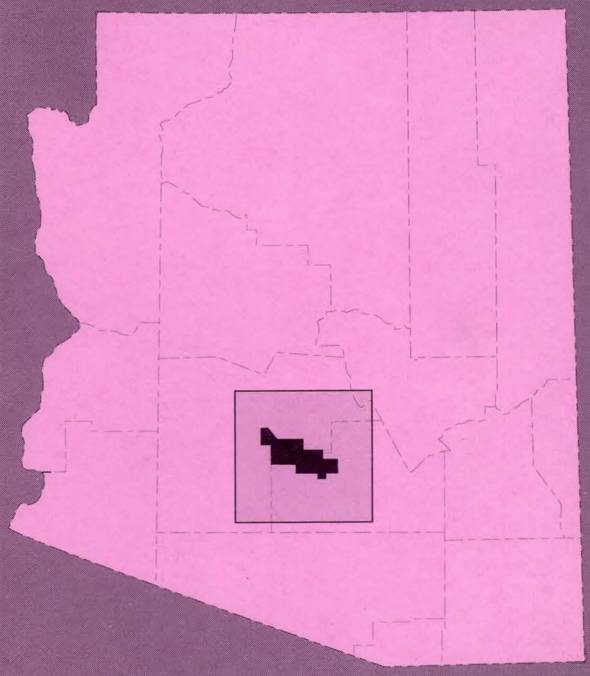
PREDEVELOPMENT HYDROLOGY OF THE GILA RIVER INDIAN RESERVATION, SOUTH-CENTRAL ARIZONA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 89—4174



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By B.W. THOMSEN and J. H. EYCHANER

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CONVERSION FACTORS

For readers who prefer to use the International System (SI) units, the conversion factors for terms in this report are listed below:

Multiply inch pound unit	By	To obtain metric unit
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	square hectometer (hm^2)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
acre-foot per acre (acre-ft/acre)	304.8	millimeter (mm)
acre-foot per square mile (acre-ft/mi^2)	0.47625	millimeter (mm)
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)
degree Farenheit (°F)	°C = 5/9 x (°F-32)	degree Celsius (°C)

Sea level: In this report "sea level" refers to the 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 "*Sea Level Datum of 1929*."

PREDEVELOPMENT HYDROLOGY OF THE GILA RIVER INDIAN RESERVATION, SOUTH-CENTRAL ARIZONA

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ABSTRACT

Indians have occupied and irrigated the reservation lands along the Gila River for centuries. Knowledge of the hydrologic conditions that existed before development of the water resources by non-Indian settlers is needed to aid in evaluation of water-right claims.

Water resources of the Gila River Indian Reservation for the period before development by non-Indian settlers were characterized by perennial flow in the Gila River and ground water near the land surface. Depths to water ranged from 10 to 70 feet and the direction of ground-water movement was from the northeast, east, and southeast toward the northwest. The ground-water reservoir was essentially in equilibrium and was sustained mainly by the infiltration of water from the Gila River.

Mesquite thickets and groves of cottonwood trees covered large parts of the flood plain and other lowlands along the Gila River. Evapotranspiration averaged 200,000 acre-feet per year. On the basis of available streamflow data and long-term runoff estimates from tree-ring data, the mean annual flow of the Gila River upstream from the reservation was estimated to be 500,000 acre-feet and the median annual flow 380,000 acre-feet. Tree-ring data do not indicate a significant change in precipitation from 1602 to 1970. Ground water was discharged by evapotranspiration by phreatophytes where water levels were shallow and by return to surface flow mainly in the western third of the reservation where bogs and sloughs were common.

A numerical model was developed to simulate ground-water flow, stream-aquifer connection, and evapotranspiration for purposes of evaluating predevelopment hydrologic conditions. The model represents average conditions in the ground-water system before the system was affected significantly by diversions upstream from the reservation. Average values for components of ground-water flow determined from the model include recharge by infiltration from the Gila River, 94,000 acre-feet per year; evapotranspiration from ground water, 96,000 acre-feet per year; and discharge to surface flow in the western third of the reservation, 29,000 acre-feet per year.

INTRODUCTION

The Gila River Indian Reservation was established in 1859 in an area along the Gila River that had been occupied and irrigated by the

Indians for centuries (Bancroft, 1889; Haury, 1976, p. 357; Ezell, 1963). Non-Indian settlers arrived in Arizona in large numbers in the 1860's and 1870's and began diverting water from the Gila River and its tributaries upstream from the Gila River Indian Reservation. The development and activities that have occurred since that time have significantly changed the hydrology of the area. The flow of the Gila River and recharge to the ground-water system on the reservation have been greatly diminished as a result of upstream diversions and storage. Water levels in wells have declined and the direction of ground-water flow has changed as a result of pumping for irrigation in areas adjacent to the reservation. General adjudication to determine water rights of water users in the Gila River watershed is being conducted in the superior courts of Arizona under authority established by Arizona Revised Statutes Title 45, Chapter 1, Article 6. In order to develop data pertinent to the adjudication process, the U.S. Bureau of Indian Affairs entered into a cooperative agreement with the U.S. Geological Survey to evaluate the hydrologic conditions that existed prior to the arrival and development of the area by non-Indian settlers.

Location, Physiography, and Climate

The study area includes about 2,200 square miles in south-central Arizona, of which about 580 square miles is in the Gila River Indian Reservation (fig. 1). The reservation consists of a parcel of land about 50 miles long and 3 to 10 miles wide on both sides of the Gila River. The study area includes part of the Salt River Valley north of the reservation and the lower Santa Cruz basin south of the reservation. The Ak-Chin Indian Reservation, the north tip of the Papago Indian Reservation, and the south edge of the Salt River Indian Reservation are within the study area.

The study area is characterized by broad desert plains dissected by arroyos, and valleys separated by rugged low-lying mountains. The altitude of the desert plains ranges from 1,600 feet above sea level east of the reservation to less than 1,000 feet at the northwest corner. To the east and northeast of the reservation, the terrain slopes irregularly upward to an altitude of more than 5,000 feet in the Superstition mountains.

The dominant native vegetation types are mesquite and saltbush along the washes and palo verde and cacti on the hills. Creosotebush covers most of the desert floor except where it has been replaced by crops. Dense thickets of mesquite and groves of cottonwood and willow covered large areas along the rivers when the non-Indian settlers arrived (Lee, 1905) but most have been removed.

Surface drainage includes parts of three major rivers—the Gila, Salt, and Santa Cruz (fig. 1). The Salt and Santa Cruz Rivers are tributaries to the Gila River and both join the Gila near the northwest corner of the Gila River Indian Reservation. The Gila River drains more than 18,000 square miles east and southeast of the reservation. The Salt River and its major tributary, the Verde River, drain more than 12,000 square miles north and northeast of the reservation. The Santa Cruz

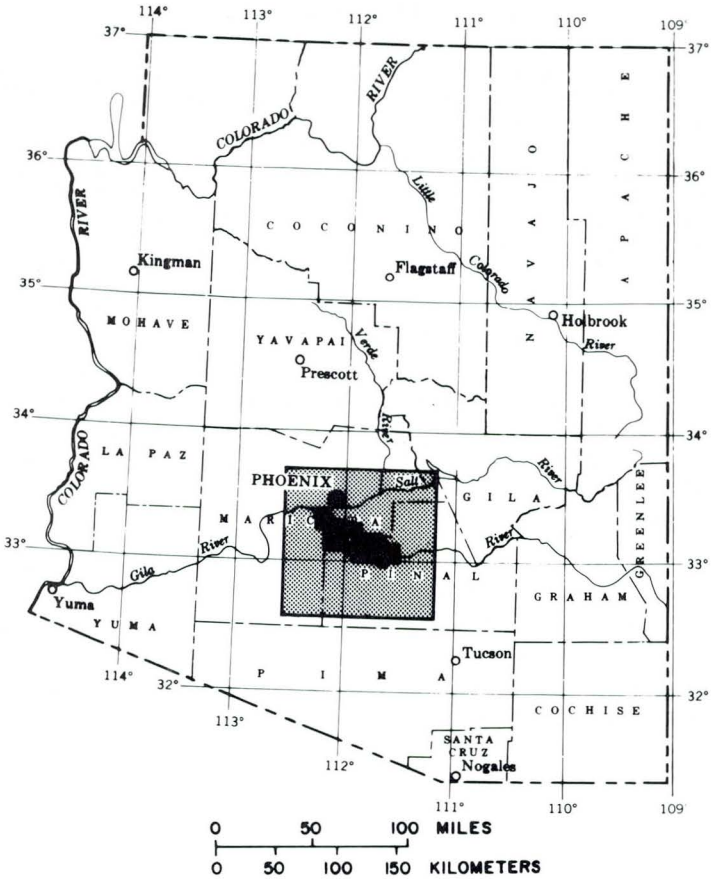


Figure 1.--Location of study area (shaded).

River drains more than 8,000 square miles south and southeast of the reservation (fig. 1). The Gila and Salt Rivers contributed perennial flow to the study area prior to the arrival of non-Indian settlers but now are only intermittent streams. The Santa Cruz River flows mainly in response to intense rainfall.

The climate is dry and incapable of supporting more than a minimum vegetation growth without irrigation. Summers are hot, and daily temperatures generally exceed 100 °F from mid-June through August. Mean daily temperatures range from about 64 °F to 105 °F. The relative humidity generally is low, ranging from about 20 to 50 percent (Sellers and Hill, 1974). Winters are mild, and average temperatures range from 60 °F to 80 °F in the afternoons and from 30 °F to 40 °F in early mornings. Subfreezing temperatures occur on only a few days during an average year (Sellers and Hill, 1974). Mean daily temperatures range from about 33 °F to 70 °F.

Annual precipitation averages about 8 inches and results mainly from two types of storms. Summer thunderstorms, which develop as a result of the flow of moist tropical air from the Gulf of Mexico, make July and August the wettest months. Regional storms from the Pacific Ocean produce gentle widespread showers during the fall and winter months. April, May, and June are the driest months. Occasional tropical storms produce large amounts of rain in the fall.

Wind movement in the area is relatively light. In 1895, the monthly average wind speed was about 5 miles per hour at Phoenix (Davis, 1897a, p. 31). U.S. Weather Bureau records for January 1948 through December 1955 at Phoenix show that average wind speeds did not exceed 8.3 miles per hour (Sellers and Hill, 1974, p. 30).

Purpose and Scope

The purpose of this report is to describe the hydrologic conditions that existed in the area of the Gila River Indian Reservation prior to development by non-Indian settlers. Non-Indian settlers were diverting significant quantities of water from the Gila River and its tributaries upstream from the reservation in the 1870's (Olberg, 1919). No pre-1870 hydrologic data are available; therefore, data collected since 1870 were used to evaluate predevelopment conditions. The results of the evaluation represent average hydrologic conditions during the 100-year period prior to 1870. The 100-year average was used in order to dampen the effect of short-term variations in hydrologic conditions.

The evaluation of hydrologic conditions prior to 1870 required estimating the flow of the Gila River upstream from the Gila River Indian Reservation and defining the ground-water system in and adjacent to the reservation. Estimates of average flow of the Gila River were made from recorded data with adjustments to represent predevelopment conditions. The adjustments were based on the effects of development on river flows and the mathematical evaluations of climatic trends. Studies of relations between streamflow and tree rings were used to help substantiate estimates of the predevelopment flow of the Gila River. The ground-water system was

evaluated by the use of a numerical model. The model parameters were estimated initially from published values and recorded field data; each parameter was estimated independently. Evapotranspiration was calculated by using old maps and photographs to determine types and areas of vegetation and applying evapotranspiration rates determined in recent studies. The model covers an area slightly larger than the reservation (fig. 1) in order to encompass parts of the mountain ranges that form physical boundaries to much of the ground-water system.

Previous Investigations

A reconnaissance of the water supply for the Gila River Indian Reservation was made by the U.S. Geological Survey in 1886-87 (Davis, 1897b, p. 8). A streamflow-gaging station was established on the Gila River at the Buttes 12 miles upstream from Florence in 1889, and records were obtained for 1 year. The station was discontinued in 1890, reestablished in 1895, and operated through September 1899 (Lippincott, 1900).

An investigation of the water supplies available for irrigation in the Salt and Gila Valleys near Phoenix, Arizona, was made in 1896 by Arthur P. Davis. This investigation dealt mainly with surface-water supplies and the results, as they pertained to irrigation waters for the Gila River Indian Reservation, were reported to the U.S. Senate (Davis, 1897b). In a more general report, Davis (1897a) described the topographic and climatic conditions, irrigation works in use and under construction, facts relating to water supply, underground waters, evaporation, silting of reservoirs, and legal problems related to storing and diverting water. Davis (1897a) recommended a more detailed investigation of potential reservoir sites on the Gila River, which was conducted by Lippincott (1900).

W.T. Lee investigated the "underground waters" of the Gila Valley (1904) and the Salt River Valley (1905). The reports present tabulations of well records, water levels, and chemical quality of ground water. Also included are descriptions of the geology, physiography, and economics of pumping ground water. Ground waters of the Arizona territory were examined as to their suitability for sanitary, irrigation, and technical uses (Skinner, 1903).

A study of the geology and water resources of the Gila River Indian Reservation was made by the U.S. Department of Agriculture (Rott, 1936). A quantitative study of the ground-water resources of the Eloy district in Pinal County, Arizona, was conducted by the Agricultural Experiment Station of the University of Arizona (Smith, 1940). The U.S. Geological Survey investigated the ground-water resources of the Queen Creek area (Babcock and Halpenny, 1942), the Santa Cruz basin (Turner and others, 1943), and western Pinal County (Hardt and others, 1964; Hardt and Cattany, 1965; Kister and Hardt, 1966).

An electrical-analog model of the ground-water system in central Arizona was constructed to determine the probable future effects of continued ground-water withdrawal (Anderson, 1968). The model was

constructed by using the known hydrologic characteristics of the water-bearing rocks and the pumping history through 1964. Predictions of future water levels were based on an extension of the pumping rate and areal distribution that existed in 1964.

Maps showing water-level changes for 1923-47 and 1923-64 were prepared and estimates of ground-water pumpage and ground water in storage were made for the Gila River Indian Reservation by Babcock (1970). Water-level altitudes were updated for the eastern part of the Salt River Valley (Laney and others, 1978) and for the lower Santa Cruz area (Konieczki and English, 1979). Descriptions of hydrologic conditions in alluvial basins (Freethey and Anderson, 1986) and distribution of aquifer materials in alluvial basins (Freethey and others, 1986) are pertinent to the study area.

History of Water Development

Prior to the arrival of non-Indian settlers, the Indians diverted water from the Gila River for the irrigation of cropland but the amount of land that was irrigated is uncertain. Olberg (1919) estimated that the largest area cultivated by the Indians at any one time (about 1885) was 15,800 acres and that an additional 11,315 acres had been previously irrigated. Land classification by the U.S. Reclamation Service shows that 44,900 acres of reservation land was cultivated or formerly cultivated (unpublished reports on proposed allotments for Gila River Indian Reservation, C.R. Olberg, Superintendent of Irrigation, September 1913). Other documents describe 25,000 to 28,000 acres of land under this classification (Paul Gregory, hydrologist, U.S. Bureau of Indian Affairs, written commun., 1987).

The development of water resources by settlers began with the diversions of water from the Gila River and its tributaries for irrigation. Diversions started in the 1860's and increased rapidly in the 1870's and 1880's. Water in the Gila River was diverted for irrigation in the valleys of the upper Gila River above Coolidge Dam, along the San Pedro River, and in the Gila Valley near Florence just upstream from the Gila River Indian Reservation.

Diversions from the Gila River near Florence after 1864 probably had the most direct effect on the quantity of streamflow available for use on the reservation. By 1885, twelve ditches—four on the north side of the Gila River and eight on the south side—were capable of irrigating 6,000 acres (Olberg, 1919).

