SIMULATION OF GROUND-WATER FLOW AND POTENTIAL LAND SUBSIDENCE, AVRA VALLEY, ARIZONA

By R.T. HANSON, S.R. ANDERSON, and D.R. POOL

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CONVERSION FACTORS

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-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per day per foot (ft/d/ft)	1	meter per day per meter (m/d/m)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

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*.

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ABSTRACT

A numerical ground-water flow model of Avra Valley, Pima and Pinal Counties, Arizona, was developed to evaluate predevelopment conditions in 1940, ground-water withdrawals from 1940 through 1984, and potential land subsidence from 1985 through 2024. The components of ground-water inflow and outflow for steady-state simulation used 18,900 acre-feet with negligible amounts of areal recharge in 1940. Transient state was simulated using 4.4 million acre-feet of pumpage resulting in 3.4 million acre-feet of water withdrawn from aquifer-system storage from 1940 through 1984. The net difference of 1.0 million acre-feet is attributed to increased recharge from irrigation return flow and infiltration of streamflow and sewage effluent in the north half of the valley after 1964.

Estimated recharge, which averaged 40,000 acre-feet per year from 1965 through 1977 and 70,000 acre-feet per year from 1978 through 1984, was the source of 40 percent of pumpage from 1965 through 1984 in the areas of Townships 11 through 15 South. Increase in recharge after 1977 was coincident with above-average streamflow in the Santa Cruz River from 1978 through 1984. Increased recharge contributed to decreased water-level decline rates after 1964 and recoveries after 1977 in the north half of the valley.

Maximum potential subsidence for the period 1985 through 2024 ranges from 0.9 feet for an inelastic specific storage of $1.0 \times 10^{-5} ft^{-1}$ to 14.7 feet for an inelastic specific storage of $1.5 \times 10^{-4} ft^{-1}$ on the basis of pumpage and recharge rates from 1973 through 1977 and a preconsolidation-stress threshold of 100 feet. The projections simulated 4.2 million acre-feet of water withdrawn from aquifer-system storage from 1985 through 2024. About 1 to 10 percent of this water will come from a permanent reduction in aquitard storage.

INTRODUCTION

Avra Valley is a 520-square-mile alluvial basin west of Tucson in Pima and Pinal Counties, Arizona (fig. 1). The valley, which is bounded on the east and west by low-lying mountains, consists of a north-trending gently sloping alluvial plain that is 7 to 15 mi wide.

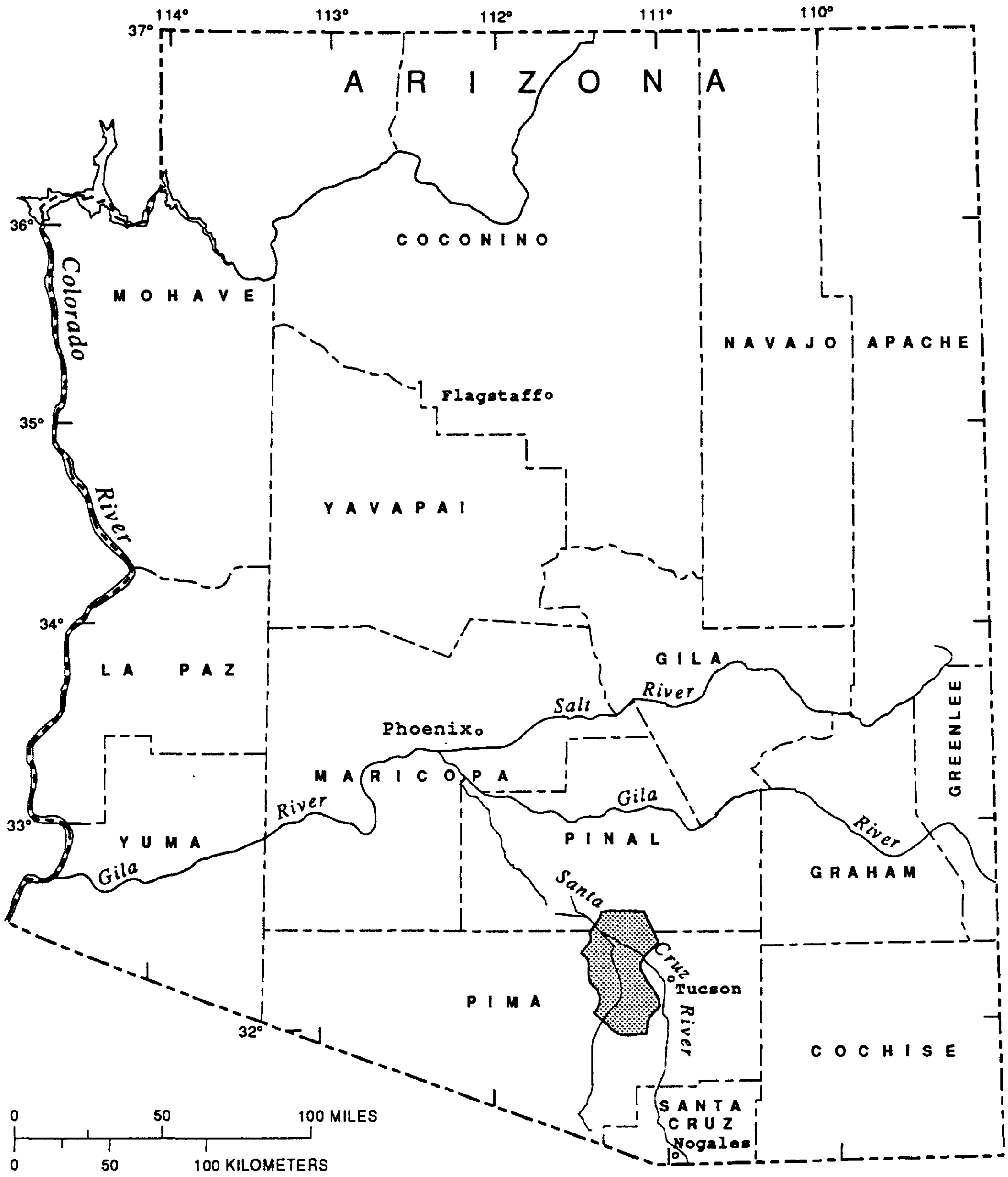


Figure 1.--Location of study area (shaded).

The area is drained by the Santa Cruz River and its tributaries, Brawley, Blanco, and Los Robles Washes. Natural streamflow is generally of short duration and occurs in direct response to precipitation, which averages about 10 in/yr on the valley floor. The valley is underlain by an extensive alluvial-aquifer system. The aquifer system consists of a wide variety of sedimentary deposits that range from gravel and conglomerate to anhydritic and gypsiferous clayey silt and mudstone.

Pumping of ground water for agriculture, public supply, and industry in Avra Valley resulted in widespread water-level declines that ranged from 50 to 150 ft from 1940 through 1984 (Cuff and Anderson, 1987). Declines were accompanied by localized compaction of the aquifer, subsidence of the land surface, and formation of earth fissures (Anderson, 1989). Continued withdrawals from the aquifer system may result in additional declines, compaction, subsidence, and fissuring. Subsidence, which ranged from 0 to 1 ft between 1950 and 1985, could ultimately exceed 10 ft in parts of the valley (Anderson, 1989). Potential consequences include permanent reduction of aquifer storage as well as damage to highways, railroads, buildings, aqueducts, irrigation systems, wells, and sewage systems. The aquifer system received sole-source designation by the U.S. Environmental Protection Agency in 1984 (U.S. Environmental Protection Agency, 1984). Management of this natural resource (ground water) may require periodic re-evaluation of the effects of compaction and subsidence in order to minimize potential environmental damage related to ground-water development.

In 1983, the U.S. Geological Survey, in cooperation with the City of Tucson, began an investigation to evaluate the potential for aquifer-system compaction, land subsidence, and earth fissures in Avra Valley (Anderson, 1989; Cuff and Anderson, 1987). The study was divided into three phases, a detailed hydrogeologic investigation (Anderson, 1989), a stress-strain analysis of extensometer data (Hanson, 1987; 1988), and the development of an areal-subsidence model. This report documents the procedures used to develop a numerical simulation of ground-water flow and subsidence of the study area. The simulation was calibrated through 1977, with an additional transient simulation through 1984, and was used to evaluate the potential for water-level decline and land subsidence from 1985 through 2024. The year 2025 was designated by the Arizona Ground-Water Management Act of 1980 (State of Arizona, 1980) as the time by which pumpage and recharge must be brought into balance.

HYDROGEOLOGIC SETTING

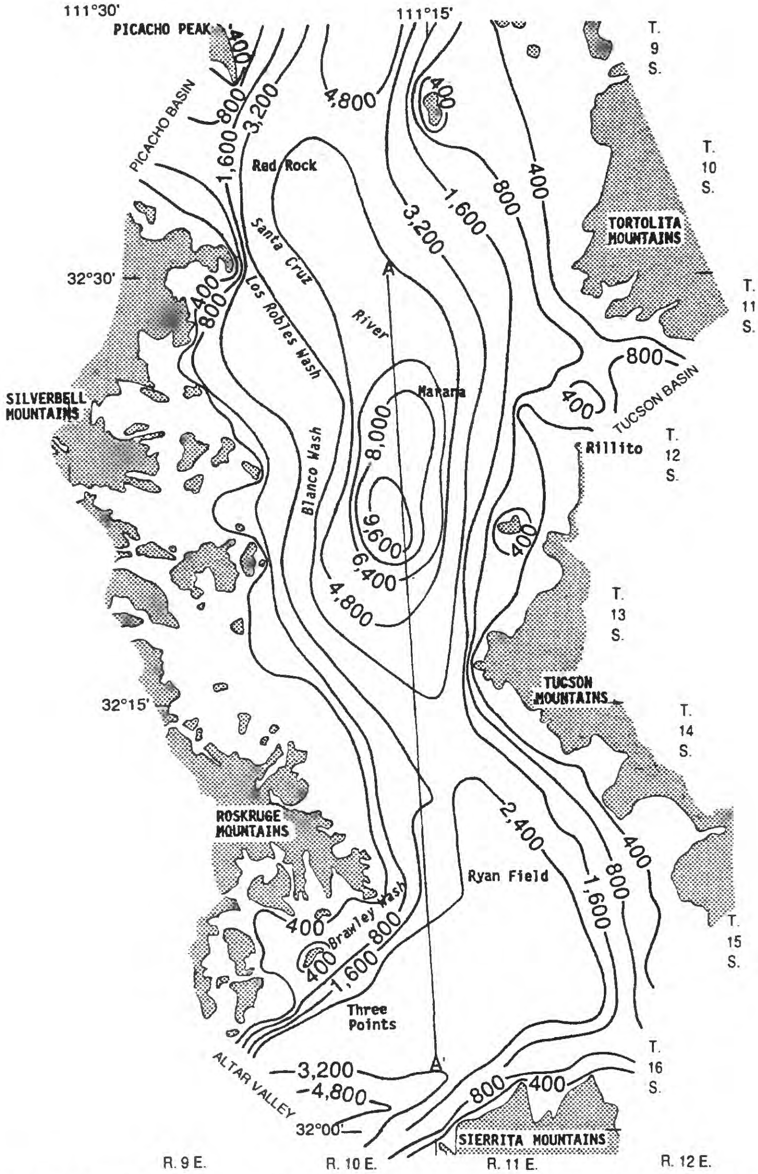
Avra Valley is in the Basin and Range physiographic province, which is characterized by block-faulted mountains separated by sediment-filled basins. The mountains are composed of granitic, metamorphic, volcanic, and sedimentary rocks of Precambrian to Tertiary age. Sediments of the basin consist of unconsolidated to indurated gravel, sand, silt, and clay of Tertiary and Quaternary age. Sediments generally are coarse grained along the margins of the basin and grade into finer-grained and evaporitic deposits in the central, downfaulted parts of the basin.

Sediments are saturated at depth and form an alluvial-aquifer system. Water stored in the aquifer system generally is unconfined to depths of 1,000 ft and moves in a northerly direction. Sources of water to the aquifer system include ground-water inflow, mountain-front recharge, infiltration of streamflow, and irrigation return flow. Discharge of water from the aquifer system includes ground-water outflow and pumpage. Ground-water pumping has greatly altered the natural flow system and caused widespread water-level declines, changes in horizontal flow paths, development of vertical-hydraulic gradients and perched zones, and compaction of the aquifer system.

Geology

Avra Valley is composed of a wide variety of igneous, metamorphic, and sedimentary rocks of Precambrian to Quaternary age. Rocks of primary interest to this study include the permeable sedimentary deposits of Tertiary and Quaternary age, referred to as alluvium (fig. 2). The mountains (fig. 2) consist mainly of low-permeability crystalline rocks that impede the movement of ground water. The bedrock along the extreme edges of the valley is overlain by a veneer of alluvium that generally is less than 100 ft thick. In the center of the basin, bedrock is buried by more than 9,000 ft of alluvium (fig. 2).

The alluvium consists of several regionally extensive sedimentary units of diverse lithology (Anderson, 1989). In this report, the alluvium is subdivided into lower and upper units on the basis of hydrogeologic characteristics (fig. 3). The lower alluvium is thousands of feet thick, consists of gravel and conglomerate along the basin margins and in the southern part of the basin, and grades into gypsiferous and anhydritic clayey silt and mudstone in the north-central part of the basin. The upper alluvium consists mainly of gravel, sand, and clayey silt, and ranges from less than 100 to about 1,000 ft in thickness. The lower alluvium is equivalent to the Pantano Formation, lower Tinaja beds, and middle Tinaja beds described by Anderson (1987, 1988, 1989) and the regional lower basin fill of Pool (1986). The upper alluvium is equivalent to the upper Tinaja beds and Fort Lowell Formation of Anderson (1987, 1988, 1989) and the regional upper basin fill and stream alluvium of Pool (1986). Geologic and geophysical data indicate that the sediments of the upper alluvium are generally much more compressible compared with those of the lower alluvium and are more likely to be compacted as a result of the withdrawal of ground water (Anderson, 1989; Tucci and Pool, 1986). Compressible deposits within the upper alluvium include those in playa and alluvial-fan subregions and a zone where fan and playa sediments interfinger, herein referred to as the interfingered-zone subregion (Anderson and Hanson, 1987). Fan and playa environments are generally characterized by clay and silt concentrations of less than 20 percent and more than 60 percent, respectively. The interfingered-zone subregion generally contains from 20 to 60 percent clay and silt. This subregion was subdivided into two adjacent zones with 20 to 40 and 40 to 60 percent clay and silt for subsidence evaluation (Anderson, 1989). The physical properties and evolution of Cenozoic deposits in Avra Valley and adjacent alluvial basins are described in more detail by Davidson (1973), Eberly and Stanley (1978), Allen (1981), Pool (1986), Tucci and Pool (1986), Anderson (1987, 1988, 1989), Hanson (1988), and Anderson and others (1990).



