HYDROGEOLOGY OF McMULLEN VALLEY, WEST-CENTRAL ARIZONA

By D. R. Pool

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4140

Tucson, Arizona
October 1987

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Federal Building, FB-44
300 West Congress Street
Tucson, Arizona 85701-1393
Telephone: (602) 629-6671

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Bldg. 810
Box 25425
Denver, Colorado 80225
Telephone: (303) 236-7476

CONTENTS

ILLUSTRATIONS

CONVERSION FACTORS

For readers who prefer to use metric (International System) units, the conversion factors for the inch-pound units used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	square hectometer (hm^2)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter [(L/s)/m]
degree Fahrenheit (°F)	(temp °F-32)/1.8	degree Celsius (°C)

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

HYDROGEOLOGY OF McMULLEN VALLEY, WEST-CENTRAL ARIZONA

By

D. R. Pool

ABSTRACT

The hydrogeology of McMullen Valley, west-central Arizona, was investigated using geologic, geophysical, and hydrologic data and a numerical model of the ground-water system. Information from these sources aided in understanding the response of the ground-water system to pumping stress. Concepts developed through the study of the basin may be applied to other basins.

Interpretation of geologic and geophysical information indicates that the main structure of McMullen Valley is a syncline that has been normal faulted on the southeast side. Basin fill that accumulated in the structural depression during late Miocene to Pleistocene time is the main aquifer and is divided into upper and lower units on the basis of lithologic information. The upper unit is a thin layer of coarse-grained sediments and generally is not saturated. The lower unit is 3,000 to 4,000 feet thick, includes a fine-grained facies in the upper 1,000 feet, and is the main source of water. The fine-grained facies is found in the southwest half of the basin and is further divided into upper and lower parts. The lower part of the fine-grained facies has a higher percentage of silt and clay than the upper part, contains evaporites, does not yield water to wells, and separates the aquifer into shallow and deep systems.

A numerical model was used to analyze the ground-water system for both steady-state and transient conditions. The steady-state model aided in evaluating the distribution of hydraulic properties and the magnitude and distribution of flow components. The transient model was used to analyze system response to pumping stress. The transient system is one of storage depletion, and water-level declines are controlled by pumping and specific-yield distributions. Water-level declines are also influenced by hydraulic properties and areal extent of the fine-grained facies. Significant water-level declines may extend to aquifer boundaries in most of the basin and in one area a nearby impermeable boundary greatly influences declines. The location of the nearby boundary was estimated through gravity-data modeling. Several hydrologic components, including hydraulic properties and areal extent of the fine-grained facies, storage properties, and aquifer boundaries, need better definition in order to develop a more accurate model of the ground-water system.

INTRODUCTION

The study of the hydrogeology of McMullen Valley was undertaken as part of the Southwest Alluvial Basins, Regional Aquifer-System Analysis (Swab/RASA) Project (Anderson, 1980). The purpose of the Swab/RASA Project was to develop a general understanding of the hydrologic systems in the alluvial basins of the study area. Most of the aquifer systems within the project area consist of a thick accumulation of sediments that fill structural troughs between the mountain ranges. Ground-water modeling was the principal tool used in the analysis. A basic assumption of the project was that certain characteristics and relations are common to many of the basins or subsets of basins. A result of the study was the grouping of the basins into categories. Specific basins selected for detailed study were those thought to typify a subset of basins and for which sufficient data were available to develop reliable numerical models.

Purpose and Scope

The purpose of this investigation was to gain an understanding of the hydrogeologic system in McMullen Valley, which has geomorphic, geologic, hydrologic, and climatic characteristics typical of the west group of basins in the Swab/RASA study area (fig. 1). The investigation included evaluation of the basin structure, the stratigraphy of the aquifer, and the hydrologic system under predevelopment and postdevelopment conditions.