The major diversion was to the Florence Canal, which first carried water in 1887. The Florence Canal and Land Company filed water claims in 1885, started construction in 1886, and diverted water into the first 16 miles of the Florence Canal in 1887. By 1889, the length of the canal had been extended to 50 miles and Picacho Reservoir, a shallow storage reservoir on McClellan Wash south of Florence, had been constructed (Southworth, 1919). The capacity of the Florence Canal was 440 cubic feet per second. The capacity of Picacho Reservoir was 24,500 acre-feet (U.S. Senate, 1890, p. 455). When the canal was built, the plans specified the irrigation of 60,000 acres (U.S. Senate, 1890). The maximum area under

irrigation however was about 7,000 acres (Southworth, 1919). The total diversion into the Florence Canal during the irrigation season of 1896 was 64,444 acre-feet and the area irrigated was 6,472 acres (Davis, 1897a). The quantity of water used was great, about 10 acre-feet per acre, because of large seepage and evaporation losses. In contrast, the average water use on the Salt River for 60,000 acres irrigated in 1895 was 4.6 acre-feet per acre (Davis, 1897a).

The number of acres irrigated from the Florence Canal was much smaller than planned probably because the quantity of water available was less than anticipated. Irrigation systems were being constructed simultaneously in the upstream valleys of the Gila River. By the end of the 19th century, at least 40 canals were being used to divert water from the Gila River and its tributaries for the irrigation of about 40,000 acres upstream from the Buttes (summation from Southworth, 1919). Diversions upstream from the Buttes probably were at least 60,000 acre-feet per year because a minimum of 1½ feet of water was needed to produce a crop (Davis, 1897a).

Water shortages that resulted from the diversion of water from the Gila River upstream from the reservation caused some Indians to move from the area near the Gila River to near the Salt River in 1872 (Olberg, 1919). The Indians abandoned old fields along the Gila and reclaimed lands at places favorable to the use of return flows of the river upstream from Sacaton. Irrigation of lands in the Gila Crossing area, not formerly used because of poor-quality water, began in the 1870's owing to the shortage of water on the Gila River farther upstream (Southworth, 1919).

As diversions from the Gila River increased, the available supply of water in the river decreased. Decreases were most noticeable during seasonal low-flow periods in the areas downstream from Florence, and the need for water storage soon became evident (Davis, 1897a). Ashurst-Hayden Dam, a diversion structure on the Gila River, was completed in 1922 and Coolidge Dam, a storage reservoir, was completed in 1928.

Because of the lack of streamflow for irrigation during parts of some years, wells were constructed for irrigation in the late 1890's (Davis, 1897a), but only small quantities of ground water were withdrawn until many years later. The demand for agricultural products during World War I caused an increase in ground-water withdrawals. The types of pumping plants available at that time had physical limitations and high operating costs; hence, quantities of water pumped remained relatively small, less than 100,000 acre-feet per year in the Florence-Casa Grande area prior to 1925. Electric power became available in the late 1920's and the quantity of water pumped increased gradually to about 350,000 acre-feet per year by 1940. These increases resulted from high cotton prices, improvement in the design and efficiency of pumping plants, and decreases in electric-power rates (Turner and others, 1943). During the 1940's, rates of ground-water withdrawal continued to increase and reached the present-day level of about 1 million acre-feet per year from the lower Santa Cruz basin in 1948 (U.S. Geological Survey, 1983).

GEOLOGY

The study area lies within the Basin and Range physiographic province (Fenneman, 1931), which is characterized by broad alluvial valleys separated by rugged mountains. The mountains are composed mainly of granitic, volcanic, and metamorphic crystalline rocks that yield very little water. The valley floors are underlain by a wide variety of sedimentary deposits that constitute the main ground-water reservoirs. These deposits consist of unconsolidated to variably consolidated sediments that are several thousand feet thick in places. The sediments were deposited in river beds, flood plains, lakes, fans at the foot of mountain slopes, and estuaries. Sediments include unconsolidated clay, silt, sand and gravel, caliche, gypsum, mudstone, siltstone, sandstone, conglomerate, and anhydrite. The degree of sorting and cementation and the distribution of the different materials vary areally and with depth. Interbedding and lensing are common, and lateral discontinuities caused by high-angle faults may be present in some older units (Laney and Hahn, 1986).

The sediments have been divided into four geohydrologic units—pre-Basin and Range deposits, lower basin-fill deposits, upper basin-fill deposits, and stream alluvium—on the basis of their geologic and hydrologic properties (Freethey and others, 1986). The pre-Basin and Range deposits range from silt, clay, and claystone to gravel and conglomerate. The lower basin-fill sediments were deposited in closed basins and consist of weakly to highly consolidated gravel, sand, silt, clay, and evaporites. The upper basin-fill sediments consist of unconsolidated to moderately consolidated gravel, sand, silt, and clay and represent deposition during and after the transition from a closed-basin to an integrated-drainage environment. The stream alluvium consists typically of well-sorted sandy gravel with some silt; the alluvium is areally extensive along the Gila and Salt Rivers and in some places exceeds 300 feet in thickness.

HYDROLOGY

The hydrologic cycle is a term used to denote the circulation of water from the ocean, through the atmosphere, to the land, and back to the ocean. The movement of water over and through the land is the main concern of this study.

Water that moves over the land surface tends to collect and become streamflow. The quantity and duration of streamflow, in general, depend on the amount, intensity, and type of precipitation and on the nature of the material over which the water passes. As streamflow moves along natural channels, some water may evaporate and thus be lost from the local system, or part or all of it may percolate into receptive materials and become either soil moisture or ground water.

Water that percolates into the earth from either precipitation or streamflow and reaches the water table, or the zone of saturation, is

called ground water. Water that is retained in the unsaturated zone above the water table is called soil moisture. Water in the subsurface may return to the land surface and become streamflow where the water table intersects the land surface. The water may move into the unsaturated zone to become soil moisture or it may be removed from the local system by evapotranspiration or by pumping.

Precipitation

Precipitation is the source of water, but not all the precipitation that reaches the land surface is available for man's use. Water that reaches the land surface as precipitation may proceed along any of three general paths. It may evaporate soon after contact with the land surface, move across the land as surface runoff, or penetrate the earth to become either soil moisture or ground water. Recorded precipitation data indicate that the quantity of precipitation may be extremely different from year to year, and studies of past climates show long-term changes in precipitation amounts (Sellers, 1965). Precipitation data were collected at U.S. Army Posts on the Gila River watershed as early as 1867 (Davis, 1897a). However, most long-term precipitation records in Arizona began between 1895 and 1915, at least 25 years after the period of interest for this study. Hence, an evaluation of the possibility of a climatic change was needed.

Precipitation in the study area averages about 8 inches per year and occurs mainly as rain. Snow falls in the upper reaches of the rivers that flow into the study area. Total precipitation averages nearly 1 million acre-feet per year, of which about 250,000 acre-feet per year falls on the reservation. Most of the rainfall on the flatlands of the study area evaporates or is used by vegetation, and virtually none reaches the ground-water reservoir. Precipitation on the mountains tends to collect in channels as run off and may be sufficient in quantity at times to provide recharge to the ground-water system along the mountain fronts.

Annual precipitation at Sacaton for 1931-72 ranged from 1.85 to 17.21 inches and averaged 8.37 inches (Sellers and Hill, 1974). Precipitation is less than potential evapotranspiration in all months, but particularly so in April, May, and June.

Two sets of annual precipitation data in and near the study area were examined for any indications of long-term climate changes. One set contains data from nine precipitation stations operated for several years prior to 1900 and again during 1941-70 (table 1). The average annual precipitation prior to 1900 is greater than that for 1941-70 for five stations and less for four stations. The average for the nine stations is 9.79 inches for the period prior to 1900 and 9.93 inches for the later period.

The other set of precipitation data (fig. 2) is for Tucson and is the longest continuous precipitation record in Arizona. During 109 years (1876-1984), annual precipitation at Tucson ranged from 5.07 to 24.17 inches and averaged 11.41 inches. The median or middle-rank value was 10.94 inches. Averages for 10-year periods were all within 25 percent

Table 1.--*Precipitation data*

[Prior to 1900 from Lee, 1904; after 1900 from Sellers and Hill, 1974. See figure 3 for location of stations]

Station	Number of years of record		Average annual precipitation, in inches	
	1873-98	1941-70	1873-98	1941-70
Casa Grande.....	14	28	5.33	8.12
Florence.....	11	30	9.74	9.50
Fort Grant.....	24	23	15.34	12.52
Fort Thomas.....	10	7	12.32	9.01
Phoenix.....	16	17	7.35	7.59
San Carlos.....	17	30	12.31	11.88
San Simon.....	14	18	4.65	8.83
Tucson.....	23	30	11.68	10.73
Willcox.....	17	30	9.42	11.19
Average.....			9.79	9.93

of the overall average. The data show no obvious long-term trend, although periods such as 1942-56 and 1964-72 were consistently above or below the average (fig. 2). Kendall's tau-b statistic (SAS Institute, 1982, p. 501-512) was used to test for trends in the data. The statistic measures the degree to which annual precipitation increases or decreases from the beginning to the end of the record. The computed tau-b was 0.0075, a value that could be expected in 90 percent of samples having no trend. Thus, the Tucson data indicate no trend in precipitation at a 90-percent confidence level.

Fritts and others (1979) used tree-ring data to evaluate climatic variations over a longer time period (1602-1970) and showed that average winter precipitation during 50-year intervals can vary by 20 percent over much of the United States. Percentage of agreement, however, between reconstructed and observed precipitation was greatest in southwestern United States, including Arizona.

Precipitation and tree-ring data indicate that the precipitation regime in the study area before 1870 probably was similar to the current regime. Therefore, precipitation estimates that are based on recorded data are considered to be representative of predevelopment time.

Streamflow

The Gila River was the main source of water for native inhabitants when the Gila River Indian Reservation was established. The river probably flowed perennially through the reservation before non-Indian settlers arrived (Brown and others, 1981). Streamflow records are

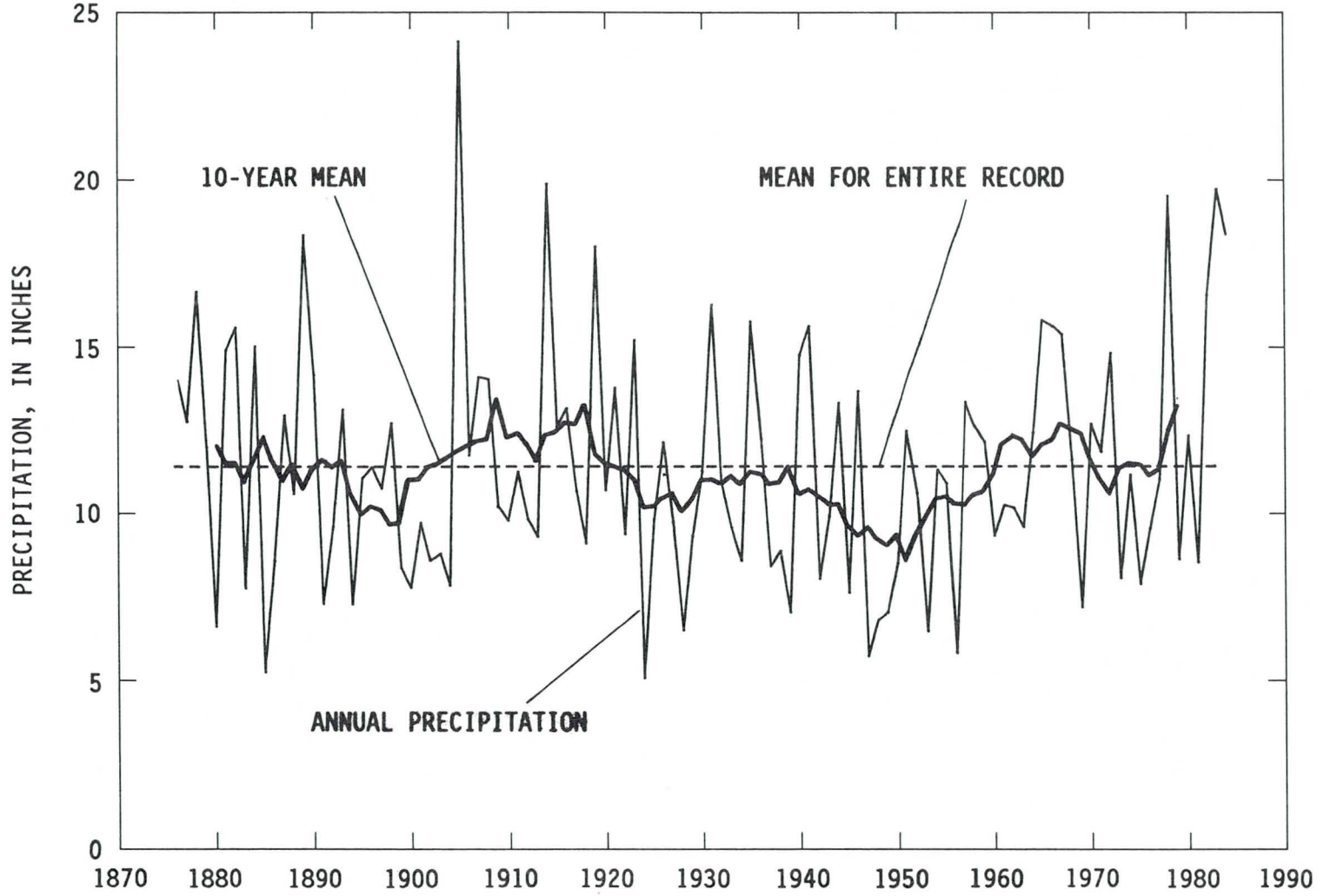


Figure 2.--Precipitation at Tucson, 1876-1984.

available for several sites on the Gila River and major tributaries (fig. 3). Streamflow measurements were made as early as 1888, but most long-term records started in 1911 or later (table 2). However, diversions of water from the Gila River upstream from the reservation began long before the earliest streamflow measurements were made and had depleted the flow of the river by 1895 (Davis, 1897b). The channel was dry throughout most of the reach from east of Florence to near Pima Butte. An exception was near Coolidge where ground water reached the surface and formed a stream of several cubic feet per second (Lee, 1904).

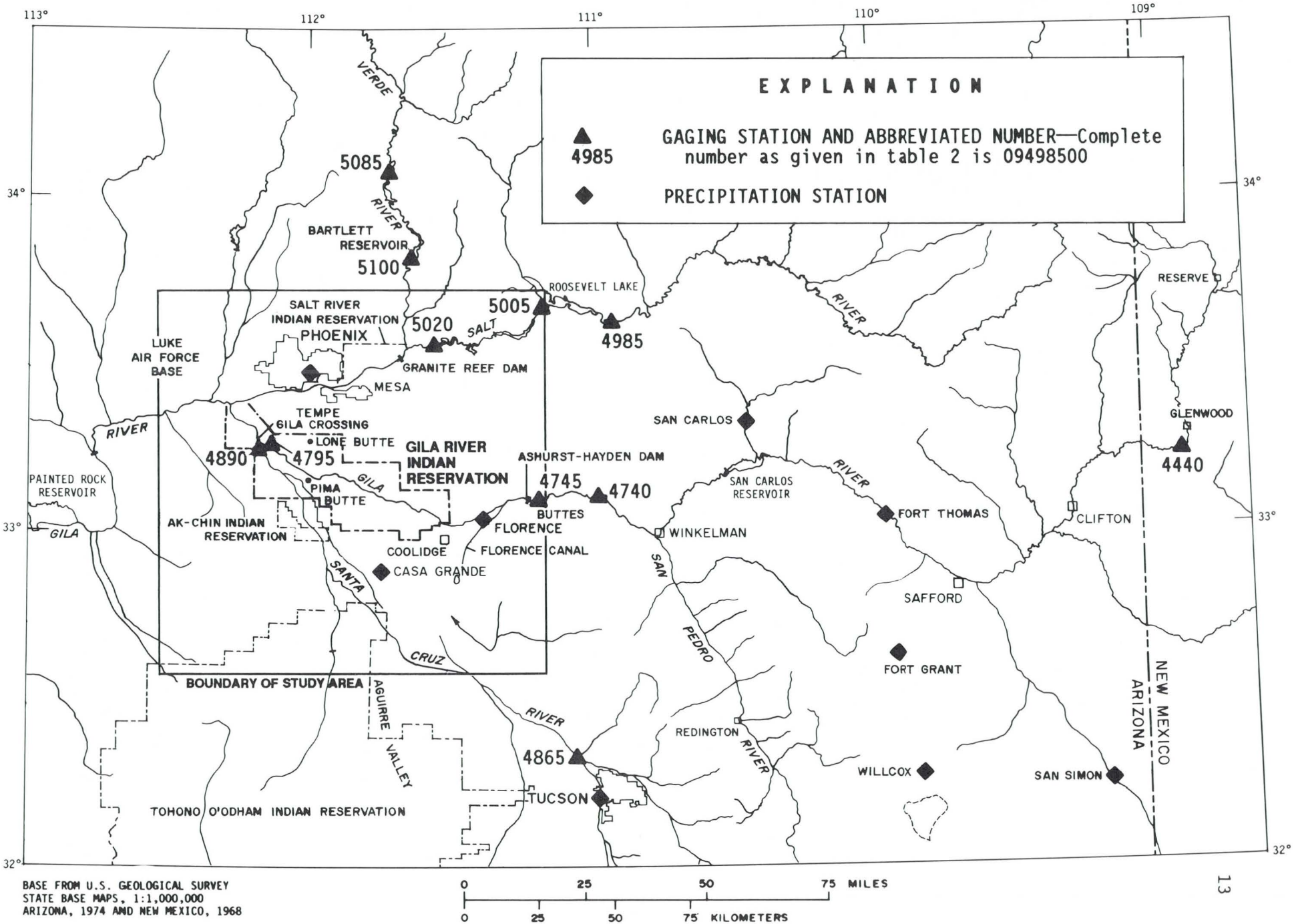
The nearest gaging-station sites on the Gila River upstream from the reservation are at the Buttes—12 miles east of Florence—and at Kelvin—28 miles east of Florence (fig. 3). The station at the Buttes was operated for a total of 5 years—1889-90 and 1895-99—and the station at Kelvin has been operated continuously since 1912. The records at the two sites are virtually equivalent because the drainage areas differ by less than 2 percent. Beginning in 1928, the flow of the Gila River at Kelvin was affected by water storage upstream in the San Carlos Reservoir. Annual runoff data used in this study were adjusted for storage.

