Electrical-Analog Analysis of the Hydrologic System, Tucson Basin, Southeastern Arizona

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1939-C

Prepared in cooperation with the city of Tucson, the U.S. Bureau of Reclamation, and the University of Arizona

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By T. W. ANDERSON

WATER RESOURCES OF THE TUCSON BASIN

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By T. W. Anderson

ABSTRACT

The water supply for the Tucson basin, Arizona, is derived entirely from ground water. The average annual pumpage for 1962–64 was about 165,000 acre-feet and was greater than the natural rate of ground-water recharge. Water-level declines of as much as 70 feet occurred from spring 1940 to spring 1965 as a result of the overdraft.

An electrical-analog model of the hydrologic system was constructed to provide a tool for determining the possible future effects of ground-water management schemes. Basic data required for the simulation of the hydrologic system in the model included periodic water-level measurements, determinations of transmissibility, and pumpage and recharge values. The model was analyzed using steady-state and storage-depletion techniques. The steady-state analysis served to determine the average annual recharge to the hydrologic system and to verify the pattern of transmissibility. The steady-state analysis indicated that 97,000 acre-feet of water was entering and leaving the ground-water reservoir annually prior to extensive development. The storage-depletion analysis for 1940–64 was made to verify that the model was a valid analog of the hydrologic system and, therefore, could be used for the prediction of future water-level conditions. The storage-depletion analysis indicated areas where some of the basic-data values and (or) the conceptual design of the hydrologic system used in the model were in error. After all the hydrologic variables simulated in the model had been adjusted, the analog model reasonably simulated the historical field data. Based on the assumption that pumpage and recharge would continue at existing rates and locations, the model was then used to predict water-level conditions in spring 1985. The results of the projection indicate a maximum water-level decline of 140 feet for 1940–84. The predicted overall shapes of the cones of depression will remain about the same as in the historical period, except that a large amount of lateral development will take place in all the cones.

INTRODUCTION

The water supply for the Tucson basin in southeastern Arizona (fig. 1) is derived entirely from ground water. From 1962 through

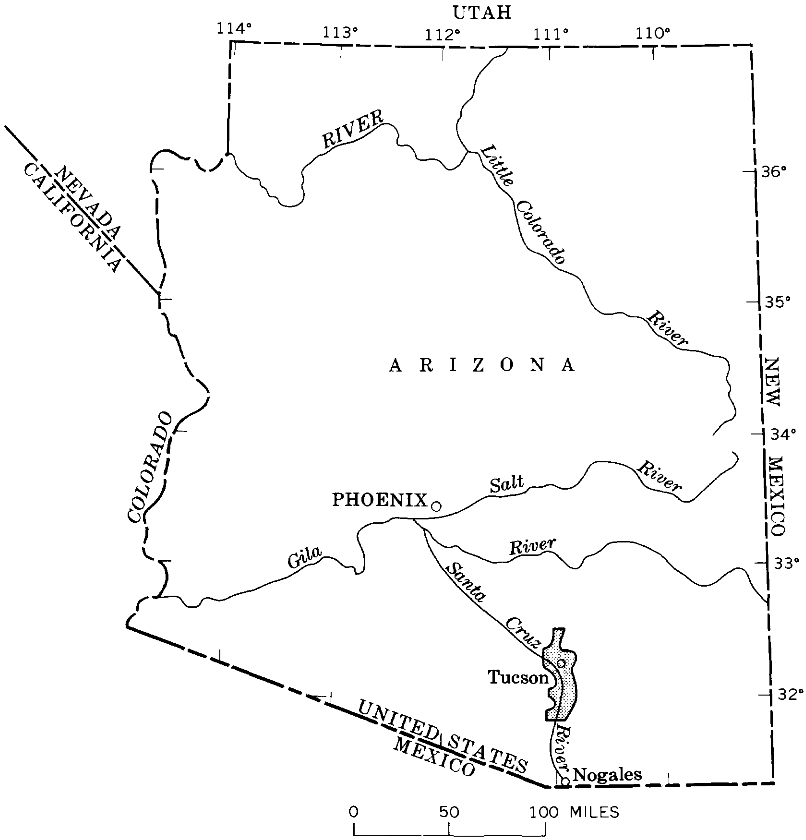


FIGURE 1.—Area of report (shaded).

1964, ground-water pumpage averaged 165,000 acre-feet per year; about 55 percent of the annual pumpage was for agricultural use, 35 percent was for domestic and municipal uses, and 10 percent was for industrial use. More than 3 million acre-feet of water was pumped from the ground-water reservoir from 1940 through 1964. A large part of the water was withdrawn from storage and was not replenished through natural recharge; water-level declines of as much as 70 feet resulted. Ground-water withdrawal for agricultural and municipal uses caused three major cones of depression to form in the Tucson basin: (1) in the southern part of the basin along the Santa Cruz River, (2) in the metropolitan Tucson area, and (3) near the confluence of the Santa Cruz River and Rillito Creek, northwest of Tucson.

The water-level declines in the Tucson basin have caused concern regarding the potential life of the ground-water reservoir and the possible effects of management practices on the system. This report is the third chapter in a series of water-supply papers that describe the water resources in the Tucson basin. The investigation was conducted by the U.S. Geological Survey in cooperation with the city of Tucson, the U.S. Bureau of Reclamation, and the University of Arizona and was under the immediate supervision of H. M. Babcock, district chief of the Water Resources Division of the U.S. Geological Survey in Arizona.

PURPOSE AND SCOPE OF INVESTIGATION

The purpose of this investigation was to compile the quantitative data necessary to construct and analyze an electrical-analog model that would accurately simulate the hydrologic system in the Tucson basin. The historical data used in the construction of the model included periodic water-level measurements, determinations of transmissibility, and pumpage and recharge values.

The model electrically duplicated the historical data and simulated the water-level conditions in 1940, when the hydrologic system was in approximate equilibrium. Changes in pumpage and recharge then were added to the model, and the water-level changes from spring 1940 to spring 1965 were duplicated. Once the analogy between the hydrologic and electrical systems had been confirmed, it was possible to predict the water-level conditions in 1985. The predicted water levels are based on the assumption that the model analogy will be valid until 1985 and that the rate and distribution of pumping and recharge will remain constant. Future uses of the model may include analyses of the effects of different water-management schemes on the hydrologic system.

LOCATION AND GEOLOGIC SETTING

The Tucson basin is a gently sloping plain that covers about 750 square miles in Pima County in southern Arizona. The basin is bounded by a nearly continuous ring of mountains. The Sierrita Mountains, Black Mountain, and the Tucson Mountains border the basin on the west, and the Tortolita, Santa Catalina, Tanque Verde, Rincon, Empire, and Santa Rita Mountains border the basin on the north and east.

The modeled area is about equal in extent to the area of the aquifer in the basin and is defined by the approximate boundary of the aquifer and by four arbitrarily selected boundaries across which the aquifer is continuous (pl. 1). The arbitrary boundary at the south end of the basin is the Pima–Santa Cruz County line and the north-south line between Rs. 11 and 12 E. that extends from the county line to the south side of the Sierrita Mountains. Although the aquifer continues beyond this boundary, the boundary was selected for use in the model because it is the line beyond which the water-level changes have been minor since 1940. Both surface water and ground water enter the basin at this boundary. The arbitrary boundary near the base of Black Mountain is the approximate ground-water divide between the Tucson basin and Avra Valley to the west. Subsurface flow does not enter the basin along this boundary. The arbitrary boundary at Rillito is a point of constriction of the aquifer because of the hard-rock barriers on both sides and is the area of all surface- and ground-water outflow from the Tucson basin. The arbitrary boundary in the valley of Canada del Oro is along the Pima-Pinal County line. The electrical-analog modeled area is about 50 miles long and is 11 miles wide at the south end, about 20 miles wide in the center, and only 4 miles wide at the outflow area near Rillito, at the northwest end of the basin.

The Tucson basin is drained by the Santa Cruz River, which flows northwestward to the Gila River. The principal tributaries to the Santa Cruz are Canada del Oro, Rillito Creek, and Pantano Wash, which drain the east side of the basin.

The principal aquifer in the basin consists mainly of semiconsolidated gravel to clay and is from a few hundred to several thousand feet thick (Davidson, 1968). The flood plains of the main streams are as much as 1 mile wide and are underlain by 40 to 100 feet of unconsolidated sand and gravel.

HYDROLOGIC SYSTEM

The ultimate source of all water in the Tucson basin is the precipitation at the higher altitudes in the Santa Cruz River basin. Ground water is stored in and transmitted through the alluvial material that underlies the Tucson basin. Ground-water movement generally is from south to north along the central part of the basin and from the edges of the basin toward the center. Water enters the ground-water reservoir by infiltration from streamflow, by underflow from adjacent ground-water basins, and by infiltration from runoff near the mountain fronts. Recharge to the ground-water reservoir from direct precipitation on the valley floor is considered negligible because of the great depth to water in most of the area and because of the large evaporation potential. Some water is returned to the ground-water reservoir by infiltration of irrigation return flow and sewage effluent that is diverted to the Santa Cruz River. Ground water leaves the basin as a result of pumping, underflow, and evapotranspiration.

The hydrologic system in the basin prior to about 1940 is considered to have been in approximate equilibrium—inflow was equal to outflow. Some of the water that previously would have been lost through evapotranspiration was being pumped for domestic and agricultural uses, but not enough was being pumped to significantly alter water levels. After 1940, pumping steadily increased, and water levels began to decline significantly. The results were a further elimination of evapotranspiration losses that had occurred in the areas of shallow ground water and an apparent increase in the amount of streamflow losses due to the large volume of unsaturated alluvium available to store the streamflow losses. Both results represented a net gain to the ground-water system.

The withdrawal of ground water from storage resulted in water-level declines in most of the basin. In spring 1965, water levels along the Santa Cruz River and Rillito Creek were 25 to 100 feet below the land surface. In the central part of the basin the depth to water ranged from 100 to 250 feet below the land surface, and southeastward, near the base of the Santa Rita Mountains, the depth to water was more than 500 feet.

METHODS OF ANALYSIS

Quantitative basic data—such as water-level altitudes and changes, aquifer characteristics, and the amount and distribution of pumpage and recharge—are essential to developing an overall concept of the hydrologic system. Once the actual system is defined quantitatively, the data can be converted to equivalent electrical units for the construction of an electrical-analog model.

The analog model is based on the analogy between the flow of electrical current and the laminar flow of fluids through a porous media. The theory and the instrumentation have been described in detail by Brown (1962), Skibitzke (1960), and many other workers in the field of electrical-analog models. The basic components of the electrical-analog model are resistors and capacitors, which are wired into a continuous network that simulates the ground-water system. Values of transmissibility of the aquifer materials are used to construct the resistor network in the electrical-analog model. A resistor impedes the flow of electrical current in a manner similar to the way aquifer material impedes the flow of ground water. The value of the resistor is inversely proportional to the transmissibility. Ground-water storage in the pore spaces of the aquifer material is simulated by capacitors that store an analogous electrical charge. Capacitor values are directly proportional to the storage coefficient of a finite volume of aquifer material.

The stress imposed on the aquifer system by pumping is simulated electrically by the withdrawal of electrical current, so the actual amount and distribution of pumpage must be known. The change in voltage that occurs on the model as a result of the current withdrawal is analogous to the change in water levels that occurs when ground water is pumped. Current in the model is equivalent to the volume rate of flow in the ground-water system; changes in water-level altitude or head in the actual system are equivalent to changes in voltage in the electrical model. Recharge is simulated in a manner similar to that of pumpage, except that electrical current is introduced into the model at the appropriate points.

The analogous units of the hydrologic and electrical systems are:

Hydrologic system	*Electrical system*
Potential, in feet of head	Potential, in volts.
Volume of water, in gallons	Electrical charge, in coulombs.
Volume rate of flow, in gallons per day	Electrical current, in amperes.
Time, in years	Time, in seconds.
Length, in miles	Length, in inches.
Transmissibility, in gallons per day per foot	Electrical resistance, in ohms.
Storage coefficient	Electrical capacitance, in farads.

A steady-state analysis was made of the electrical-analog model in which the hydrologic regimen was simulated for the equilibrium period. Inflow and outflow were imposed on the model, and the potential distribution was measured on the resistor network. Data were obtained from the model by reading the voltage at selected points on the network and then converting the voltage to water-level altitude. A storage-depletion analysis was made in which pumpage, simulated by current withdrawal, and recharge, simulated by current inflow, were imposed on the model, and the resulting change in voltage was compared with the measured water-level declines. The shape of the time–voltage change curve, shown on the oscilloscope screen, should be equivalent to the water-level hydrograph for a corresponding place and period of time in the hydrologic system. These comparisons provide a method for verifying the analogy between the electrical network and the hydrologic system.

QUANTITATIVE MODEL INPUT DATA

The electrical-analog model of the Tucson basin was built to incorporate and simulate known quantitative hydrologic data for the period 1940–1964. The data were used to define the physical characteristics of the aquifer system, the historical development and utilization of the ground-water supply, and the effects of this development on regional water-level conditions.