Numerical models of the hydrologic system under predevelopment and postdevelopment conditions were developed in order to evaluate the controls on the hydrologic system. Information on the predevelopment conditions is sparse and allowed only a general analysis. Relatively abundant data on pumpage and water-level declines make the area particularly suitable for an analysis of the ground-water system under postdevelopment conditions and its response to stress.

Development of a conceptual model of the aquifer system and a numerical model of the hydrologic system requires information on stratigraphy, areal extent, and hydrologic properties of the aquifer. Subsurface lithologic information was used to delineate the aquifer stratigraphy. Gravity data were collected and analyzed to help determine the shape of the basin and extent of the aquifer. Field observations aided in understanding the structural and geomorphic development of the basin and in recognizing lithologic units in the subsurface. Hydrologic properties of the aquifer include hydraulic conductivity, transmissivity, specific storage, and quantities and locations of recharge and discharge. A general lack of data on hydrologic properties in the study area prevented direct determination of values; however, estimates were obtained by indirect methods and verified by the use of the numerical model.

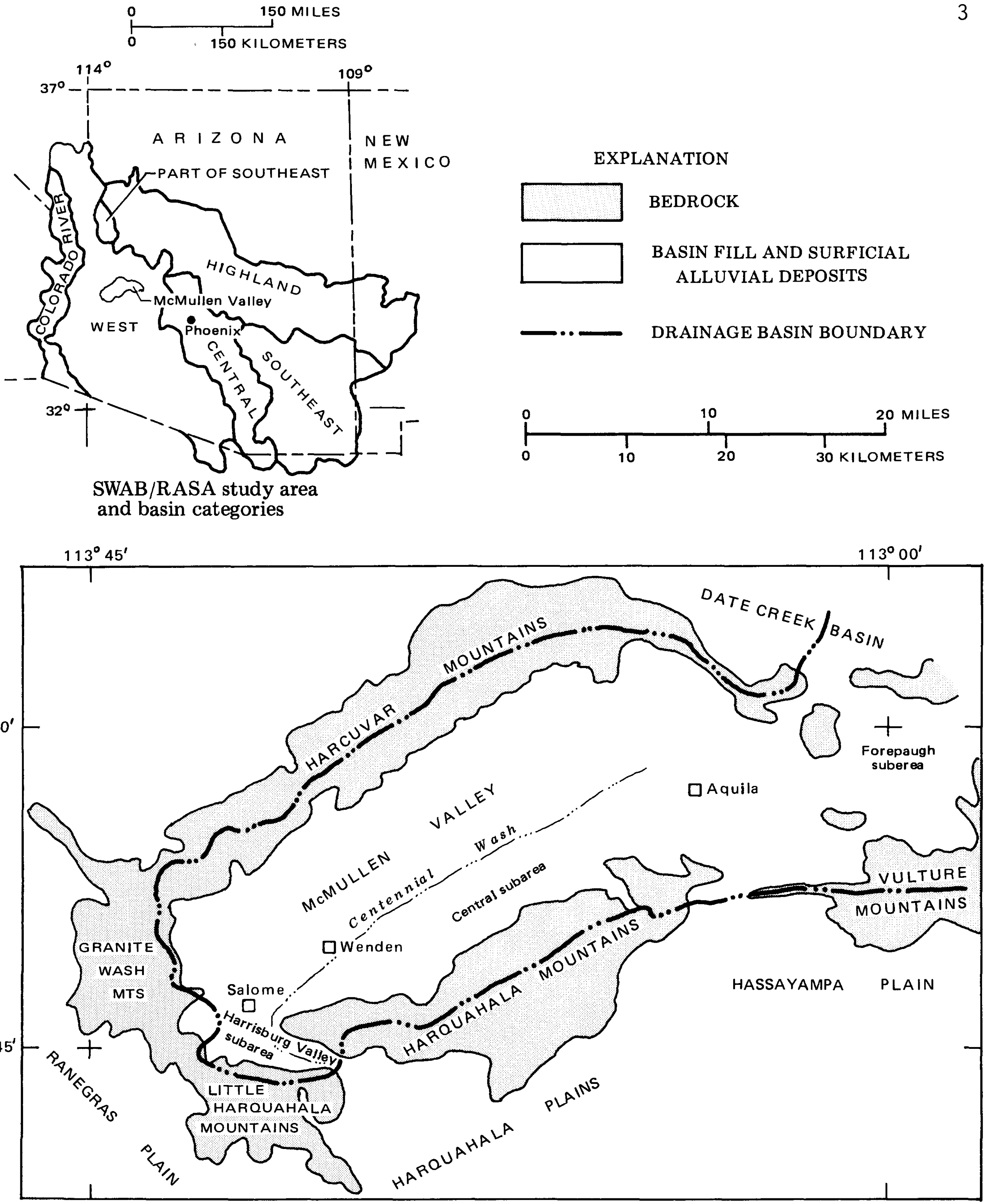


Figure 1. -- SWAB/RASA study area, basin categories, and McMullen Valley study area.

Acknowledgments

Much of the work and results of this study could not have been accomplished without the assistance of the University of Arizona Geophysics Laboratory and the Arizona Bureau of Geology and Mineral Technology. The University of Arizona Geophysics Laboratory provided a gravimeter, gravity data, and gravity-data reduction programs. Well cuttings are on file at the well-cuttings library maintained by the Arizona Bureau of Geology and Mineral Technology; their ongoing geologic work in the area influenced interpretations presented in this document.

Previous Investigations