Annual runoff of the Gila River at Kelvin upstream from the Gila River Indian Reservation ranged from 16,700 acre-feet in 1974 to 2,246,000 acre-feet in 1915 (fig. 4). For the period of record 1912-84, the mean annual runoff was 359,000 acre-feet and the median annual runoff was 238,000 acre-feet. The mean is the arithmetic average of the annual values. The median is the middle-ranked value; that is, half the values are larger and half are smaller than the median. Streamflow data for the Gila River at the Buttes or Kelvin for three periods of record are summarized in table 2. For each period, the mean is larger than the median, which is the typical relation for runoff data. In addition, median runoff during later periods is smaller than earlier periods.

The flow of the Gila River upstream from the Gila River Indian Reservation prior to 1870 was estimated from recorded streamflow with adjustments to account for changes since 1870 (fig. 4). A plot of the annual runoff data indicates a decreasing trend of runoff with time (fig. 4). A test of the data for 1912-84 using Kendall's tau-b statistic (SAS Institute, 1982, p. 501-512) showed a highly significant trend of decreasing runoff. The decrease in runoff probably was caused by increasing upstream diversions and not by decreasing precipitation. Median flows for 5-year periods were computed from the 1912-84 data, and the trend of the medians was estimated (fig. 4). The trend lines represent long-term median runoff; the 5-year medians fall both above and below the trend lines during some periods. Median runoff about 1870 was estimated from the trend at 360,000 ±80,000 acre-feet per year.

Tree-ring data were also used to estimate runoff prior to 1870. Trees preserve a record of climatic variations in their annual growth rings. Long-term growth records and a shorter term streamflow record can be used to estimate streamflow for the longer period using statistical multiple regression (Fritts, 1976).

Long-term runoff estimates using tree-ring data were made for three sites on tributaries of the Gila River (Stockton, 1971, 1975; Smith, 1981; Smith and Stockton, 1981), but no equivalent estimates are available for the Gila near the reservation. The three sites with long-term



BASE FROM U.S. GEOLOGICAL SURVEY
STATE BASE MAPS, 1:1,000,000
ARIZONA, 1974 AND NEW MEXICO, 1968

Figure 3.--Location of streamflow and precipitation stations.

Table 2.--*Streamflow data*

Station number	Station name	Water years	Annual runoff: Mean, Acre-feet	Annual runoff: Mean, Inches[1]	Annual runoff: Median, Acre-feet
	Gila River:				
09474500	at the Buttes	1890, 1896-99	466,000	0.48	450,000
09474000	at Kelvin	1912-28	550,000	.57	405,000
	at Kelvin[2]	1912-84	359,000	.37	238,000
09479500	near Laveen	1941-46, 1949-84	22,700	.02	8,900
	Salt River:				
09500500	at Roosevelt	1888-1907, 1910-13	756,000	2.44	491,000
09498500	near Roosevelt	1913-84	646,000	2.81	502,000
09502000	below Stewart Mountain Dam[2]	1931-84	713,000	2.15	430,000
	Verde River:				
09508500	below Tangle Creek	1945-84	409,000	1.39	292,000
09510000	below Bartlett Dam[2]	1888-1984	498,000	1.51	396,000
	Santa Cruz River:				
09486500	at Cortaro	1940-46, 1951-82	33,200	.18	23,200
09489000	near Laveen	1941-46, 1949-84	16,300	.04	8,000
	San Francisco River:				
09444000	near Glenwood, NM	1927-84	57,400	.65	36,000

[1]One inch of runoff is the volume equivalent to a layer of water one inch deep over the entire watershed.

[2]Data adjusted for changes in storage in major upstream reservoirs.

The complete 8-digit station number for each station, such as 09474500, includes the 2-digit part number "09" plus the 6-digit downstream order number "474500," of which only the first four digits are used on figure 3.

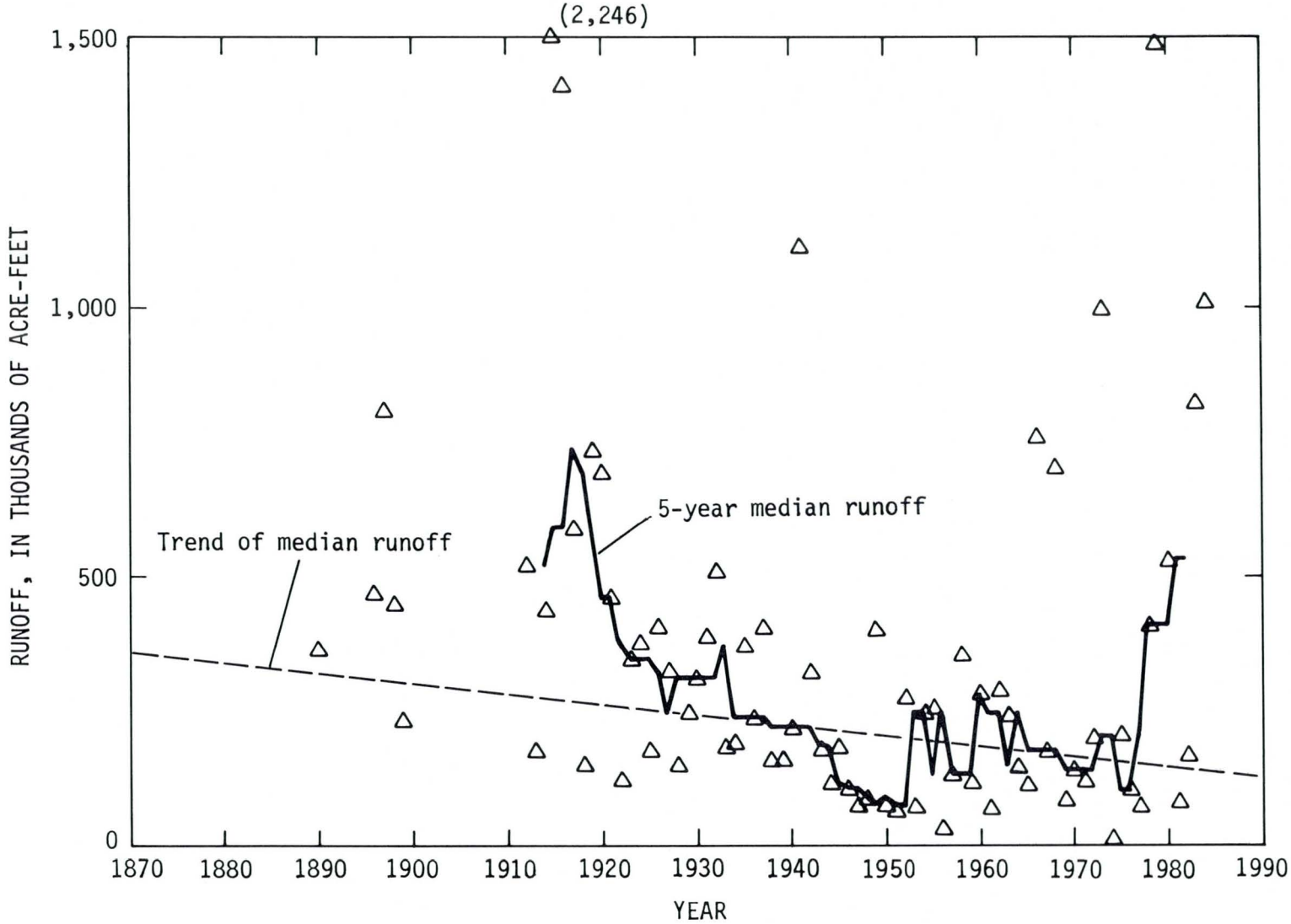


Figure 4.--Annual runoff of the Gila River at Kelvin.

streamflow estimates are Salt River near Roosevelt, Verde River below Tangle Creek, and San Francisco River near Glenwood, New Mexico (fig. 3). The Verde River basin is most similar to the Gila River basin (table 3), but the long-term streamflow estimates are for winter only. Because summer streamflow records on the Verde River are affected by increasing irrigation diversions, a consistent base period is not available for calibrating the regression equations (Smith, 1981, p. 40-41).

Estimates of annual runoff using tree-ring data are available for the Salt and San Francisco Rivers. The Salt and San Francisco River basins are smaller, wetter, at higher altitudes, and more heavily forested than the Gila River basin (table 3). The Salt River basin is more similar to the Gila River basin in size, elevation, and channel slope, however, and is least influenced by irrigation diversions. Thus, the tree-ring estimates of runoff for the Salt River were selected as a basis for estimating predevelopment flow of the Gila River at Kelvin. The 100-year period 1770-1869 was selected to represent predevelopment conditions. The ratio of median annual estimated runoff during 1770-1869 to median annual recorded runoff during two periods for the Salt River near Roosevelt was used to estimate predevelopment flow of the Gila River at Kelvin. The earliest recorded runoff was least affected by diversions and therefore provides the most reliable estimate of median runoff during 1770-1869. The resultant estimate of median annual runoff of the Gila River is 525 cubic feet per second or 380,000 ±50,000 acre-feet, which is within the range of 360,000 ±80,000 acre-feet estimated from the trend of median runoff (fig. 4). Mean runoff on the Gila River for the period of record generally is 20 to 40 percent higher than the median. Mean annual runoff for predevelopment conditions probably was also 20 to 40 percent higher and therefore about 500,000 ±75,000 acre-feet. The estimated mean is consistent with the estimate of 510,600 acre-feet per year as the average runoff of the Gila River at Kelvin during 1868-1941 (Corps of Engineers, unpublished report, 1945).

Ground water was discharging into the Gila River channel in the western third of the reservation in 1895 when the channel was dry in most other places on the reservation (Davis, 1897b). Discharge measurements made on June 1, 1903, of the flow in six diversion ditches and the river channel near Gila Crossing totaled about 51 cubic feet per second (Lee, 1904). Fifty measurements of flow of the Gila River at Gila Crossing, including flow in irrigation ditches, made during 1934-40 ranged from 6.1 to 48.4 cubic feet per second (C.J. Moody, U.S. Indian Irrigation Service, written commun., 1940). A streamflow-gaging station was established on the Gila River near Laveen (at Gila Crossing) in 1940. At that time, flow in the river was perennial and base flow was estimated from daily flow records for the gaging station and measurements of diversion upstream from the gage (U.S. Geological Survey, 1941). The average annual base flow at Gila Crossing decreased gradually from a high of 25 cubic feet per second in the 1941 water year to 0 in 1957 (fig. 5). The decrease in base flow (ground-water discharge) resulted from lowering of the ground-water level.

During 1929-40, miscellaneous measurements, which were made monthly of the flow of the Gila River at the junction with the Salt River, indicate that the base flow was about twice the base flow at Gila Crossing and decreased with time. Average discharge was 57.2 cubic feet per second

Table 3.--Comparison of basin characteristics

Stream	Drainage area, in square miles	Annual precipitation, in inches	Annual snowfall, in inches	Mean altitude, in feet	Forest area, in percent	Channel slope, in feet per mile	Irrigated area, 1982, in acres per square mile
Gila River at Kelvin.....	18,011	15.7	23	5,150	13	18	4.6
Salt River near Roosevelt.....	4,306	22.0	44	6,190	71	23	0.9
Verde River below Tangle Creek.....	5,499	18.4	32	5,470	67	16	2.3
San Francisco River near Glenwood, New Mexico.....	1,653	17.6	52	7,780	85	55	1.2

for 1929-34 and 45 cubic feet per second for 1934-40 (P.V. Hodges, U.S. Indian Irrigation Service, written commun., 1941).

Other streams that affect the reservation's water resources are the Salt and Santa Cruz Rivers; Queen Creek; Santa Rosa, Greene, and Vekol Washes; and many small streams along mountain fronts. The Salt River was perennial when non-Indian settlers arrived. The Santa Cruz River was ephemeral except near the confluence with the Gila River (Brown and others, 1981). Queen Creek was perennial in the upper reaches but most of the flow infiltrated into the alluvium near the contact with the bedrock. Santa Rosa, Greene, and Vekol Washes and other ephemeral channels that drain the mountains in and around the study area carry water only in response to heavy rainfall. Flow in the ephemeral channels generally travels only a short distance onto the valley floor before all the water infiltrates into the underlying material.

Ground-Water Flow

Recharge to the ground-water system occurs mainly from infiltration of streamflow. Prior to major diversion of water for irrigation, the Gila River was the main source of recharge. Queen Creek; the Santa Cruz River; Santa Rosa, Greene, and Vekol Washes; and other ephemeral channels that drain the mountains in and around the study area probably contributed minor amounts of recharge periodically. The Salt River was a source of recharge from the head of the valley—near the site of Granite Reef Dam—to a point about 10 miles downstream (Lee, 1905). A map of predevelopment water levels (Thomsen and Baldys, 1985) indicates that recharge from the Salt River may have reached the Gila River in the western third of the reservation.