Transmissibility data were determined from about 240 aquifer tests conducted by the Agricultural Engineering Department of the University of Arizona. The results of each test were plotted on a map, and contour lines were drawn to determine the regional pattern of transmissibility. In areas where no data were available, the pattern was assumed or estimated from specific-capacity and exploratory-drill-hole data. The transmissibility map provided the basis for the construction of an electrical-resistor network analogous to the aquifer system.

The hydrologic system in the Tucson basin was assumed to have been in approximate equilibrium in 1940, which was about the last point in time when the average inflow equaled the average outflow. The water-level conditions in 1940 were simulated using the electrical-potential distribution by a trial and error method of balancing inflow-outflow conditions. Inflow to the system was through underflow at the arbitrary boundaries, recharge along the periphery of the basin, and infiltration of streamflow, and outflow was through pumping, underflow out of the basin, and evapotranspiration. The inflow-outflow data were necessary to simulate the water budget of the Tucson basin under equilibrium conditions. In order to duplicate changes in conditions between 1940 and 1965, quantitative data on changes, with time, of the amount and distribution of pumpage, recharge, and water-level declines were needed; values for the storage coefficients of the aquifer material also were required. Because some of the elements of the flow system needed for the steady-state and storage-depletion analyses were not known, the general approach was one of trial and error to balance the system by varying the unknowns and leaving the known quantities fixed.

TRANSMISSIBILITY

Transmissibility is the ability of the aquifer to transmit water from areas of recharge to areas of discharge. The regional transmissibility pattern was used to construct the electrical-resistor network. The coefficient of transmissibility is defined as the rate of flow of water, in gallons per day, through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent (Ferris and others, 1962, p. 72–73). Transmissibility can be determined from aquifer tests, in which the rate of water-level drawdown caused by a known pumping rate is measured in the pumped well or a nearby well; it can also be determined by measuring the rate of water-level recovery after pumping stops.

Relative transmissibility is estimated from specific-capacity data. Specific capacity is the discharge of a well divided by the drawdown caused by pumping and is expressed in gallons per minute per foot of drawdown. Transmissibility and specific-capacity data from about 240 aquifer tests are shown on plate 2.

Values of specific capacity were available for many wells where aquifer tests could not be made. Generally, specific-capacity data may be used to estimate transmissibility if the wells are developed properly and if they have about the same efficiencies. The specific capacity of a well is dependent not only upon the energy losses associated with the movement of water through the aquifer but also upon the energy losses as the water enters the well. The part of the drawdown caused by energy losses during water entry into wells is not small or uniform in the Tucson basin; therefore, no relation was apparent between the transmissibility and specific-capacity data used in this study. The lack of a good correlation between the transmissibility and specific-capacity data probably was the result of the lack of uniformity in well construction and development techniques and the fact that the wells were being pumped at near maximum capacity. The specific-capacity data for the basin could be used only to indicate relative transmissibility of the aquifer.

The aquifer tests were made on irrigation and municipal wells and, therefore, were concentrated in the areas of greatest ground-water development. At the north end of the Santa Rita Mountains, in the southeastern part of the basin, the transmissibility pattern was estimated on the basis of drill-hole cuttings and core samples obtained from several test holes drilled by the Bureau of Reclamation. Most of the aquifer tests were of short duration—a 3- to 4-hour pumping-drawdown period followed by a similar recovery period. The standard method of analysis was a straight-line semilog plot of drawdown and recovery. The accuracy of the transmissibility values from these tests was dependent on how nearly the field conditions corresponded to the assumed conditions on which the equations used in the analysis were based. Factors influencing the transmissibility values were heterogeneity of the alluvial material in the basin, only partial penetration of the aquifer, delayed drainage, aquifer boundary conditions, and interference caused by pumping of adjacent wells. The accuracy of the aquifer-test data was not as critical in this study as it may be in other types of studies. The values of the resistors used to represent transmissibility in the analog model were based on the average transmissibility determined from aquifer tests, and the overall pattern of transmissibility was generalized.

The thickness of aquifer material represented by the transmissibility value depended on the depth of the well. Also, the material penetrated by wells in the Tucson basin is heterogeneous and ranges from clay to gravel. Thus, the measured transmissibility in any well was considered to be an average value for the material within the radius of influence of the well. The model response, then, is based on the average transmissibility and is accurate only if the heterogeneity of the aquifer does not result in a response appreciably different from that exhibited by a homogeneous aquifer with the same coefficient of transmissibility. In the construction of the model, this average transmissibility was assumed to be valid for the entire period of study. However, because of the heterogeneity of the aquifer material and the dewatering of the upper part of the aquifer by pumping, the transmissibility may decrease with time. Such a decrease would be a limiting factor on the length of time that the model can be used for the extrapolation of data. The model will be a valid analog of the hydrologic system only as long as the resistor network correctly simulates the average transmissibility.

Along the stream channels, where the surface material is coarser and less consolidated than the principal aquifer material, the assumption of uniform transmissibility as a function of time is not true. The values of transmissibility used in the model were for 1963–68, when most of the upper stream deposits were already completely or partially dewatered; this fact will seriously affect the early years of the time-dependent storage-depletion analysis and the steady-state analysis. The transmissibility values and the storage coefficient were higher prior to dewatering the upper part of the aquifer, and, therefore, more water could be transmitted and stored within this zone.

Values of transmissibility from individual aquifer tests ranged from 500,000 to less than 5,000 gallons per day per foot. The generalized pattern used in the construction of the analog model is shown on plate 2. The depths of the wells tested averaged 300 feet in the areas near the streams and about 450 feet in the areas farthest from the streams, where the depth to water is greater.

The approximate boundary of the aquifer (pl. 1) was selected using the locations of low-production wells, the intersection of the water table with low-permeability or hard-rock areas, and the general shape of the water-table contours. The boundary follows the zone where the hydraulic gradient changes markedly and flattens toward the center of the basin.

WATER-LEVEL ALTITUDE AND GROUND-WATER MOVEMENT

In the Tucson basin, ground water generally is under unconfined (water-table) conditions. In a few areas, however, ground water is under semiconfined conditions owing to the heterogeneity of the alluvial material. The degree of confinement and the extent of these areas are not well defined.

In 1940, prior to significant ground-water development, the shape of the water table conformed, in general, to that of the land surface. Ground water moved from south to north, and surface water and ground water left the basin near Rillito. The altitude of the water table ranged from about 3,000 feet above mean sea level at the south end of the basin and at the upper end of Canada del Oro to less than 2,000 feet at the outlet near Rillito. The depth to water was from 0 to more than 500 feet below the land surface.

In general, large-scale development of the ground-water reservoir through spring 1965 did not alter the flow pattern. Some water that had formerly flowed out of the basin was being diverted, and a large volume of water had been removed from storage; however, no reversals in gradients had occurred. As indicated by the general shape of the water-table contour lines shown on plate 3, ground water enters the basin along most of the periphery and flows from the edges toward the central axis of the basin. The only exception is in the area along the base of the Tucson Mountains; there, the contours are nearly perpendicular to the boundary, which indicates that little or no ground water enters in that area.

The 1940 hydraulic-potential distribution (water-level altitude) was used to determine the approximate water budget for the equilibrium period. Inflow was equal to outflow, and the steady-state analog-model analysis electronically duplicated the components of flow and the areal potential distribution.

STREAMFLOW LOSSES AND RECHARGE

The sandy channels of the ephemeral streams in the Tucson basin provide an efficient mechanism by which ground-water recharge takes place during periods of surface-water flow; however, the annual amounts of streamflow and correlative recharge are extremely variable. Burkham (1970) computed the annual streamflow losses in the basin for 1936–63. Burkham's computations represent the upper limit for the amount of ground-water recharge

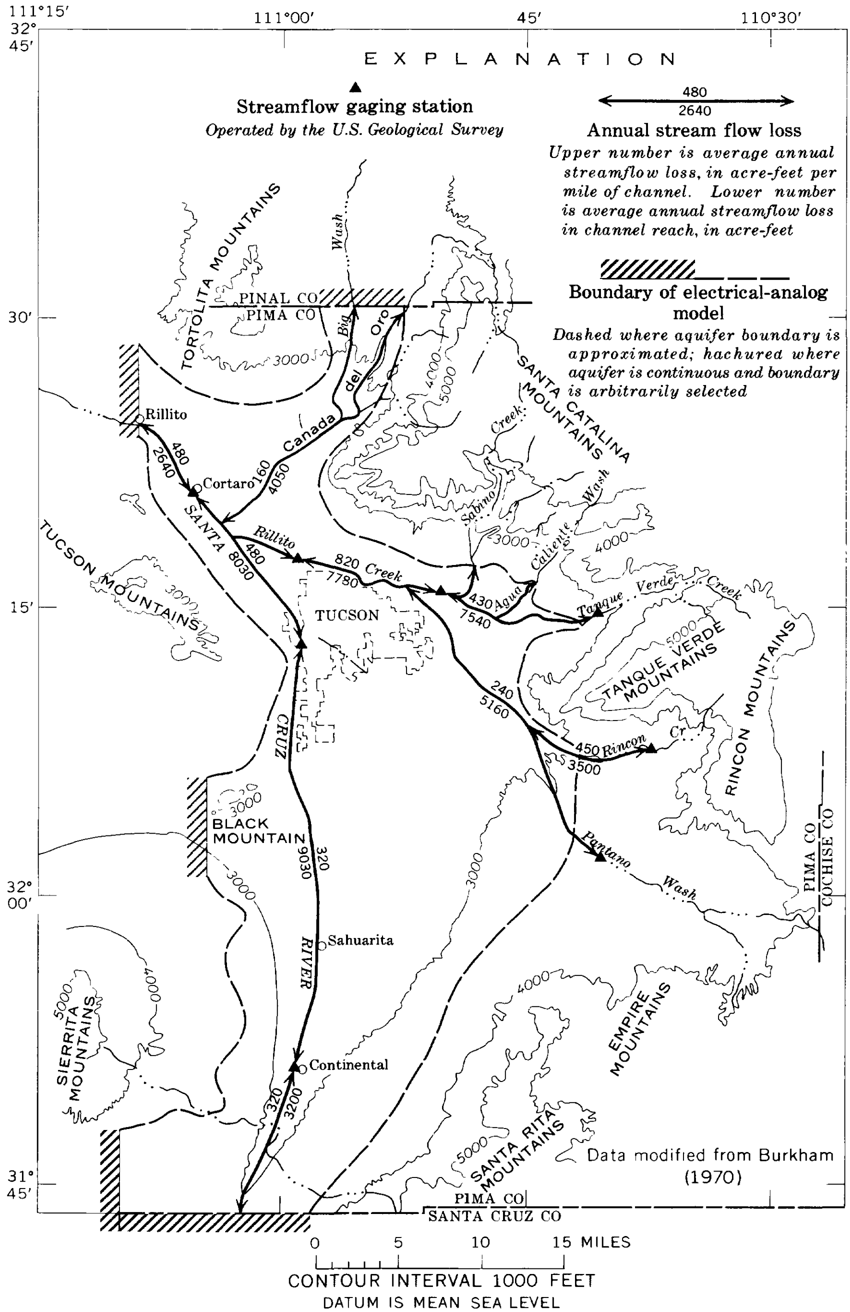


FIGURE 2.—Computed average annual streamflow losses in reaches of the main channels, 1936–63.

from streamflow losses because only part of the water reaches the ground-water reservoir. The rest of the water is lost through evaporation or transpiration shortly after a flow event. The percentage of the streamflow losses that represents water that actually reached the ground-water reservoir was estimated through the trial and error methods used to balance the 1940 water budget.

The average annual streamflow losses for the major drainages in the Tucson basin during 1936–63 are shown in figure 2. The losses range from 160 acre-feet per mile in Canada del Oro to 820 acre-feet per mile in the reach of Rillito and Tanque Verde Creeks upstream from the gaging station on Rillito Creek (fig. 2). The total average annual volume of streamflow losses was about 51,000 acre-feet.

PUMPAGE

More than 3 million acre-feet of water was pumped from the ground-water reservoir in the Tucson basin from 1940 through 1964. From 1962 through 1964, about 55 percent of the annual pumpage was for agricultural use, 35 percent was for municipal and domestic uses, and 10 percent was for industrial use. Much of the water was withdrawn from storage and was not replenished through natural recharge.

Development of the ground-water supply was gradual during the early 1900's, and data on the amount and location of withdrawals in the basin are meager. Some water was diverted from Rillito Creek for irrigation and from the Santa Cruz River for municipal use by the city of Tucson. Municipal use increased gradually—from 846 acre-feet in 1899 to 6,159 acre-feet in 1940—according to records of the city of Tucson. An infiltration gallery in the Santa Cruz River and shallow dug and drilled wells furnished the municipal supply. The ground-water withdrawals did not cause any long-term decline in water levels because streamflow losses that recharged the ground-water reservoir returned the water table to its original position annually.

Municipal and domestic water use in the Tucson basin increased from about 6,200 acre-feet in 1940 to 55,100 acre-feet in 1964 (table 1); the greatest rate of increase was from 1955 to 1960. Industrial water use increased gradually and was about 17,500 acre-feet in 1964, as a result of increased copper-mining activities in the west side of the basin, near the Sierrita Mountains.