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

Geology from Wilson and others (1969).
Depth to bedrock modified from
Oppenheimer and Sumner (1981)

0 5 10 MILES
0 5 10 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

ALLUVIUM—Clay, silt sand, and gravel

BEDROCK—Granitic, metamorphic, volcanic, and indurated sedimentary rocks of the mountains

—800— LINE OF EQUAL DEPTH TO BEDROCK—Interval 400, 800, and 1,600 feet

A—A' LINE OF HYDROGEOLOGIC SECTION—Figure 3

Figure 2.--Extent of alluvium and depth to bedrock in Avra Valley.

Aquifer System

The lower and upper alluvium are saturated at depth and form a regional alluvial-aquifer system (fig. 3). The aquifer system, which generally is unconfined to depths of 1,000 ft, is underlain and bounded on the east and west by low-permeability crystalline rock. Ground-water inflow to the aquifer system occurs through gaps in the bedrock from Altar Valley and Tucson basin near Three Points and Rillito, respectively (fig. 1). Ground-water outflow from the aquifer system occurs south of Picacho Peak. Previous estimates of ground-water inflow from Altar Valley near Three Points range from 6,790 acre-ft/yr to 16,600 acre-ft/yr (table 1). Estimates of ground-water inflow from Tucson basin near Rillito range from 11,450 acre-ft/yr to 20,100 acre-ft/yr (table 1). Previous estimates of ground-water outflow near Picacho Peak range from 18,670 acre-ft/yr to 34,700 acre-ft/yr (table 1). On the basis of geochemical data, ground-water inflow is the primary source of recharge to the aquifer system in the south half of the valley (Conner, 1986). Areal recharge may be significant relative to ground-water inflow in the north half of the valley during some time periods (table 1).

Before 1965, areal recharge from combined sources probably was less than 15,000 acre-ft/yr (table 1). The main sources of recharge since 1965 include return flow of water applied to fields in the north half of the valley and infiltration of streamflow and sewage effluent along the channel and flood plain of the Santa Cruz River (Anderson, 1983). Actual changes in recharge through time are poorly known. Irrigation return flow, however, will likely decrease through time because of improved methods of irrigation and decreased irrigated acreage. Recharge along

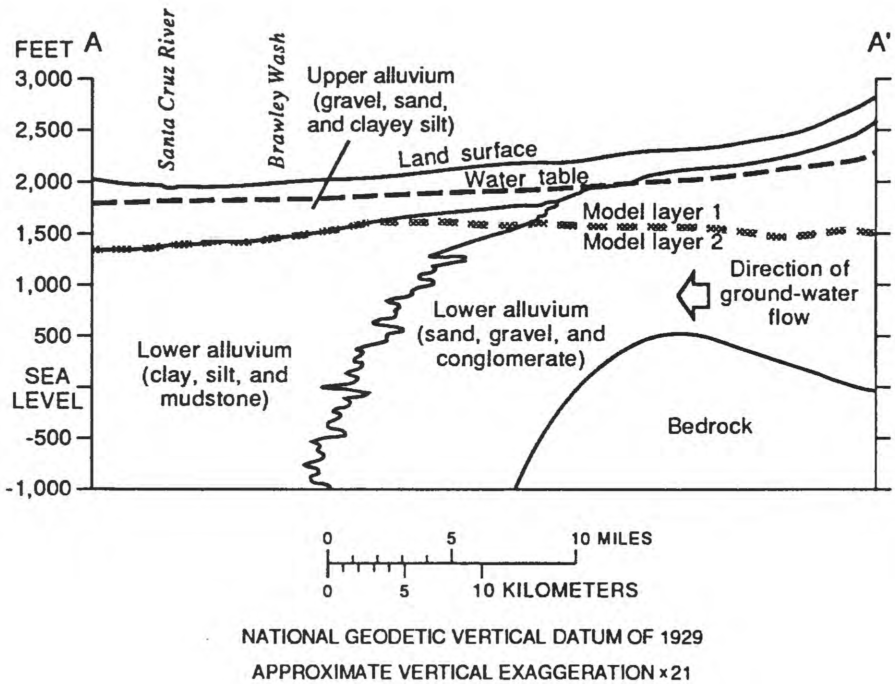


Figure 3.--Generalized hydrogeologic section of Avra Valley.

Table 1.--Summary of estimated ground-water flow components for Avra Valley

[Rates are in acre-feet per year. Dashes indicate that component was not applicable to study]

Time period	Stress period	Source	Inflow: Mountain-front recharge	Inflow: Stream-flow infil-tration	Inflow: Under-flow[1]	Inflow: Additional recharge or reduced pumpage[2]	Inflow: Total[3]	Outflow: Evapo-trans-pira-tion	Outflow: Under-flow	Outflow: Estimated pumpage	Outflow: Total[3]
		Predevelopment									
1940		Moosburner (1972)..	[4]<3,000	([5])	[6]9,000 / 13,000	([5])	22,000	([5])	22,000	[4] [7]10,000	22,000
		Anderson (1972)....	------	------	------ / [8]17,500	-------	------	-----	------	-------	------
		Whallon (1983).....	([5])	([5])	16,600 / 20,100	([5])	36,700	([5])	34,700	([5])	34,700
		Clifton (1981).....	500	([5])	[9]6,790 / 11,450	0	18,740	0	[9]18,670	0	18,670
		Osterkamp (1973)...	7,100	14,700	([5])	([5])	21,800	([5])	([5])	([5])	------
		Freethey and Anderson (1986)[10]..........	9,000	5,000	12,400	0	26,400	7,400	19,000	([5])	26,400
		Steady-state model[11]...........	0	0	9,900 / 9,000	0	18,900	0	18,900	0	18,900
		Development									
1940-64		Moosburner (1972)..	[4]<3,000	([5])	[6]9,000 / 13,000	([5])	------	([5])	[6]22,000	[6]72,500	[6]75,600
1957-58		Turner (1959)......	([5])	([5])	14,700 / ------	([5])	------	([5])	([5])	([5])	------
1970-72		Brown (1976).......	5,300	12,100	9,000 / 10,000	([5])	------	([5])	22,000	[12]135,600	------
1960-80		Travers and Mock (1984)[13].....	[13]6,780	[13]11,340	[13]6,300 / 6,830	[14] [15]8,290 / 12,570	33,250		[13]18,850	[1]94,370 / 113,990	[14]94,370 / 113,990
		Transient-state model									
1940-50	1	([11])	------	------	9,900 / 9,000	0	18,900	-----	18,900	25,000	25,000
1951-55	2	([11])	------	------	9,900 / 9,000	0	18,900	-----	18,900	100,000	100,000
1956-60	3	([11])	------	------	9,900 / 9,000	14,500	33,400	-----	18,900	[16]148,500	134,000
1961-64	4	([11])	------	------	9,900 / 9,000	14,500	33,400	-----	18,900	[16]148,500	134,000
1965-72	5	([11])	------	------	9,900 / 9,000	69,000	87,900	-----	18,900	160,100	91,100
1973-77	6	([11])	------	------	9,900 / 9,000	58,000	76,900	-----	18,900	170,700	112,700
1978-84	7	([11])	------	------	9,900 / 9,000	85,800	104,700	-----	18,900	104,300	18,500

[1]Top number is inflow from Altar Valley, and lower number is inflow from Tucson basin. Otherwise, a single number represents total underflow.

[2]Includes streamflow infiltration, irrigation return flow, sewage-effluent return flow, and retirement of agricultural land.

[3]Total of estimated inflow or outflow values used by investigator. In the transient-state model, total outflow represents net change in storage as an average rate over the specified period of time.

[4]Inflow and outflow estimates reported by investigator but not used.

[5]Budget component that was not estimated by investigator or was considered negligible and was not used.

[6]Average values for 1940-65.

[7]From White and others (1966).

[8]Underflow for 1940.

[9]Average values for invarse-model simulations with and without estimated uncertainty in heads.

[10]Basin estimates include an area north of Avra Valley. Estimates are inclusive but may not be directly comparable.

[11]This report.

[12]Reported as consumptive use plus municipal pumpage for 1970-72.

[13]Average values for 1960-80.

[14]Top number is average rate for transient-model calibration period, 1960-69, and bottom number is average rate for transient-simulation period, 1970-80. Most actual rates vary from cell to cell for each yearly stress period.

[15]Average totals are reductions in reported agricultural pumpage and do not include reductions made for the remainder of agricultural pumpage estimated directly as consumptive use.

[16]Pumpage for these stress periods is average for 1956-64.

stream channels probably was greatest during the water years of 1978, 1979, and 1984 (fig. 4) and may increase through time from increased discharge and infiltration of sewage effluent. Discharge of sewage effluent into the Santa Cruz River near Tucson began in 1950, averaged 5,600 acre-ft/yr from 1951 through 1964, and increased to more than 49,000 acre-ft/yr by 1985 (Davis and Stafford, 1966; Dave Esposito, Environmental Planning Management, Pima County Wastewater Management Department, oral commun., 1988).

Direction of ground-water movement generally is northward in the southern part of the valley and northwestward in the northern part. Movement and storage of ground water is controlled by the distribution of hydraulic head and by the transmissive and storage properties of the aquifer. Hydraulic properties of the lower and upper alluvium vary considerably from place to place, depending on lithologic factors such as sediment grain size, sorting, and cementation. In general, the lower alluvium has lower permeability and lower porosity than the upper alluvium but stores a much greater volume of water because of greater thickness.

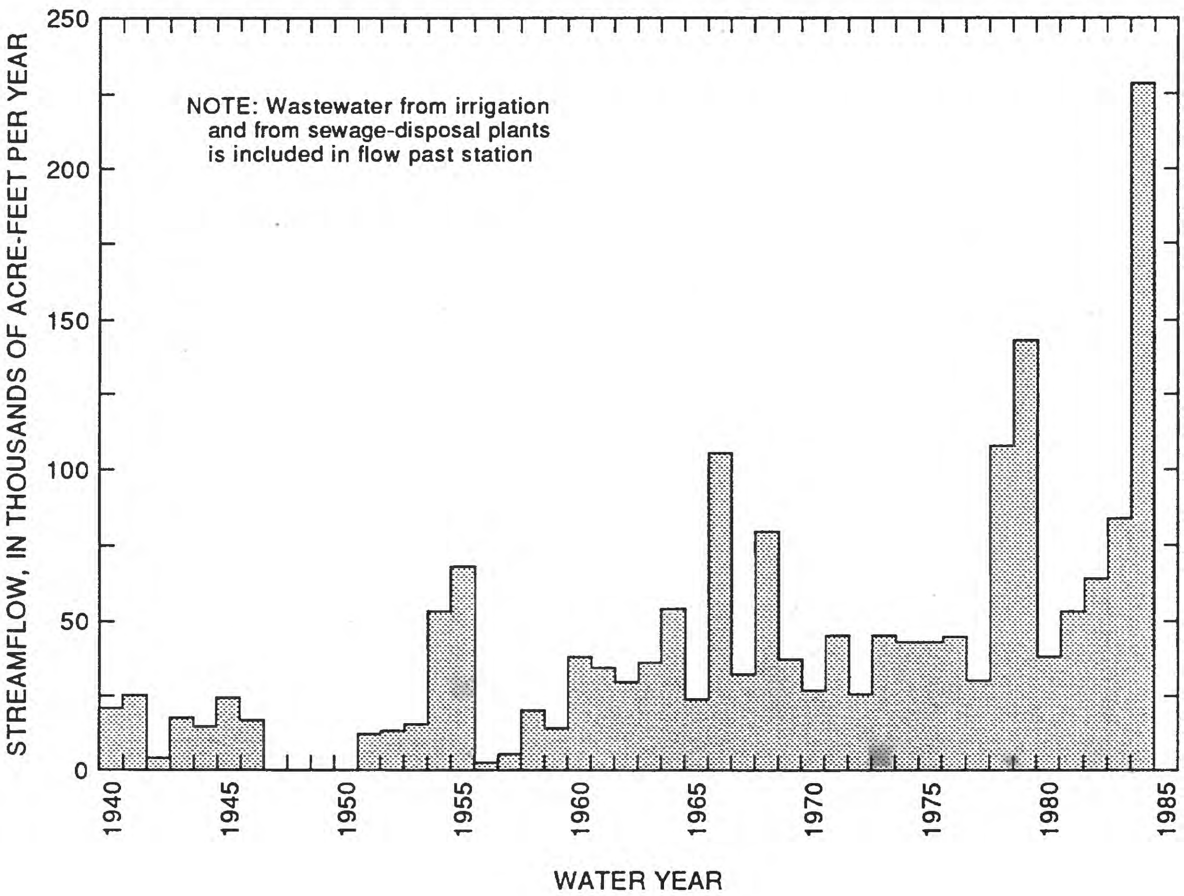


Figure 4.--Annual streamflow in the Santa Cruz River at Cortaro, Tucson basin, 1940-84.

Permeability of the aquifer system is greatest in the upper alluvium along the channel of the Santa Cruz River and least in the mudstone of the lower alluvium. Hydraulic conductivity and transmissivity of the aquifer system range from about 2 to 255 ft/d and 1,000 to 50,000 ft^2/d on the basis of aquifer-test data from several sources (Clifton, 1981; unpublished data from the files of Tucson Water, City of Tucson). Hydraulic conductivity ranges from 20 to 50 ft/d in the lower alluvium, 30 to 40 ft/d in most of the upper alluvium, and 50 to 100 ft/d in the river gravels of the upper alluvium that underlie the channel of the Santa Cruz River. Transmissivity ranges from 1,500 to 40,000 ft^2/d in the upper alluvium and 1,000 to 50,000 ft^2/d in the lower alluvium. Estimates of composite transmissivities of the upper and lower alluvium are based on calibration of a one-layer electric-analog model of the aquifer system and generally range from 4,000 to 30,000 ft^2/d throughout most of the valley and exceed 40,000 ft^2/d along the Santa Cruz River (Moosburner, 1972).

Storage properties of the aquifer system probably vary considerably and are difficult to determine. Estimates of storage properties generally are average values determined from water-budget calculations and model calibration. Estimates of specific yield in the upper part of the aquifer system average about 0.15 (White and others, 1966; Moosburner, 1972; Anderson, 1972; Whallon, 1983; Freethey and others, 1986). Storage coefficients of the aquifers below 1,000 ft probably average about 1×10^{-4}. Estimates of the total volume of recoverable water stored in the upper 1,200 ft of the aquifer system range from 16.5 million acre-ft (White and others, 1966) to 24 million acre-ft (Freethey and Anderson, 1986).

Ground-Water Development

Ground water in Avra Valley is withdrawn for livestock, domestic, industrial, municipal, and irrigation uses. The main use of ground water is for irrigation of crops. The first irrigation wells in Avra Valley were drilled in the Marana area in 1937, and by 1954 more than 100 irrigation wells were in use in the north half of the valley (White and others, 1966; Whallon, 1983). Agricultural activity was greatest from 1954 to 1977. In 1972, the City of Tucson began to purchase and retire farmland in exchange for municipal ground-water rights in the valley (Johnson, 1980; Whallon, 1983). Gradual retirement of agricultural lands resulted in major reductions in pumpage from 1976 through 1984. Major ground-water users in 1984 included agriculture, the City of Tucson, utilities, and copper mines.