Water is discharged from the ground-water system by surface flow, underflow, and evapotranspiration. Discharge of ground water into the Gila and Salt Rivers occurred regularly prior to development but seldom occurs now. In the western third of the reservation, water was discharged from

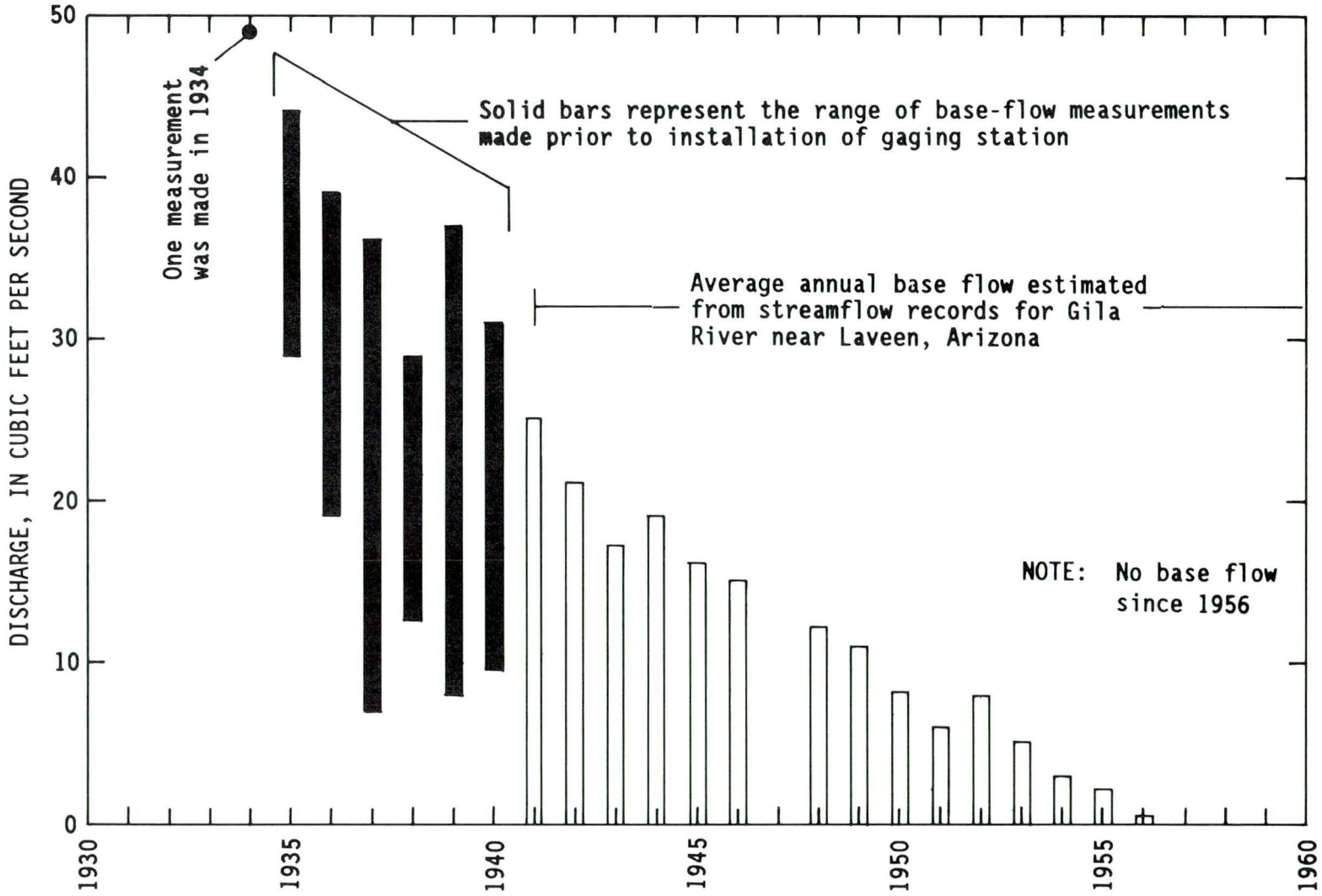


Figure 5.--Average annual base flow of the Gila River near Gila Crossing.

the aquifer to the Gila River channel and adjacent bogs and sloughs (Lee, 1904). As water in the aquifer moved northwestward between Sierra Estrella and South Mountain, the reduced cross-sectional area of the aquifer forced part of the water to the surface. The predevelopment ground-water discharge to the Gila and Santa Cruz Rivers in the western third of the reservation is estimated on the basis of streamflow measurements to have averaged 33,000 acre-feet per year. Ground-water discharge near Coolidge probably averaged about 3,000 acre-feet per year.

Ground water occurs mainly under water-table or unconfined conditions in the sedimentary material that underlies much of the Gila River Indian Reservation and the surrounding area. The water table is that surface in an unconfined water body at which the pressure is atmospheric. The water table is defined by the levels at which water stands in wells that penetrate the water body. Prior to development of the area by non-Indian settlers, water levels were 10 to 70 feet below the land surface and the water table was a surface of low relief, sloping in general with the grade of the river (Lee, 1904). The water level at Sacaton was 15 feet below the land surface. The direction of ground-water movement in 1900 was from the northeast, east, and southeast toward the northwest, and ground-water discharge occurred through the gap between South Mountain and Sierra Estrella (Thomsen and Baldys, 1985). The ground-water reservoir was in equilibrium and was sustained mainly by the infiltration of water from the Gila River. Ground water was discharged to the Gila River in the western part of the reservation. The movement of water from the Salt River to the ground-water reservoir and back to the Salt River affected a small part of the study area but had little effect on the overall ground-water system.

Mountain ranges that lie within the study area impede the movement of ground water. The rocks that form the mountains are generally not water bearing but may, where fractured, yield as much as a few tens of gallons per minute of water to wells. The stream alluvium and the upper basin fill yield as much as 4,000 gallons per minute of water to wells (Laney and Hahn, 1986). In places, the upper basin fill contains layers of fine-grained material that restrict the downward migration of water. The lower basin fill generally yields less than 50 gallons per minute of water to wells. The pre-Basin and Range unit is more permeable than the lower basin fill. Water in the pre-Basin and Range unit is under confined conditions in areas where the unit is overlain by the lower basin fill. Elsewhere, water in the upper basin fill and the pre-Basin and Range unit is in a common and generally unconfined water body.

Underflow

Underflow through permeable materials underlying the surface drainages recharges the ground-water system in the study area. Underflow is the subsurface movement of water from one basin to another. The Gila and Salt Rivers and Queen Creek enter from areas underlain by crystalline rocks; hence, the underflow from these drainages probably was negligible. The Santa Cruz River and Santa Rosa, Greene, and Vekol Wash drainages are underlain by thick alluvium, so the potential exists for a moderate amount of underflow through the alluvium. Underflow along the Santa Cruz, Santa

Rosa, and Vekol drainages is indicated by predevelopment water levels (Thomsen and Baldys, 1985).

Underflow from the Santa Cruz River drainage probably was about 25,000 acre-feet per year (Turner and others, 1943; Hardt and Cattany, 1965). Underflow from Santa Rosa and Vekol Washes was about 1,500 and 500 acre-feet per year, respectively (Turner and others, 1943). Underflow derived principally from runoff in the Picacho Mountains may range from 2,000 to 3,000 acre-feet per year. Total underflow into the area probably is about 30,000 acre-feet per year.

Underflow from the area occurs mainly through the gap between South Mountain and Sierra Estrella. The quantity of underflow may have been as much as 10,000 acre-feet per year on the basis of transmissivity data and estimates of the cross-sectional area. The alluvial material is about 1,000 feet thick at the narrowest part of the gap (H.J. Thiele, consultant, written commun., 1958). The deepest wells in the area are about 700 feet deep.

Hydraulic Characteristics of the Ground-Water Reservoir

The hydraulic characteristics of the ground-water reservoir are the physical properties that control the ability of the material to store and transmit water. These properties depend mainly on the size of openings or interstices and their shape, arrangement, and interconnection. The hydraulic characteristics commonly used to describe ground-water reservoirs are storage coefficient and transmissivity, which provide a measure of the amount of water stored in the reservoir and the rate at which the reservoir will transmit water. The movement of ground water through a section of aquifer can be expressed by the equation:

$$Q = TIW, \tag{1}$$

where

Q = flow, in cubic feet per day;
T = transmissivity, in feet squared per day;
I = hydraulic gradient (dimensionless); and
W = width of section, in feet.

Transmissivity is a function of the hydraulic conductivity and saturated thickness of the reservoir and may be expressed by the equation:

$$T = KM, \tag{2}$$

where

K = hydraulic conductivity, in feet per day, and
M = saturated thickness, in feet.

Hydraulic conductivity is the volume of water at the existing kinematic viscosity that will move in unit time under a unit of hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972). Hydraulic conductivity is expressed in units of length per unit time, such as feet per day.

Transmissivity is the rate at which water at the existing kinematic viscosity is transmitted through a unit width of aquifer (saturated thickness of ground-water reservoir) under a unit hydraulic gradient. Transmissivity is expressed in consistent units of volume (L^3) per unit time (T) per unit width (L), which reduces to L^2T^{-1}. In the English system, transmissivity is expressed in cubic feet per day per foot, which reduces to feet squared per day.

The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Lohman and others, 1972). In an unconfined water body, it is virtually equal to the "specific yield," which is the volume of water that water-bearing material will yield by gravity drainage. The storage coefficient is expressed as a ratio of the volume of water removed to the volume of the material dewatered and is, therefore, dimensionless.

Quantitative data on the hydraulic characteristics of ground-water reservoirs are obtained from field data on water levels, water-level fluctuations, and natural or artificial discharges (Ferris and others, 1962; Bentall, 1963). In general, transmissivity values in the study area range from about 1,500 to 30,000 feet squared per day (Anderson, 1968), but values of about 100,000 feet squared per day have been determined for some local areas. Anderson (1968) defined a regional pattern of average transmissivity values for 1923-64. Many of these values were obtained after the upper part of the aquifer, which in many areas is the most transmissive, had been at least partly dewatered; hence, the values are less than they would have been prior to dewatering. The greatest values of transmissivity are in the area from Mesa southward through Chandler westward toward Gila Crossing and in an area south of Maricopa (Anderson, 1968). Stratification in alluvial material causes transmissivity values to be much greater parallel to the bedding plane than perpendicular to the bedding plane.

The average storage coefficients for central Arizona range from 0.15 to 0.20 (Anderson, 1968, p. 10). In computing the amount of recoverable ground water in storage beneath the Gila River Indian Reservation, Babcock (1970) used a storage coefficient of 0.15 for the upper 600 feet of sediments and 0.10 for the 600- to 1,000-foot interval. Anderson (1968) used a storage coefficient of 0.19 for most of the water-bearing zones in central Arizona but reduced the value to 0.15 in the area east of Mesa along the southwest slopes of the Superstition Mountains and to 0.10 in the area west of Casa Grande extending from the Sacaton Mountains on the north to the Table Top Mountains on the south. Storage coefficients, or more appropriately "specific yields," are relatively low in water-bearing zones that contain a large proportion of fine-grained material.

The horizontal hydraulic gradient averaged about 0.001 and ranged from 0.0006 to 0.008 prior to ground-water withdrawals by the non-Indian

settlers. Horizontal hydraulic gradients of 0.02 are common in heavily pumped areas today.

Evapotranspiration

Evapotranspiration is defined as "water withdrawn from a land area by *evaporation* from water surfaces and moist soil and plant *transpiration*" (Langbein and Iseri, 1960). Evaporation is commonly measured by noting the change in water level in an open pan during a given time period. Such measurements, however, do not accurately reflect evaporation from natural water bodies because of differences in water temperature, vapor pressure, and water-surface roughness. The rate of evaporation from a small pan generally far exceeds that from a large reservoir or lake. The ratio of lake evaporation to pan evaporation is referred to as the pan coefficient. Annual evaporation from a U.S. Weather Bureau Class A pan at Mesa during 1963-73 averaged 106.31 inches (Sellers and Hill, 1974). In the study area, the pan coefficient is about 0.67 and the average annual lake evaporation is about 70 to 75 inches (U.S. Department of Commerce, 1968). Annual lake evaporation, in feet, multiplied by an area of water surface, in acres, is equal to the volume of water evaporated, in acre-feet per year.

Plants obtain water from precipitation and soil moisture, and deep-rooted plants called phreatophytes obtain much of their water from the capillary fringe and the saturated zone. The rate of transpiration by phreatophytes depends on the availability of water and on the species, the cover density and size, and the stage of maturity of the plants. The quantity of water withdrawn from the ground-water reservoir by phreatophytes depends on the depth to ground water. The use of water is greatest when ground water is shallow and decreases as depth to water increases (fig. 6). The relation between water use and depth to water is not well defined for all phreatophyte species but is fairly well defined for mesquite (Anderson, 1976). Little is known about the relation between ground-water use and the total water use by phreatophytes.

The most common species of phreatophytes indigenous to southern Arizona are cottonwood, willow, baccharis (seepwillow), and mesquite (Gatewood and others, 1950). These species probably were the main woodland types of vegetation on the Gila River Indian Reservation prior to the arrival of the non-Indian settlers. In 1936, mesquite thickets covered about 22,500 acres, tamarisk 6,500 acres, cottonwood 5,000 acres, and scattered mesquite 20,000 acres for a total of about 54,000 acres of phreatophytes on the reservation (U.S. Soil Conservation Service, 1936). Rott (1936) referred to the tamarisk as a recent invasion, having come in during the 6 to 10 years prior to 1936. Robinson (1965) stated that the date of introduction of tamarisk, better known as saltcedar, is not known, but it had spread enough to become noticeable in the 1920's. Turner (1974) noted that saltcedar did not occur in the upper Gila River Valley until after the flood of 1916 and that the increase in saltcedar has been almost wholly at the expense of baccharis.

An investigation of the consumptive use of water by phreatophytes was made in 1963-71 to determine evapotranspiration before and after clearing phreatophytes on 15 miles of Gila River flood plain (Culler and

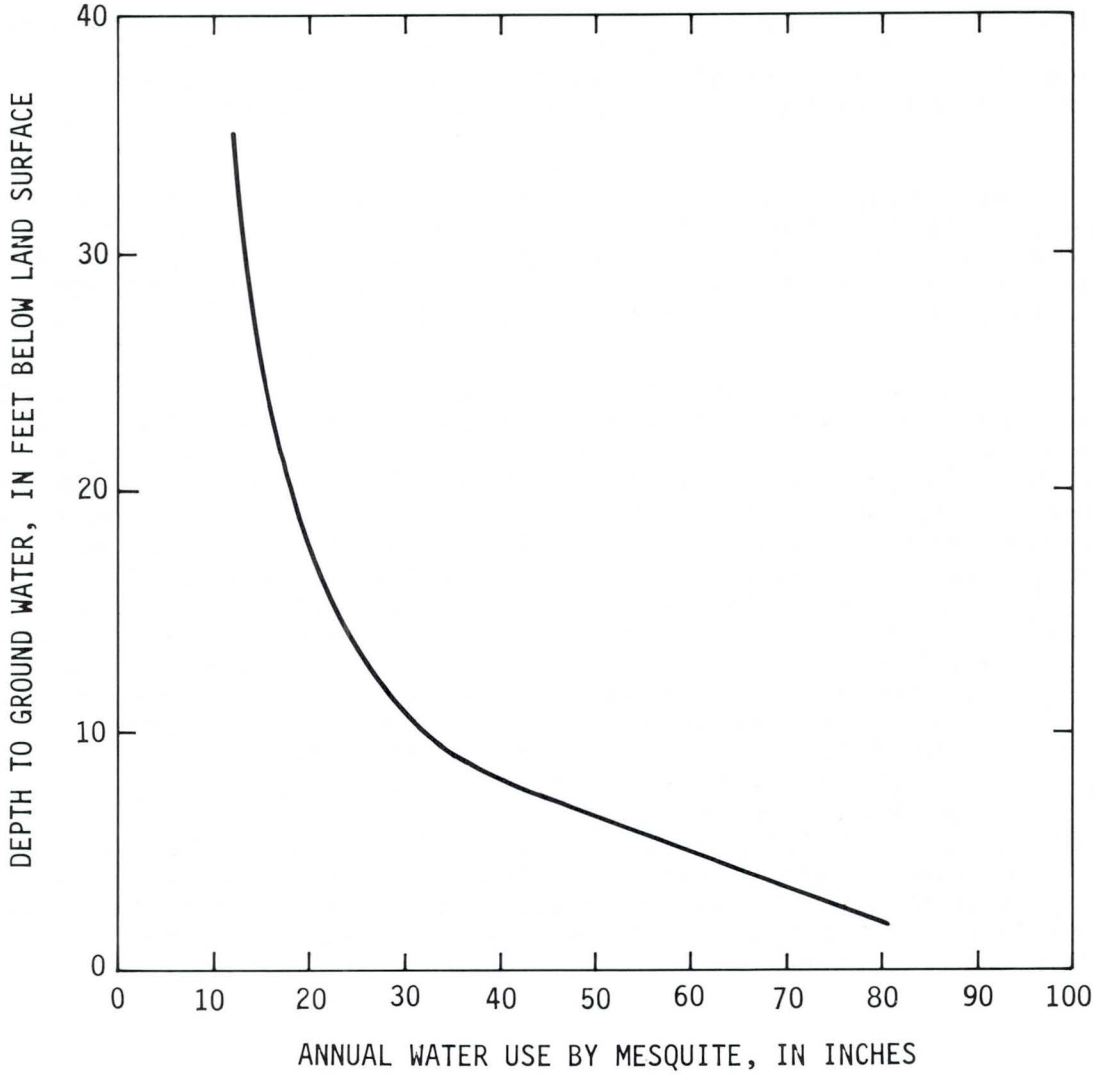


Figure 6.--Relation between depth to ground water and annual water use by mesquite (from Anderson, 1976, fig. 10, p. 46).

