevations of drain bottoms compiled by Tucci (1982). At two locations along the Palo Verde drain, the water-surface altitudes were determined by monthly water-level measurements. The configuration of the water table for calendar year 1981 probably is the same as that shown in figure 5.

The contours indicate areas north and south of Poston wasteway under which ground water drains to the river. In this report, these two areas are referred to as the subarea drained by the river (fig. 5). Ground water under the rest of the land in Parker Valley above Palo Verde Dam on the Arizona side drains to the drainage ditches or flows to the area south of Palo Verde Dam. This area is referred to as the subarea drained by drainage ditches (fig. 5).

The location of the irrigated land (fig. 2) was determined from crop mapping by the U.S. Soil Conservation Service (H. C. Millsaps, written commun., 1982) and the U.S. Geological Survey (L. H. Raymond, written commun., 1983). Data for about 2,300 fields in the valley indicate that in 1981 about 71,500 acres of land were irrigated in both subareas. About 5,400 acres are in the subarea drained by the river and 66,100 acres are in the subarea drained by drains. The areas of the fields were determined from aerial photographs. Double-cropped acreage was counted only once. The areal distribution of the double-cropped acreage was not known and therefore was assumed to be distributed uniformly over the total irrigated area. In addition to crops, about 2,800 acres of phreatophytes are in the subarea drained by the river and 25,100 acres are in the subarea drained by drains.

Step 2—Estimate Diversions to Irrigated Land

Records of diversions to subareas in the valley are not available, therefore the diversions must be estimated. One approach to estimating diversions to the subareas is based on the assumption that applied irrigation and canal losses are uniform throughout the irrigated area. If this assumption is valid, the diversion to the subarea drained by the river is the fraction of the total diversion, minus the regulatory waste, that corresponds to the ratio of irrigated acreage in the subarea to the total irrigated acreage. Diversions to the subarea drained by the drains are the total diversion to the valley minus diversions to the other subarea.

The total diversion to the valley can be determined from measured diversions at Headgate Rock Dam, estimated canal-seepage losses between the dam and the valley, and measured diversions by pumps in the river near Palo Verde Dam. In 1981, 608,100 acre-ft of water was diverted from the river at Headgate Rock Dam and 1,600 acre-ft was diverted by pumps in the river about 3 mi upstream from Palo Verde Dam. Part of the diversion from Headgate Rock Dam seeps from a

2.4-mile unlined reach of the main canal between Headgate Rock Dam and the valley. Boyle Engineering Corp. (1976) estimated that the annual seepage losses over this reach are about 2,400 acre-ft. The estimate was based on length of the reach, wetted perimeter of the reach, and an estimated seepage rate of 0.256 ft/d. The seepage rate was estimated from a study of the relations between known seepage rates and the soil texture underlying the canals (Boyle Engineering Corp., 1976, p. II-5, II-6). The method of estimating seepage is approximate; however, information is not available for estimating seepage using other methods. The estimate of 2,400 acre-ft of canal-seepage losses annually therefore is used to compute the net diversion of 607,300 acre-ft for 1981.

About 1 percent of the total regulatory waste in the valley for 1981 is in the subarea drained by the river. For this study, the assumption is made that all the water diverted to the subarea drained by the river evaporates from water surfaces, seeps from canals, or is applied to the fields; regulatory waste therefore is assumed to be zero. The total diversion minus regulatory waste is computed to be 557,100 acre-ft or 7.8 ft per irrigated acre. The diversion to the subarea drained by the river therefore is estimated to be:

557,100 acre-ft x (5,400 acres/71,500 acres) = 42,100 acre-ft.

The balance of the diversion, 565,200 acre-ft, which includes regulatory waste, is associated with the subarea drained by drains.

A more involved approach to estimating diversions to the subareas is based on the assumption that the amount of diversion to each subarea is proportional to irrigation requirements within that subarea. The term "irrigation requirement" as used for this study is the volume of water per unit area required to grow a crop. The quantity includes consumptive use by the crop, leaching requirements, deep percolation, and evaporation from water and soil surfaces. Irrigation requirements can be estimated on the basis of crop types, soil texture, and irrigation-management practices. With an estimate of relative irrigation requirements for the subareas, the total diversion minus regulatory waste can be prorated among the subareas delineated by ground-water divides.