Agricultural water use increased from about 41,600 acre-feet in 1940 to 140,700 acre-feet in 1954. Between 1954 and 1964, pumping of ground water for irrigation generally decreased because of the conversion of some agricultural land to urban development and also because of the more efficient use of irrigation water. Prior to 1954, the part of the total pumpage used for irrigation was more than 80 percent, but by 1964 it had decreased to about 55 percent.

In order to duplicate the pumping stress in an electrical-analog-model system, the quantity and areal distribution of ground-water withdrawals had to be known. The areal distribution in time and the quantity of water pumped were fairly well known for uses other than agriculture. The amount of water withdrawn for agricultural use had to be calculated from annual power-consumption records of electric and gas companies, but the areal distribution of pumping could not be determined.

TABLE 1.—*Estimated annual ground-water pumpage in the Tucson basin, 1940–64*

[Numbers rounded to the nearest hundred acre-feet]

Year	Agricultural use	Municipal and domestic use	Industrial use	Total
1940	41,600	6,200	500	48,300
1941	46,900	7,300	700	54,900
1942	69,600	8,800	1,200	79,600
1943	68,900	9,500	1,600	80,000
1944	73,700	11,400	1,900	87,000
1945	70,300	13,900	3,400	87,600
1946	66,300	15,100	4,000	85,400
1947	90,100	17,500	3,700	111,300
1948	83,600	18,600	4,400	106,600
1949	77,600	19,000	4,900	101,500
1950	99,900	20,200	4,900	125,000
1951	118,700	20,300	5,000	144,000
1952	133,200	21,500	5,300	160,000
1953	135,100	22,800	6,100	164,000
1954	140,700	23,100	6,200	170,000
1955	134,600	23,900	6,500	165,000
1956	124,500	28,100	7,400	160,000
1957	110,900	31,800	7,300	150,000
1958	99,200	37,500	7,600	144,300
1959	93,200	40,900	9,600	143,700
1960	74,100	51,200	10,100	135,400
1961	75,700	53,200	13,000	141,900
1962	100,600	54,400	15,800	170,800
1963	93,200	55,500	17,300	164,000
1964	86,500	55,100	17,500	159,100

The general method used to determine annual pumpage for agricultural use involved deriving an average value of power consumption per acre-foot of water pumped. This factor was then used to relate the total power used to the quantity of water pumped. The factor was averaged for large subareas within the Tucson basin and was assumed to be constant throughout each subarea; however, the factor was dependent on pumping lift and on the efficiency of the pumping plants, which were not uniform throughout the subareas. The method was the only available means of determining the total agricultural pumpage within the basin and was reliable only to the extent to which the average power per acre-foot factor was accurate.

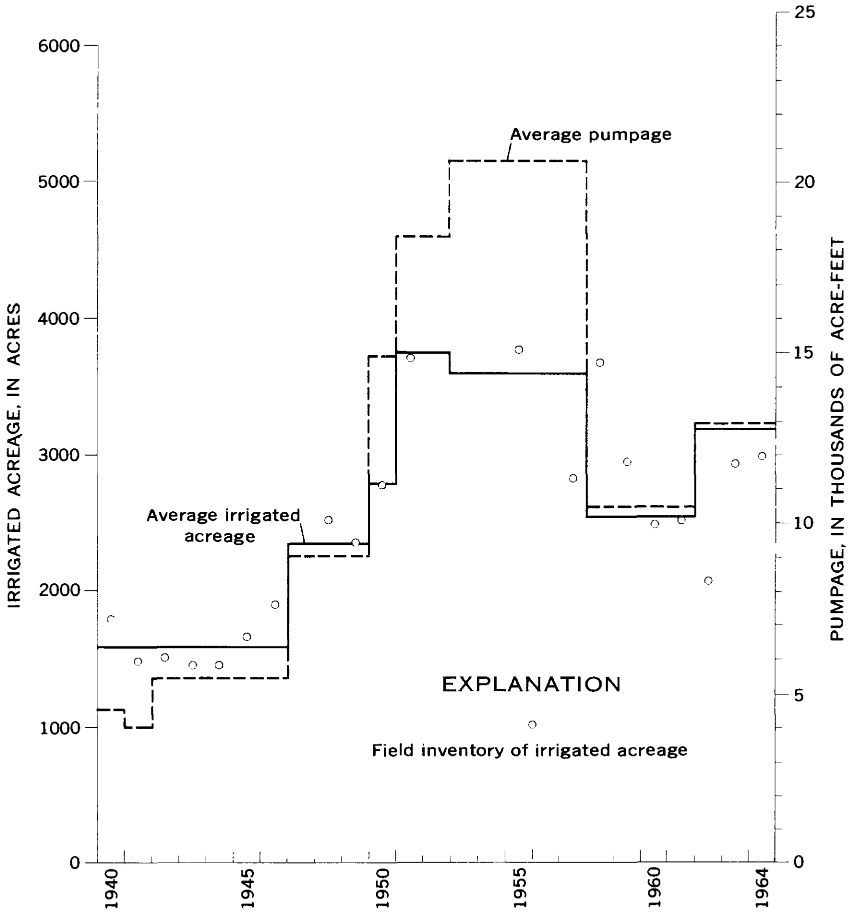


FIGURE 3.—Method used in averaging irrigated acreage and determining pumpage, T. 18 S., R. 13 E.

The determination of the areal distribution of agricultural pumpage was based on the assumption that the pumpage was proportional to the irrigated acreage. Eight time periods were used to simulate the increase or decrease in pumpage with time in each township. The total average irrigated acreage for the basin for each time period was divided into the total average pumpage for the same period to determine the basinwide average water use per acre. The figure was then applied to the irrigated-acreage figure for the individual township to determine the pumpage within that township. Figure 3 shows the method used in averaging irrigated acreage and determining pumpage for one township. The periods used to simulate pumpage in the model were from 1 to 5 years long; the pumping periods—1941, 1942–46, 1947–49, 1950, 1951–52, 1953–57, 1958–61, and 1962–64—were selected on the basis of significant changes in pumpage patterns somewhere within the basin. The general pattern of pumpage development is shown on plate 4, and the average annual pumpage for each township is shown in bar-graph form for 1940–64. For model input, the pumpage by township was further divided into one-square-mile units and was distributed in the township on the basis of known well locations.

The pumpage simulated in the model represented the increase in pumpage since the equilibrium period (1940). The amount of water being pumped in 1940 was not included in the pumpage input to the model because the pumpage in 1940 did not result in any long-term water-level declines. The model output represented the decline in water levels from spring 1940 to spring 1965 that resulted from the increased withdrawal.

WATER-LEVEL DECLINES

From spring 1940 to spring 1965, water-level declines of as much as 70 feet occurred in the Tucson basin (pl. 5). Three major cones of depression developed: (1) in the southern part of the basin, along the Santa Cruz River, (2) in the metropolitan Tucson area, and (3) near the confluence of the Santa Cruz River and Rillito Creek northwest of Tucson. The cones were caused by the withdrawal of ground water from storage at a rate greater than the rate of natural recharge.

The cone of depression in the southern part of the basin, along the Santa Cruz River, formed as a result of ground-water withdrawal for irrigation use and was accentuated later by withdrawal for use by the copper-mining industry. The cone is elongated in a north-south direction and underlies the cultivated area along the river. Water levels declined as much as 70 feet from spring 1940 to spring 1965 in this area. From 1958 through spring 1965, declines of as much as 5 feet per year were common, whereas before 1958 the maximum rate of decline was only about 3 feet per year in the deepest parts of the cone.

The cone of depression in the metropolitan Tucson area, in the north-central part of the basin, formed as a result of the withdrawal of ground water for municipal and domestic use. From spring 1940 to spring 1965, the maximum water-level decline was 64 feet; the rate of decline was as much as 3.5 feet per year in the later part of the period.

The cone of depression near the confluence of the Santa Cruz River and Rillito Creek, northwest of Tucson, probably formed as a result of pumping for irrigation. From spring 1940 to spring 1965 the maximum water-level decline was more than 60 feet. In this area the rate of decline was greatest between 1950 and 1955—about 6 feet per year in places. From 1955 through spring 1965, the maximum rate of decline was about 2 feet per year.

The three cones of depression overlap, and they have affected water levels throughout the basin. The area of least water-level change has been along the base of the Santa Rita Mountains, in the southern half of the basin, where water levels declined only a few feet between 1940 and spring 1965.

STEADY-STATE ANALYSIS

The electrical-analog model of the Tucson basin was constructed using resistors wired together to simulate the shape and transmissibility of the ground-water aquifer on a scale of 1 inch equals half a mile. The techniques used in the construction of the model were similar to those discussed by Robinove (1962). The water budget for the natural inflow to and outflow from the basin was simulated by a steady-state analysis of the analog model. The spring 1940 water levels were assumed to represent those of an equilibrium period; although some ground-water development had taken place by 1940, no long-term water-level changes had resulted. The assumption that the 1940 water levels represented equilibrium conditions in the basin may not have been entirely accurate; however, 1940 was the earliest year for which adequate data were available to construct a water-level contour map. The water-level contours were assumed to represent the long-term average potentiometric surface prior to extensive development, and the derived inflow-outflow quantities were assumed to represent the long-term average of the individual components of the flow system. The averages, then, were assumed to represent a long time period and not to be associated with only 1 year.

A small amount of water-level data is available in the areas where some development had taken place prior to 1940. The withdrawal of ground water from shallow wells and infiltration galleries along the stream courses began about the turn of the century, but the withdrawals caused no permanent change in the water levels because infiltration from surface runoff provided sufficient recharge to return the water levels to their original positions. Large-scale pumping for irrigation began in 1919 in the extreme northwestern part of the basin between Cortaro and Rillito, and from 1919 to 1940 the water level in that area declined an average of about 1.5 feet per year (Schwalen and Shaw, 1957, p. 76). Although the hydrologic system there obviously was not in exact equilibrium in 1940, the extent of the area affected by the water-level decline was only about 3 percent of the entire basin. A comparison of Smith's (1910) 1908 water levels with those for 1940 shows that only small increases and decreases in water-level altitudes occurred elsewhere in the basin, mainly along the stream courses. Therefore, the 1940 water levels were assumed to be a reasonable representation of equilibrium conditions.

Electrical current scaled to the amount of actual ground-water recharge was added and adjusted at the appropriate locations in the model until the model-derived potentiometric surface closely simulated the 1940 water-level conditions. Electrical current simulating underflow into the Tucson basin from adjacent ground-water basins was added at the southern boundary of the model (at the Pima–Santa Cruz County line and the north-south range line) and at the upstream end of the model (at the Pima-Pinal County line) (fig. 4). Recharge from sources other than underflow was also simulated by the addition of current to the model system. Current was added along the stream courses to simulate recharge from infiltration of streamflow and along the mountain fronts to simulate recharge from direct underflow through joints and other openings in the rocks of the mountains and to simulate recharge from infiltration of the flow in the many small washes that drain the mountains. Outflow from the basin was simulated in the model by current-controlling resistors; the current flow through the resistors repesenting outflow was in the opposite direction from that of inflow. Some current was withdrawn from the model to simulate consumptive water use through evapotranspiration and pumping in the basin. The rest of the outflow was modeled as ground-water underflow leaving the basin near Rillito. The values derived by this procedure were assumed to represent the approximate amounts of inflow to and outflow from the basin under equilibrium conditions; the amount of streamflow that infiltrated to the aquifer and was lost through evaporation or transpiration in a short time was not included in the values. These evaporation and transpiration losses occurred along the stream courses where the water levels were at or within a few feet of the land surface in equilibrium time.