Published hydrologic investigations have furnished most of the water-level and agricultural-development information used in this study. The well inventory conducted in 1917 by Ross (1923) provides a description of McMullen Valley and the hydrologic system prior to development. Kam (1964) discussed the ground-water conditions in the early stages of development and described the hydrogeology. Ground-water conditions were updated in 1965 by Briggs (1969) and again in 1980 by Remick (1981). Many geologic investigations have been conducted in and near McMullen Valley; however, the report by Kam (1964) is the only one that describes the water-bearing units. Lasky and Webber (1949), Reyner and others (1956), Sherborne and others (1979), and Otton (1981) described the lithologic characteristics and structure of related rocks in nearby areas. Reynolds (1980) provided a summary of the regional geology and structure of west-central Arizona.

DESCRIPTION OF THE AREA

Location and Physiography

McMullen Valley is a roughly rectangular, northeast- to southwest-trending basin in west-central Arizona (fig. 1). The surface-water drainage area occupies about 720 mi^2 and is separated into three subareas—Forepaugh, central, and Harrisburg Valley—for purposes of discussion. The Forepaugh subarea includes about 165 mi^2 at the northeast end of the drainage and is separated from the central subarea by some low hills in T. 7 N., R. 8 W., and T. 8 N., R. 8 W., and an unnamed ridge that extends southeastward from the northeast end of the Harcuvar Mountains. The central subarea, which is the main part of the basin, is about 15 mi wide, 35 mi long, occupies about 540 mi^2, and includes the major agricultural areas of Wenden, Salome, and Aquila. The Harrisburg Valley subarea occupies only about 16 mi^2, is at the south end of the basin, and is oriented perpendicular to the major basin trend.

Mountains of low to moderate relief border the basin on all sides. The Harquahala and Harcuvar Mountains to the southeast and northwest, respectively, have peaks of more than 5,000 ft above sea level. The Granite Wash and Little Harquahala Mountains on the southwest range from 2,000 to 3,000 ft in altitude. In the Forepaugh subarea the basin is bounded by the Vulture Mountains—about 3,000 ft in altitude—to the south and east and by several low-lying hills and an indistinct surface-water divide to the northeast and northwest. Altitude of the valley floor is about 1,700 ft in Harrisburg Valley, 2,200 ft near Aquila, and more than 2,400 ft in the Forepaugh subarea.