Annual ground-water pumpage increased from 12,000 acre-ft in 1940 to a maximum of 174,000 acre-ft in 1975 and declined to 59,000 acre-ft by 1984 for the part of Avra Valley in Pima County (fig. 5, unpublished data on file with the Tucson, Ariz., office of the U.S. Geological Survey). Estimates of total water withdrawn from the aquifer system from 1940 through 1984 are 4.2 million acre-ft on the basis of reported pumpage values for this part of Avra Valley (fig. 5). From 1940 through 1984, 96 percent of the withdrawal in Pima County was for agriculture, and most of the remainder was for public supply and industry. Peak agricultural pumpage was 162,000 acre-ft in 1975, and peak municipal pumpage was 18,000 acre-ft in 1980. Ground-water withdrawals for

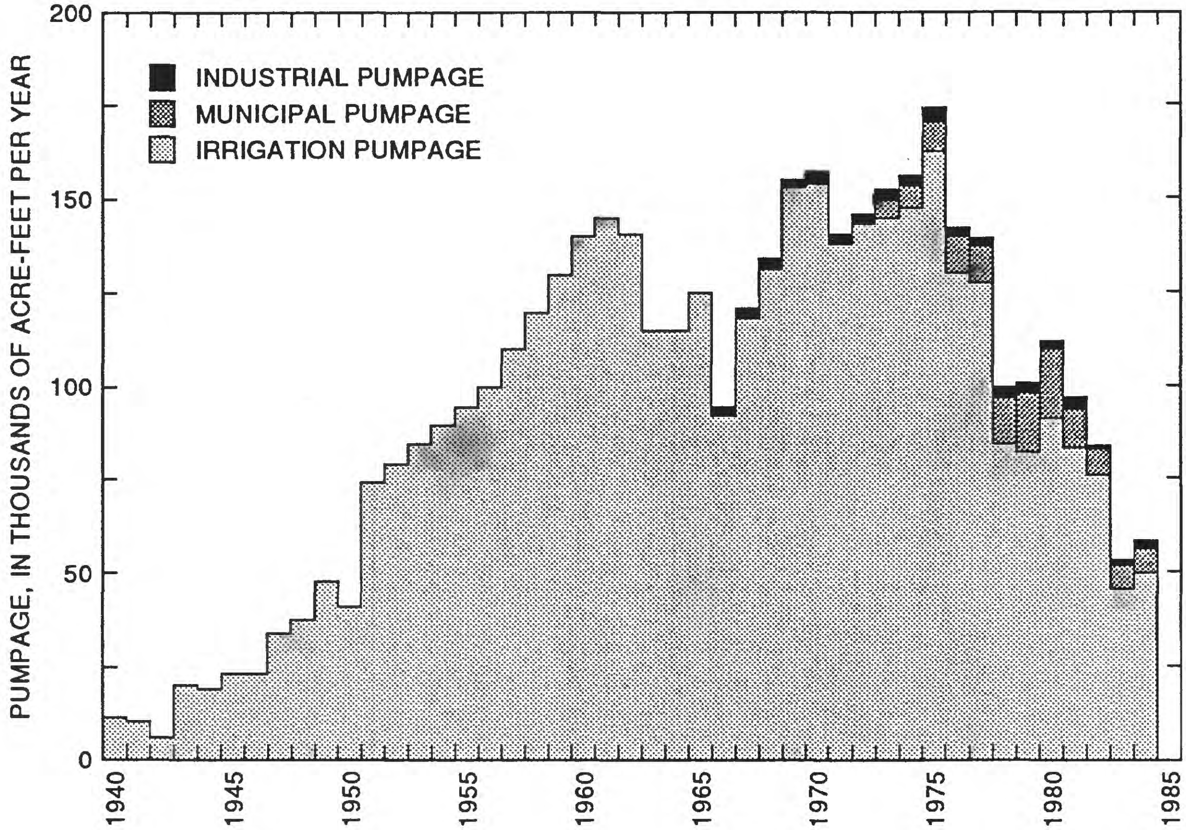


Figure 5.--Annual ground-water pumpage in the part of Avra Valley in Pima County, 1940-84.

industrial use averaged 2,400 acre-ft/yr from 1966 through 1984. In 1984, agricultural pumpage was 85 percent of the total withdrawal from the Avra Valley aquifer system in Pima County. Additional pumpage in the Red Rock area, which is in the part of Avra Valley in Pinal County, ranged between an estimated 12,000 acre-ft/yr in the early 1950's to an average withdrawal on the order of 20,000 acre-ft/yr in the 1960's and 1970's (Travers and Mock, 1984). Ground-water withdrawals in this area decreased to about 11,000 acre-ft/yr in the mid-1980's.

Before extensive ground-water development, the hydrologic system in Avra Valley was in approximate equilibrium, and movement and storage of water in the aquifer system were controlled by natural recharge, discharge, and lithologic relations. Ground-water pumpage in excess of recharge greatly altered the natural flow system through time. From 1940 to 1985, water levels in the aquifer system declined more than 100 ft throughout most of the valley north of T. 14 S. and more than 200 ft south of Picacho Peak (Cuff and Anderson, 1987). Other effects of pumping include a shift of natural flow paths toward pumping centers, the development of perched ground water above the aquifer system in areas underlain by shallow fine-grained beds (Cuff and Anderson, 1987), a decrease in transmissivity resulting from dewatering of permeable sediments, and the increased vertical effective stress resulting in compaction of the aquifer system (Anderson, 1989).

SIMULATION OF GROUND-WATER FLOW

A numerical ground-water flow model of Avra Valley was developed to simulate steady-state flow conditions for 1940 and transient-state flow conditions for 1940-84 in the aquifer system. Trial-and-error adjustment of hydraulic properties and boundary conditions for steady-state simulation was used to match predevelopment heads. Calibration of the transient-state simulation required trial-and-error adjustment of storage and recharge to match water-level hydrographs. Simulations were made using a three-dimensional finite-difference ground-water flow model developed by McDonald and Harbaugh (1988). Transient-state simulations were calibrated for the period 1940 through 1977, and an additional transient simulation was done for the period 1978 through 1984. A sensitivity analysis was used to evaluate the sensitivity of simulated heads to changes in hydraulic parameters.

A two-layer model was developed with an active flow region in the upper layer that was divided into 437 square cells that have dimensions of 1 mi per side (fig. 6). In the aquifer system north of T. 14 S., model layer 1 includes the upper alluvium, and model layer 2 includes the lower alluvium (fig. 3). South of T. 13 S., the upper alluvium is unsaturated and the model-layer boundary was extended horizontally at an altitude of about 1,500 ft above sea level to coincide with upper and lower parts of the lower alluvium.

Constant-head inflow and outflow cells were specified for steady-state calibration, and constant-flux cells were specified for sensitivity analysis. On the basis of similar estimates through time of ground-water inflow and outflow (table 1), inflow and outflow cells were specified as constant-flux cells for transient-state simulations (fig. 6). No-flow boundaries were specified for all other boundary cells. All pumpage data for transient simulations were distributed within the upper layer. Pumpage data for the years before 1965 were estimated from power consumption by wells. Pumpage data for 1965 to 1977 were estimated by a combination of crop requirements and power consumption.

Hydraulic conductivity of layer 1, transmissivity of layer 2, storage properties for both layers, and vertical leakance between layers were specified for the simulations. Initial estimates of hydraulic conductivity, transmissivity, and specific yield were derived from the analog model (Moosburner, 1972). Transmissivity of layer 1 was calculated by the model using saturated thickness and specified hydraulic conductivity. Storage was simulated by specifying the specific yield in layer 1 and the storage coefficient in layer 2. Vertical flow between layers was simulated with leakance values derived from cell-by-cell horizontal hydraulic conductivities and assumed constant anisotropy ratios of 1:100 within layer 1 and 1:1,000,000 within layer 2. The leakance was estimated as a harmonic mean of both layers (Trescott, 1975; Trescott and Larson, 1976, Appendix II, equation 26c). The resulting vertical leakance between layers ranged from 9×10^{-2} to 9×10^{-4} ft/d/ft.

Steady-state and transient-state simulations were used to calibrate the model to measured water levels in selected wells, hand-drawn contours of measured water levels, and hand-drawn contours of water-level change that generally represent average conditions in the upper 1,000 ft

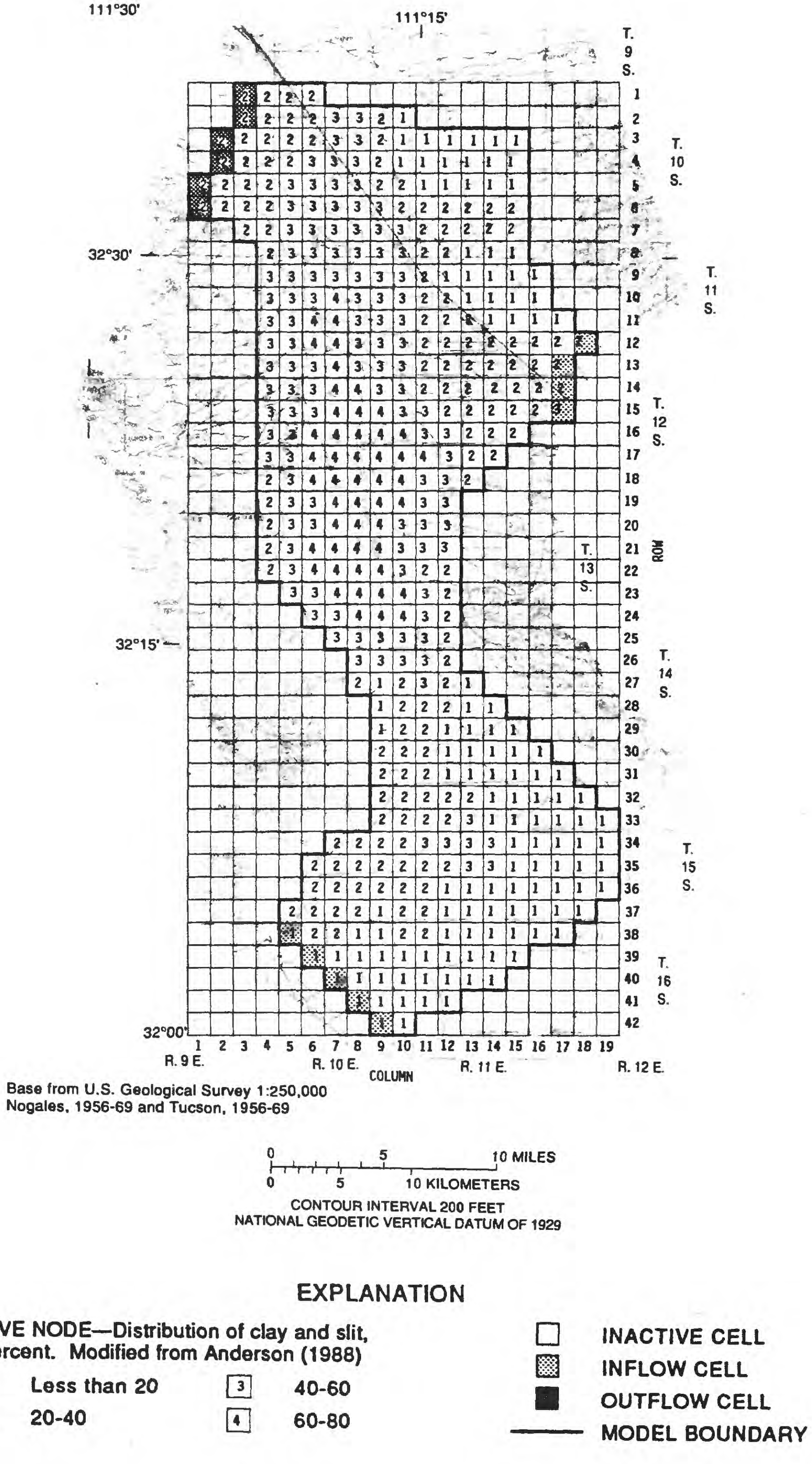


Figure 6.--Finite-difference grid of Avra Valley ground-water model.

of the aquifer system and model layer 1. Simulated water levels were interpolated to the well location of measured water levels for point comparisons of calibration error. Hydrographs showing point comparisons through time were used for transient-state model comparisons. Most hydrograph data used for transient comparisons are from index wells used by the Arizona Department of Water Resources (Reeter and Cady, 1982) and the City of Tucson (Babcock and others, 1987) to monitor the aquifer system in Avra Valley.

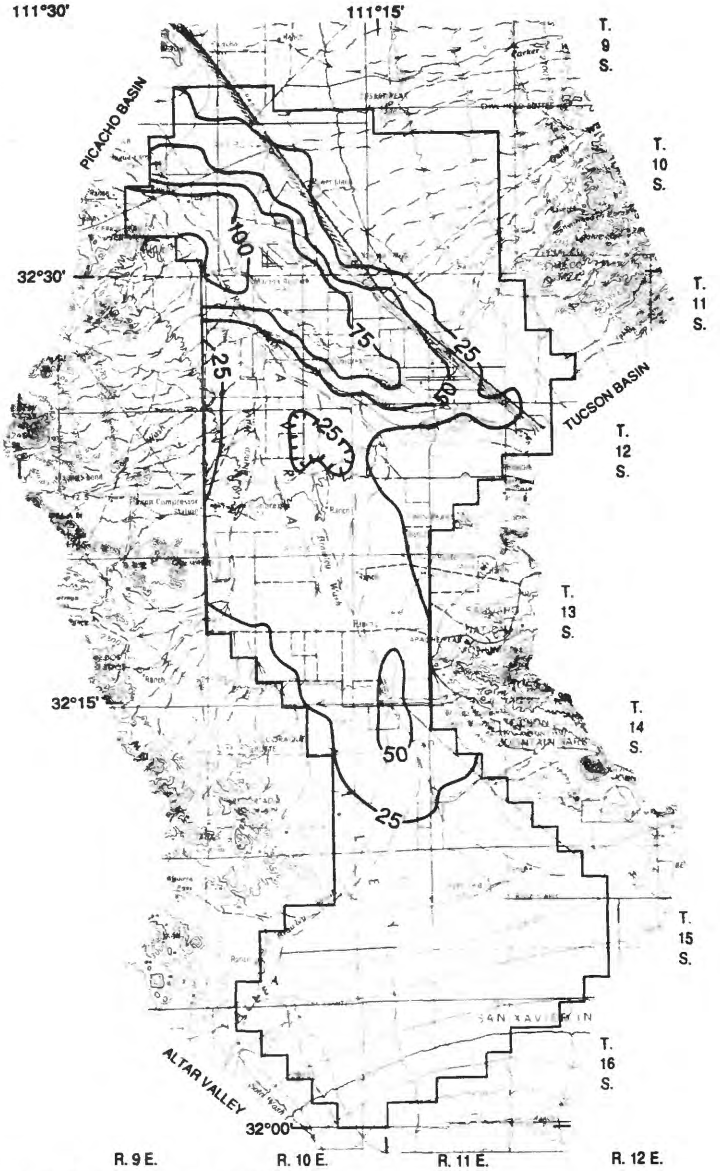
Steady-State Simulation

Simulation of ground-water flow in 1940 allowed for evaluation of steady-state conditions in the aquifer before extensive ground-water development. The simulation required zero change in storage (inflow equal to outflow) and agreement between measured and simulated head and estimates of steady-state inflow and outflow. The steady-state model was calibrated by adjusting hydraulic conductivity, transmissivity, and vertical leakance within the limits of field estimates.