The shape of the water-level contours for spring 1940 (pl. 3) shows that, in addition to the underflow entering the basin at the arbitrary boundaries, recharge was entering the ground-water reservoir along the mountain fronts and along the major streams. Although the actual amounts were unknown, approximations were made by adding current to the model in one small area at a time and determining the reaction within the electrical system. The amount

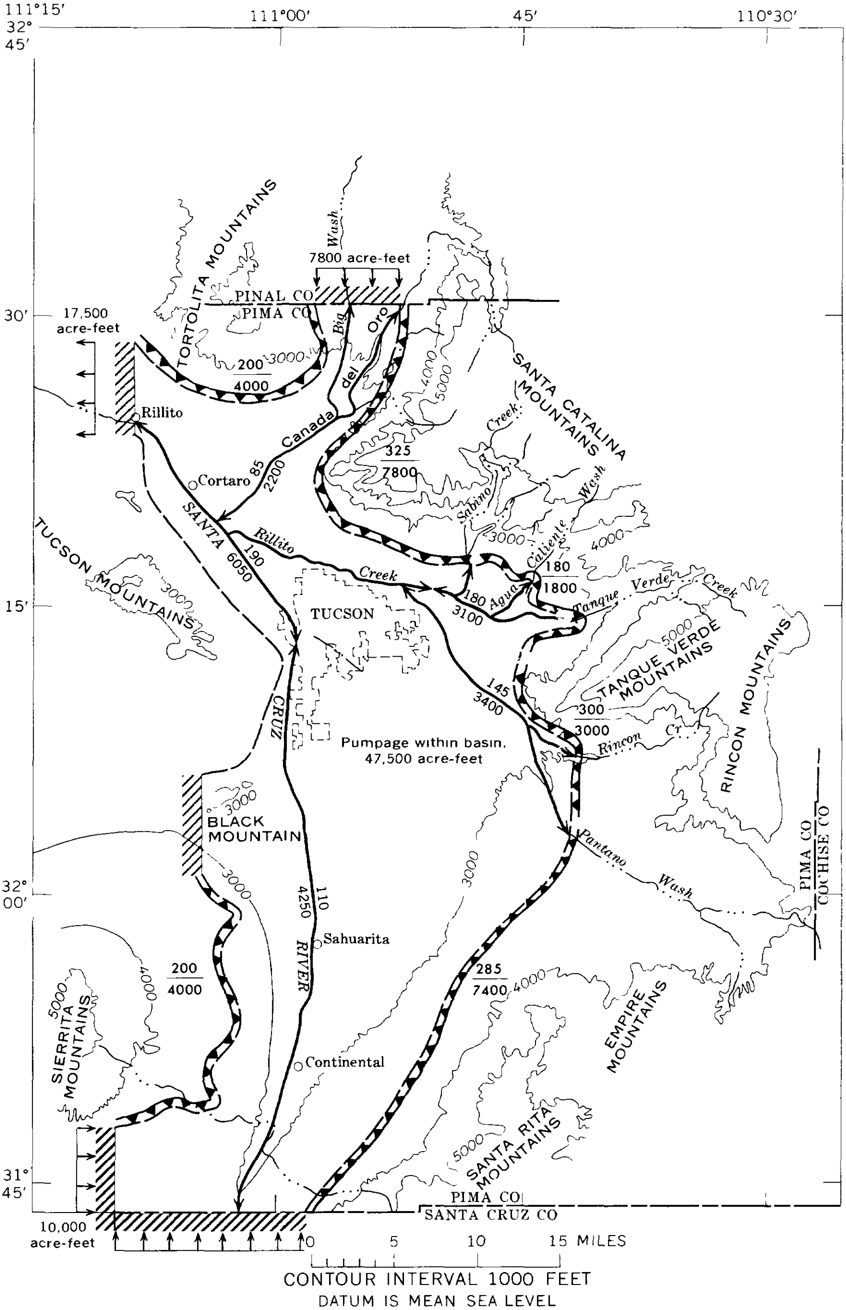


FIGURE 4.—Results of the steady-state analysis, 1940 inflow-outflow conditions.

EXPLANATION

7800 acre-feet

Annual underflow entering and leaving basin

$\frac{325}{7800}$

Annual recharge along mountain fronts

Upper number is annual recharge rate, in acre-feet per mile. Lower number is total annual recharge, in acre-feet

$\frac{180}{3100}$

Annual recharge along streams

Upper number is average annual recharge, in acre-feet per mile of channel. Lower number is total average annual recharge in channel reach, in acre-feet

Boundary of electrical-analog model

Dashed where aquifer boundary is approximated; hachured where aquifer is continuous and boundary is arbitrarily selected

Explanations of symbols in figure 4.

of recharge entering the basin was then determined by measuring the amount of current flow when the model potential distribution best matched the shape of the 1940 ground-water surface (pl. 3). The initial step in determining these quantities was to establish the total gradient through the system by inducing current representing underflow into and out of the model at the appropriate locations. Next the recharge along the mountains was simulated in the model to produce the general shape of the regional water-level contours. Then the recharge along the streams was simulated to bring the water-level altitude to the appropriate value.

The quantities of current flow needed to simulate water levels along the mountain fronts indicated that the recharge ranged from 0 to 325 acre-feet per year per mile of mountain front (fig. 4). The highest recharge rate was along the base of the Santa Catalina Mountains; the recharge rate in the west side of the basin along the base of the Tucson Mountains was so low that current did not have to be added to the model in this area. The model indicated that the amount of inflow along the mountain fronts was 28,000 acre-feet per year.

Recharge from infiltration of streamflow also was established through trial and error techniques. The average annual volume of streamflow losses—51,000 acre-feet—for 1936–63 was assumed to represent the upper limit of recharge during the equilibrium period. In order to model the recharge from streamflow, the stream channels were divided into five reaches: (1) Canada del Oro and Big Wash within the boundaries of the model, (2) the Santa Cruz River from Tucson to Rillito and Rillito Creek from its mouth to near the confluence of Tanque Verde Creek and Pantano Wash, (3) Tanque Verde Creek and Sabino and Agua Caliente Creeks within the model boundaries, (4) Pantano Wash and Rincon Creek, and (5) the Santa Cruz River from Tucson upstream to the model boundary.

The reaches were similar to those used by Burkham (1970) in computing streamflow losses in the basin, except that some were combined. The recharge necessary for the model-derived data to best match the actual 1940 water levels ranged from 33 to 54 percent of the computed mean annual streamflow losses. The recharge simulated in the model for the different reaches ranged from 85 to 190 acre-feet per year per mile of channel. The total recharge from streamflow losses was about 19,000 acre-feet per year, or about 37 percent of the total average annual losses, which represents only the volume of ground water that was required to replace the withdrawals for consumptive use. In places along the streams the depth to water was 5 to 10 feet below the land surface in 1940, so evapotranspiration of ground water was continuous. Part of the streamflow losses circulated within a cycle of infiltration through evapotranspiration and could not be measured in either the hydrologic or the analog systems.

The measured and model-simulated water-level altitudes for 1940 (pl. 3) matched about as well as could be expected. In some areas slight errors in the transmissive characteristics of the aquifer or in the flow quantities affected the differences in location of the water-level contours; however, the reasonable match between measured and model-simulated data indicated that the pattern of transmissibility was reasonably accurate—a fact that had to be determined before a storage-depletion analysis could be made. The pattern of transmissibility was used in the storage-depletion analysis, and any lack of correspondence between the measured and model-simulated data could be attributed to other causes.

The steady-state analysis indicated that about 97,000 acre-feet of water was entering the basin annually. The amount of inflow required to satisfy the potential distribution, however, was only about 65,000 acre-feet per year. Recharge along the mountain fronts was about 28,000 acre-feet per year, and the amount of recharge from infiltration along the stream channels was about 19,000 acre-feet per year. Underflow into the basin was about 18,000 acre-feet per year; about 10,000 acre-feet entered the basin at the south end, and about 8,000 acre-feet entered at Canada del Oro. Thus, about 32,000 acre-feet of the water entering the basin under steady-state conditions was unaccounted for; this amount represented the difference between the estimated average annual streamflow losses (51,000 acre-feet) and the amount of recharge from streamflow losses (19,000 acre-feet) required in the model. The reason the large volume of streamflow losses was not required in the electrical-analog system is related to the difference in the actual and modeled transmissibility and coefficient of storage values along the streams.

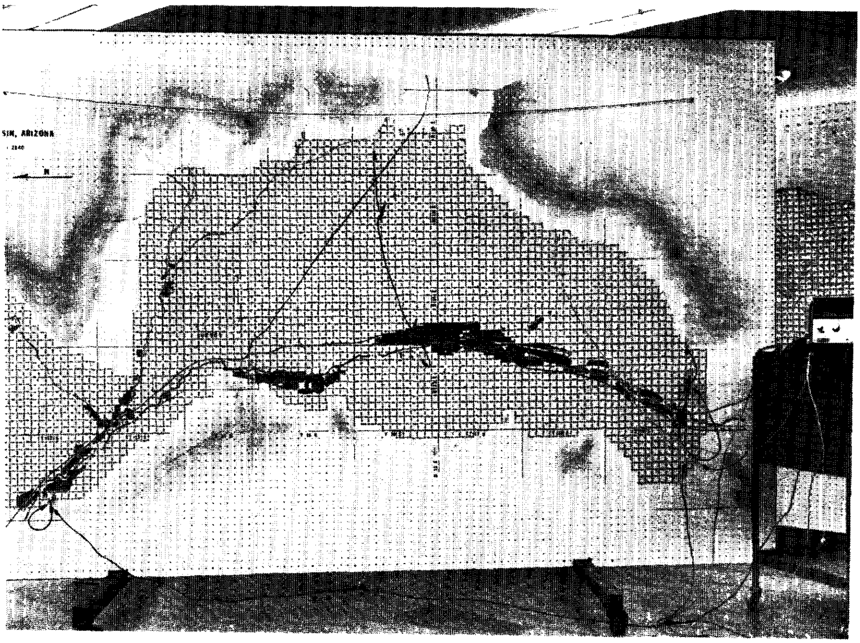
At the time the transmissibility values were determined, the stream alluvium had been completely or partially dewatered, and, as a result, the values used in the model were not indicative of the capability of the aquifer to transmit and store water prior to the development of the ground-water system.

As measured in the analog system, outflow from the basin was about 65,000 acre-feet per year prior to ground-water development; this amount did not include the amount of streamflow losses that were not accounted for in the recharge to the ground-water reservoir. The steady-state analysis indicated that about 17,500 acre-feet of water was leaving the basin annually as underflow at Rillito, and 47,500 acre-feet was being pumped. In the early 1900's a volume of water equivalent to this discharge by pumping may have been leaving the system through runoff and evapotranspiration; after the early 1900's, the discharge was gradually converted to man's use.

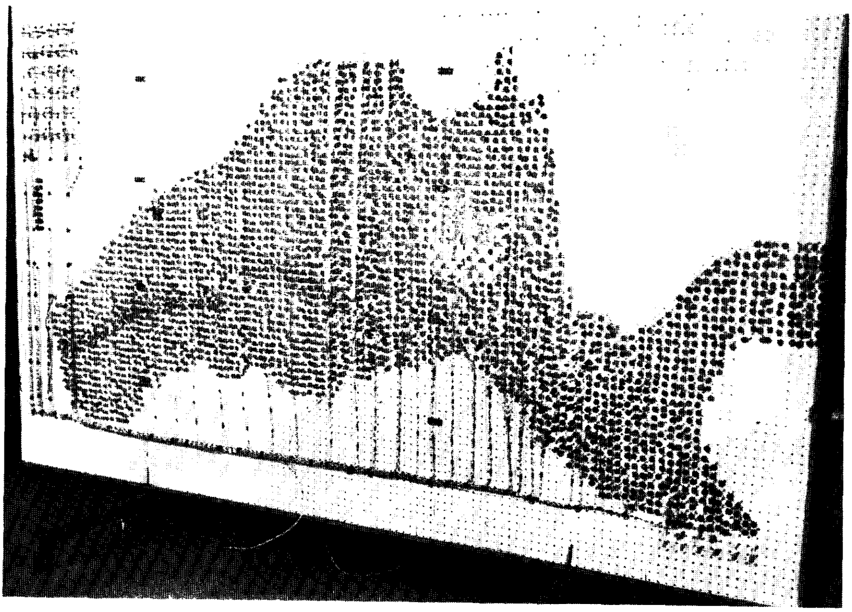
The amounts of inflow and outflow given do not include all the losses or gains that may have occurred within the system on a short-term basis. The 32,000 acre-feet of water unaccounted for in streamflow losses must be included in order to obtain the absolute value of flow into and out of the system in an average year under equilibrium conditions. This discrepancy was caused either by modeling inaccuracies or by water being evaporated soon after flow events and thus being lost as recharge to the ground-water reservoir. The amount of inflow to the ground-water reservoir was estimated by adding the approximate amount of streamflow losses not included in the model—32,000 acre-feet per year—to the measured inflow-outflow volume of about 65,000 acre-feet, which then gave a total annual volume of inflow and outflow of about 97,000 acre-feet.

STORAGE-DEPLETION ANALYSIS

The effects of large long-term withdrawals of ground water on the regional water levels were simulated by a storage-depletion or transient analysis of the electrical-analog model. The storage-depletion analysis served to verify the analogy between the electrical and hydrologic systems throughout the period of development, 1940–64. Using the measured field data, the cause-and-effect relation between discharge or recharge and ground-water storage depletion was determined for the hydrologic system; after the model was adjusted so that it was analogous to the hydrologic system throughout the historical period of development, it was assumed to be a valid electrical analog of the future hydrologic conditions. The model can be used to evaluate different future management schemes of withdrawal and (or) recharge and the effects of these schemes on the ground-water regimen.



A



B

FIGURE 5.—Electrical-analog model. *A*, Front view. *B*, Back view.

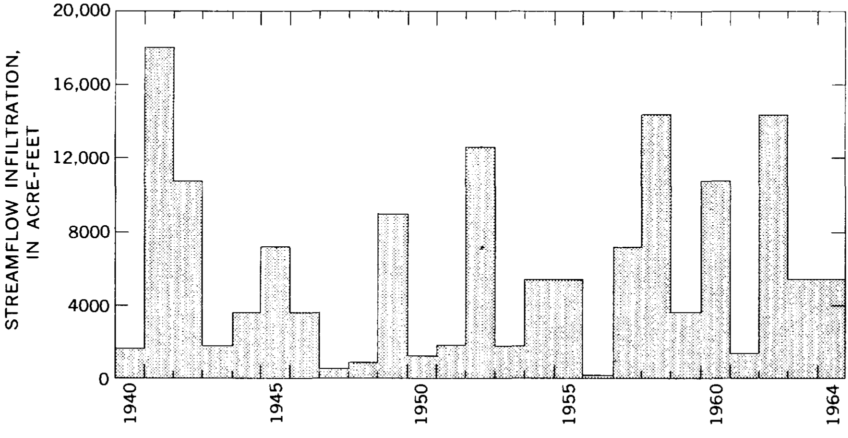
After verification of the transmissibility pattern in the steady-state analysis, the resistor network was complemented by capacitors to simulate storage in the aquifer (fig. 5). The capacitors were added on the back of the model at 1-inch intervals to represent the storage in the aquifer within quarter-square-mile areas.