Centennial Wash, an ephemeral stream, is the major surface-water drainage in McMullen Valley. The stream is axially located and flows toward the southwest in the central part of the valley, abruptly turns to the southeast near Salome, and exits through Harrisburg Valley into the Harquahala Plains. Many small tributary washes, which flow perpendicular to Centennial Wash, drain the surrounding mountains.

McMullen Valley and the surrounding basins have some geomorphic features that may have hydrologic significance such as pediments and surface-water drainage areas that do not coincide with the areal extent of structural basins. Exposed bedrock pediments or shallow buried pediments limit the extent of the aquifer. Kam (1964) noted that a pediment occurs at the base of the Granite Wash Mountains. A partially buried, basinward-sloping bedrock surface, which may be a pediment, extends from the southwest end of the Harquahala Mountains. The drainage area of Centennial Wash does not coincide with the structural boundaries of McMullen Valley. The northernmost part of the drainage area extends into the Date Creek structural basin. At the southwest end of McMullen Valley, a small part of the Centennial Wash drainage is being captured through headward erosion by the Ranegras Plain drainage at Granite Wash Pass (Metzger, 1951; Kam, 1964). Headward erosion by adjacent drainages and the resultant capture of area from the Centennial Wash drainage occurs because valley-floor altitudes in adjacent basins are 400 to 1,000 ft lower than those in McMullen Valley.

Climate and Vegetation

Climate in McMullen Valley generally is arid and average rainfall is less than 10 in./yr (Sellers and Hill, 1974). No rainfall data exist for the Harquahala and Harcuvar Mountains so rainfall can only be estimated to exceed 10 in./yr in those areas. Potential evapotranspiration greatly exceeds precipitation during most of the year. High temperatures of more than 100°F are common in the summer and low temperatures of 30° to 40°F often occur in the winter. The mean annual temperature is about 66°F at Salome and Aguila (Sellers and Hill, 1974). Desert vegetation is common in the valley. Mesquite and palo verde trees are found along Centennial Wash and in Harrisburg Valley.

History of Development

Withdrawals of ground water in McMullen Valley were not significant until the early 1950's, although development of the ground-water resources began in the 1800's. Most early wells were used for mining, livestock, and domestic purposes. Kam (1964) reported that several irrigation wells were drilled in Harrisburg Valley in 1952; at least five irrigation wells had been drilled near Salome and Harrisburg Valley prior to 1952. In the mid-1950's, increased agricultural activity and significant ground-water withdrawals occurred near Wenden, Salome, and Aguila; these activities continued into the mid-1960's. From 1954 to 1959, 27 irrigation wells were completed near Aguila and 23 wells were completed near Wenden, Salome, and Harrisburg Valley (Kam, 1964). The total irrigated area was about 11,000 acres in 1958 and 16,600 acres in 1965 (Briggs, 1969). In 1965 about 33 percent of the cultivated land was near Wenden and Salome and 67 percent was near Aguila. By 1972, about 30,000 acres was under cultivation—37 percent near Wenden and Salome and 63 percent near Aguila. The same general distribution of agriculture has continued to the time of this study.

Ground-water pumpage before 1945 was less than 500 acre-ft/yr and increased to about 2,000 acre-ft/yr during 1945-51. Ground-water withdrawals increased from 5,000 acre-ft in 1952 to 7,000 acre-ft in 1954 (fig. 2). The ground-water supply began to be extensively developed near Wenden, Salome, and Aguila from 1955 to 1959 as annual pumpage increased from 9,000 to 50,000 acre-ft. Pumpage continued to increase to 90,000 acre-ft in 1964 and about 100,000 acre-ft/yr in the late 1960's. The maximum withdrawal of 139,000 acre-ft/yr occurred in 1975. Ground-water withdrawals decreased to 115,000 acre-ft/yr in 1978 and 1979.