others, 1982). Results of the study showed that the annual evapotranspiration averaged 3.7 feet and ranged from 4.7 feet for dense stands of phreatophytes to 2.1 feet on areas of no phreatophytes. Vegetation consisted mainly of saltcedar and mesquite with scattered cottonwood, seepwillow, seepweed, and arrowweed. Depth to ground water on the flood plain ranged from 5 feet near the river to 20 feet near the outer boundaries of the flood plain. Removal of phreatophytes resulted in a reduction in evapotranspiration that averaged 1.6 feet per year and ranged from 1.2 to 2.2 feet per year owing to the differences in the density of phreatophytes. Evapotranspiration after the removal of phreatophytes consisted of evaporation from bare ground and transpiration from annual vegetation. Because phreatophytes obtain their water supply primarily from ground water, the reduction in evapotranspiration that resulted from

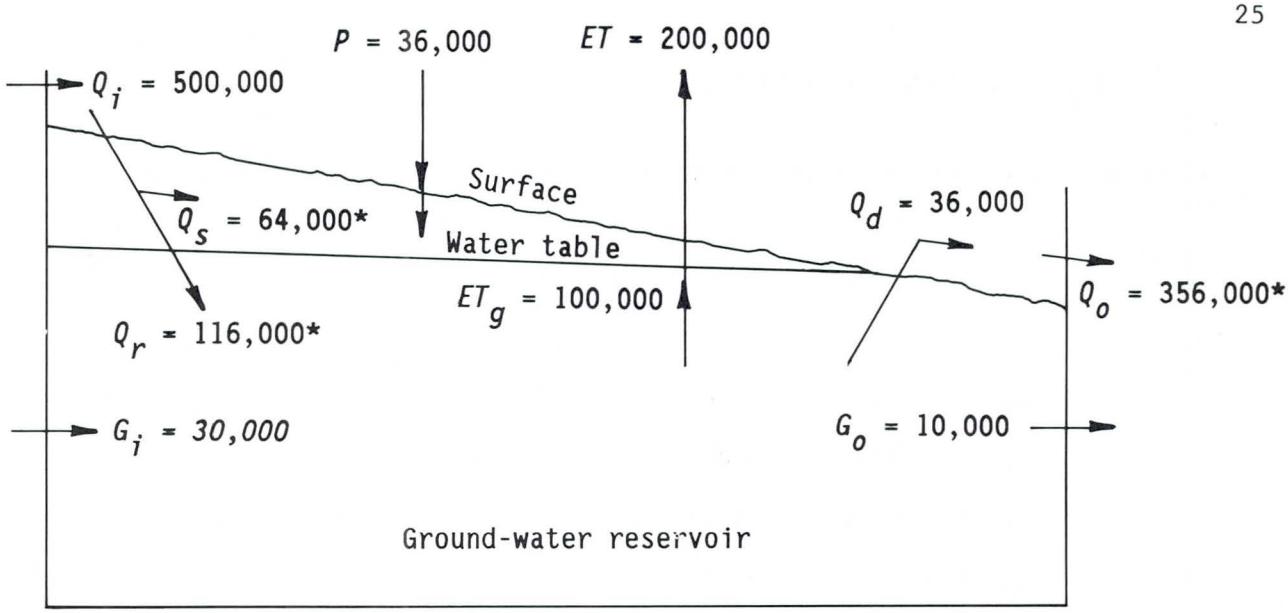
removal of the phreatophytes is considered to represent a measure of ground-water withdrawal by phreatophytes. Precipitation and soil moisture provide a significant part of the water removed by evapotranspiration during the period of high potential evapotranspiration (Culler and others, 1982).

Evapotranspiration by phreatophytes was responsible for the withdrawal of large quantities of ground water along the Gila River when water levels were shallow. Evapotranspiration along the Gila River from near Coolidge to the Salt River probably ranged from 100,000 to 150,000 acre-feet per year (Turner and others, 1943).

On the basis of the assumption that the number of acres of phreatophytes was about the same in 1870 as in 1936, the average evapotranspiration in 1870 was about 200,000 acre-feet per year. Of that amount, about 100,000 acre-feet per year was withdrawn from the ground-water reservoir by phreatophytes and 100,000 acre-feet per year was from precipitation and soil moisture. Total evapotranspiration was estimated by using the maximum evapotranspiration rate of 4.7 feet per year (Culler and others, 1982) for about 34,000 acres of cottonwood, tamarisk, and mesquite thickets (Rott, 1936) and the minimum evapotranspiration rate of 2.1 feet per year for 20,000 acres of scattered mesquite. The magnitude of the withdrawal from the ground-water reservoir by phreatophytes, 100,000 acre-feet, was estimated by using the the maximum reduction in evapotranspiration of 2.2 feet per year that resulted from the removal of phreatophytes on the upper Gila River (Culler and others, 1982) for the 34,000 acres of dense phreatophytes and the minimum reduction in evapotranspiration of 1.2 feet per year for 20,000 acres of scattered mesquite. The average annual precipitation of 8 inches for the 54,000 acres of phreatophytes accounts for 36,000 acre-feet per year of the total evapotranspiration. The remaining 64,000 acre-feet per year probably was from soil moisture that was replenished periodically by surface flow.

WATER BUDGET

Water budgets were prepared for the ground-water reservoir and for the study area as a whole. A water budget must account for all inflows, outflows, and changes in storage. Because aquifers were in equilibrium prior to development by non-Indian settlers, the average change in ground-water storage during the 100-year period prior to 1870 was considered zero. There was no surface storage. Hence, the sum of all inflows must have equaled the sum of all outflows. Most of the inflows and outflows for the study area as a whole, as well as for the ground-water reservoir, occurred along the Gila River. Thus, the components considered in the water budgets relate to the area along the Gila River and to the ground-water reservoir that underlies the study area (fig. 7). Precipitation on the area of evapotranspiration—the 54,000 acres used in computing evapotranspiration—was included in the water budget of the study area because precipitation provides a significant part of the evapotranspiration (Culler and others, 1982). Precipitation on the rest of the study area was not a significant factor in the water budget. One intermediate component of water movement appears in figure 7 but is not included in either water budget. This component, Q_s represents Gila River flow that entered the



*Computed as a residual

Figure 7.--Conceptual longitudinal section showing initial estimates of average annual values, in acre-feet, of water-budget components.

soil zone and subsequently was evaporated or used by plants. The value of Q_s was calculated as a residual of the evapotranspiration computation.

The average annual water budget for the ground-water reservoir is expressed by the equation

$$G_i + Q_r = G_o + Q_d + ET_g, \tag{3}$$

where

G_i = subsurface inflow,
Q_r = recharge from the Gila River,
G_o = subsurface outflow,
Q_d = discharge to the Gila and Santa Cruz Rivers, and
ET_g = evapotranspiration from the ground-water reservoir.

All components were evaluated independently except Q_r which was computed as a residual. Average predevelopment values are as follows:

G_i = 30,000 acre-feet per year ±25 percent.
Q_r = 116,000 acre-feet per year.
G_o = 10,000 acre-feet per year ±25 percent.
Q_d = 36,000 acre-feet per year ±25 percent.

ET_g = 100,000 acre-feet per year ±25 percent.

The average annual water budget for the study area is expressed by the equation

$$Q_i + G_i + P = Q_o + G_o + ET, \tag{4}$$

where

Q_i = surface inflow of the Gila River,

G_i = subsurface inflow,

P = precipitation on the area of evapotranspiration,

Q_o = surface outflow of the Gila River,

G_o = subsurface outflow, and

ET = evapotranspiration from the flood plains of the Gila and Santa Cruz Rivers and minor tributaries.

All components were evaluated independently except Q_o, which was computed as a residual. Average predevelopment values are as follows:

Q_i = 500,000 acre-feet per year ±20 percent.

G_i = 30,000 acre-feet per year ±25 percent.

P = 36,000 acre-feet per year ±15 percent.

Q_o = 356,000 acre-feet per year.

G_o = 10,000 acre-feet per year ±25 percent.

ET = 200,000 acre-feet per year ±20 percent.

The uncertainty associated with the budget-component values is the judgment of the authors and results from a combination of intrinsic errors of measurement, inadequacy of methods used in calculations, and extent of interpolation and (or) extrapolation of data.

SIMULATION OF GROUND-WATER FLOW

A simulation model is a group of mathematical equations that describe the flow of water through an aquifer in relation to aquifer characteristics, the amount of water in storage, and rates of inflow and outflow. Use of a simulation model provides an integrated analysis of estimates of water-budget items and regional aquifer characteristics and

thus permits evaluation of the compatibility and reasonableness of the estimates. A calibrated model is one for which all the estimates are collectively within acceptable limits.

Model equations generally cannot be solved analytically when they represent large or complex areas. Equations can be solved numerically, however, by using a digital computer or by using an electric-analog model that utilizes the similarity of the equations for ground-water flow and for electrical flow in a resistor-capacitor network (Walton and Prickett, 1963).

Anderson (1968) used an analog model to evaluate ground-water conditions in the study area and an adjacent area north of the Salt River. The analog model treated transmissivity as a constant for the entire period of simulation (1923-63) and assumed that water-level changes in time were independent of the pre-existing water-level gradients. Both assumptions are correct for a confined aquifer or for an unconfined aquifer in which water-level changes are a minor part of the aquifer thickness. During 1923-84, however, major water-level declines dewatered the stream alluvium in much of the area (Freethey and others, 1986), causing a substantial reduction in transmissivity. The fixed transmissivity in Anderson's (1968) simulation represents an average value for 1923-84. Analog models also are limited in the treatment of head-dependent boundary flows such as evapotranspiration and streamflow interactions.

With the development of digital computers, numerical solution of the model equations has become preferred. The numerical approach allows greater flexibility in defining boundary conditions and permits the level of detail to be varied across the study area. The model in this study primarily simulates the ground-water system although it maintains a simplified account of streamflow.

The present model represents average conditions in the system during the 100-year period, 1771-1870, before significant effects of non-Indian diversions upstream from the reservation. The system was simulated as being in equilibrium, or steady state, which assumes that inflow to the ground-water system was equal to outflow from it and that the quantity of water in storage did not change through time.

Computer Program

Several computer programs have been written to solve the ground-water flow equation. A model program by Trescott and others (1976) was used in this study. Because aquifer characteristics are not uniform throughout the study area, the area was divided into rectangular blocks in each of which the aquifer characteristics were assumed to be uniform. The model program uses a node at the center of each block to represent all hydraulic characteristics of the block. The program solves for the head and flow at each node by using a two-dimensional, finite-difference approximation to the partial differential equation for ground-water flow. For steady-state conditions, the two-dimensional approximation provides equivalent results to those from a more complicated three-dimensional model. Simulated heads using the two-dimensional model represent the

average hydraulic head in the vertical column of aquifer within each block and may be higher or lower than the water table, depending on the magnitude of vertical-flow components. Various processes of inflow and outflow at a block are described by additional equations. The analytic equations and their finite-difference approximations are described in the model program documentation (Trescott and others, 1976, p. 1-26).

Input to the model program includes data that describe the physical extent of the aquifer, the elevation of streams and the land surface, the array of blocks used in computations, and the initial estimates of head in each block. In general, these data were not changed during calibration. Other required data describe the water budget and the hydraulic characteristics of the aquifer. These data were modified during calibration.

The locations of the blocks used to simulate the aquifer are shown on plate 1. Each block is a rectangle with sides ranging from 0.5 to 3 miles. The grid is oriented approximately northwest to southeast and includes 45 rows and 60 columns. The block size was selected to provide greater detail in the area of complex interactions between the river, the aquifer, and the phreatophytic vegetation. The block sizes were expanded away from the Gila River. Use of larger blocks allows computational efficiency without loss of required detail. Because the simulation equations were solved assuming average conditions over each block, the results may not reflect conditions that changed in an area smaller than one block. In contrast, conditions that were uniform over several blocks generally are represented adequately.

Hydrologic conditions of the study area are affected by precipitation, streamflow, infiltration, underflow, recharge, discharge, and evapotranspiration. Each of these processes is simulated in the model. Ground-water flow is simulated by change in head and transmissivity. Mountain areas are assigned zero transmissivity and simulated as no-flow boundaries. Precipitation is simulated by a constant-inflow rate added to areas of phreatophytic vegetation along the Gila River. In the rest of the area, precipitation is assumed to have no direct effect on the ground-water systems. Some precipitation in mountainous areas collects as runoff in ephemeral streams and recharges the aquifer. Mountain-front recharge is simulated as a constant-inflow rate along many boundary blocks.

The hydraulic connection of the aquifer in the study area with aquifers in adjacent areas is simulated by constant flux nodes on the east and south boundaries and by constant head nodes on the west boundary (pl. 1). This simulation permitted outflow to balance with other water-budget components. Recharge from and return flow to the Salt River was simulated by constant-head nodes. Along the Gila and lower Santa Cruz Rivers, the interaction of streamflow with the aquifer was simulated by a leakage function that makes the transfer of water proportional to the head difference between the aquifer and the rivers. Perennial flow was assumed at all leakage nodes. Return flow was assumed not to accumulate and raise river head. Water use for evapotranspiration by phreatophytic vegetation was simulated near the Gila River by a function that varied the flow rate in proportion to the depth to the ground water. Evapotranspiration was not simulated along the Salt River northeast of South Mountain or in areas more than 10 miles from the Gila River. Because evapotranspiration and stream

interactions occurred mainly in the same areas along the Gila River, the simulated heads and water-budget components were determined largely by a composite of the leakage and evapotranspiration functions.

Estimation of Model Parameters

Model parameters were estimated initially and independently on the basis of field data. During the subsequent calibration process, information for each parameter was used to confirm or improve estimates of other parameters. After calibration adjustments, estimated parameters were considered collectively more reliable than the initial independent estimates.

Initial estimates of transmissivity are from Anderson (1968, pl. 2). Values, which were derived from data on specific capacities of wells and a flow-net analysis, were adjusted on the basis of other hydraulic data during calibration.

Initial head estimates for the model were derived from water-level contours for about 1900 (Thomsen and Baldys, 1985, sheet 1), which are based on data from several sources. The data may have been affected by seasonal diversion of water before 1900 from the Gila River near Florence and from the Salt River near Mesa. The effect of diversions on water levels probably were minimal, hence initial estimates were used throughout model calibration.

Initial estimates of ground-water inflow and mountain-front recharge were derived from Freethey and Anderson (1986, sheet 2). Appropriate inflow rates were assigned to model nodes in intermontane gaps, and mountain-front recharge was distributed along the flanks of the highest mountains.

Average land-surface altitude for evapotranspiration nodes was estimated from topographic maps. Average altitudes of streams and dry channels were also derived from topographic maps. The stream altitudes were used for the constant-head boundary along the Salt River and for the leaky boundary along the Gila and lower Santa Cruz Rivers.

Leakance, which is the ratio of the vertical hydraulic conductivity to the distance across which the head differential acts, was needed to estimate leakage between the Gila and Santa Cruz Rivers and the aquifer. Average horizontal hydraulic conductivity of the saturated deposits was about 130 feet per day. Assuming that vertical conductivity is 10 times smaller than horizontal, the vertical conductivity is about 13 feet per day. Because computed head in the two-dimensional model represents the average head in a column of the aquifer, the computed differential head acts across half the aquifer thickness, or 500 feet. The leakance is thus 13/500 or 0.026 per day for the actual wetted perimeter of the streams. Because the model program computes leakage as acting over the entire area of a block, the basic leakance coefficient was adjusted for the area of each block and the length of channel within it, assuming that the

Gila River channel averaged 500 feet wide and the lower Santa Cruz channel 50 feet wide.

Calibration

Calibration is the process of adjusting the model input to achieve agreement between simulated and observed water levels and budget components. The parameters of the calibrated model are not unique; many combinations of input data could produce similar results. The effects of nonuniqueness and the magnitude of the uncertainties involved in this approach are discussed in the section on sensitivity analysis.