In a preliminary study of agriculture on the Colorado River Indian Reservation in the Parker area, S. H. Stipe (U.S. Economic Research Service, written commun., 1983) estimated irrigation requirements for crops for 3 soil textures and 10 categories of resource treatment applied (RTA). The soil textures—fine, medium, and coarse—were based on ranges of water-intake rates established by the U.S. Soil Conservation Service (H. C. Millsaps, written commun., 1983). The RTA categories incorporated the following factors: slope type of field, water-management practices, type of irrigation ditch, and run length of field. Estimates of the total cropped area in each RTA category had been made; however, the distribution of the RTA categories throughout the irrigated area in Parker Valley was not known (S. H. Stipe, oral commun., 1983). Variations in irrigation requirements resulting from different combinations of management practices in each of the two subareas could not be determined.

The irrigation requirements for crops by soil type in Parker Valley were estimated by taking the average irrigation requirement weighted by the area estimated to be in each RTA category. The estimated irrigation requirements for alfalfa, cotton, and wheat for the three soil textures are given in table 1. Irrigation requirements for all other crops were assumed to be 5.0 ft regardless of soil texture. The soil texture for each of more than 2,300 fields in the valley was taken from an unpublished soil map by the U.S. Soil Conservation Service (H. C. Millsaps, written commun., 1983). The irrigation requirement for each field was computed using soil texture, crop type, and area of the field. The irrigation requirements shown in table 2 were computed by summing the values from individual fields in each subarea.

The irrigation requirement for both areas is computed to be 502,100 acre-ft (table 2). Irrigation requirements for the subarea drained by drains and the subarea drained by the river are 91.3 and 8.7 percent of the total irrigation requirement, respectively. The irrigation requirement per unit irrigated area for the subarea drained by the river is higher because the area (a) has proportionately more alfalfa, which has a high irrigation requirement for all soil types, and (b) generally is on coarser soils.

Table 1.--Estimated irrigation requirements for alfalfa, cotton, and wheat for three soil textures

[Adapted from unpublished data of the U.S. Economic Research Service (S. H. Stipe, written commun., 1983)]

Crop	Soil texture	Irrigation requirement,[1] in feet
Alfalfa	Fine	9.5
	Medium	9.5
	Coarse	10.9
Cotton	Fine	5.7
	Medium	5.7
	Coarse	6.6
Grains (wheat)	Fine	3.3
	Medium	3.3
	Coarse	3.8

[1]Includes consumptive use by the crop, leaching requirements, deep percolation, and evaporation.

Table 2.--Irrigation requirements and consumptive use by vegetation in Parker Valley, Arizona, 1981

[Subarea east of ground-water divide is drained by drains; subarea west of ground-water divide is drained by the river]

Vegetation type	Consumptive use, in feet	Area, in acres			Irrigation requirement, in acre-feet			Consumptive use, in acre-feet		
		East of divide	West of divide	Total	East of divide	West of divide	Total	East of divide	West of divide	Total
Alfalfa	[1]5.3	21,800	2,600	24,400	222,000	27,500	249,500	115,500	13,800	129,300
Cotton	[1]3.2	31,100	2,600	33,700	185,800	15,600	201,400	99,500	8,300	107,800
Grains	[1]1.9	9,900	200	10,100	34,100	600	34,700	18,800	400	19,200
Other crops	[2]2.0	3,300	0	3,300	16,500	0	16,500	6,600	0	6,600
Phreatophytes	[3]2.3	25,100	2,800	27,900	-------	-------	------	57,700	6,400	64,100
Total		91,200	8,200	99,400	458,400	43,700	502,100	298,100	28,900	327,000

[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]Estimated by L. H. Raymond (written commun., 1983).

[3]Metzger and others (1973, p. 51).

If the assumption that diversions are proportional to irrigation requirements is valid, the subarea drained by the river requires 8.7 percent of the total diversion minus regulatory waste. The diversion to the subarea drained by the river therefore is computed to be 8.7 percent of 557,100 acre-ft or 48,500 acre-ft. The diversion to the subarea drained by drains is computed to be 607,300 acre-ft minus 48,500 acre-ft or 558,800 acre-ft.

The diversion to the subarea drained by the river estimated using irrigation requirements is about 15 percent higher than that estimated by proportion of irrigated acreages (42,100 acre-ft versus 48,500 acre-ft). The diversion estimated using irrigation requirements is probably better than that using irrigated areas because areal variations in cropping patterns and soil types affect the areal distribution of applied water.