The storage coefficient of an aquifer was defined by Ferris, Knowles, Brown, and Stallman (1962, p. 74) as the volume of water the aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The storage coefficient for the aquifer material in the Tucson basin could not be determined from available data and, therefore, was estimated. In the first tests of the model a storage coefficient of 15 percent was assumed for the entire area on the basis of storage coefficients determined for nearby basins.

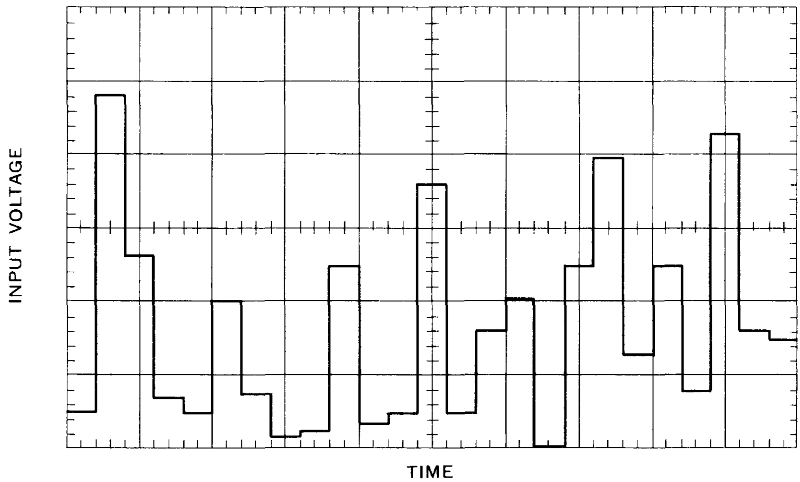
In the storage-depletion analysis, pumping was simulated electrically by the withdrawal of current from the model at rates proportional to the generalized changes in pumping rates computed for the basin. The time-pumpage relation was a generalized square-wave, steplike function having time intervals that corresponded to those used in determining pumpage distribution (fig. 3). The average annual rate of ground-water withdrawal for each township for each time period was converted to an equivalent electrical current, and the amount of electrical current withdrawn was controlled by resistors at each center of pumping. At any one point on the model, the pumping history from 1940 through 1964 was represented by as many as eight resistors, each of which controlled the quantity of current withdrawn for one time interval.

The amount of recharge from the infiltration of streamflow also changes with time because it is a function of runoff, which is extremely variable. Recharge from infiltration was simulated in the analog model on an annual basis. Figure 6 shows Burkham's (1970) computed and model-simulated annual infiltration in the reach from the mouth of Canada del Oro upstream to the boundary of the electrical-analog modeled area. The streamflow-loss rate was assumed to be the same in the entire reach. Burkham's computed annual streamflow losses represent the upper limit for the amount of ground-water recharge from streamflow. Recharge along the mountain fronts was assumed to be constant as a function of time; therefore, it was not considered in the storage-depletion analysis.

Water-level-change maps, which represent the change in static water level since spring 1940, were used to verify the analogy between the electrical and hydrologic systems. Four check periods—1940–46, 1940–52, 1940–57, and 1940–64—were used to verify the temporal continuity of the analogy between the systems.



A. COMPUTED



B. SIMULATED

FIGURE 6.—Computed and simulated annual infiltration from the mouth of Canada del Oro upstream to the boundary of the electrical-analog modeled area. Computed data from Burkham (1970).

The analysis of storage depletion was approached by trial and error because the input functions—such as pumpage, recharge, and storage coefficient—were based on estimates. Pumpage data were probably the least accurate of the data used to design and analyze the analog model. When discrepancies occurred between the model-derived and measured water-level declines, the differences were attributed to pumpage. Although the storage-coefficient and recharge inputs also could account for errors, the pumpage distribution was adjusted first in order to determine the magnitude of the required change in pumpage; if a change in pumpage of the required magnitude was not logical, then the storage coefficient was altered for areas where recharge was insignificant. In areas where recharge was significant, such as along the stream courses, this input function was assumed to be the second least accurate, and adjustments were made accordingly.

ADJUSTMENTS IN PUMPAGE

The stresses on the electrical system were added separately; pumpage was the only stress put on the system in the first test, which indicated those areas where the pumpage pattern was seriously in error. Initially, only the general shape of the model-derived water-level contour lines was adjusted to correspond with that of the measured water levels. The exact magnitude of water-level decline—a function of pumpage, recharge, and storage coefficient—was considered after the pumpage distribution had been better defined. The adjustments in pumpage distribution necessary to produce a reasonable fit generally were caused by small errors in pumpage volume or by improper placement of the pumping point in the model in relation to the actual center of pumping in the basin. The current-withdrawal points used to simulate pumping in the model generally were located in the center of areas representing 1 square mile. In some instances, however, these points did not coincide with the actual centers of pumping in the basin.

Northwest of Tucson between Rillito Creek and the Santa Cruz River, the modeled pumpage resulted in a cone of depression smaller and farther northwest than the actual cone. The pumpage distribution for the model was based on well locations and irrigated acreage and was fairly uniform throughout the area. The shape of the water-level contours determined from field measurements indicated that part of the pumpage assigned to the downstream end of the area should be redistributed in the center of the cone of depression.

Other changes in pumpage distribution were necessary after the general shape of the modeled and field water-level contours were compared. The changes were minor and consisted of moving the current-withdrawal points to the apparent centers of pumping as indicated by the field data.

ADJUSTMENTS IN STORAGE COEFFICIENT

After the pumpage redistribution, the assumed storage coefficient of 15 percent was adjusted by trial and error methods in the one area where the water-level decline indicated by the model was less than that measured in the field. (The opposite condition—modeled decline greater than measured decline—could be affected by recharge as well as possible errors in storage coefficient.) This area was in the cone of depression in the metropolitan Tucson area, where the maximum model-simulated decline from spring 1940 to spring 1965 was 50 feet and the measured decline was 64 feet. The model-simulated decline for each check period was slightly deficient throughout most of the cone, which indicated that there was an error in pumpage, that the storage coefficient was lower than the original estimate of 15 percent, or that possibly some water-level head differential with depth was affecting the water-level data. The most probable source of error was in the pumpage data (Davidson, 1971) ; however, because of the general uniformity of the discrepancy throughout the area and because of the apparent temporal uniformity, the storage coefficient was altered. In order for the model-derived and measured water-level declines to be similar, the storage coefficient had to be changed to 4.5 percent for the 4-square-mile area of secs. 11, 12, 13, and 14, T. 14 S., R. 14 E., and to 7.5 percent for a 1-mile-wide transitional zone surrounding the low area. These adjustments in storage coefficient were the only ones necessary; whether or not the arbitrary model solution was correct will be proven in subsequent years by more accurate pumpage records and water-level measurements.

Altering the pumpage in the area may have given an identical solution. An estimate of the amount by which the pumpage was deficient can be obtained from the average pumpage-population relation for the Tucson urban area (Davidson, 1971). The deficiency necessarily would be assumed to have resulted from underestimation of municipal and domestic pumpage in the problem area. The deficiency indicated by the pumpage-population relation appears to be in the correct order of magnitude for model requirements; if the required amount of pumpage were added, model declines would nearly match the actual declines with no required change in the storage coefficient.

STORAGE-DEPLETION AND RECHARGE RELATION

Recharge—from infiltration along the boundaries of the modeled area, from infiltration of streamflow along stream courses, from infiltration of sewage effluent released to the stream channel, from irrigation return flow, and from salvaged or recaptured evapotranspiration losses—was the last element of the hydrologic system to be programed into the analog model. The recharge input was the element having the greatest temporal variability.

Infiltration along the boundaries of the modeled area was assumed to be uniform with time, which simplified the model analysis—if there was no change in recharge, no input along the boundary would be required in the model. The assumption of temporal uniformity of infiltration probably is most valid for the areas along the mountain fronts, where the large pulses of infiltrated water in years of large runoff would be damped as the water moved through the aquifer toward the center of the basin. Along the arbitrarily selected boundaries of the area, the assumption is less valid; however, the changes in underflow at the arbitrary boundaries on Canada del Oro and the Santa Cruz River probably are small enough to be considered negligible. The underflow out of the system near Rillito changed from about 17,500 acre-feet in 1940 to about 10,000 acre-feet in 1964. The change was assumed to be a linear function with time.

Infiltration was simulated in the model on an annual basis (fig. 6) to best match the computed infiltration. Initially, 100 percent of the infiltration was used as input to the model; subsequently, 75 percent and 50 percent of the computed annual infiltration were used as model input.

Figure 7 shows the effects of different input volumes on the water level at a point in the electrical system compared with the actual water-level measurements made in a well 4 miles downstream from the Tucson waste-water-treatment plant. The 50-percent input was the best estimate of the amount of infiltration that reached the ground-water reservoir, as can be seen from a comparison of the generalized rates of decline for the different time periods (fig. 7). In some places, however, the rate of decline determined from the model did not match the measured rate of decline for some time periods; for other time periods the match was good. The difference from one time period to another was assumed to be caused by some other factor, such as sewage-effluent recharge, irrigation return flow, or salvaged evapotranspiration losses. Beginning in the early 1950's, the water level in the well near the Tucson waste-water-treatment plant apparently was affected by recharge from water released by the plant to the Santa Cruz River (fig. 7). The releases to the river began in 1951, when the water was no longer diverted for irrigation. Beginning in 1955, some of the plant effluent was sold for irrigation use, and a part of this eventually reached the river, in addition to the direct releases at the treatment plant. The total amount of sewage effluent that reached the river averaged about 7,100 acre-feet per year from 1951 through 1964. The model input consisted of 100 percent of the effluent in the first test. The final test of the model indicated that about 80 percent of the volume that reached the river was required as recharge in the reach downstream from the treatment plant. The large percentage of effluent required as recharge, when

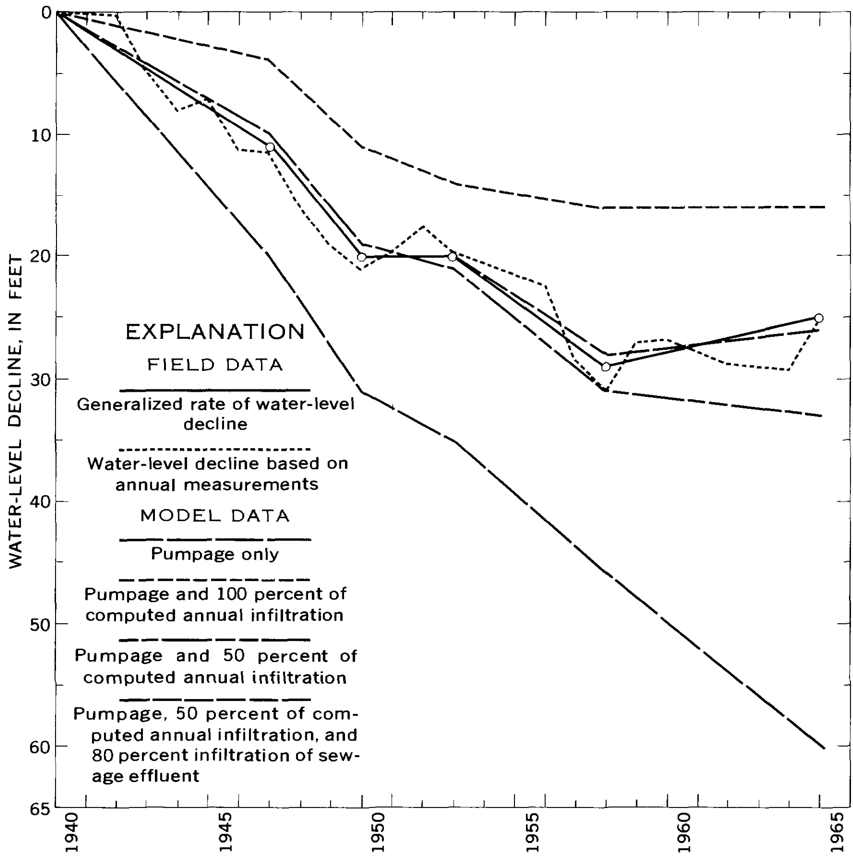


FIGURE 7.—Effects of different model inputs on the measured water level in a well 4 miles downstream from the Tucson waste-water-treatment plant (sec. 1, T. 13 S., R. 12 E.).

compared with the 50 percent of streamflow infiltration required as recharge, may indicate that a constantly wet streambed, a result of daily sewage-plant releases, may provide the most efficient method of ground-water recharge.