Computed outflow balanced within 0.09 percent of specified inflow and was similar in magnitude to previous estimates of underflow (table 1). The steady-state simulation, which is similar to those by Moosburner (1972) and Clifton (1981), required negligible mountain-front recharge and no streamflow infiltration (table 1). About half the total estimated inflow—9,900 acre-ft/yr—entered the basin as underflow near Three Points, and the other half—9,000 acre-ft/yr—entered the basin as underflow near Rillito. Two-thirds of the inflow near Three Points and most of the inflow near Rillito occurred in layer 1. Total computed outflow was 18,900 acre-ft/yr with about 99 percent occurring in layer 1 near Picacho Peak.

Hydraulic conductivity (layer 1, fig. 7) and transmissivity (layer 2, fig. 8) were estimated from existing data and the analog model (Moosburner, 1972). Initial estimates of hydraulic conductivity and transmissivity were adjusted during calibration to produce the final distributions. Transmissivity of layer 1 (fig. 9) was calculated on the basis of saturated thickness (fig. 10) and specified hydraulic conductivity. Magnitude and distribution of hydraulic conductivity and transmissivity are comparable with those determined by other studies (Moosburner, 1972; Clifton, 1981; Whallon, 1983).

The steady-state simulation produced little difference between head distributions in layers 1 and 2; however, vertical flow between layers was indicated and was greatest in the south half of the valley. About two-thirds (2,800 acre-ft/yr and 15 percent of total basin budget) of net upward flow simulated in the model from layer 2 to layer 1 occurs south of T. 13 S. Vertical flow south of T. 12 S. probably is the result of the combined effects of convergence of lateral flow paths caused by narrowing of the valley, increased resistance to northerly flow in layer 2 caused by the abundance of silt, clay, and mudstone in the subsurface north of T. 14 S., and upwelling of deep flow in layer 2 caused by the presence of a shallow bedrock saddle in T. 14 S. (figs. 2 and 3). Vertical flow in the north half of the valley, unlike that in the south half, is restricted in places by impermeable layers of silt, clay, and mudstone.



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

0 5 10 MILES
0 5 10 KILOMETERS

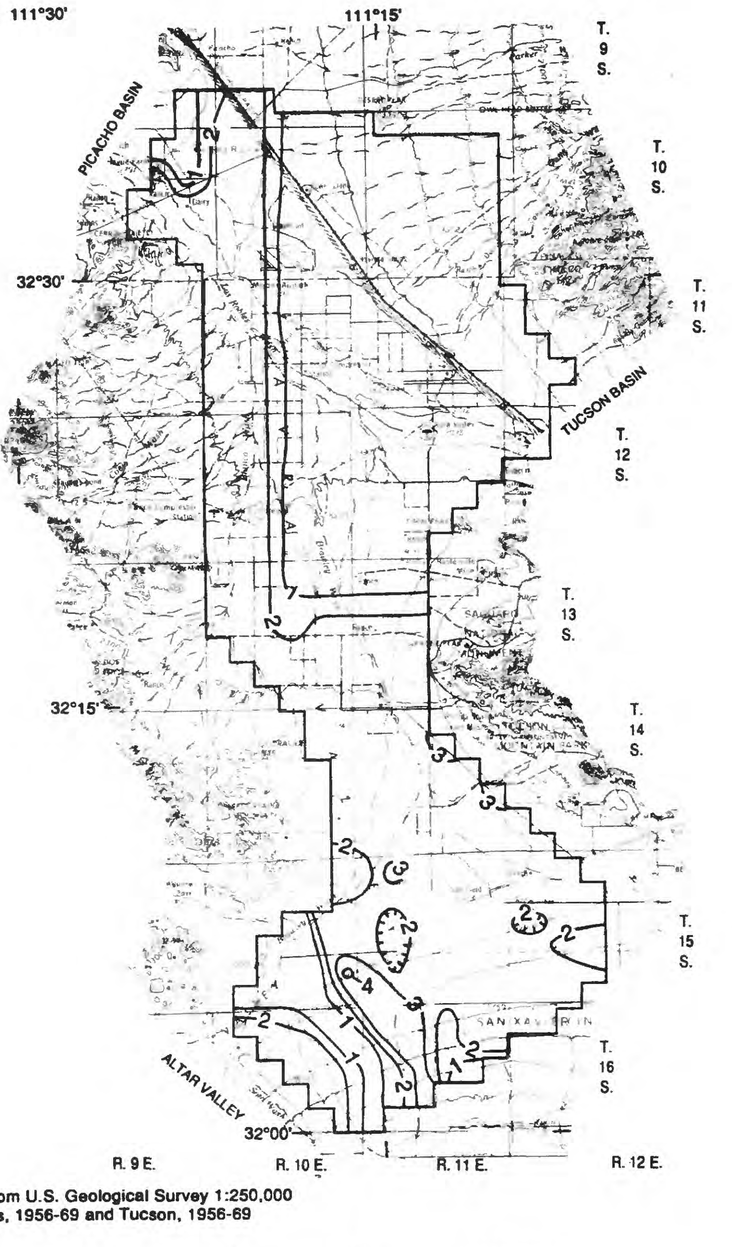
CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

—50— LINE OF EQUAL HYDRAULIC CONDUCTIVITY—Interval 25 feet per day. Hachures indicate closed area of lower hydraulic conductivity

——— MODEL BOUNDARY

Figure 7.--Hydraulic conductivity of model layer 1.

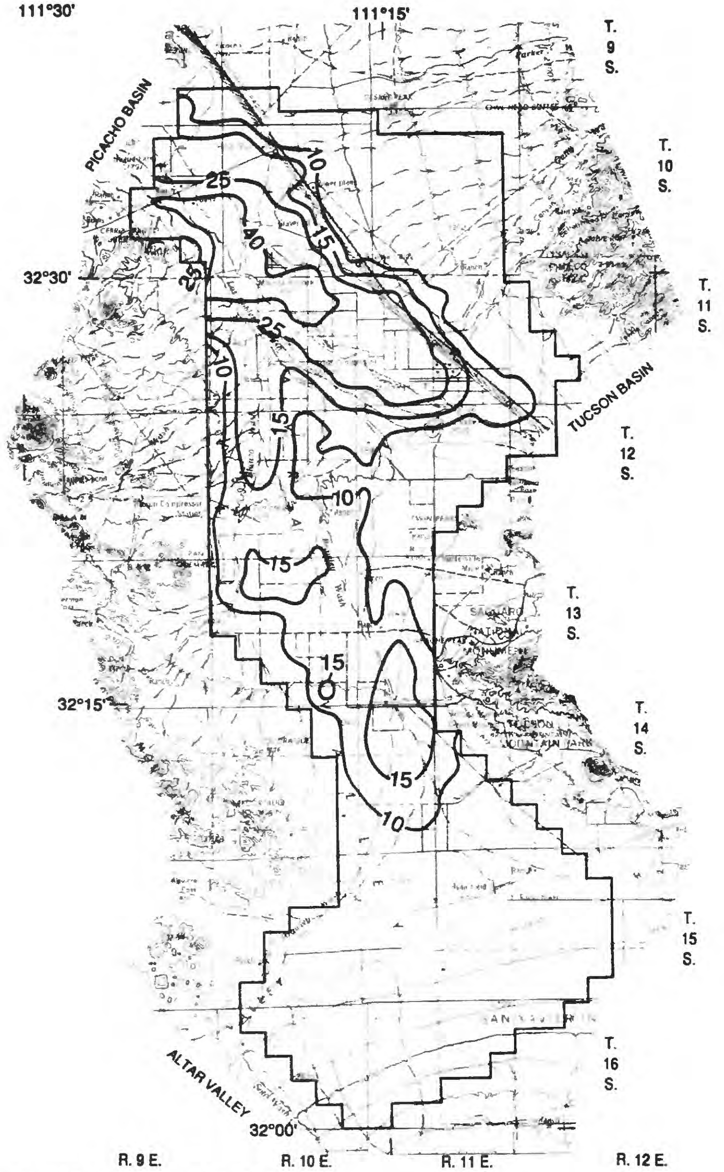


EXPLANATION

— 2 — LINE OF EQUAL TRANSMISSIVITY—Interval in thousands of feet squared per day. Hachures indicate closed area of lower transmissivity

——— MODEL BOUNDARY

Figure 8.--Transmissivity of model layer 2.



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

0 5 10 MILES
0 5 10 KILOMETERS

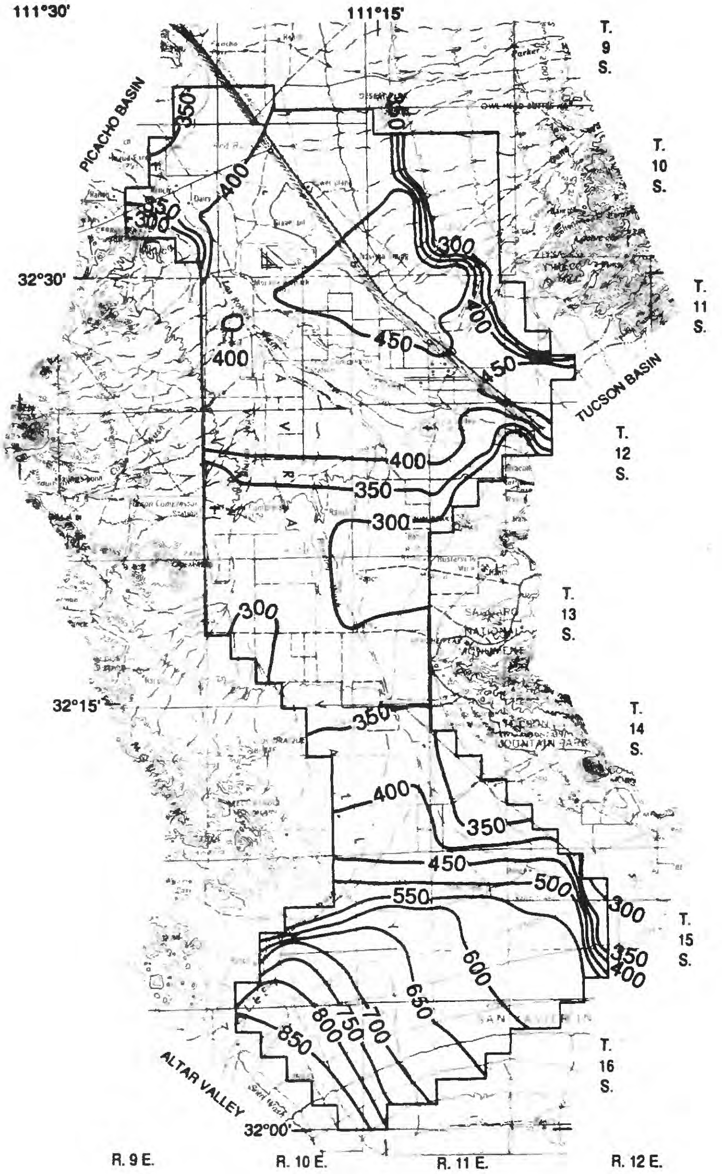
CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

—10— LINE OF EQUAL TRANSMISSIVITY—Interval 5, 10, and 15 thousands of feet squared per day

——— MODEL BOUNDARY

Figure 9.--Predevelopment transmissivity of model layer 1.



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

0 5 10 MILES
0 5 10 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

—300— LINE OF EQUAL SATURATED THICKNESS— Interval 50 feet

——— MODEL BOUNDARY

Figure 10.--Predevelopment saturated thickness of model layer 1.

The root-mean-square difference between measured and simulated water levels in 100 wells was 16 ft. This comparison data set included 85 of the 99 water levels used for an inverse solution of steady-state heads by Clifton (1981). Most errors were negative, indicating that simulated water levels were slightly higher than measured (fig. 11). The largest negative errors occurred mainly in the southwestern part of the model area near Three Points where estimates of heads and aquifer components are less certain than elsewhere. Differences between hand-drawn contours of measured water levels and simulated head for layer 1 generally ranged from 5 to 10 ft north of T. 14 S. to 20 ft south of T. 14 S. with the largest difference of about 40 ft in the south half of the valley (fig. 12). Water-level gradients and contour shapes were similar north of T. 14 S. South of T. 13 S., gradients of simulated heads were not as steep as gradients of measured heads, and contours of simulated heads were less arcuate than hand-drawn contours of measured head. Steep water-level gradients and arcuate hand-drawn contours of measured heads along the model boundary in Tps. 14 and 15 S. may indicate possible ground-water inflow or mountain-front recharge along the northern flanks of the Sierrita Mountains and some streamflow infiltration along Brawley Wash that were not included in the steady-state simulation.

Transient-State Simulation

Simulation of ground-water flow from 1940 through 1984 allowed for evaluation of the response of the aquifer system to pumping and recharge through time. Transient-state simulations used hydraulic characteristics determined from the steady-state simulations. Transient simulations included yearly time steps within seven pumping (stress) periods—1940-50, 1951-55, 1956-60, 1961-64, 1965-72, 1973-77, and 1978-84. Model simulated pumpage was computed as the net effect of estimated pumpage minus estimated recharge from irrigation return flow and streamflow infiltration.

The transient-state simulation was calibrated by adjusting estimates of specific yield and recharge to match hydrographs and contour maps of measured and simulated heads. The calibrated simulation provided estimates of changes in head, recharge, and the quantity of water removed from storage through time. Transient calibration was done over two time periods, 1940-64 and 1965-77. The first time period was considered to represent a storage-depletion system and allowed for calibration of storage properties and comparison with analog-model results (Moosburner, 1972). The second time period was characterized by changing pumpage distributions caused by retirement of irrigated land and was affected by an apparent increase in recharge. Increased recharge may have been caused by deep percolation of irrigation return flow that reached the water table and by increased streamflow infiltration resulting from greater sewage effluent and greater streamflow.