The following table summarizes quantities from the above discussions:

Component	Unit	Subarea under which ground water drains to Colorado River	Subarea under which ground water drains to drainage system	Total	Remarks
1. Irrigated area	acres	5,400	66,100	71,500	Estimated from delineation of ground-water divide and crop mapping
2. Phreatophyte area	acres	2,800	25,100	27,900	Do.
3. Total area	acres	8,200	91,200	99,400	Item 1 + item 2
4. Diversion	acre-ft			609,700	Measured
5. Regulatory waste	acre-ft		50,200	50,200	Estimated; water discharges directly into wasteways and drains
6. Canal loss outside of Parker Valley	acre-ft			2,400	Estimated; occurred between Headgate Rock Dam and north end of valley
7. Net diversion to valley	acre-ft			607,300	Item 4 - item 6
8. Net diversion for irrigation use	acre-ft			557,100	Item 7 - item 5
9. Diversion for irrigation calculated by irrigated area	acre-ft	42,100	515,000	557,100	Estimated
10. Diversion for irrigation calculated by irrigation requirement	acre-ft	48,500	508,600	557,100	Estimated, 8.7 percent of item 7
11. Irrigation requirement	acre-ft	43,700	458,600	502,300	Estimated
12. Consumptive use by vegetation	acre-ft	28,900	298,100	327,000	Estimated

Step 3—Estimate Consumptive Use

Estimates of consumptive use in the subarea drained by the river are required in estimating ground-water return flow to the river. The estimates were made from the consumptive use in the subarea drained by drains calculated from a water budget. Major components of a water budget in the subarea drained by drains are surface-water diversions, surface-water returns, and consumptive use. The term "consumptive use" as used in this analysis includes transpiration by vegetation and evaporation from water and soil surfaces. This quantity is essentially equivalent to "consumptive use" defined in the decree by the U.S. Supreme Court (1964, p. 1) as diversions less return flows. Because the diversions and returns generally are well defined, consumptive use can be computed as the residual of the budget.

For the water-budget calculation, change in ground-water storage was assumed to be negligible. This assumption probably is valid if a 1-year period is used because river-surface altitudes, ground-water heads, and irrigation-water deliveries generally follow a 1-year cycle. The system of drainage ditches in the valley has been in existence for many years, and the amount of irrigated land in the valley has been relatively constant for at least 4 consecutive years including 1981 (fig. 4). Annual changes in ground-water storage could be caused by year-to-year variations in river-surface altitudes; however, the effects of the changes in storage probably are insignificant in the computation of consumptive use.

A water budget for 1981 is presented in table 3. Only the surface-water diversions and discharge from the drainage system were based on measurements of flow; all other quantities were estimated. The consumptive use of 357,500 acre-ft for 1981 includes evaporation from water and soil surfaces and transpiration by crops, phreatophytes, and other plants.

The consumptive use in the subarea drained by the river may be estimated by assuming that the consumptive use per unit area is the same on both sides of the ground-water divide. This assumption neglects the absence of evaporation from drains in the subarea drained by the river. Evaporation from drains is an insignificant part of the 357,500 acre-ft of consumptive use computed for the subarea drained by drains. The subarea drained by the river includes 5,400 acres of crops and 2,800 acres of phreatophytes. The consumptive use of 357,500 acre-ft for the subarea drained by drains applies to an area of 91,200 acres of crops and phreatophytes. The consumptive use for the subarea drained by the river can be computed as:

$$(5{,}400 \text{ acres} + 2{,}800 \text{ acres}) \times 357{,}500 \text{ acre-ft}/91{,}200 \text{ acres} = 32{,}100 \text{ acre-ft}.$$

A more complex method of estimating consumptive use involves computing relative total consumptive use for the two subareas on the basis of vegetation types within each subarea and the estimated annual

Table 3.--Water budget for 1981 for subarea drained by drains

	Amount, in acre-feet
Inflow:	
Surface-water diversions	558,800
Ground-water seepage from the Colorado River	20,000
Ground-water inflow to east side of the valley	12,400
Effective precipitation	16,100
Total	607,300
Outflow other than consumptive use:	
Discharge from drainage system to the Colorado River	246,800
Ground-water outflow to area south of Palo Verde Dam	3,000
Total	249,800
Consumptive use (Inflow minus outflow)	357,500

consumptive-use rates for the vegetation types. This method assumes that the total consumptive use in each subarea is proportional to consumptive use by vegetation in the subarea. The areas and consumptive-use values for crops and phreatophytes in each of the two subareas in 1981 are given in table 2. The consumptive-use values for alfalfa, cotton, and grains were determined by the U.S. Soil Conservation Service (H. C. Millsaps, oral commun., 1983) on the basis of soil-moisture depletion studies in Parker Valley. The rest of the crops, mostly melons and grasses, were assumed to consume 2.0 ft annually. The areas of the crops within the subareas were determined from crop-mapping efforts of the U.S. Soil Conservation Service and the U.S. Geological Survey (L. H. Raymond, written commun., 1983).