In the agricultural area along the Santa Cruz River in the southern part of the basin, the model-derived decline rates were greater than the measured decline rates from 1940–57, which indicated that additional recharge was required in the model. The deficient modeled recharge may have been related to the application of excess irrigation water to the land or to inaccuracies in the estimated amount of pumpage. In order for the model to simulate the actual decline, an increase in recharge equivalent to about 25 percent of the total pumpage was needed. A recharge element was added to the model because there was no basis for altering the pumpage. For the years 1958–64, the recharge-pumpage ratio had to be decreased to produce a match of the modeled and measured declines. The decrease in the amount of recharge required may have been related to more efficient use of irrigation water or to more accurate pumpage records.

The water-level decline and the total drawdown simulated by the model were much greater than the measured declines in two other areas—in an area extending about 8 miles along the Santa Cruz River downstream to Tucson and along a 10-mile reach of Rillito Creek extending 8 to 18 miles upstream from the mouth. In these areas several factors may have caused all or any part of the difference between the measured and modeled data. For example, the storage coefficient used in the model may have been too small; instead of 15 percent, the storage coefficient in these areas may be as much as 25 or 30 percent. Data from several aquifer tests made near the stream channels indicate the possible existence of a partial recharging boundary condition whose existence would substantiate this theory. Another factor is the decrease in evapotranspiration losses since 1940. In the early 1900's the streams were perennial in these reaches, but since that time the areas have undergone a modification in the type of riparian vegetation (Turner and others, 1943), probably owing to the increasing depth to water. The decrease in evapotranspiration losses has resulted in an apparent increase in recharge, and more water may be available for discharge by pumping. Both the storage-coefficient and evapotranspiration factors would have a similar effect, in that the discharge per unit water-level decline would be greater in these alluvial areas along the stream channels than in areas away from the stream channels; the degree of influence of either factor could not be determined from the available basic data.

The difference between the model-derived and measured water-level declines was corrected by the addition of enough electrical current in the model to satisfy the apparent deficiency in storage or the increased recharge. The addition was accomplished by the use of diodes, which controlled the amount of current input. The diode would conduct current only after a fixed change in voltage (equivalent to water-level decline) had occurred on the analog-resistor network. The quantity of current would change proportionally with any additional change in voltage until the upper limit of the current-conducting capacity of the diode was reached, and then the current input remained constant. Using this method, the input gradually increased as the water level declined. The current required to satisfy this disparity increased to an equivalent of 22,000 acre-feet of water in 1964. The increase was gradual—from 0 in 1940–41, to about 14,000 acre-feet in 1955, to 22,000 acre-feet in 1964.

RESULTS OF ANALYSIS

After the adjustment of all hydrologic factors—transmissibility, storage coefficient, pumpage, and recharge—the model results reasonably simulated the field data. The model-simulated water-level declines for each of the four check periods were in reasonable agreement with the measured water-level declines. The measured and simulated water-level contour lines for the spring 1940 to spring 1965 period (pl. 5) show a reasonable match in shape of contour lines and amount of decline in most of the area. In addition to the water-level contour lines, hydographs of the depth to water in wells, as determined from the model and measured data, were compared to check the water-level trends between the check periods. After the adjustments of the stresses on the electrical system, most of the hydrographs indicated a good match in the general water-level trends for all time periods.

Prior to 1940, about 97,000 acre-feet of water was entering and leaving the ground-water reservoir annually in the Tucson basin. From 1940 through 1964, however, discharge from the basin increased to as much as 190,000 acre-feet per year, and from 1962 through 1964 the average annual discharge from the ground-water reservoir was about 185,000 acre-feet, of which about 165,000 acre-feet per year was withdrawn by pumping, about 10,000 acre-feet per year was lost through evapotranspiration, and about 10,000 acre-feet per year was discharged as underflow from the basin near Rillito. Inflow to the basin from 1940 through 1964 probably ranged from about 70,000 acre-feet in a dry year to about 150,000 acre-feet in a relatively wet year. The result was an annual overdraft, or storage depletion, which for 1958 through 1964 averaged about 90,000 acre-feet per year (fig. 8), as determined from the volume of dewatered sediments. The difference between total outflow and the amount of water removed from storage was about 95,000 acre-feet per year for the period 1962–64 (fig. 8); if the 1964 pumping pattern were maintained, a sustained pumping rate of 95,000 acre-feet per year would result in no further depletion of storage, and if underflow and evapotranspiration losses were fully utilized, the pumping rate could conceivably be increased to 115,000 acre-feet annually without causing further depletion in storage.

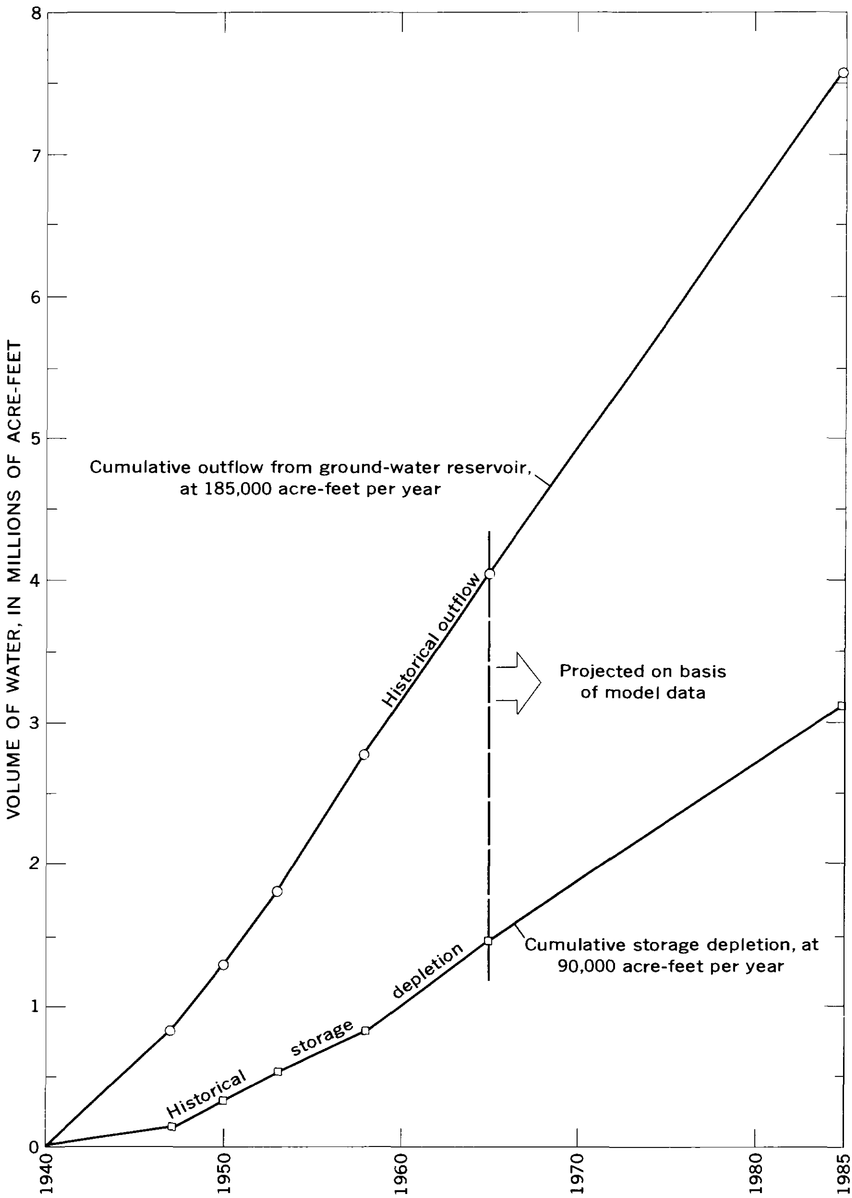


FIGURE 8.—Cumulative outflow from and storage depletion in the ground-water reservoir, 1940–85.

Overall, from 1940 through 1964, more than 3 million acre-feet of water was pumped from the ground-water reservoir. The results of the model analysis indicated that 1.45 million acre-feet, or 46 percent of the total pumpage, was removed from ground-water storage; the remainder was replenished by recharge. For 1962–64, about 54 percent of the pumpage was removed from storage.

MODEL-DERIVED FUTURE WATER-LEVEL DECLINES

Once the analogy between the hydrologic and electrical systems had been verified, predictions of water-level conditions in spring 1985 were made on the basis of an assumed recharge-discharge regimen. The aquifer transmission and storage characteristics were assumed to be constant for the entire period from 1940 through the spring of 1985. The general recharge-discharge functions were assumed to be constant for the period 1965–84 only because no other management program had been proposed at the time (1969).

The pumping pattern used to extrapolate water-level declines to 1985 was based on the 1962–64 pattern, and it was assumed that the amount and areal distribution would remain exactly the same. It was also assumed that 3.3 million acre-feet of ground water would be pumped during the 20-year period from spring 1965 to spring 1985. The projected recharge along the stream channels during the 20-year period was based on the recurrence interval of infiltration for 1940–64. The temporal distribution of infiltration was entirely random, and it was assumed that about 50 percent of the infiltration would become recharge to the ground-water reservoir—the same amount as was determined from the model for the historical period. Recharge from sewage effluent was projected as a constant, although this is not a likely assumption.

In the southern part of the basin, where ground water is pumped for mining and irrigation, the predicted maximum water-level decline for the 45-year period from spring 1940 to spring 1985 is about 140 feet (pl. 6). This represents a maximum decline of 70 feet and an average decline in the deepest parts of the cone of depression of about 65 feet for the 20-year period from spring 1965 to spring 1985. The magnitude of the decline for the 20-year period is about equal to the decline that occurred from 1940 to spring 1965.

The cone of depression in the metropolitan Tucson area and the cone near the confluence of the Santa Cruz River and Rillito Creek northwest of Tucson appear to be merging (pl. 6). The predicted maximum water-level decline in these areas for the period 1940–84 is 95 feet, which is only a 50 percent increase over the 64-foot decline measured in 1940–64; however, the extent of the cones will be much greater by spring 1985. The results of the model prediction indicate that the rates of decline will gradually decrease, perhaps because the cones are expanding laterally and drawing water from a larger area.

SUMMARY

Water levels declined as much as 70 feet in the Tucson basin between spring 1940 and spring 1965 as a result of the pumping of ground water in excess of the natural rate of replenishment. The average annual pumpage for 1962–64 was 165,000 acre-feet, and the average annual ground-water depletion rate for 1958–64, as determined from the volume of dewatered sediments, was 90,000 acre-feet.

An electrical-analog model of the hydrologic system was constructed to provide a hydrologic tool for use in the study of future ground-water management schemes. The model was constructed using all the available hydrologic data. The model was analyzed for the steady-state and storage-depletion phases of the hydrologic system. The steady-state analysis verified the areal transmissibility pattern and provided an estimate of the recharge from the different sources under undisturbed conditions. The results of the steady-state analysis indicated that about 97,000 acre-feet of water per year was entering and leaving the ground-water reservoir prior to extensive development. Total inflow included about 18,000 acre-feet of water per year entering the basin as underflow and about 28,000 acre-feet entering as peripheral recharge. The average annual volume of streamflow losses was about 51,000 acre-feet per year, but only about 19,000 acre-feet was being recharged to the ground-water reservoir; the remaining 32,000 acre-feet was being lost and had no long-term effect on the system. Total outflow included about 17,500 acre-feet per year of underflow out of the basin. An unaccounted-for 32,000 acre-feet was being lost, and the remaining 47,500 acre-feet was being pumped for consumptive use within the basin.

The storage-depletion analysis duplicated the historical changes in water levels that had resulted from the increasing withdrawals of ground water and verified the analogy between the electrical and hydrologic systems. The results of the storage-depletion analysis indicated that about 54 percent of the average annual pumpage for 1962–64 was derived from ground-water storage.

The model was used to predict the water-level conditions for spring 1985, based on the assumption that all the elements of the flow system will continue along the same trends as those existing immediately prior to 1964. Results of the extrapolation indicated

that the general shapes of the cones of depression will be about the same in 1985 as in 1965 and that the maximum decline will be about 140 feet for the period 1940–84.

SELECTED REFERENCES

Brown, R. H., 1962, Progress in ground-water studies with the electric-analog model: Am. Water Works Assoc. Jour., v. 54, no. 8, p. 943–956.

Burkham, D. E., 1970, Depletion of streamflow by infiltration in the main channels of the Tucson basin, southeastern Arizona: U.S. Geol. Survey Water-Supply Paper 1939–B, 36 p.

Davidson, E. S., 1968, Water-resources investigation in a semiarid basin in Arizona, U.S.A.: Istanbul, Internat. Assoc. Hydrogeologists Mem., v. 8, p. 552–558.

———1971, Geohydrology and water resources of the Tucson basin, Arizona: U.S. Geol. Survey Water-Supply Paper 1939–E. [In press.]

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

Matlock, W. G., Schwalen, H. C., and Shaw, R. J., 1965, Progress report on study of water in the Santa Cruz Valley, Arizona: Arizona Univ., Agr. Expt. Sta. Rept. 233, 55 p.

Rillito Creek Hydrologic Research Committee of the University of Arizona and the U.S. Geological Survey, 1959, Capturing additional water in the Tucson area: U.S. Geol. Survey open-file report, 59 p.