An additional transient simulation for the period 1978-84 applied pumpage distributions for 1973-77 and accounted for 1978-84 pumpage and recharge volumes but did not account for spatial changes in pumpage that may have occurred through time. The 1978-84 pumpage was identical to 1973-77 pumpage except that all pumpage was assumed to be zero from the Pima County line (model row 8) to just south of the Tucson

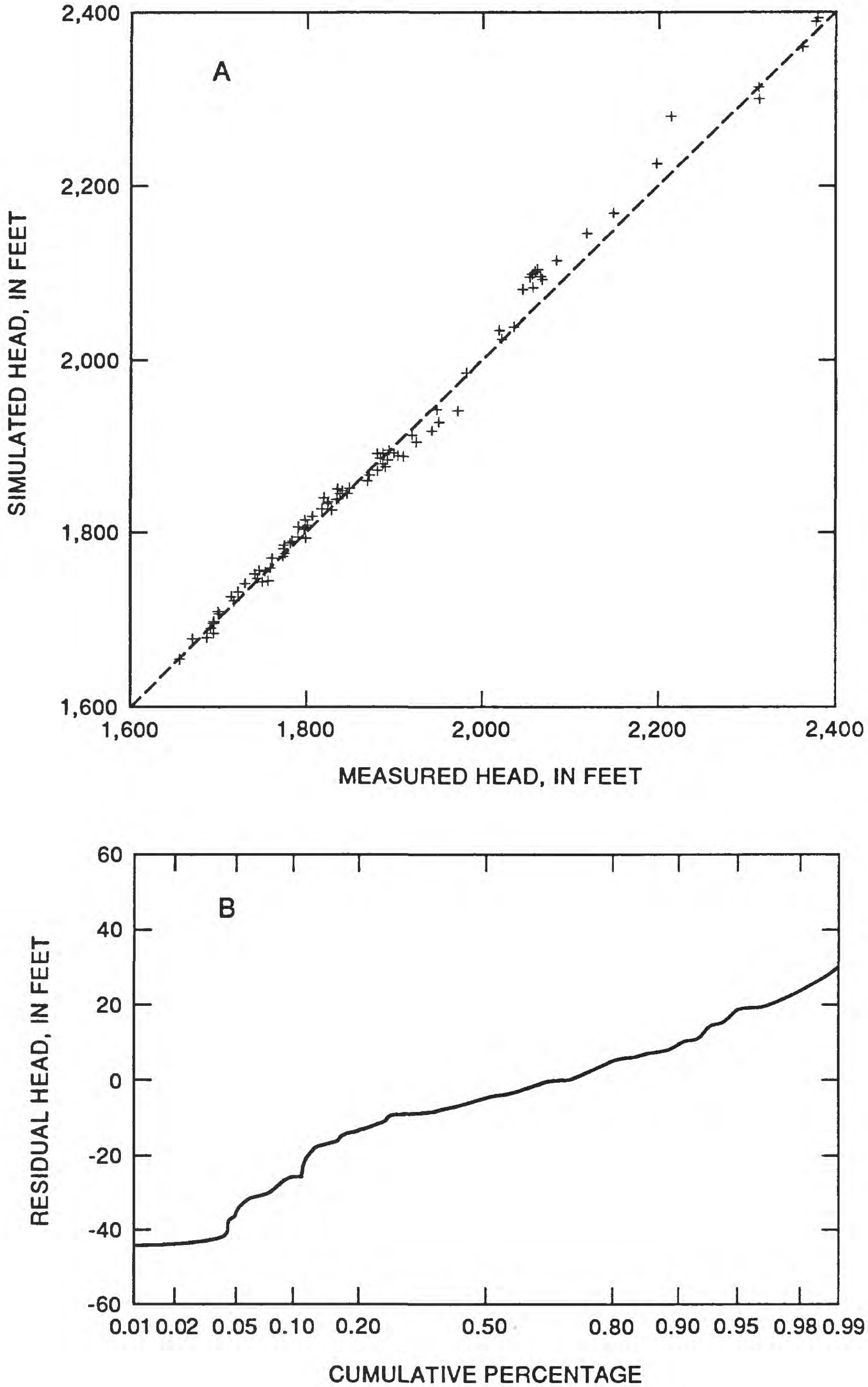
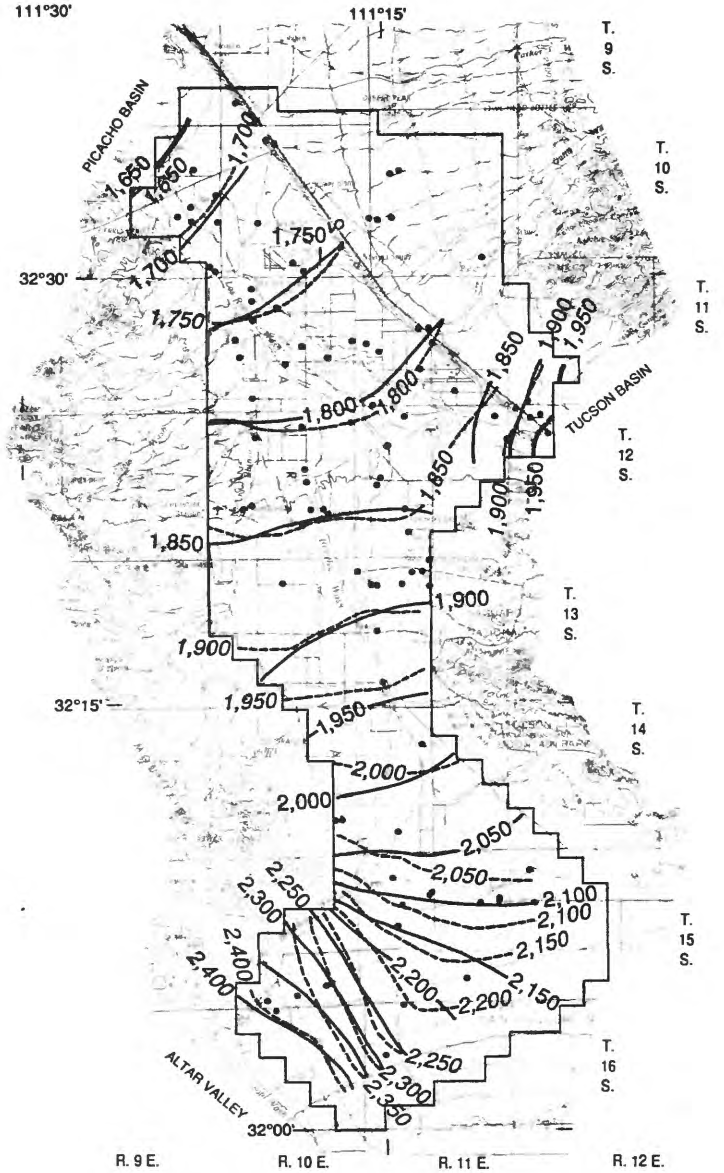


Figure 11.--(A) Deviation of simulated heads from measured heads; (B) Weibull probability plot of head residuals.



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

0 5 10 MILES
0 5 10 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

---*2,100*--- WATER-LEVEL CONTOUR FROM MEASURED 1940 DATA (MOOSBURNER, 1972)—Shows altitude of water level. Contour interval 50 feet. Datum is sea level

—2,100— WATER-LEVEL CONTOUR FROM SIMULATED 1940 DATA—Shows altitude of water level. Contour interval 50 feet. Datum is sea level

——— MODEL BOUNDARY

• WELL

Figure 12.--Measured and simulated ground-water levels in Avra Valley, 1940.

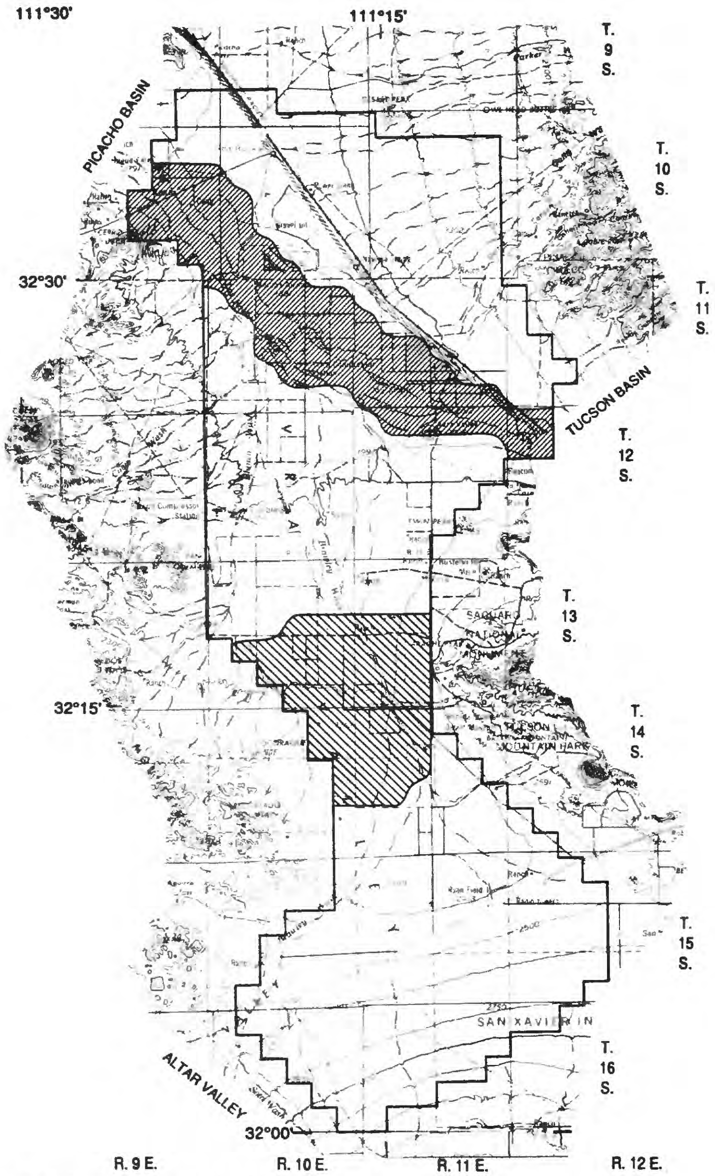
Mountains (model row 32) (fig. 6). The reduction in pumpage is assumed to coincide with increased recharge and retirement of agricultural land.

Transient-state storage was simulated by specific yield in layer 1 to reflect water-table decline in the unconfined part of the aquifer system and by storage coefficient in layer 2 for the confined part of the aquifer system. The initial storage value was specified as 0.12 for layer 1 and $1x10^{-4}$ for layer 2. A specific yield adjustment was required for calibration of the 1940-64 period. Specific yield in layer 1 was adjusted to 0.18 along the Santa Cruz River and 0.10 in Tps. 13 and 14 S. (fig. 13) to agree with aquifer lithology and to obtain rates of decline that were closer to measured conditions. Adjusted values, which were within the range of previous estimates of specific yield (White and others, 1966; Moosburner, 1972; Anderson, 1972; Whallon, 1983; Freethey and others, 1986), provided an acceptable representation of measured head and analog-model results and were used for later simulation periods. The upper layer remained saturated at all active cells through the end of 1984. Most of the water derived from storage was from the interfingered-zone subregions where most pumping occurred.

Recharge was within the range of computational and estimated pumpage errors from 1940 through 1964 (Moosburner, 1972) but increased dramatically after 1964 (table 1). Average pumpage increased slightly from 1965 to 1977 even though the City of Tucson retired sufficient agricultural land to reduce pumpage by about 53,000 acre-ft/yr. Using the estimated pumpage created model drawdowns that were much greater than field measurements indicated. For example, total recharge in the northern part of Avra Valley was estimated to range from 45,000 to 60,000 acre-ft/yr, which includes effluent and streamflow infiltration. In the Santa Cruz River, the maximum possible recharge from sewage effluent and natural flow is about 18,000 acre-ft/yr—about one-third of the recharge required to match measured decline rates. Clearly, another recharge source is needed to match heads and decline rates; this source probably is irrigation return flow. Simulated pumpage, therefore, was reduced by 30 percent to account for an irrigation efficiency of about 70 percent in northern Avra Valley.

Estimated and simulated pumpage (fig. 14; table 1) averaged over the simulation intervals from 1940 through 1984 indicate several differences. From 1940 through 1964, when recharge was assumed to be less than 15,000 acre-ft/yr, estimated pumpage averaged 6,000 acre-ft/yr less than simulated pumpage. From 1965 through 1984, when recharge from irrigation return flow and streamflow infiltration was greater than 50,000 acre-ft/yr, estimated pumpage averaged 71,000 acre-ft/yr more than the simulated pumpage required for calibration of heads. Differences between estimated and simulated pumpage indicate a minimum of 1 million acre-ft of recharge to the aquifer system from 1965 through 1984 in areas of Tps. 11, 12, 13, 14, and 15 S. that are largely coincident with irrigated fields and the Santa Cruz River. Recharge from irrigation return flow and streamflow infiltration was the source of 40 percent of estimated pumpage from 1965 through 1984 for this part of Avra Valley.

The match between measured and simulated water-level decline generally was better in the north half of the valley than south of T. 14 S. on the basis of hydrographs and contours of water-level change (figs. 15-17). Differences between measured and simulated water levels



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

0 5 10 MILES
0 5 10 KILOMETERS
CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

SPECIFIC YIELD

0.10

0.12

0.18

MODEL BOUNDARY

Figure 13.--Specific yield of model layer 1.

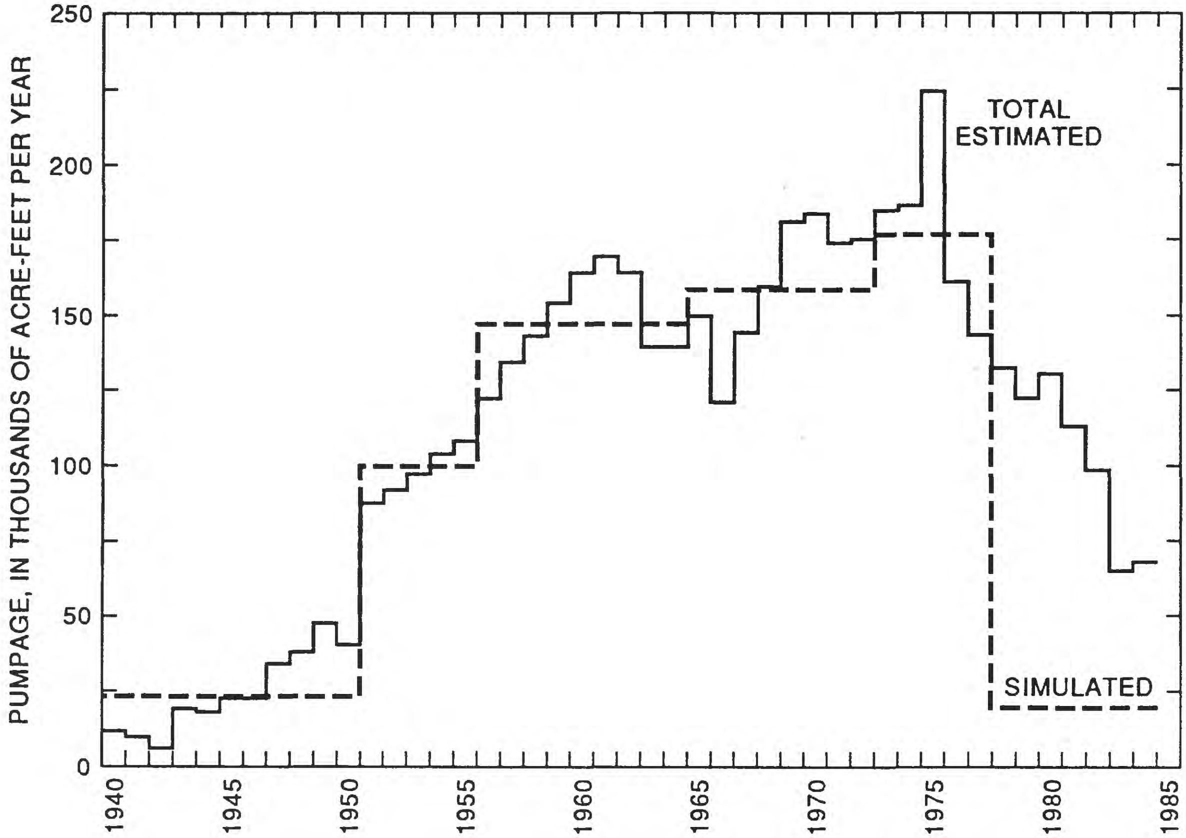


Figure 14.--Estimated and simulated average yearly pumpage, by simulation interval, in Avra Valley, 1940-84.

generally ranged from less than 5 to 25 ft in the north half of the valley and from 25 to 50 ft south of T. 14 S. (figs. 15-17). Hydrograph slopes were matched by simulated declines, especially during the period of decline from 1940 through 1964. Changes in measured and simulated hydrograph slopes matched the recovery that occurred in many wells after 1964 with a 1- to 3-year lag due in part to the use of multiyear pumping periods. Recovery was greatest from 1978 through 1984 during a period of above-average streamflow in the Santa Cruz River. Simulated declines ranged from 1 to 188 ft for 1940-77 and from 2 to 157 ft for 1940-84 (figs. 16 and 17). Contours of measured and simulated decline generally are similar in shape and distribution throughout the valley.