During calibration, simulation results were compared with predevelopment water levels in 41 wells and with nonmodel budget estimates. Estimated evapotranspiration from ground water was 100,000 acre-feet per year. Estimated ground-water return flow to the Gila and Santa Cruz Rivers in the western part of the reservation was 33,000 acre-feet per year. Return flow to the Gila River near Coolidge was 3,000 acre-feet per year.

Transmissivity was adjusted during model calibration. Transmissivity was increased by a factor of five in the southern part of the study area along the Santa Cruz River for agreement between simulated and observed head. Transmissivity was also increased by a factor of five along the Gila River channel. Calibrated transmissivities, which range from 5,000 to 120,000 feet squared per day (pl. 2), are equal to initial values in the Queen Creek and Mesa areas (model rows 2-12) and are five times greater than initial values along and south of the Gila River (rows 15-44).

The estimating function for evapotranspiration was changed during calibration. The model treats evapotranspiration as a linear function of the average head in a block below the average land surface (Trescott and others, 1976, p. 7-9). The function is the simplest representation of the process and can be defined by two values—QET, the rate when water is at the land surface, and ETDIST, the depth at which all evapotranspiration from ground water ceases (fig. 8). Studies of water use by single crops with constant density support the use of a linear function (van Hylckama, 1974, fig. 34). In the study area, however, vegetation is of several types and densities, which results in a curvilinear relation between rate of evapotranspiration and depth to water. Hence, a generalized hyperbola was selected to represent the curvilinear evapotranspiration function so that the curve would pass smoothly through a specified relative rate and depth value, R (fig. 8). A family of functions can be defined by changing the value of R, which is designated the coefficient of curvature for use in this report. The function was implemented in the model program by a piecewise linear approximation and used the same explicit and implicit solution technique as the original program. The values initially selected for the curvilinear function were QET = 3.5 feet per year, ETDIST = 30 feet, and R = 0.33. These values produced reasonable results and were used for the remainder of the calibration. The maximum evaporation rate of 3.5 feet per year used in the simulation is less than has been measured in various studies on small plots. In the simulation the value includes only that water withdrawn from the zone of saturation; it excludes water that plants draw from the soil zone.

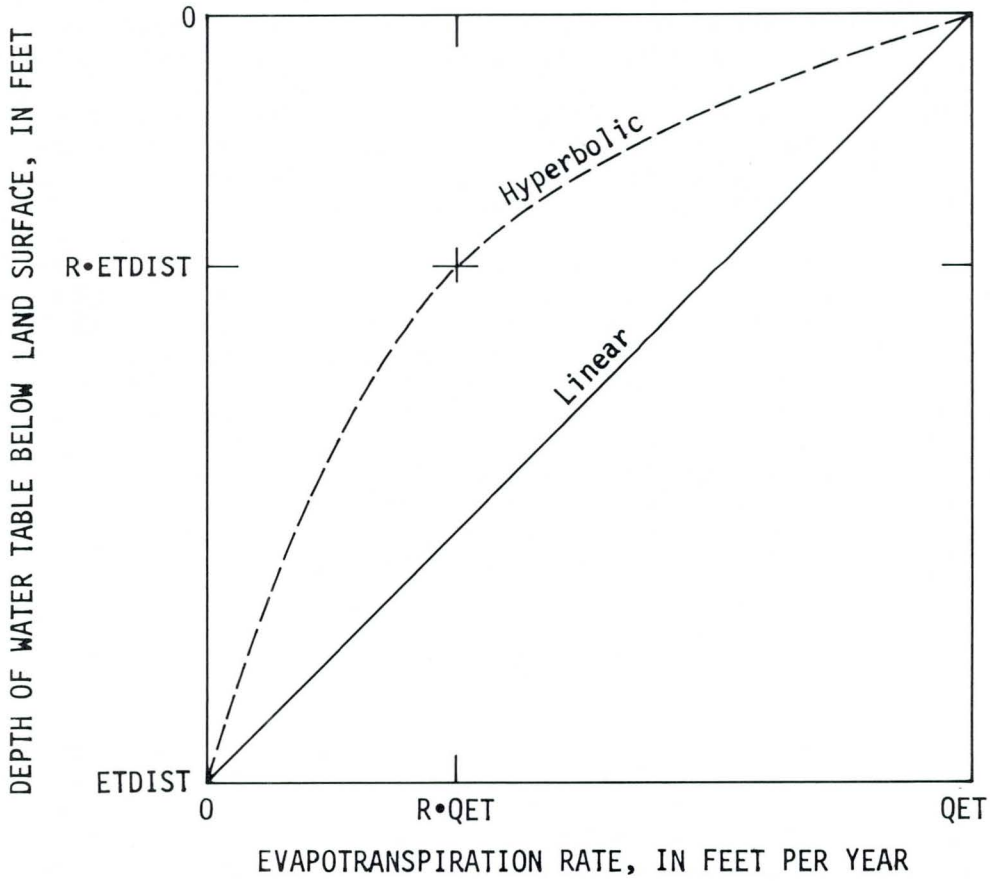


Figure 8.--Functions for estimating evapotranspiration.

Simulation Results

Simulated water levels (pl. 2) for 41 wells in the study area averaged 10.6 feet higher or lower than measured values. The largest differences occurred in small areas near Casa Grande and east of South Mountain. In both areas, water levels in upstream and downstream wells are in good agreement with simulated values, which indicates that the areas with large differences are local and do not affect the overall system. The calibrated water levels for all model nodes average 12 feet different from the initial estimates.

The simulated water budget (table 4) shows that the Gila River recharged about 94,000 acre-feet per year to the aquifer in two reaches from the Buttes to near Pima Butte before 1870. About 3,000 acre-feet per year returned to the stream near Coolidge and about 29,000 acre-feet per year returned in the lower reaches of the Gila and Santa Cruz Rivers, a result that is consistent with observed data. Values of infiltration and returns listed in table 4 are the net amounts for reaches specified. When all flows were accounted for without regard to location, total infiltration from the Gila River was simulated as 100,800 acre-feet per year and total return flow to the Gila and Santa Cruz Rivers as 38,800 acre-feet per year. Simulations indicate that the Gila River changed from a losing stream to a gaining stream within a mile of the old railroad crossing at Pima Butte where Lee (1904, p. 24) reported water rising in the dry riverbed after upstream diversions had cut off the surface flow.

Simulations indicate that predevelopment evapotranspiration from the ground-water system was 96,000 acre-feet per year. The area of simulated evapotranspiration was generally within 2 miles of the Gila River from its confluence with the Salt River to a point 3 miles west of Florence. The area extends southward along the Santa Cruz River and McClellan Wash and northward near Lone Butte in the area formerly known as the lake (Lee, 1904, p. 24). The area of simulated evapotranspiration is substantially greater than the 84 square miles of phreatophytic vegetation mapped by the U.S. Soil Conservation Service (1936) because the model simulated evapotranspiration for each model block in which the computed water level was within 30 feet of average land altitude.

Sensitivity Analysis

The sensitivity of simulated head and flux to changes in the input data, in combination with the uncertainty of nonmodel estimates of the data values, provides an indication of the model's reliability. Sensitivity was assessed by holding all input values constant except the one being analyzed and varying that value through a range that included the uncertainty in the value. The simulation results following each such perturbation were compared with the independent estimates of water-budget components and predevelopment water levels in wells in the same way that calibration runs were checked. The input value being analyzed was deemed reasonable if the simulation results were similar to the independent estimates. The input value was considered unlikely if the results were quite different from the estimates.

Water-budget components generally were sensitive to changes in the input data. As the input was changed, total flow through the system increased or decreased and the proportion of flow accounted for by each process changed. These results were compared with the independent estimates of 100,000 acre-feet per year for evapotranspiration and 33,000 acre-feet per year for return flow to the Gila and Santa Cruz Rivers in the western third of the reservation. Water-budget results for the sensitivity analyses are shown in figures 9-12. Each graph shows three budget components as functions of the input value that was analyzed. The components are simulated evapotranspiration, simulated recharge by infiltration from the Gila River between the east edge of the model and Pima Butte, and simulated return flow from the aquifer to the Gila and

Table 4.--*Simulated predevelopment ground-water budget*

	Cubic feet per second	Acre-feet per year
INFLOW		
Underflow and infiltration from:		
Santa Cruz River near Picacho Peak.....	26.2	19,000
Santa Rosa and Aguirre Valleys and Queen Creek.....	6.2	4,500
Recharge along mountain fronts and minor underflows.....	11.9	8,600
Net infiltration of streamflow along:		
Gila River from the Buttes to Coolidge.....	33.0	23,900
Gila River from Coolidge to Pima Butte.....	96.7	70,100
Salt River east of South Mountain.....	3.2	2,300
Underflow along Salt River west of South Mountain.....	29.4	21,300
Total.....	206.6	149,700
OUTFLOW		
Evapotranspiration from ground water.....	132.7	96,100
Net return flow from aquifer to:		
Gila River near Coolidge.....	3.6	2,600
Gila and Santa Cruz Rivers southeast of Gila Crossing.....	25.8	18,700
Gila River northwest of Gila Crossing.....	14.6	10,600
Underflow along Gila River west of confluence with Salt River.....	29.9	21,700
Total.....	206.6	149,700

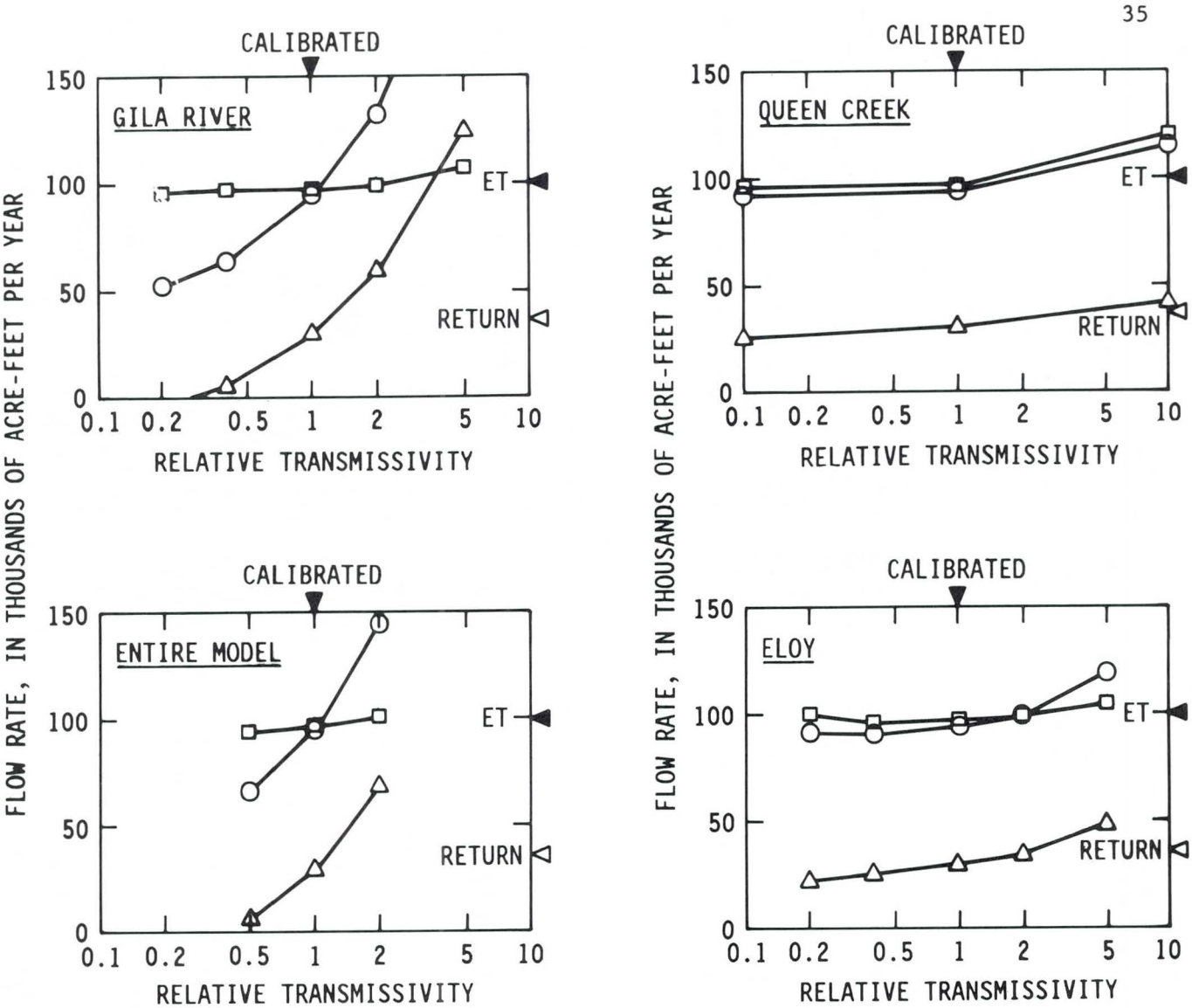
Santa Cruz Rivers west of Pima Butte. The recharge and return flow values are the sum by reaches of simulated net leakage between the aquifer and the streams.

The difference between measured water levels in 41 wells and simulated levels in the corresponding model blocks was checked for each sensitivity run. Simulated water levels in the Eloy and Queen Creek subareas differed from the calibrated values by more than 100 feet for most sensitivity runs in which transmissivity or the specified flow rate was changed. Simulated water levels on the reservation within 2 miles of the river differed from the calibrated values by less than 5 feet for most sensitivity runs.

The sensitivity of model results to variations in transmissivity was analyzed by varying transmissivity values for the entire model and in three subareas—model rows 2-12 were the Queen Creek subarea, rows 15-28 the Gila River subarea, and rows 31-44 the Eloy subarea (fig. 9). The two rows between each subarea were used to make the transitions less abrupt. Model input was varied by multiplying each transmissivity value in a subarea by a relative transmissivity factor. This process preserved the distribution of transmissivity magnitudes within each subarea and for the total area. Simulated evapotranspiration was insensitive to increases or decreases in transmissivity by as much as 10 times for the entire model or any subarea (fig. 9). Stream recharge and return flow were insensitive to changes in transmissivity in the Eloy and Queen Creek subareas, which are far from the river, but were very sensitive to changes in transmissivity along the Gila River and for the entire model. Change by a factor of two in transmissivity along the Gila River resulted in simulated return flow that was outside the range of independent estimates. The average difference between simulated and measured water levels in 41 wells was larger than the calibrated 10.6 feet for most changes in transmissivity. The average ranged from 3 feet smaller than calibrated values in the Gila River subarea to more than 100 feet larger than calibrated values in the Eloy and Queen Creek subareas for the relative changes in transmissivity.

The sensitivity of model results to evapotranspiration was analyzed by varying the components QET, ETDIST, and R of the evapotranspiration simulation function separately (fig. 10). Simulated total evapotranspiration, recharge, and return flow were sensitive to all three components of the evapotranspiration function, and evapotranspiration and return flows were substantially different from initial estimates in many runs. Simulated increase of evapotranspiration was accompanied by both increased recharge and reduced return flow. Results were more sensitive to changes in the maximum evapotranspiration rate than to changes in the extinction depth or the coefficient of curvature. The average difference between simulated and measured water levels in 41 wells was roughly proportional to total evapotranspiration; average difference ranged from 9.3 feet for the lowest evapotranspiration to 13.2 feet for the highest evapotranspiration.

Leakance, the coefficient controlling the leakage rate, was one of the least-known parameters of the model and was varied through a wide range (fig. 11). Recharge and return flow were simulated as products of leakance and the head differential between the stream and the aquifer. Both recharge and return flow increased as the coefficient of leakance was increased. Simulated evapotranspiration was about equal to the initial



EXPLANATION

○——○ SIMULATED RECHARGE TO THE AQUIFER BY INFILTRATION FROM THE GILA RIVER BETWEEN THE EAST EDGE OF THE MODEL AND PIMA BUTTE

△——△ SIMULATED RETURN FLOW TO THE GILA AND SANTA CRUZ RIVERS WEST OF PIMA BUTTE

□——□ SIMULATED EVAPOTRANSPIRATION

ET◀ INITIAL ESTIMATE OF EVAPOTRANSPIRATION

RETURN◁ INITIAL ESTIMATE OF RETURN FLOW TO THE GILA AND SANTA CRUZ RIVERS WEST OF PIMA BUTTE

Figure 9--Sensitivity of water-budget components to variations in transmissivity.