Robinove, C. J., 1962, Ground-water studies and analog models: U.S. Geol. Survey Circ. 468, 12 p.

Schwalen, H. C., and Shaw, R. J., 1957, Ground-water supplies of the Santa Cruz Valley of southern Arizona between Rillito Station and the international boundary: Arizona Univ., Agr. Expt. Sta. Bull. 288, 119 p.

———1961, Progress report on study of water in the Santa Cruz Valley, Arizona: Arizona Univ., Agr. Expt. Sta. Rept. 205, 39 p.

Skibitzke, H. E., 1960, Electronic computers as an aid to the analysis of hydrologic problems: Gentbrugge, Belgium, Internat. Assoc. Sci. Hydrology, Comm. Subterranean Waters, Pub. 52, p. 347–358.

———1963, The use of analog computers for studies in ground-water hydrology: London, Inst. Water Engineers Jour., v. 17, no. 3, p. 216–230.

Smith, G. E. P., 1910, Groundwater supply and irrigation in the Rillito Valley, Arizona: Arizona Univ., Agr. Expt. Sta. Bull. 64, 244 p.

———1938, The physiography of Arizona valleys and the occurrence of ground water: Arizona Univ., Agr. Expt. Sta. Tech. Bull. 77, 91 p.

Turner, S. F., 1946, Ground water in the Tucson quadrangle, Arizona: U.S. Geol. Survey open-file report, 15 p.

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

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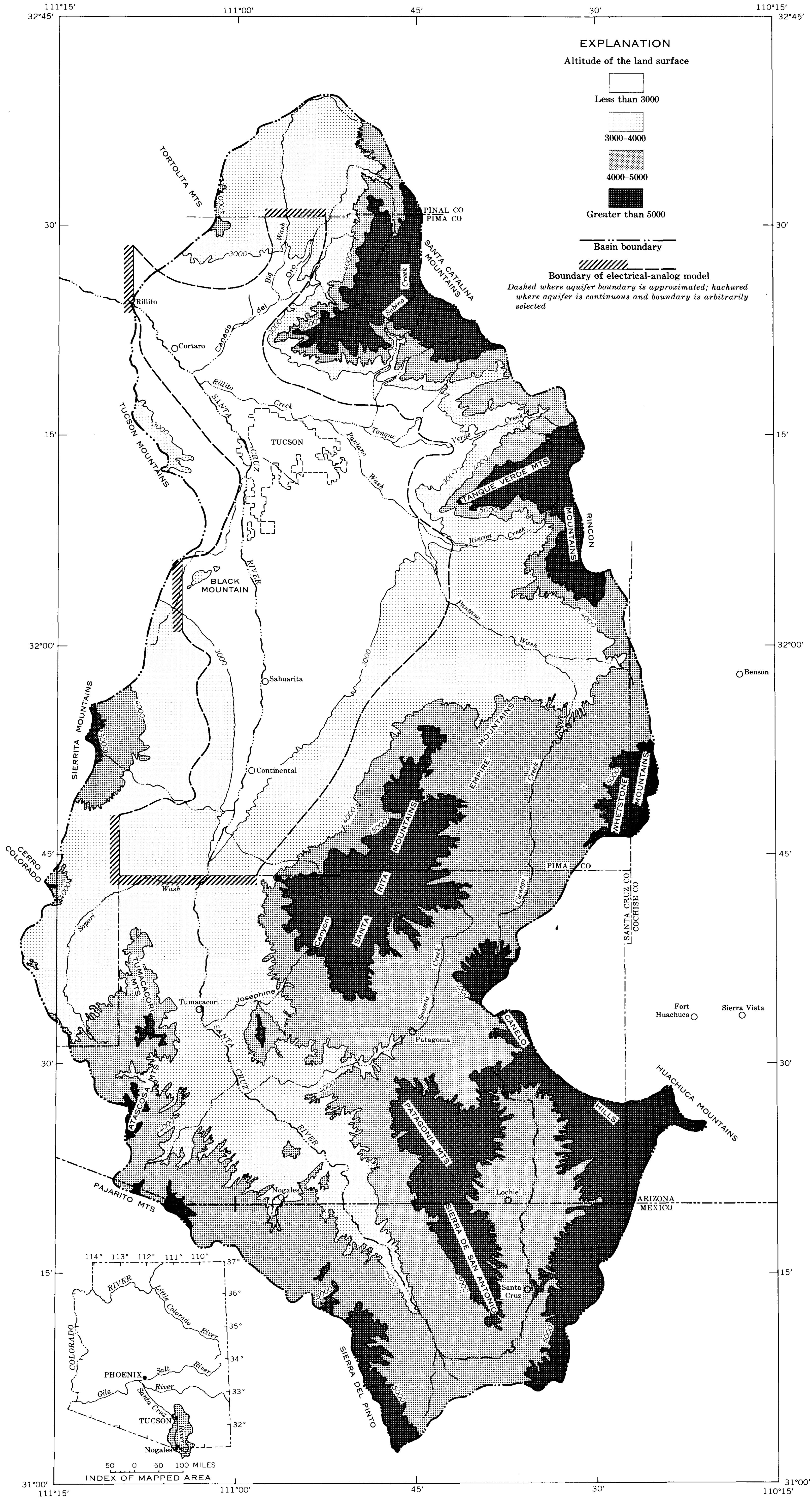


Base from U.S. Geological Survey

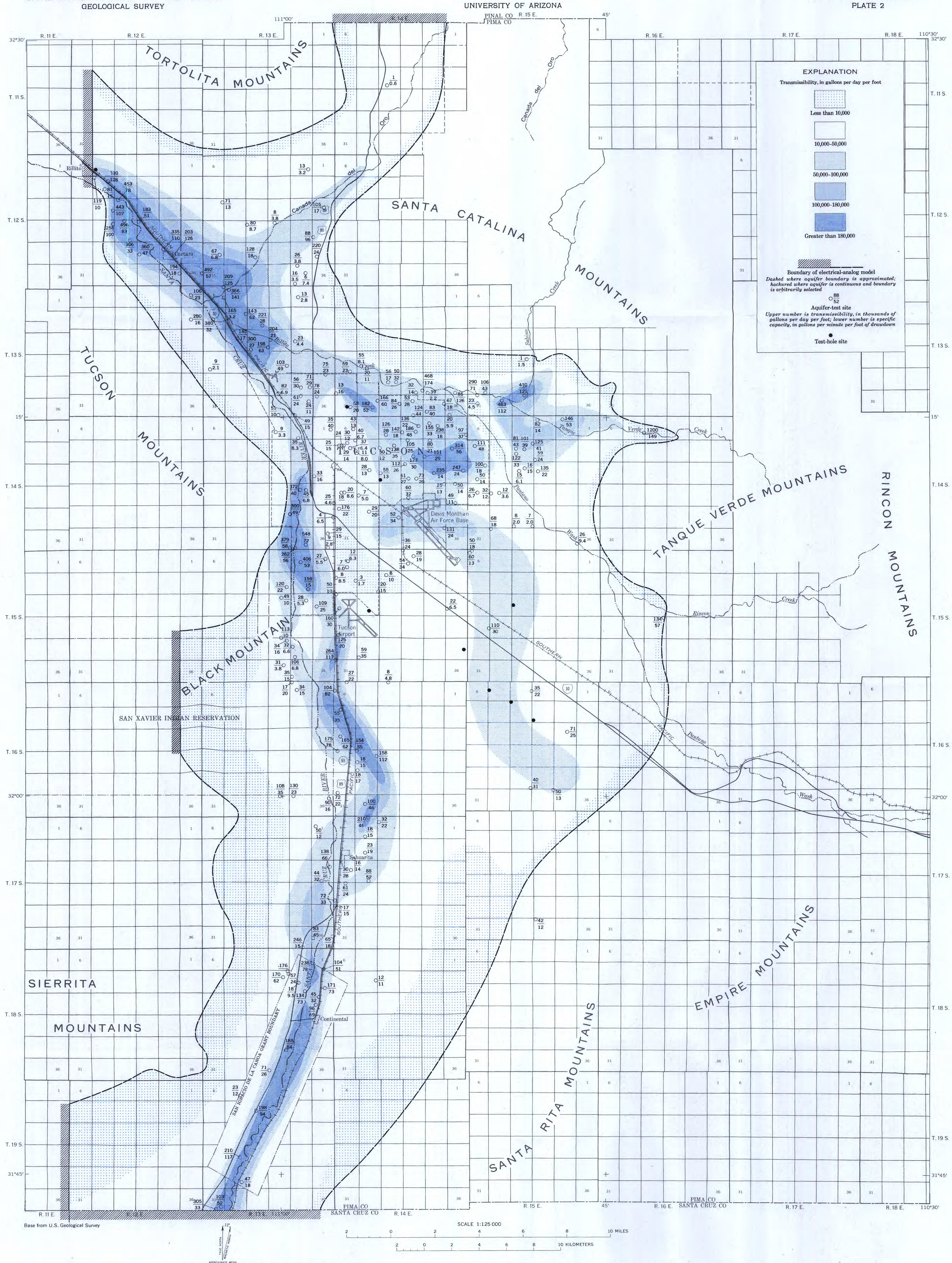
SCALE 1:500 000

5 0 5 10 15 MILES

5 0 5 10 15 KILOMETERS

CONTOUR INTERVAL 1000 FEET
DATUM IS MEAN SEA LEVEL

TOPOGRAPHIC MAP OF THE SANTA CRUZ RIVER BASIN, SHOWING BOUNDARY OF THE ELECTRICAL-ANALOG MODEL AREA, SOUTHEASTERN ARIZONA