The development of perched aquifers became noticeable in many areas after 1964 but the perched aquifers were not simulated. Zones of suspected perched ground water that existed north of T. 12 S. in 1985 are shown in figure 17. These zones, which are characterized by elevated water levels in shallow wells and cascading water in deep wells, may be the result of mounding of irrigation return flow above fine-grained interbeds (aquitards). Wells A, B, C, F, G, and I (figs. 15 and 17) lie within the perched zones and post-1964 water levels in these wells may be elevated with respect to the aquifer system.

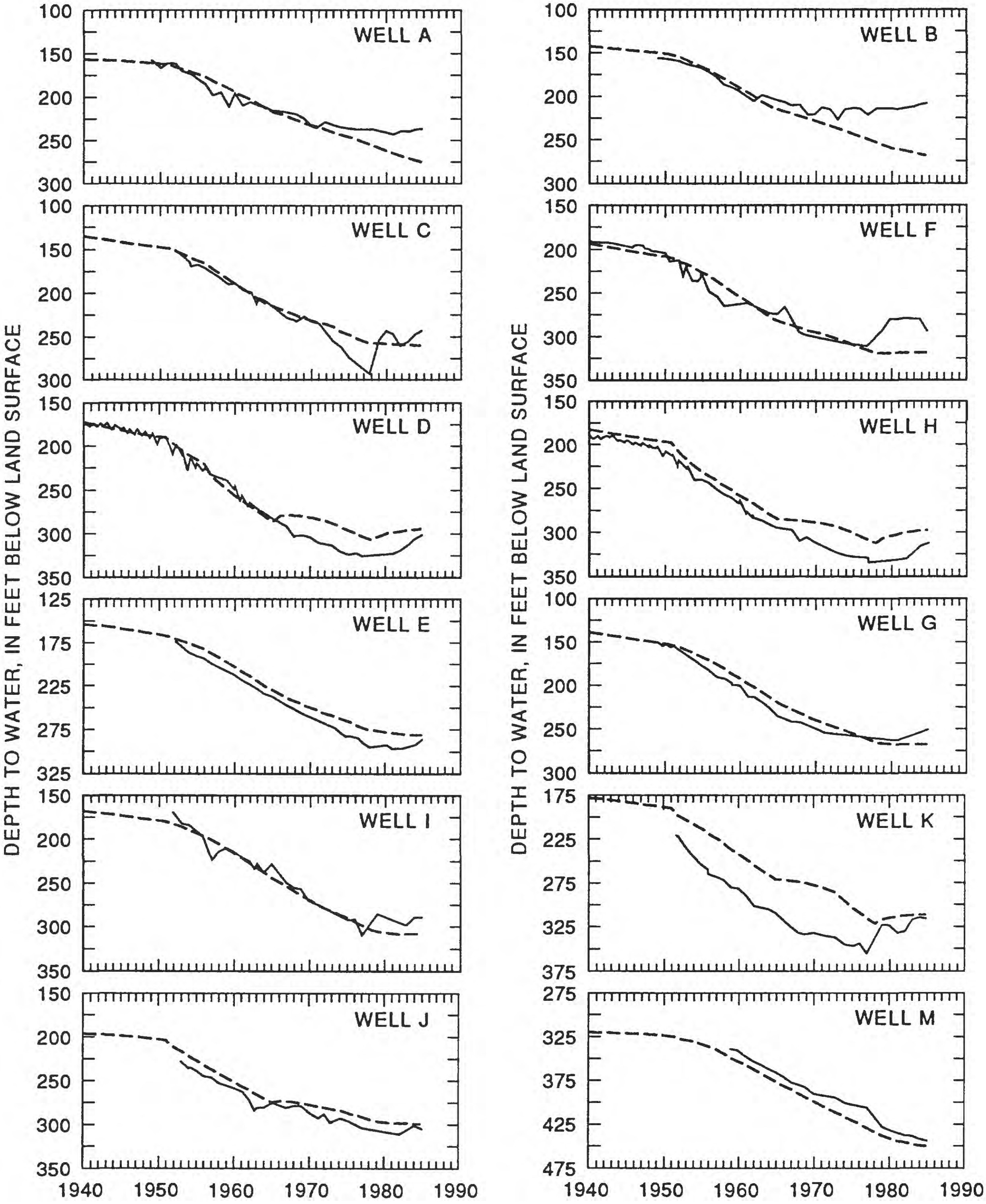


Figure 15.--Measured and simulated depth to water in selected wells in Avra Valley, 1940-85.

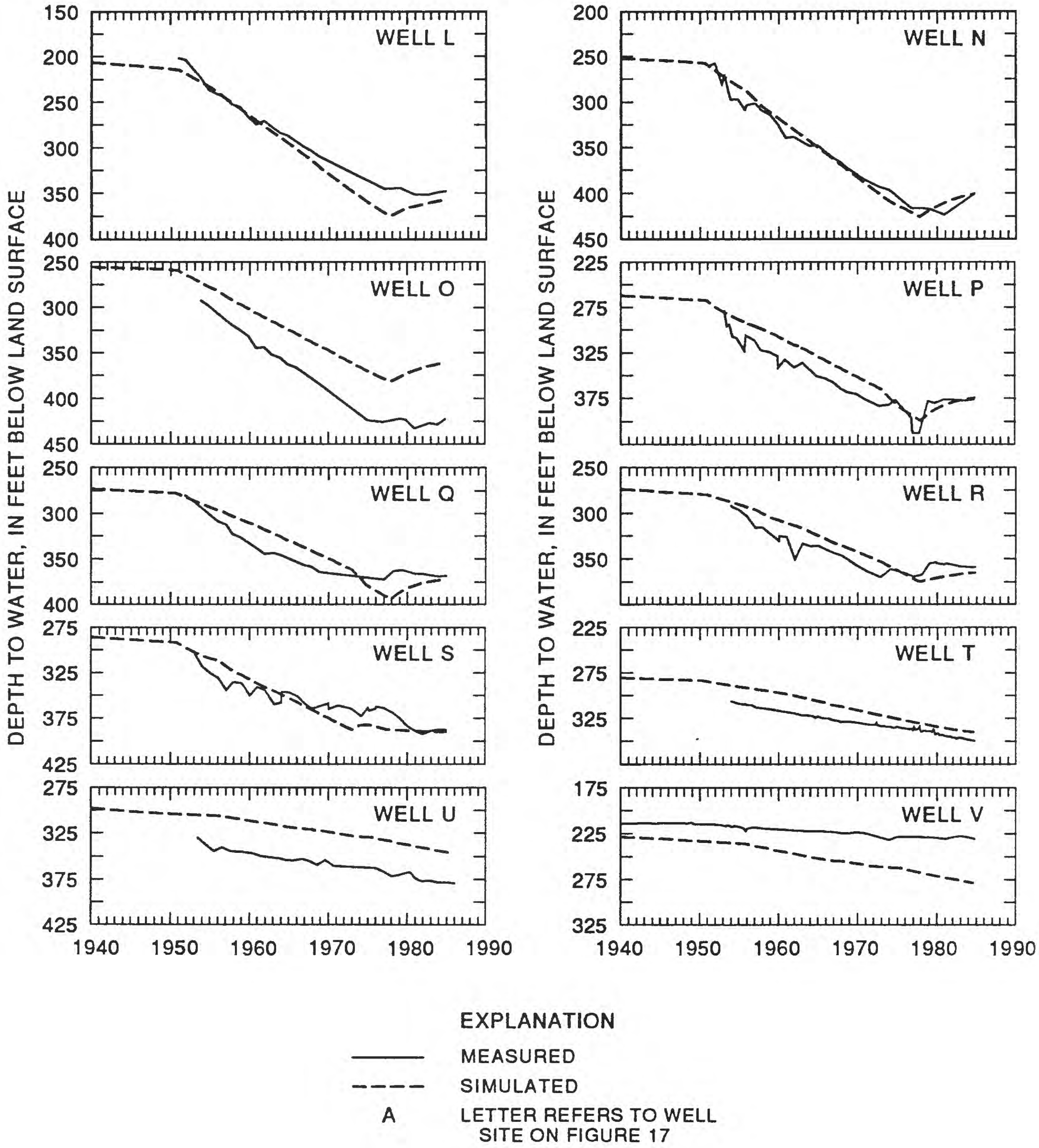
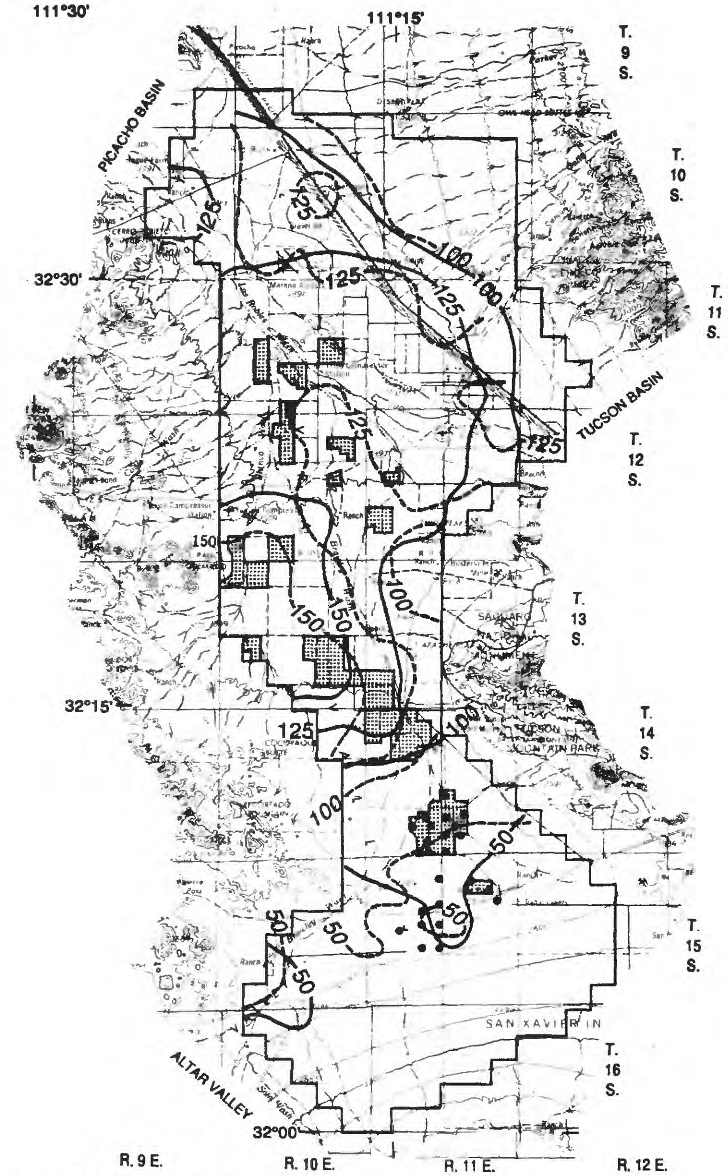


Figure 15.--Measured and simulated depth to water in selected wells in Avra Valley, 1940-85.--Continued



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

0 5 10 MILES
0 5 10 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

RETIRED FARMLAND, 1972-78

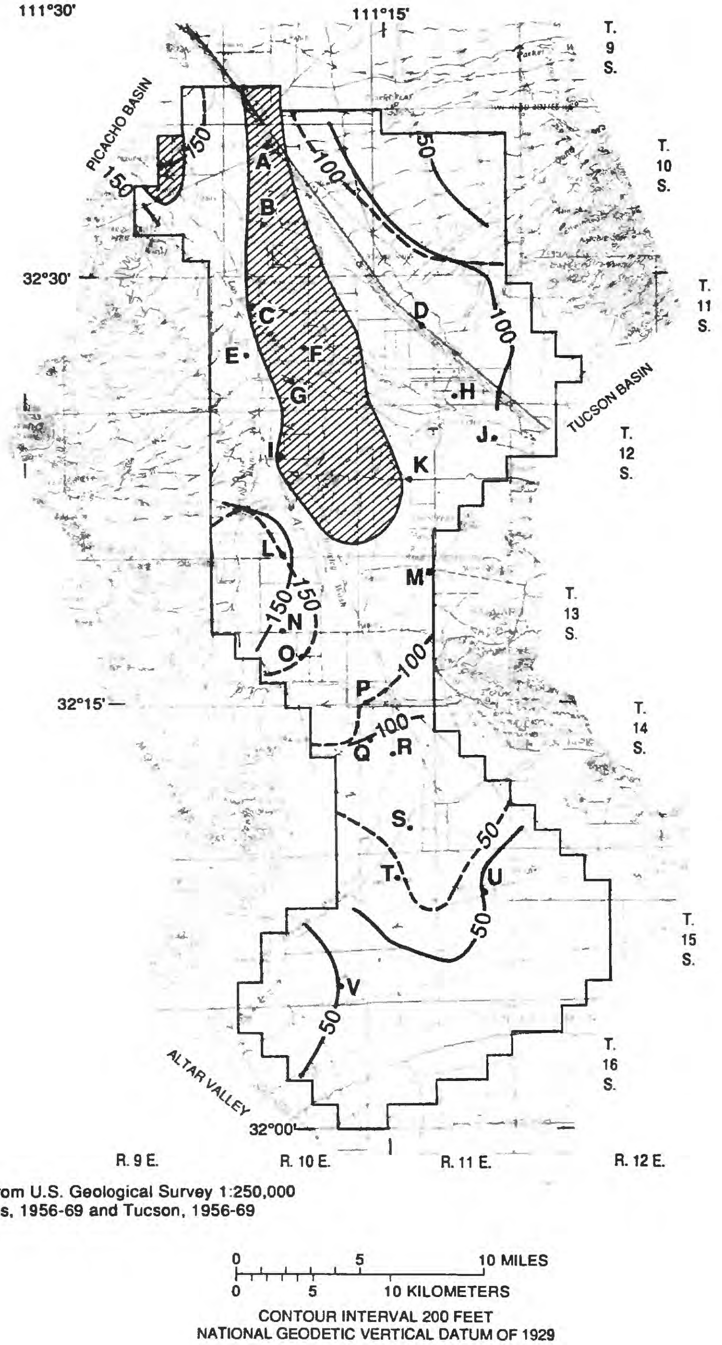
---150--- LINE OF EQUAL WATER-LEVEL DECLINE FROM MEASURED DATA, 1940-78—Interval 25 and 50 feet

—150— LINE OF EQUAL WATER-LEVEL DECLINE FROM SIMULATED DATA, 1940-78—Interval 25 and 50 feet

——— MODEL BOUNDARY

• CITY OF TUCSON PUBLIC-SUPPLY WELL, 1978

Figure 16.--Measured and simulated water-level declines in Avra Valley, 1940-78.