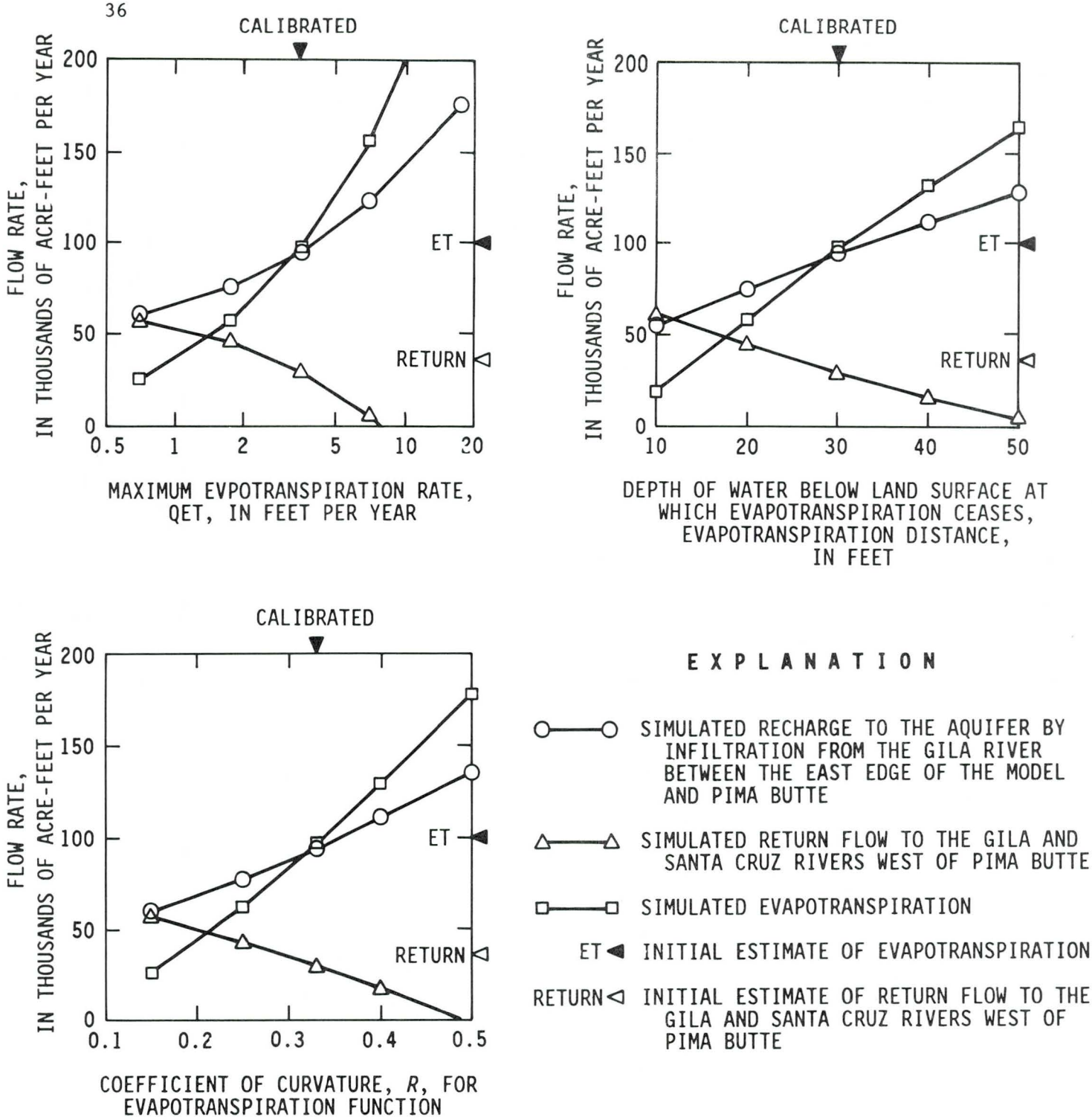
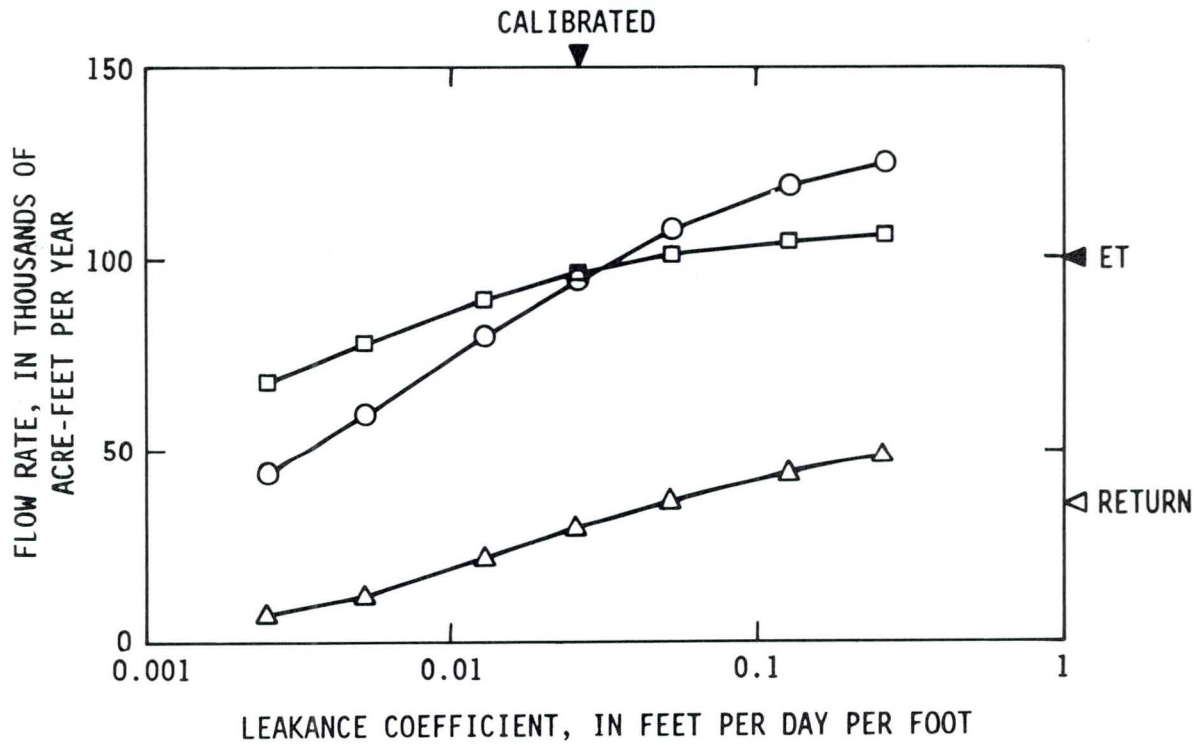


Figure 10--Sensitivity of water-budget components to variations in evapotranspiration.



EXPLANATION

○——○	SIMULATED RECHARGE TO THE AQUIFER BY INFILTRATION FROM THE GILA RIVER BETWEEN THE EAST EDGE OF THE MODEL AND PIMA BUTTE
△——△	SIMULATED RETURN FLOW TO THE GILA AND SANTA CRUZ RIVERS WEST OF PIMA BUTTE
□——□	SIMULATED EVAPOTRANSPIRATION
◀ET	INITIAL ESTIMATE OF EVAPOTRANSPIRATION
◁RETURN	INITIAL ESTIMATE OF RETURN FLOW TO THE GILA AND SANTA CRUZ RIVERS WEST OF PIMA BUTTE

Figure 11--Sensitivity of water-budget components to variations in the leakance coefficient.

estimate for all values of leakance greater than about half the calibrated value. Return flow was in the range of initial estimates for coefficients of leakance from half to twice the calibrated leakance. Evapotranspiration and return flow were relatively insensitive to changes in leakance. For sensitivity runs with leakance values greater than calibration, the average difference between simulated and measured water levels in 41 wells was 0.3 feet less than in calibrated runs.

The sensitivity of model results to changes in mountain-front recharge and underflow rates was also examined (fig. 12). Simulated return flows were insensitive to changes in these fixed inflows. For mountain-front recharge and underflow rates greater than calibration, however, evapotranspiration increased, recharge from the Gila River decreased, and simulated water levels showed large changes in the Eloy and Queen Creek subareas but were generally within 5 feet of calibration near the Gila River.

SUMMARY

The Gila River Indian Reservation is in an area of broad desert plains separated by rugged mountains and transected by the Gila River. Ground water occurs mainly under unconfined conditions in unconsolidated to variably consolidated sedimentary material that underlies the desert plains.

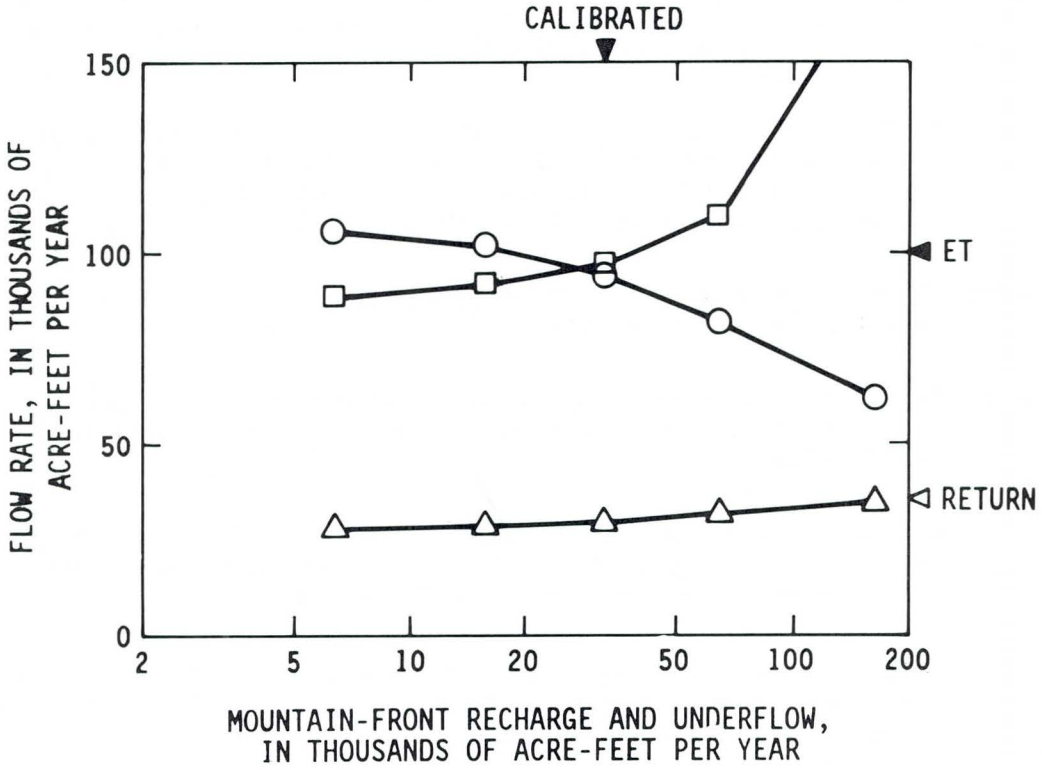
Before 1870, flow was perennial in the Gila River. The median annual flow at the Buttes was estimated to be 525 cubic feet per second or 380,000 acre-feet per year. Ground water was 10 to 70 feet below the land surface in most of the reservation because infiltration from the river maintained water levels at shallow depths. In the western third of the reservation, where the cross section for ground-water flow is constricted, water returned to the surface to form large marshy areas. This return flow continued long after most surface inflow to the system was cut off due to diversions for irrigation, but it gradually decreased to zero as the upper part of the aquifer was drained.

Simulated ground-water flow for the predevelopment period indicates that average recharge of the aquifer by infiltration of Gila River water was 94,000 acre-feet per year. Evapotranspiration from ground water by phreatophytes was about 96,000 acre-feet per year, and return flow in the western third of the reservation was 29,000 acre-feet per year.

SELECTED REFERENCES

Anderson, T.W., 1968, Electrical-analog analysis of ground-water depletion in central Arizona: U.S. Geological Survey Water-Supply Paper 1860, 21 p.

_____1976, Evapotranspiration losses from flood-plain areas in central Arizona: U.S. Geological Survey Open-File Report 76-864, 91 p.



EXPLANATION

○——○	SIMULATED RECHARGE TO THE AQUIFER BY INFILTRATION FROM THE GILA RIVER BETWEEN THE EAST EDGE OF THE MODEL AND PIMA BUTTE
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□——□	SIMULATED EVAPOTRANSPIRATION
◀ET	INITIAL ESTIMATE OF EVAPOTRANSPIRATION
◁RETURN	INITIAL ESTIMATE OF RETURN FLOW TO THE GILA AND SANTA CRUZ RIVERS WEST OF PIMA BUTTE

Figure 12--Sensitivity of water-budget components to variations in mountain-front recharge and underflow.

Babcock, H.M., 1970, Ground-water conditions in the Gila River Indian Reservation, Pinal and Maricopa Counties, Arizona: U.S. Geological Survey open-file report, 14 p.

Babcock, H.M., and Halpenny, L.C., 1942, Records of wells, well logs, water analyses, and map showing locations of wells in the Queen Creek area, Maricopa and Pinal Counties, Arizona: U.S. Geological Survey open-file report, 41 p.

Bancroft, H.H., 1889, History of Arizona and New Mexico 1530-1888: The History Co., San Francisco, 829 p.

Bentall, Ray, 1963, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 243-341.

Brown, D.E., Carmony, N.B., and Turner, R.M., 1981, Drainage map of Arizona showing perennial streams and some important wetlands: Arizona Game and Fish Department map, scale 1:1,000,000.

Cooley, M.E., 1973, Map showing distribution and estimated thickness of alluvial deposits in the Phoenix area, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-845-C, 1 sheet.

Culler, R.C., Hanson, R.L., Myrick, R.M., Turner, R.M., and Kipple, F.P., 1982, Evapotranspiration before and after clearing phreatophytes, Gila River flood plain, Graham County, Arizona: U.S. Geological Survey Professional Paper 655-P, 67 p.

Davis, A.P., 1897a, Irrigation near Phoenix, Arizona: U.S. Geological Survey Water-Supply and Irrigation Paper No. 2, 98 p.

_____1897b, Report on the irrigation investigation for the benefit of the Pima and other Indians on the Gila River Indian Reservation, Arizona: Senate Doc. No. 27, Fifty-fourth Congress, second session, 1897, 56 p.

Ezell, P.H., 1963, Is there a Hohokam-Pima culture continuum?: American Antiquity, vol. 29, no. 1, p. 61-66.

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill, 534 p.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, p. 69-174.

Freethey, G.W., and Anderson, T.W., 1986, Predevelopment hydrologic conditions in the alluvial basins of Arizona and adjacent parts of California and New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA-664, 3 sheets, scale 1:500,000.

Freethey, G.W., Pool, D.R., Anderson, T.W., and Tucci, Patrick, 1986, Description and generalized distribution of aquifer materials in the alluvial basins of Arizona and adjacent parts of California and New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA-663, 4 sheets, scale 1:500,000.

Fritts, H.C., 1976, Tree rings and climate: London, Academic Press, 567 p.

Fritts, H.C., Lofgren, G.R., and Gordon, G.A., 1979, Variations in climate since 1602 as reconstructed from tree rings: Quaternary Research, v. 12, p. 18-46.

Gatewood, J.S., Robinson, T.W., Colby, B.R., Hem, J.D., and Halpenny, L.C., 1950, Use of water by bottom-land vegetation in lower Safford Valley, Arizona: U.S. Geological Survey Water-Supply Paper 1103, 210 p.

Hardt, W.F., and Cattany, R.E., 1965, Description and analysis of the geohydrologic system in western Pinal County, Arizona: U.S. Geological Survey open-file report, 92 p.

Hardt, W.F., Cattany, R.E., and Kister, L.R., 1964, Basic ground-water data for western Pinal County, Arizona: Arizona State Land Department Water Resources Report 18, 56 p.

Haury, E.W., 1976, The Hohokam—Desert farmers and craftsmen: Tucson, Arizona, University of Arizona Press, 412 p.