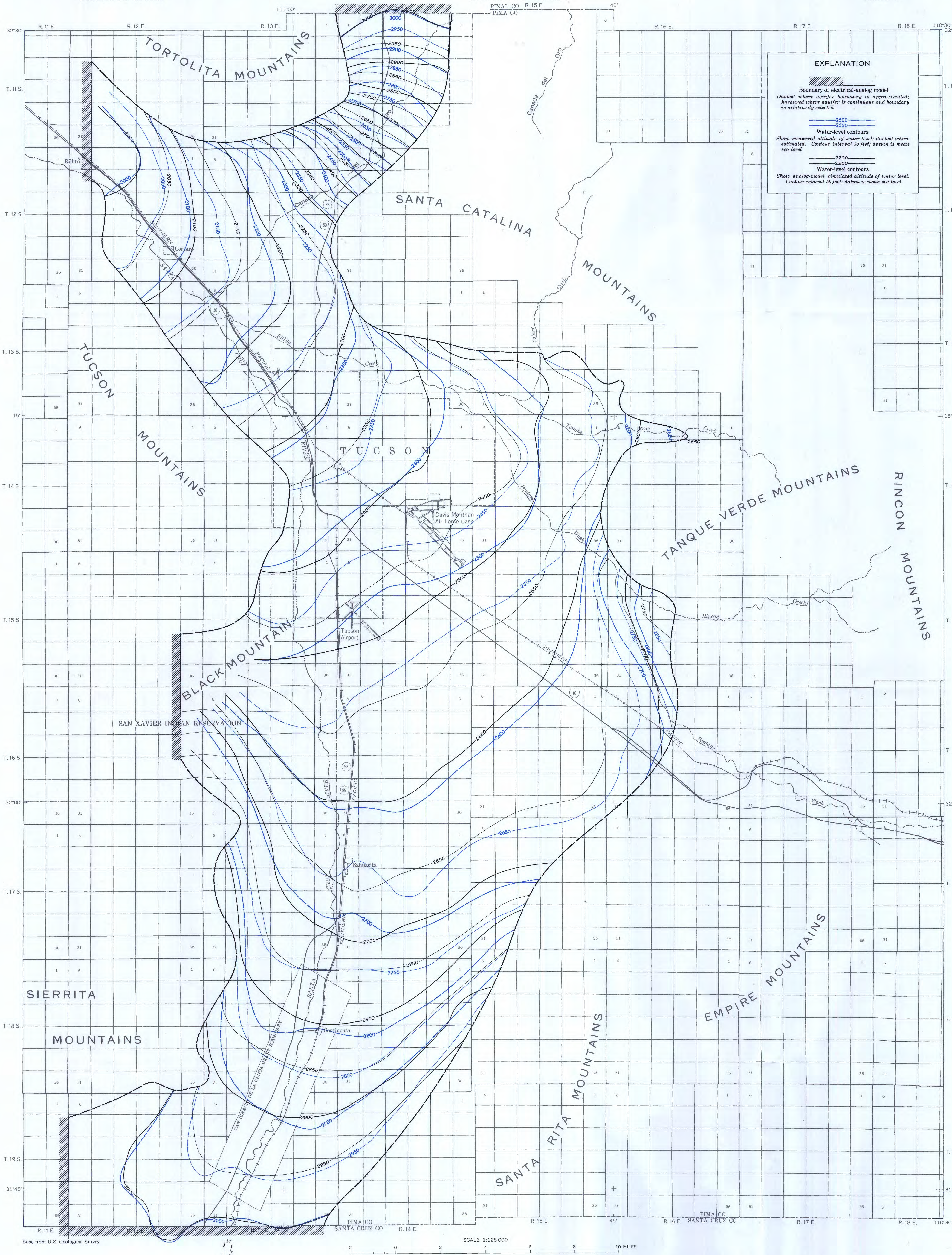


MAP SHOWING GENERALIZED TRANSMISSIBILITY PATTERN USED IN ELECTRICAL-ANALOG MODEL, TUCSON BASIN, SOUTHEASTERN ARIZONA

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
CITY OF TUCSON
U.S. BUREAU OF RECLAMATION
UNIVERSITY OF ARIZONA

WATER-SUPPLY PAPER 1939-C
PLATE 3



MAP SHOWING MEASURED AND ANALOG-MODEL SIMULATED WATER-LEVEL ALTITUDES, SPRING 1940, TUCSON BASIN, SOUTHEASTERN ARIZONA

UNITED STATES DEPARTMENT OF THE INTERIOR
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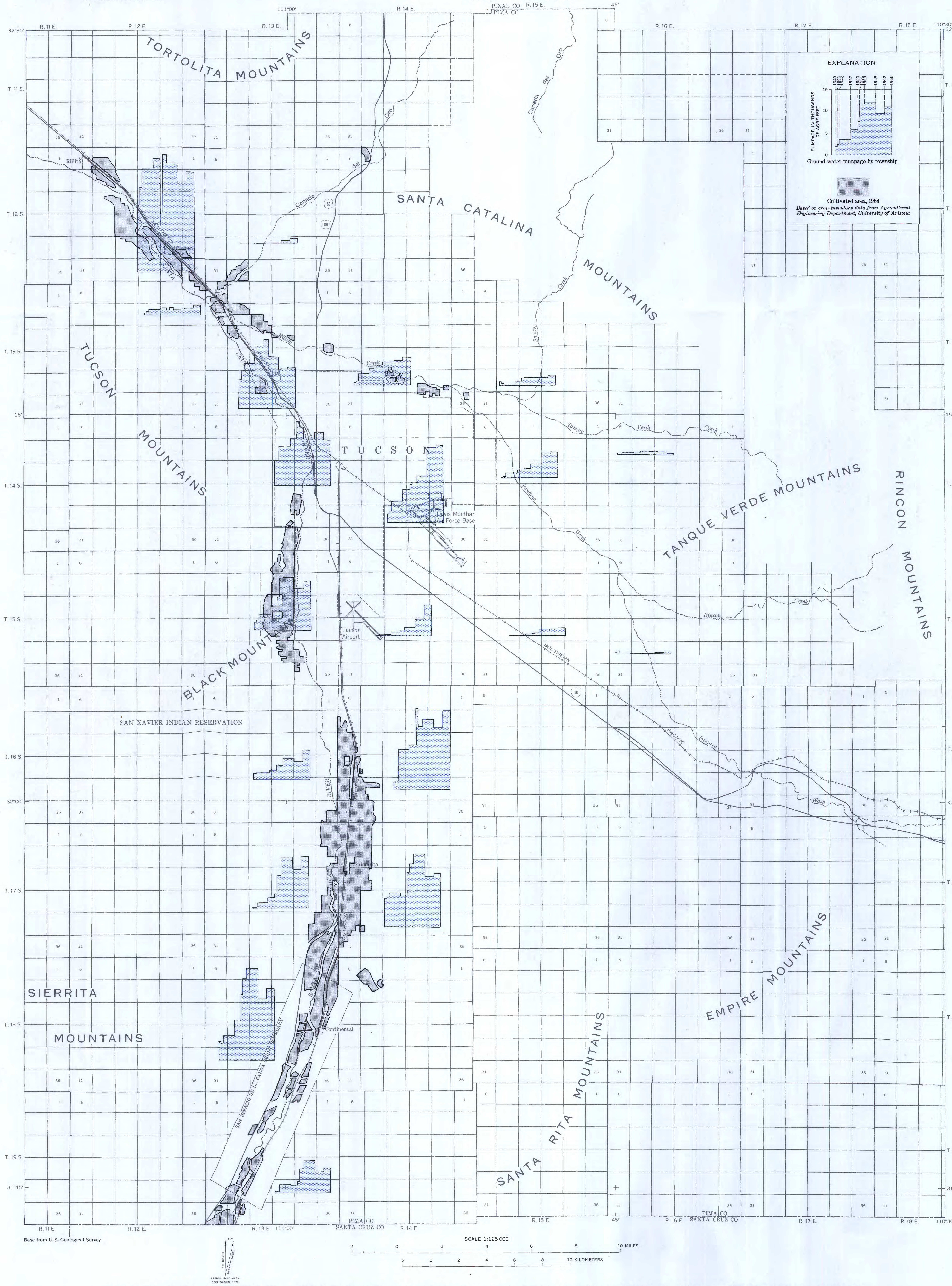
WATER-SUPPLY PAPER 1939-C
PLATE 4



MAP SHOWING CULTIVATED AREAS, 1964, AND PUMPAGE BY TOWNSHIP, 1940–64, TUCSON BASIN, SOUTHEASTERN ARIZONA

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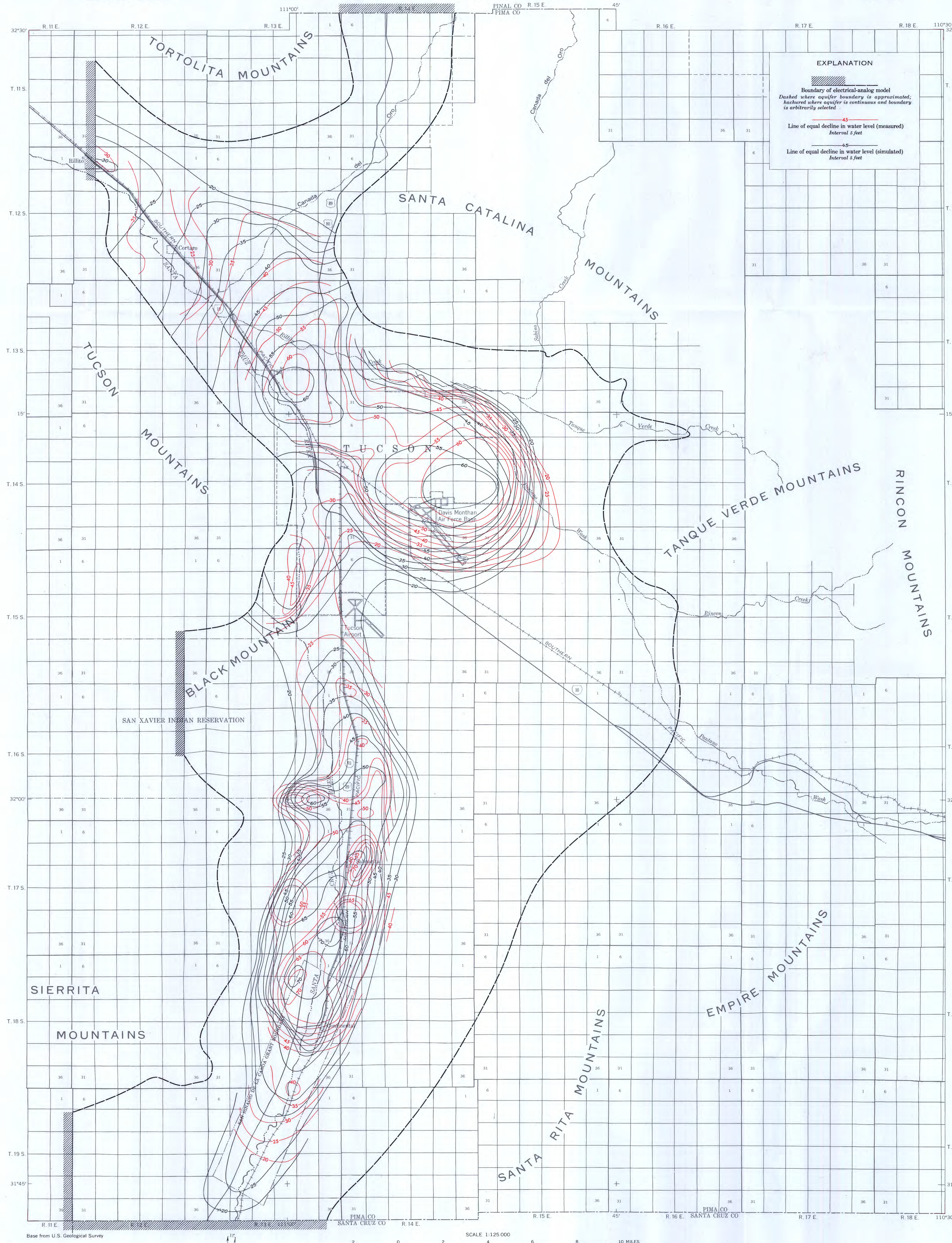
WATER-SUPPLY PAPER 1939-C
PLATE 5



MAP SHOWING MEASURED AND SIMULATED WATER-LEVEL DECLINES, SPRING 1940 TO SPRING 1965, TUCSON BASIN, SOUTHEASTERN ARIZONA

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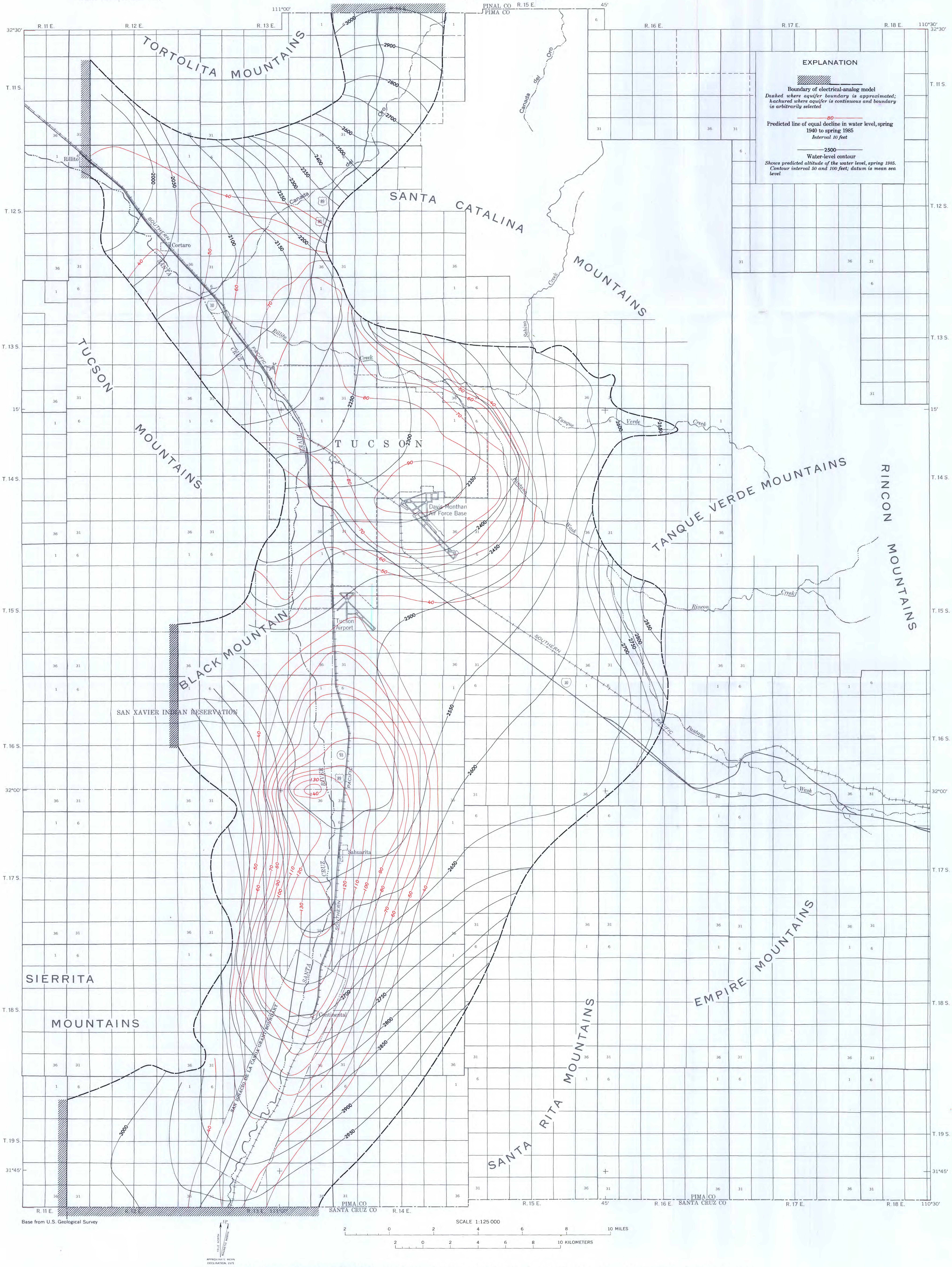
WATER-SUPPLY PAPER 1939-C
PLATE 6



MAP SHOWING PREDICTED WATER-LEVEL CHANGES, SPRING 1940 TO SPRING 1985, AND WATER-LEVEL ALTITUDES, SPRING 1985, TUCSON BASIN, SOUTHEASTERN ARIZONA