EXPLANATION

[hatched box]	ZONE OF SUSPECTED PERCHED GROUND WATER, 1985 (CUFF AND ANDERSON, 1987)	—150—	LINE OF EQUAL WATER-LEVEL DECLINE FROM SIMULATED DATA, 1940-85—Interval 50 feet
---150---	LINE OF EQUAL WATER-LEVEL DECLINE FROM MEASURED DATA, 1940-85—Interval 50 feet	———	MODEL BOUNDARY
		A	WATER-LEVEL MONITORING WELL—Letter, A, corresponds to hydrograph in figure 15

Figure 17.--Measured and simulated water-level declines in Avra Valley, 1940-85.

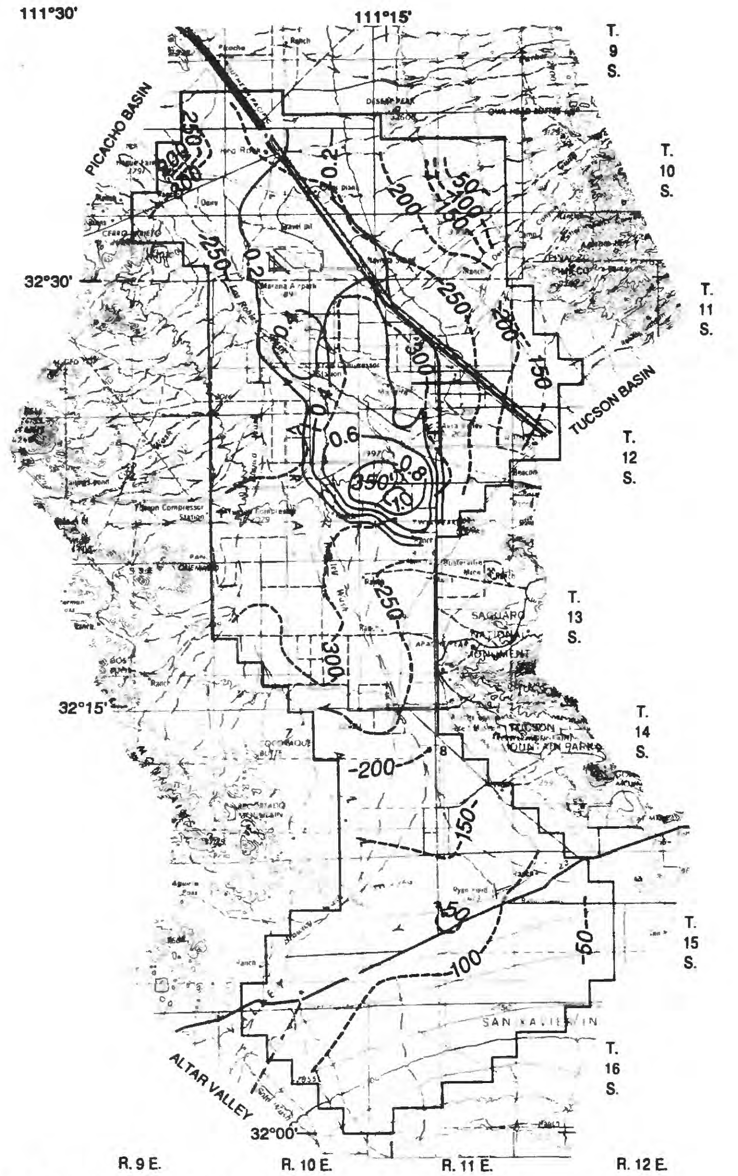
Pumpage and recharge greatly altered water levels and flow paths in the aquifer system from 1940 through 1984. Transient simulation indicated little difference between head distributions in layer 1 and layer 2 through 1984. A 32-percent decrease of net upward flow occurred from steady-state conditions in the area south of T. 12 S. A decrease in net vertical flow from 2,800 acre-ft/yr of upward flow to about 830 acre-ft/yr occurred from 1940 through 1984 north of T. 13 S. Pumping and storage depletion occurred mainly in interfingered-zone subregions from 1940 through 1984 (fig. 18). Aquifer-system storage depletion caused by pumping in excess of recharge was the major source of ground-water withdrawals. Simulated net withdrawal of water from aquifer-system storage from 1940 through 1984 was about 3.4 million acre-ft on the basis of model simulations. Percentage net withdrawal of water from aquifer-system storage (fig. 18) was greatest from interfingered-zone subregions (fig. 6, zones 2 and 3) and least from alluvial-fan and playa subregions (fig. 6, zones 1 and 4).

Sensitivity Analysis

Systematic change of selected hydraulic characteristics and boundary conditions allowed for evaluation of model sensitivity and potential simulation error. Sensitivity analysis indicated that the model was most sensitive to changes in transmissivity of layer 2 and specific yield of layer 1 and least sensitive to changes in transmissivity of layer 1 and leakance between layers (table 2). Because changing gradients were believed to occur at inflow and outflow areas, flux across boundaries at these locations may change with time. To assess the impact of decreasing heads and changing gradients, new constant heads were incorporated with each pumping period. This simulation indicated that flux across the boundaries did not change appreciably from steady-state inflows and outflows. Alternative conditions, such as specific yield in layer 2 and complete restriction of flow between layers, resulted in unacceptable differences between measured and simulated head. Evaluation of model sensitivity indicate a reasonable choice of aquifer-system components and boundary conditions for simulation of ground-water flow through 1984.

SIMULATION OF POTENTIAL LAND SUBSIDENCE

Subsidence simulations were used to demonstrate the relation between inelastic storage and sediment textural facies on the basis of four subregions of average clay-silt fraction (fig. 6) that generally coincide with playa (zone 4), alluvial fan (zone 1), and interfingered-zone (zones 2 and 3) depositional environments (Anderson, 1989; Anderson and Hanson, 1987). In order to simulate potential land subsidence, the ground-water flow model was coupled with a numerical-subsidence routine developed by Leake and Prudic (1988). The subsidence routine computes the ultimate compaction caused by water-level decline. When water-level decline exceeds the preconsolidation-stress threshold, compaction becomes inelastic and nonrecoverable (Poland and others, 1972; Hanson, 1988). When decline is less than the stress threshold, compaction is elastic and recoverable. Elastic and inelastic compaction of fine-grained aquifer-system interbeds, herein referred to as aquitards (Poland and



Base from U.S. Geological Survey 1:250,000
Nogales, 1956-69 and Tucson, 1956-69

0 5 10 MILES
0 5 10 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

—— *150* —— LINE OF EQUAL POTENTIAL WATER-LEVEL DECLINE, 1940-2025—Interval 50 feet. Simulation includes release of water from aquitard storage after 1985

—— 0.6 —— LINE OF EQUAL POTENTIAL MINIMUM LAND SUBSIDENCE, 1985-2025—Interval 0.2 foot. Simulation based on an inelastic specific storage of 1.0×10^{-5} foot^{-1}

———— MODEL BOUNDARY

Figure 18.--Potential water-level decline and minumum land subsidence in Avra Valley, 1940-2025.

Table 2.--*Summary of sensitivity analysis*

[Dashes, hydraulic components not applicable]

Hydraulic component[1]	Range in calibrated values	Multi-plier	Change in flow, in percent[2]	Change in head for layer 1, in feet[3]	Difference in head for layer 2 minus layer 1, in feet
Transmissivity of layer 1, in feet squared per day	1,000 to 45,000	0.67	-2.9	-1 to 9	0 to 8
		1.33	30.9	-6 to 1	0
Transmissivity of layer 2, in feet squared per day	1,000 to 3,000	.1	-11.3	-38 to 8	0
		.5	-6.6	18 to 0	0
		1.4	61.2	0 to 37	0 to 11
		10.0	120.8	1 to 84	0 to 17
Vertical-leakance factor, in feet per day per foot	10^{-2} to 10^{-4}	100	-.9	0 to 2	0
		10^{-2}	-.5	-6 to 0	0 to 16
		10^{-4}	-2.7	-25 to 21	0 to 72
Specific yield of layer 1	.10 to .18	.8	-----	-1 to -43	1 to -4
		1.2	-----	0 to 56	1 to -4

[1]All hydraulic components except specific yield are evaluated for the steady-state simulation.
[2]Percent of calibrated steady-state total model flow.
[3]Change in head with respect to calibrated, steady-state head surface over active part of model grid.

others, 1972), results in drainage of pore water from the aquitards into adjacent coarse-grained aquifers. Thus, the contribution to withdrawals from aquitard storage and subsequent reduced declines in the aquifer system from this additional source of water are estimated implicitly through this coupled approach to subsidence simulation.

Two potential scenarios of water-level decline and subsidence that may occur from the continued withdrawal of ground water are presented in this report. A minimum subsidence estimate was based on the assumption that aquitard inelastic compressibility will remain within the range of 1986 values determined from calibration of one-dimensional compaction simulations (Hanson, 1989). A maximum subsidence estimate was based on the assumption that rates of compaction will increase to potential ultimate inelastic compressibility early within the pumping period (Anderson, 1989). Subsidence projections, which reflect large inherent uncertainties related to the determination of aquifer-system compressibility and stress thresholds, are intended only to show the relation between potential subsidence and the minimum and maximum compressibilities. Refinement of results in the future, however, may be attained through periodic recalibration of the model using field data from existing subsidence- and compaction-monitoring networks (Anderson, 1989; Hanson, 1987, 1988; Schumann and Anderson, 1988).

Potential subsidence through 2024 was simulated using 1985 model-computed heads as initial conditions and the aquifer properties derived from historical calibration. Subsidence projections used pumpage and recharge values from 1973 through 1977, which were characterized by average pumpage of 153,000 acre-ft/yr and average recharge of 40,000 acre-ft/yr. Simulations included yearly time steps from 1985 through 2024. Simulation of compaction was limited to the upper alluvium (Anderson, 1989).

The effects of compaction within the lower alluvium; inelastic timelag; subsidence before 1985; and lateral changes in sediment layering, sorting, cementation, and density were evaluated indirectly. Compaction within the lower alluvium was considered unlikely on the basis of probable stress ranges and geologic characteristics (Anderson, 1989). Inelastic timelag (Hanson, 1987, 1988) was considered small in relation to the projection pumping period of 40 years. Subsidence before 1985 ranged from 0 to 1.1 ft in the north half of the valley along the Southern Pacific Railroad and I-10 (Strange, 1983), was uncertain elsewhere in the valley (Anderson, 1989), and was assumed small compared with maximum subsidence projections. Sediment heterogeneities were simulated indirectly on the basis of assignment of inelastic specific storage values (Anderson, 1989; Hanson, 1988) and determination of average aquitard thickness from composite clay and silt distributions (fig. 6). In general, average aquitard thickness increases and layering frequency decreases with increasing clay and silt content (Anderson and Hanson, 1987; Hanson, 1988).

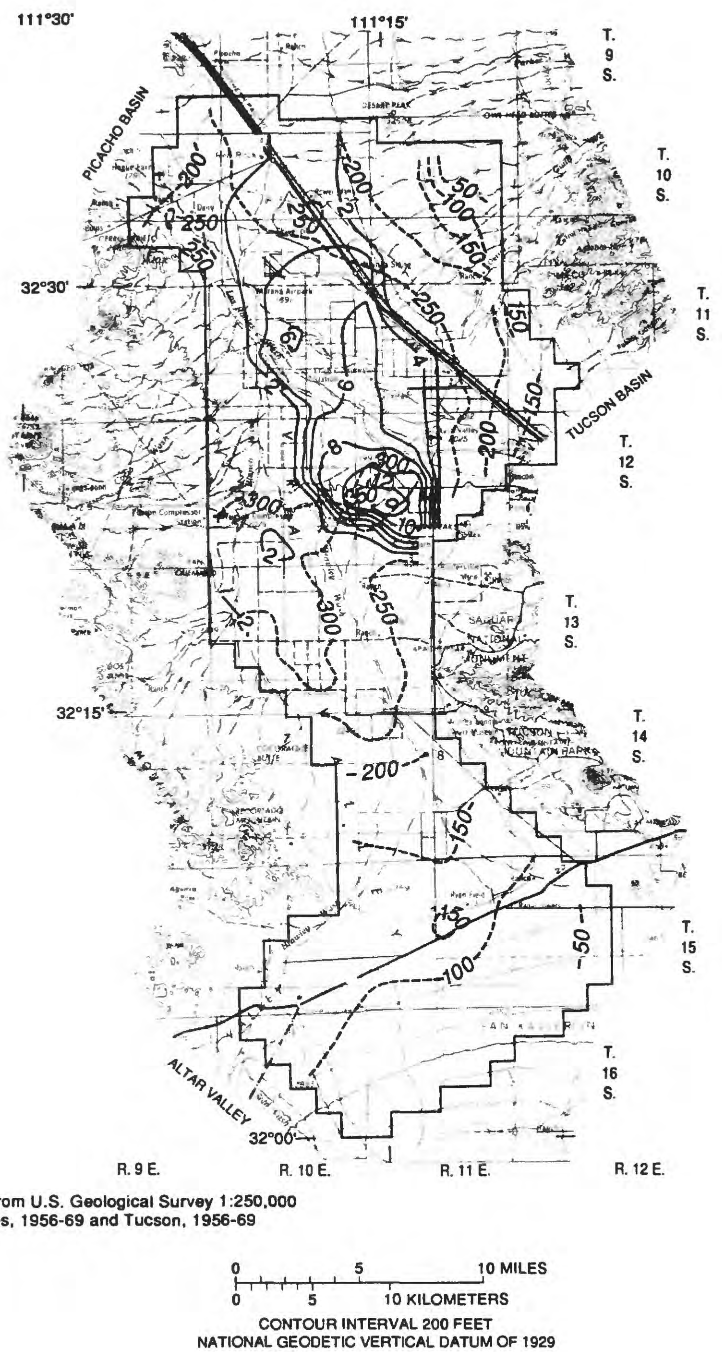
On the basis of model simulations (Helm, 1975, 1976), aquitard inelastic specific storage may be as large as about $1.5\times10^{-4}ft^{-1}$ for lacustrine and playa sediments (Ireland and others, 1982; Hanson, 1987; Epstein, 1987) and at least $1.0\times10^{-5}ft^{-1}$ for interfingered-zone and alluvial-fan deposits (Hanson, 1987). Maximum and minimum elastic and inelastic aquitard storage values were calculated for the upper alluvium in each cell of the upper layer from 1985 saturated thickness, average percent clay and silt concentration (fig. 6), and elastic and inelastic specific storage (Poland and others, 1972; Ireland and others, 1984; Anderson, 1989; Epstein, 1987; Hanson, 1988). Elastic specific storage was specified as $5.0\times10^{-6}ft^{-1}$ for the minimum case (Helm, 1975, 1976; Ireland and others, 1982; Epstein, 1987; Hanson, 1987, 1988) and $1.0\times10^{-5}ft^{-1}$ for the maximum case (Anderson, 1989). Inelastic specific storage was specified as $1.0\times10^{-5}ft^{-1}$ for the minimum case (Hanson, 1988) and $1.5\times10^{-4}ft^{-1}$ for the maximum case (Helm, 1975, 1976; Ireland and others, 1982; Anderson, 1989; Epstein, 1987). Minimum storage values were derived from model (Helm, 1975, 1976) calibration of historical extensometer data (Hanson, 1988). Because of the small net compaction of less than 0.14 ft between 1984 and 1986, minimum storage values may represent transition from elastic to inelastic compaction of the aquifer system (Hanson, 1988). Maximum storage values were estimated from model (Helm, 1975, 1976) calibration of field data from alluvial basins where inelastic compaction is in excess of several feet (Helm, 1975, 1976; Ireland and others, 1982; Epstein, 1987).