The annual consumptive-use value for phreatophytes of 2.3 ft given in table 2 is the value used by Metzger and others (1973, p. 51). L. H. Raymond (written commun., 1983) delineated areas of phreatophytes of all types in each of the ground-cover classes from 0 to 25 percent, 25 to 50 percent, 50 to 75 percent, and 75 to 100 percent. Raymond assigned a consumptive-use value to each ground-cover class on the basis of studies done by Culler and others (1982). The resulting area-weighted average annual consumptive use is 2.2 ft. Boyle Engineering Corp. (1976, p. II-7) suggested an average annual consumptive use of 2.0 ft for phreatophytes in the area north of Palo Verde Dam. The estimates made by Raymond and by Boyle Engineering Corp. support the estimate by Metzger and others (1973).

The consumptive use computed for each of the subareas is given in table 2. The amount of consumptive use in each subarea, 298,100 acre-ft in the subarea drained by drains and 28,900 acre-ft in the subarea drained by the river, corresponds to consumptive-use values of about 3.3 ft and 3.5 ft, respectively. The consumptive use in the subarea drained by the river is larger because a greater percentage of the total cropped area is alfalfa, which has a large consumptive use.

The consumptive use by vegetation of 298,100 acre-ft for the subarea drained by drains is about 17 percent less than the total consumptive use computed in the water budget (table 3). The difference in the two values may be attributed in part to the following factors: (1) total consumptive use from the water budget includes evaporation from water and soil surfaces and (2) total consumptive use includes use by multiple crops grown in the same fields. Analyses of consumptive use by vegetation did not include use by multiple crops because the areal distribution of multiple-cropped acreage was unknown.

The consumptive use calculated on the basis of vegetation types indicates that consumptive use per unit area is about 8 percent higher in the subarea drained by the river than in the subarea drained by drains. This difference is assumed to apply to overall consumptive use as computed in step 3; therefore, the effects of the higher consumptive use on estimated ground-water return flow can be evaluated. Using the consumptive use and total area of crops and phreatophytes in each subarea, the ratio of the consumptive use per unit area for the two subareas can be computed as:

(28,900 acre-ft/8,200 acres)/(298,100 acre-ft/91,200 acres) = 1.078.

This ratio multiplied by the consumptive-use value of 32,100 acre-ft for the subarea drained by the river previously determined in this step results in an adjusted consumptive-use value of 34,600 acre-ft. This adjusted value incorporates areal variations of vegetation types that consume different amounts of water and is likely to be closer to the actual value.

Step 4—Compute Ground-Water Return Flow

Ground-water return flow may be estimated with a water budget of the subarea drained by the river. The major components of the water budget are diversions, consumptive use, and ground-water return flow to the river (table 4). Ground-water return flow can be estimated as a residual in the budget if the other quantities are known. The consumptive-use value was estimated in step 3 to be 34,600 acre-ft and the diversions were estimated in step 2 to be 48,500 acre-ft. The residual of the budget, 15,400 acre-ft of ground-water flow to the river, is the end product of the method.

Table 4.--Water budget for 1981 for subarea drained by the river

	Amount, in acre-feet
Inflow:	
Surface-water diversions to area	48,500
Effective precipitation	1,500
Total	50,000
Outflow other than ground-water return flow to river:	
Consumptive use	34,600
Ground-water return flow to river (Inflow minus consumptive use)	15,400

SENSITIVITY ANALYSES

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 33 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 the irrigation requirements for cotton and alfalfa and to the discharge from drains to the river.

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,

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

[Source: M, measured; E, estimated. Sensitivity: Percentage change in computed ground-water return flow for a +10 percent change in value of primary variable]