Judd, B.I., Laughlin, J.M., Guenther, H.R., and Handegarde, B., 1971, The lethal decline of mesquite on the Casa Grande National Monument: Great Basin Naturalist, v. 31, no. 3, p. 153-159.

Kister, L.R., and Hardt, W.F., 1966, Salinity of the ground water in western Pinal County, Arizona: U.S. Geological Survey Water-Supply Paper 1819-E, 21 p.

Konieczki, A.D., and English, C.S., 1979, Map showing ground-water conditions in the lower Santa Cruz area, Pinal, Pima, and Maricopa Counties, Arizona—1977: U.S. Geological Survey Water-Resources Investigations 79-56, 4 sheets.

Laney, R.L., and Hahn, M.E., 1986, Hydrogeology of the eastern part of the Salt River Valley area, Maricopa and Pinal Counties, Arizona: U.S. Geological Survey Water-Resources Investigations 86-4147, 4 sheets.

Laney, R.L., Ross, P.P., and Littin, G.R., 1978, Maps showing ground-water conditions in the eastern part of the Salt River Valley area, Maricopa and Pinal Counties, Arizona—1976: U.S. Geological Survey Water-Resources Investigations 78-61, 2 sheets.

Langbein, W.B., and Iseri, K.T., 1960, General introduction and hydrologic definitions: U.S. Geological Survey Water-Supply Paper 1541-A, 29 p.

Lee, W.T., 1904, The underground waters of Gila Valley, Arizona: U.S. Geological Survey Water-Supply and Irrigation Paper 104, 71 p.

_____1905, Underground waters of the Salt River Valley, Arizona: U.S. Geological Survey Water-Supply and Irrigation Paper 136, 196 p.

Lippincott, J.B., 1900, Storage of water on Gila River, Arizona: U.S. Geological Survey Water-Supply and Irrigation Paper 33, 98 p.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms—revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Olberg, C.R., 1915, Unpublished report on the water supply and the estimated cost of the proposed San Carlos irrigation project on the Gila River, Arizona: U.S. Indian Irrigation Service, Department of the Interior, Los Angeles, California, 224 p.

_____1919, Report on the San Carlos Irrigation Project: Indians of the U.S., Hearing before the Committee on Indian Affairs, House of Representatives, 66th Congress, 1st session, v. 2, Appendix A, p. 1-102.

Robinson, T.W., 1965, Introduction, spread, and areal extent of saltcedar (Tamarix) in the western states: U.S. Geological Survey Professional Paper 491-A, 12 p.

_____1970, Evapotranspiration by woody phreatophytes in the Humboldt River Valley near Winnemucca, Nevada: U.S. Geological Survey Professional Paper 491-D, 41 p.

Rott, E.H., Jr., 1936, Report on the geology and water resources of the Gila River Indian Reservation: U.S. Department of Agriculture, Soil Conservation Service unpublished report, 91 p.

SAS Institute, 1982, SAS User's guide—Basics, 1982 edition: Cary, N.C., SAS Institute, Inc., 584 p.

Sellers, W.D., 1965, Physical climatology: The University of Chicago Press, Chicago and London, 272 p.

Sellers, W.D., and Hill, R.H., 1974, Arizona climate 1931-1972: Tucson, Arizona, University of Arizona Press, 616 p.

Skinner, W.W., 1903, The underground waters of Arizona—their character and uses: Tucson, Arizona, University of Arizona Agriculture Experiment Station Bulletin 46, p. 273-287.

Smith, G.E., 1940, The groundwater supply of the Eloy district in Pinal County, Arizona: University of Arizona, College of Agriculture, Agricultural Experiment Station, 41 p.

Smith, L., 1981, Long-term streamflow histories of the Salt and Verde Rivers, Arizona—as reconstructed from tree rings: University of Arizona, Laboratory of Tree-Ring Research, Report for U.S. Army Corps of Engineers Contract DACW-09-80-C-0071, 129 p.

Smith, L., and Stockton, C.W., 1981, Reconstructed streamflow for the Salt and Verde Rivers from tree-ring data: Water Resources Bulletin, v. 17, no. 6, p. 939-947.

Southworth, C.L., 1919, The history of irrigation along the Gila River: Indians of the U.S., Hearing before the Committee on Indian Affairs, House of Representatives, 66th Congress, 1st session, v. 2, Appendix A, p. 103-291.

Stockton, C.W., 1971, The feasibility of augmenting hydrologic records using tree-ring data: University of Arizona, unpublished Ph.D. dissertation, 172 p.

_____1975, Long-term streamflow records reconstructed from tree rings: Tucson, Arizona, University of Arizona Press, Laboratory of Tree-Ring Research Paper 5, 111 p.

Thomsen, B.W., and Baldys, S., III, 1985, Ground-water conditions in the Gila River Indian Reservation, south-central Arizona: U.S. Geological Survey Water-Resources Investigations 85-4073, 2 sheets, scale 1:250,000.

Trescott, C., Pinder, G.F., and Larson, S., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

Turner, R.M., 1974, Quantitative and historical evidence of vegetation changes along the upper Gila River, Arizona: U.S. Geological Survey Professional Paper 655-H, 20 p.

Turner, S.F., and others, 1943, Ground-water resources of the Santa Cruz basin, Arizona: U.S. Geological Survey open-file report, 84 p.

U.S. Bureau of Reclamation, 1977, Geology and ground-water resources report, Maricopa and Pinal Counties, Arizona: U.S. Bureau of Reclamation duplicated report, 105 p. Appendix.

U.S. Department of Commerce, 1968, Climatic atlas of the United States: Environmental Science Services Administration, U.S. Department of Commerce, Washington, D.C., 80 p.

U.S. Geological Survey, 1941, Surface water supply of the United States, 1941, Part 9, Colorado River Basin: U.S. Geological Survey Water-Supply Paper 929, 311 p.

_____1983, Annual summary of ground-water conditions in Arizona, spring 1981 to spring 1982: U.S. Geological Survey Open-File Report 82-1009, 1 sheet.

U.S. Senate, 1890, Irrigation and reclamation of arid lands: Report of the special Committee of the U.S. Senate, 51st Congress, 1st session, v. 6, Washington, Government Printing Office, 573 p.

U.S. Soil Conservation Service, 1936, Woodland type map, Gila River Indian Reservation, Arizona: U.S. Department of Agriculture, Soil Conservation Service map, 1 sheet, scale 1:62,500.

van Hylckama, T.E.A., 1974, Water use by saltcedar as measured by the water budget method: U.S. Geological Survey Professional Paper 491-E, 30 p.

Walton, W.C., and Prickett, T.A., 1963, Hydrogeologic electric analog computers: Journal of the Hydraulics Division, American Society of Civil Engineers, v. 89, No. HY6, p. 67-91.

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Base from U.S. Geological Survey 1:250,000
Ajo, 1953-69; Mesa, 1954-69; Phoenix,
1954-69; and Tucson, 1956-69

5 0 5 10 MILES
5 0 5 10 KILOMETERS

TOPOGRAPHIC CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Geology from M.E. Cooley (1973)

EXPLANATION

BLOCKS—Each block includes 0.5 to 6 square miles of the aquifer and is represented in the model by a node at the center of the block. The model simulates the movement of water between blocks. Inflow and outflow processes simulated are:

Constant flux—Water entering the model area at a constant rate as underflow from adjacent basins or as recharge along mountain fronts

Constant head—Water entering or leaving the model area at a sufficient rate to maintain a constant water level along the Salt River and at the north end of Sierra Estrella

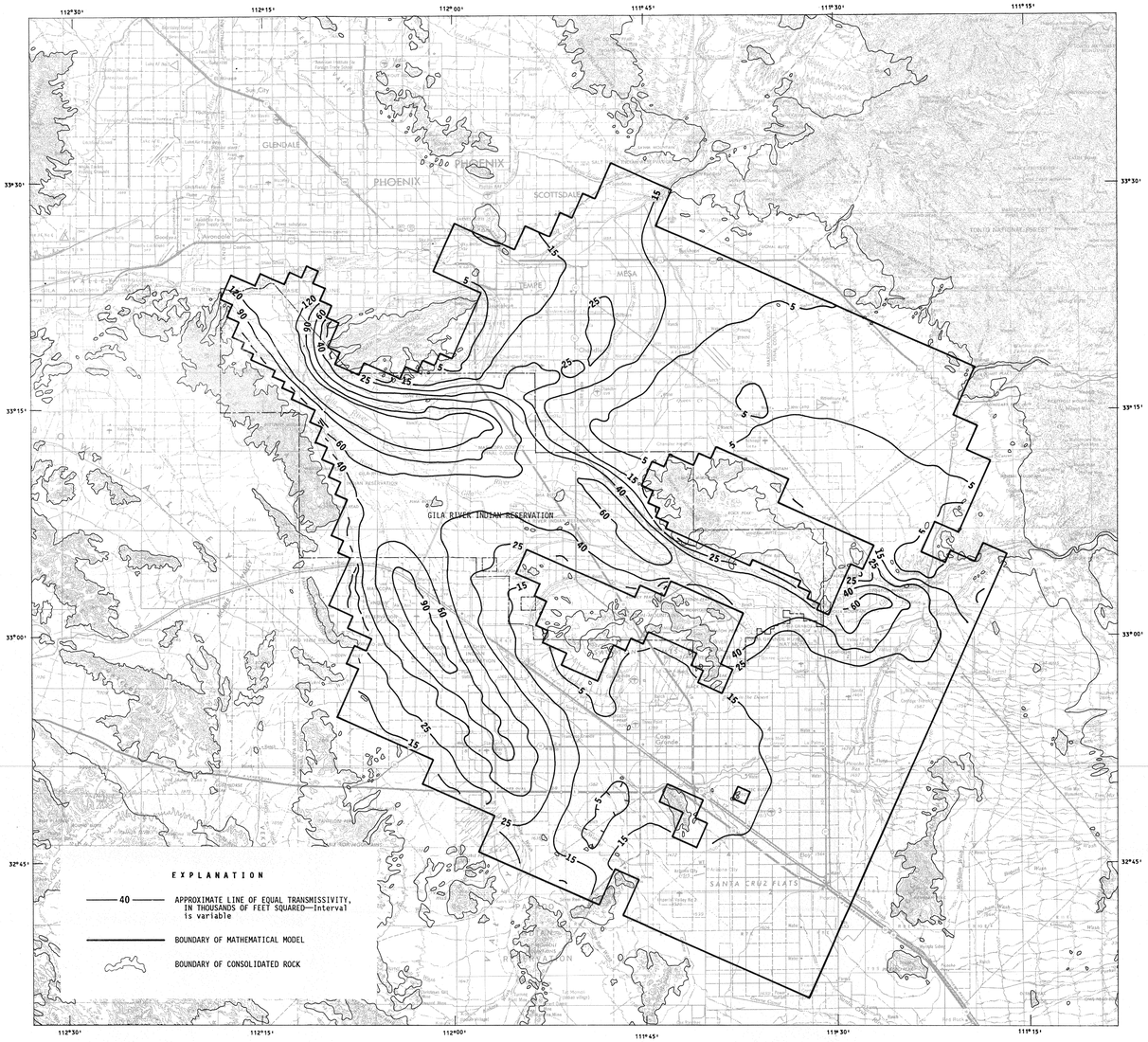
Evapotranspiration—Water leaving the water table by evaporation or by transpiration of plants

Streambed leakage—Water entering or leaving the aquifer along the channels of the Gila and Santa Cruz Rivers

BOUNDARY OF MATHEMATICAL MODEL—Simulated ground-water flow across boundary is zero

BOUNDARY OF CONSOLIDATED ROCK

FINITE-DIFFERENCE GRID AND BOUNDARY CONDITIONS USED IN THE MATHEMATICAL MODEL, GILA RIVER INDIAN RESERVATION



Base from U.S. Geological Survey 1:250,000
A)o, 1953-69; Mesa, 1954-69; Phoenix,
1954-69; and Tucson, 1956-69

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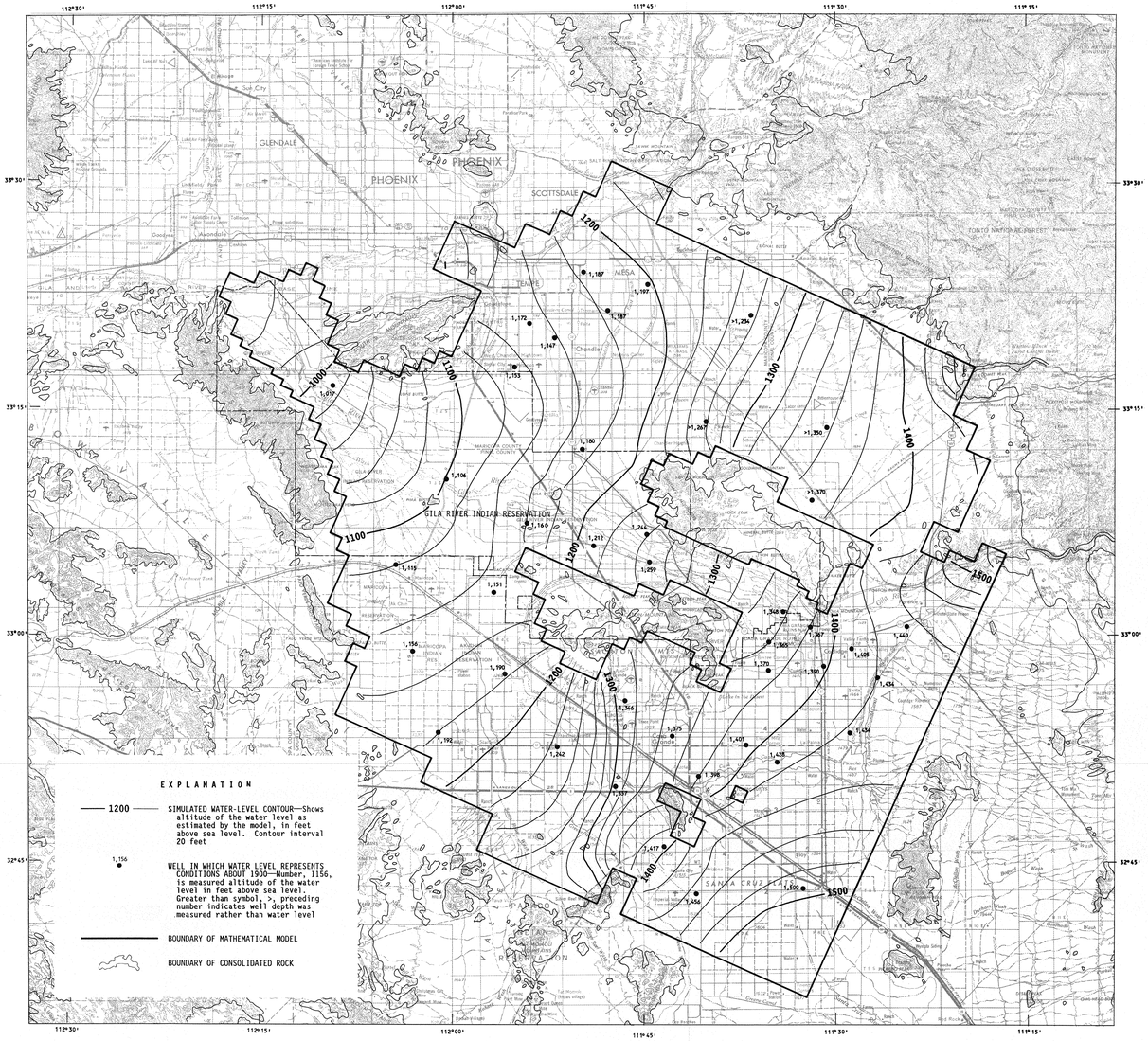
TOPOGRAPHIC CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

CALIBRATED TRANSMISSIVITY



Base from U.S. Geological Survey 1:250,000
A)o, 1953-69; Mesa, 1954-69; Phoenix,
1954-69; and Tucson, 1956-69

Geology from M.E. Cooley (1973)

5 0 5 10 MILES
5 0 5 10 KILOMETERS

TOPOGRAPHIC CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

B. SIMULATED WATER LEVELS AND MEASURED WATER LEVELS

CALIBRATED TRANSMISSIVITY, SIMULATED WATER LEVELS, AND MEASURED WATER LEVELS, GILA RIVER INDIAN RESERVATION