Transition between elastic and inelastic compaction occurs when the water level at each cell falls below a critical head. Water-level decline from predevelopment conditions to the critical head is defined as the preconsolidation-stress threshold (Hanson, 1988). The preconsolidation-stress threshold, which may range from 50 ft in fine-grained sediments to 150 ft in coarse-grained sediments, probably averages about 100 ft (Holzer, 1981; Anderson, 1989; Hanson, 1988). Insufficient data precluded the use of spatially distributed preconsolidation-stress thresholds for subsidence projections. The preconsolidation-stress threshold was assumed to be either 100 ft of decline from predevelopment conditions or the maximum transient-simulation head declines of greater than 100 ft in 1978 and 1985 (figs. 16 and 17). These maximum water-level declines were used for 1985 estimates of critical head in the upper layer. Ground-water declines ranged from 100 to 150 ft throughout much of the north half of the valley through 1984 (Cuff and Anderson, 1987). Subsidence data were not available to determine if ground-water declines since predevelopment conditions in this area were greater than preconsolidation-stress thresholds for initial simulation time steps.

Simulation results indicate that an order-of-magnitude difference in potential subsidence and tens-of-feet difference in potential water-level decline are related to the range of assumed inelastic specific storage (fig. 19). Maximum simulated subsidence for a value of $1.0x10^{-5}ft^{-1}$ was 0.9 ft compared to 14.7 ft for a value of $1.5x10^{-4}ft^{-1}$. From 1985 through 2024, maximum simulated ground-water decline ranged from 190 to 220 ft and was greatest for the smaller value of inelastic specific storage. The difference in simulated water-level decline is a result of the irreversible release of water from aquitard storage. Although potential decline may be less for larger inelastic specific storage and subsidence, the lesser decline will be accompanied by greater permanent reduction of aquifer-system storage and greater pumping-level drawdowns.

Simulated drawdowns indicate a potential for localized complete dewatering of the upper alluvium north of T. 14 S. from 2005 through 2024. Dewatering (fig. 20), which may be accompanied by a 35-percent decrease in yearly pumping rates, indicates that pumping rates and distributions of 1973-77 could not be sustained within the upper alluvium during the last 20 years of the 40-year projection. Alternative distributions of pumpage were not simulated but probably would have resulted in greater water-level declines. Potential for greater declines within dewatered cells did not affect subsidence projections because the assumption was made that compaction did not occur in the lower layer for the range of applied stress. Because of the large uncertainty in future pumpage, the projections were used only to demonstrate the impact on subsidence simulations from varying aquitard-storage properties.

Simulations indicate a potential maximum net withdrawal of water from aquifer-system storage of 4.2 million acre-ft from 1985 through 2024 for the assumed pumpage and recharge. Irreversible loss of storage is 1 percent from aquitard storage for an inelastic specific storage



EXPLANATION

—150— LINE OF EQUAL POTENTIAL WATER-LEVEL DECLINE, 1940-2025—Interval 50 feet. Simulation includes release of water from aquitard storage after 1985

—6— LINE OF EQUAL POTENTIAL MAXIMUM LAND SUBSIDENCE, 1985-2025—Interval 2 feet. Simulation based on an inelastic specific storage of 1.5×10^{-4} $foot^{-1}$

——— MODEL BOUNDARY

Figure 19.--Potential water-level decline and maximum land subsidence in Avra Valley, 1940-2025.

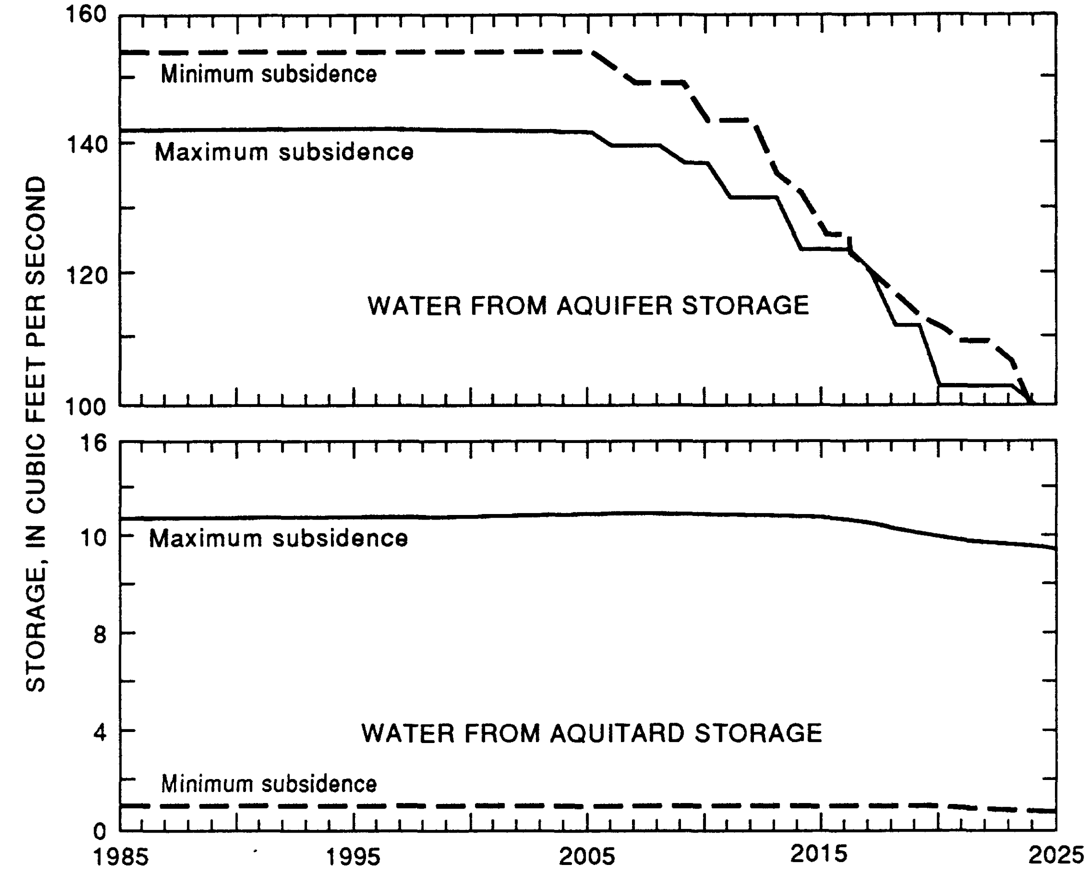


Figure 20.--Subsidence projection budget components for Avra Valley model, 1985-2025.

of $1.0 \times 10^{-5} ft^{-1}$ and 10 percent for a value of $1.5 \times 10^{-4} ft^{-1}$. The potential aquifer-system loss of 1 to 10 percent from aquitard storage is much less than that determined for other subsidence areas on the basis of volumetric ratios of land subsidence to ground-water withdrawal. Volumetric estimates of aquifer-system loss from regions with more than 10 ft of subsidence include 17 to 22 percent in the Galveston-Houston area, Texas (Jorgensen, 1975), 33 percent in the San Joaquin Valley, California (Poland and others, 1975), and 21 to 37 percent in the Picacho basin northwest of Avra Valley. Variations in aquitard-storage loss probably are related to several factors, such as visco-elastic effects (Bear and Corapcioglu, 1984), variations in aggregate thickness of compressible layers, formation-dependent preconsolidation-stress thresholds in layered sedimentary environments, and the general proportion of confined aquifers within an aquifer system. Simulation results suggest that contributions from aquitard storage may be smaller from predominantly unconfined aquifer systems such as Avra Valley and greater from largely confined systems such as the San Joaquin Valley.

Distribution of potential ground-water decline and subsidence indicate that maximum decline and subsidence probably will occur in the north half of the valley in Tps. 9, 10, 11, and 12 S. (figs. 18 and 19). Decline probably will be accompanied locally by dewatering of the upper alluvium. Use of the minimum value of inelastic specific storage results in larger areas with more than 300 ft of water-level decline and potential subsidence of less than 1 ft (fig. 18). Simulations using a maximum value of inelastic specific storage indicate a potential for as much as 15 ft of land subsidence but the area with more than 300 ft of ground-water decline is smaller and is restricted to the western part of T. 12 S., R. 11 E., by the year 2025 (fig. 19). Maximum subsidence results are comparable to previous estimates by Anderson (1989) and are similar to conditions in the Picacho basin northwest of Avra Valley where as much as 12.5 ft of land subsidence and 300 ft of water-level decline had occurred by 1977 (Laney and others, 1978). The subsidence projections indicate a high potential for differential subsidence between the center and edges of the valley north of T. 13 S. (figs. 18 and 19). These simulations used a single value of inelastic specific storage for playa, alluvial-fan, and interfingered-zone subregions. This approach does not account for any additional differential subsidence that may result if ultimate inelastic specific-storage values of playa sediments are large in relation to storage values for deposits within interfingered-zone and alluvial-fan subregions.

SUMMARY

Avra Valley is a 520-square-mile alluvial basin in southern Arizona from which ground water is withdrawn for agriculture, public supply, and industry. Ground-water withdrawals have caused water-level declines to exceed the preconsolidation-stress threshold of the alluvial deposits, resulting in aquifer compaction, land subsidence, and the formation of fissures at the land surface. Because of widespread water-level declines, the potential for future land subsidence in Avra Valley is high. The alluvial-aquifer system received sole-source designation by the U.S. Environmental Protection Agency in 1984. This report presents the results of the third phase of a long-term land-subsidence study in Avra Valley.

The alluvium in Avra Valley consists of upper and lower sedimentary units that are saturated at depth and form a complex alluvial-aquifer system. The upper alluvium includes playa, alluvial-fan, and interfingered-zone depositional environments. Deposits generally are fine grained north of T. 12 S. and coarse grained in the south half of the valley. Geologic data indicate that the upper alluvium is more likely to compact from the withdrawal of ground water than the lower alluvium.

The aquifer system generally is unconfined to depths of 1,000 ft and is bounded by impermeable bedrock at depth and on the east and west boundaries. Ground-water inflow occurs near Three Points and Rillito, and outflow occurs south of Picacho Peak. Inflow and outflow were about 18,900 acre-ft/yr in 1940 before significant ground-water development began. Combined recharge from infiltration of streamflow, irrigation return flow, and mountain-front recharge averaged less than 15,000 acre-ft/yr from 1940 through 1964, about 65,000 acre-ft/yr from

1965 through 1977, and about 86,000 acre-ft/yr from 1978 through 1984. Movement of water in the aquifer system generally is south to north in the southern part of the valley and southeast to northwest in the northern part. Transmissivity ranges from 1,500 to 40,000 ft^2/d in the upper alluvium and 1,000 to 50,000 ft^2/d in the lower alluvium. Simulated specific yield generally is 0.12 and ranges from 0.10 in Townships 13 and 14 South to 0.18 along the Santa Cruz River.

Annual ground-water pumpage increased from 12,000 acre-ft in 1940 to 174,000 acre-ft in 1975; pumpage in 1984 was 59,000 acre-ft for the part of Avra Valley in Pima County. Of the 4.2 million acre-ft of water withdrawn from 1940 through 1984 in Pima County, 96 percent was used for agriculture and the rest was for public supply and industry. Ground-water pumping has altered the natural flow system. Flow paths have shifted toward pumping centers, perched aquifers have developed above the aquifer system, transmissivity has decreased, and the vertical effective stress has increased, resulting in compaction of the aquifer system.

A numerical ground-water flow model of Avra Valley was developed to simulate predevelopment conditions in 1940, ground-water withdrawals from 1940 through 1984, and potential subsidence from 1985 through 2024. Simulations indicate a substantial increase in recharge from irrigation return flow and streamflow infiltration after 1964 resulting in smaller declines and some recovery of water levels. Recovery was greatest from 1978 through 1984 during a period of above-average streamflow in the Santa Cruz River from sewage effluent and floodflows. Recharge from irrigation return flow and streamflow from infiltration was more than 1 million acre-ft and the source of 40 percent of estimated pumpage from 1965 through 1984 in the areas of Townships 11 through 15 South. Simulated ground-water declines were as much as 188 ft by 1978 and 157 ft by 1984. The simulated net withdrawal from aquifer-system storage from 1940 through 1984 was about 3.4 million acre-ft and was derived largely from interfingered-zone subregions where most pumping occurs.

Potential land subsidence was simulated from final transient-state model results. Two potential scenarios of ground-water decline and subsidence were simulated—a minimum subsidence projection that used 1985 estimates of inelastic specific storage of $1.0 \times 10^{-5} ft^{-1}$ and a maximum projection that used a potential ultimate inelastic specific storage of $1.5 \times 10^{-4} ft^{-1}$. Simulated subsidence in the upper alluvium was assumed to occur after a ground-water decline of 100 ft from predevelopment conditions. The two simulations indicate a range in potential maximum subsidence of 0.9 to 14.7 in the playa and interfingered-zone subregions of northern Avra Valley. Simulated ground-water declines ranged from 190 to 220 ft from 1985 through 2024 and were greatest for the least potential subsidence. Projections indicate a potential maximum net withdrawal from aquifer-system storage of 4.2 million acre-ft. The permanent loss from aquitard storage ranges from 1 to 10 percent of total water withdrawn for these two scenarios. The maximum projected subsidence is comparable to estimates made by Anderson (1989) and to field conditions in 1977 in the Picacho basin northwest of Avra Valley (Laney and others, 1978).

Simulation results indicate that the use of combined ground-water and subsidence modeling help to improve the understanding of the hydrologic framework of the alluvial-aquifer system. Combined modeling can also be useful to those who must make decisions regarding development of the aquifer system by demonstrating the effects of subsidence and irreversible loss of storage. Transient-state simulations indicate the need for better estimates of areal recharge, extent of perched aquifers, and distribution of vertical head through time. Subsidence projections indicate the need for refined estimates of inelastic specific storage, the vertical and areal distribution of aquitards, and active management of ground-water withdrawals to minimize the effect of subsidence. A periodic postaudit of the flow model would help to refine estimates of the hydraulic components and boundary conditions of the aquifer system as they change through time.

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