Variable	Source	Value	Sensitivity
Diversions at Headgate Rock Dam	M	608,100 acre-ft	0.6
Diversion by pumps in river	M	1,600 acre-ft	0.0
Seepage from 2.4-mile reach of canal	E	2,400 acre-ft	-0.0
Regulatory waste	E	50,200 acre-ft	3.2
Areas of vegetation in subarea drained by the river:			
Alfalfa	M	2,600 acres	10.9
Cotton	M	2,600 acres	6.6
Wheat	M	200 acres	0.3
Other crops	M	0 acres	0.0
Phreatophytes	M	2,800 acres	5.1
Areas of vegetation in subarea drained by drains:			
Alfalfa	M	21,800 acres	-8.5
Cotton	M	31,100 acres	-7.4
Wheat	M	9,900 acres	-1.4
Other crops	M	3,300 acres	-0.5
Phreatophytes	M	25,100 acres	-4.3
Irrigation requirement in subarea drained by the river:			
Alfalfa	E	27,500 acre-ft	-20.0
Cotton	E	15,600 acre-ft	-11.4
Wheat	E	600 acre-ft	-0.4
Other crops	E	0 acre-ft	0.0
Irrigation requirement in subarea drained by drains:			
Alfalfa	E	222,000 acre-ft	14.8
Cotton	E	185,800 acre-ft	12.5
Wheat	E	34,100 acre-ft	2.4
Other crops	E	16,500 acre-ft	1.2
Average consumptive use:			
Alfalfa	E	5.3 feet	2.0
Cotton	E	3.2 feet	-1.0
Wheat	E	1.9 feet	-1.1
Other crops	E	2.0 feet	-0.5
Phreatophytes	E	2.3 feet	0.7
Inflow:			
From river seepage	E	20,000 acre-ft	1.3
From the east side of valley	E	12,400 acre-ft	0.8
Ground-water underflow to the south	E	3,000 acre-ft	-0.2
Discharge from drains to the river	M	246,800 acre-ft	-15.8
Effective precipitation:			
In subarea drained by the river	E	1,400 acre-ft	-0.9
In subarea drained by drains	E	16,100 acre-ft	1.0

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 33 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. Measured surface-water quantities, diversions at Headgate Rock Dam, and discharge from drains to the river were assumed to have a coefficient of variation of 0.05.

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	5,500
0.20	0.63	10,200
0.30	0.96	15,800

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 Headgate Rock Dam because ground-water return flow is a small fraction of the total.

CONCLUSIONS AND DATA NEEDS

Application of the method presented in this report results in an estimated ground-water return flow of about 15,400 acre-ft in Parker Valley in 1981. The total return flow from the point of diversion at Headgate Rock Dam includes the following quantities for 1981:

	Amount, in acre-feet
Canal seepage from 2.4-mile reach of canal between Headgate Rock Dam and irrigated area	2,400
Ground-water return flow	15,400
Surface-water return flow (includes ground water that seeps into drains and subsequently discharges to the river as surface-water flow)	246,800
Total	264,600

The decree by the U.S. Supreme Court (1964) stipulates that the United States shall keep complete, accurate, and detailed records of return flow by point of diversion. The return-flow value, 264,600 acre-ft, is the total return flow for the point of diversion at Headgate Rock Dam. The ground-water return flow, 15,400 acre-ft, is less than 6 percent of the total. The sensitivity analysis performed for this study indicated the possibility of large percentage errors in the estimate of ground-water return flow. Because of the relative magnitudes of the quantities, these errors have a minor effect on the accuracy of the total return flow.

Any future analyses similar to those presented in this report could benefit from consideration of the following data needs:

1. Contours of equal water-table altitude (fig. 5) indicate that all but a small part of the irrigated land south of Poston wasteway drains to drainage ditches. The average annual water-surface altitudes in the river, as determined from a step-backwater computer model and one river-stage gage, were nearly equal to the estimated average annual water-surface altitudes in the

adjacent Palo Verde drain over part of the reach below Poston wasteway. The amount of adjacent irrigated land that drains to the river could vary significantly with changes in the average annual water-surface altitudes in the river. The location of the ground-water divide south of Poston wasteway is more likely to shift than is the location of the divide above Poston wasteway. Priority should be given therefore to the collection of water-level data in the aquifer, river, and Palo Verde drain south of Poston wasteway.

2. Above Poston wasteway, average annual water levels from the lines of piezometers generally are adequate to locate the position of the ground-water divide without data from river-stage gages. Monthly water-level measurements seem adequate to define the average annual water levels in the aquifer. Studies could be carried out to determine if data collected every 2 or 3 months can be used to locate the position of the ground-water divide. River-stage data above Poston wasteway are not needed and therefore need not be collected except at one gaging station near Poston wasteway.

3. Areal variations in irrigation requirements and consumptive use were found to be significant. The year-to-year changes in these quantities for the subareas drained by the river and by drains are not known. Analyses similar to the ones presented in this report should be performed for 1 or more years to determine the temporal variability of consumptive use and irrigation requirements in the subareas. Information on the variability of these quantities will indicate the need for future analyses.

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