DATA COLLECTION AND ANALYSIS

Water-level data for the predevelopment and postdevelopment periods were derived mainly from previous reports and basic-data files of the U.S. Geological Survey. Data on transmissivity, hydraulic conductivity, and specific yield were lacking for the study area and were obtained by indirect means. Transmissivity distribution was estimated from a flow-net analysis of predevelopment water levels and specific-capacity data for 31 wells in the study area (fig. 3). Hydraulic conductivity was derived from estimated transmissivity and aquifer thickness. An average specific yield for the aquifer in the major agricultural centers of Wenden, Salome, and Aguila was estimated by dividing the total pumpage from 1957 to 1980 by the volume of sediments dewatered during the same period.

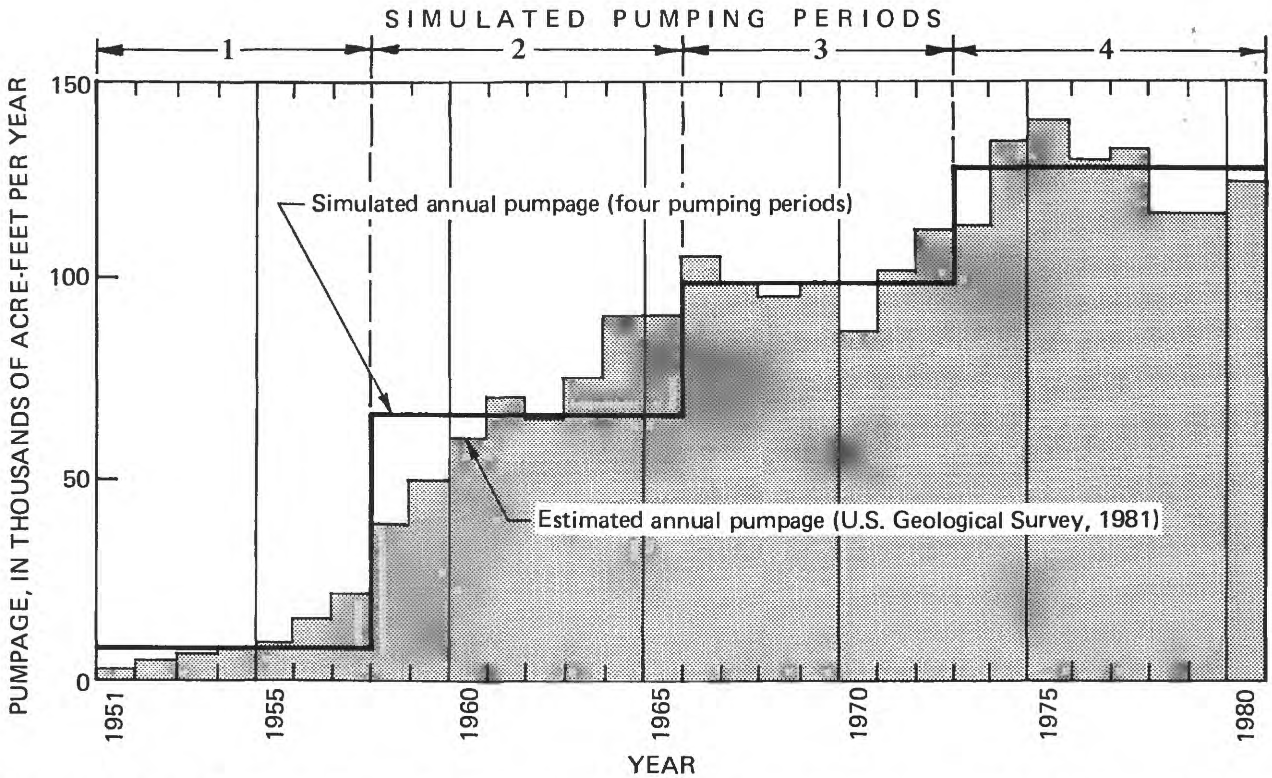
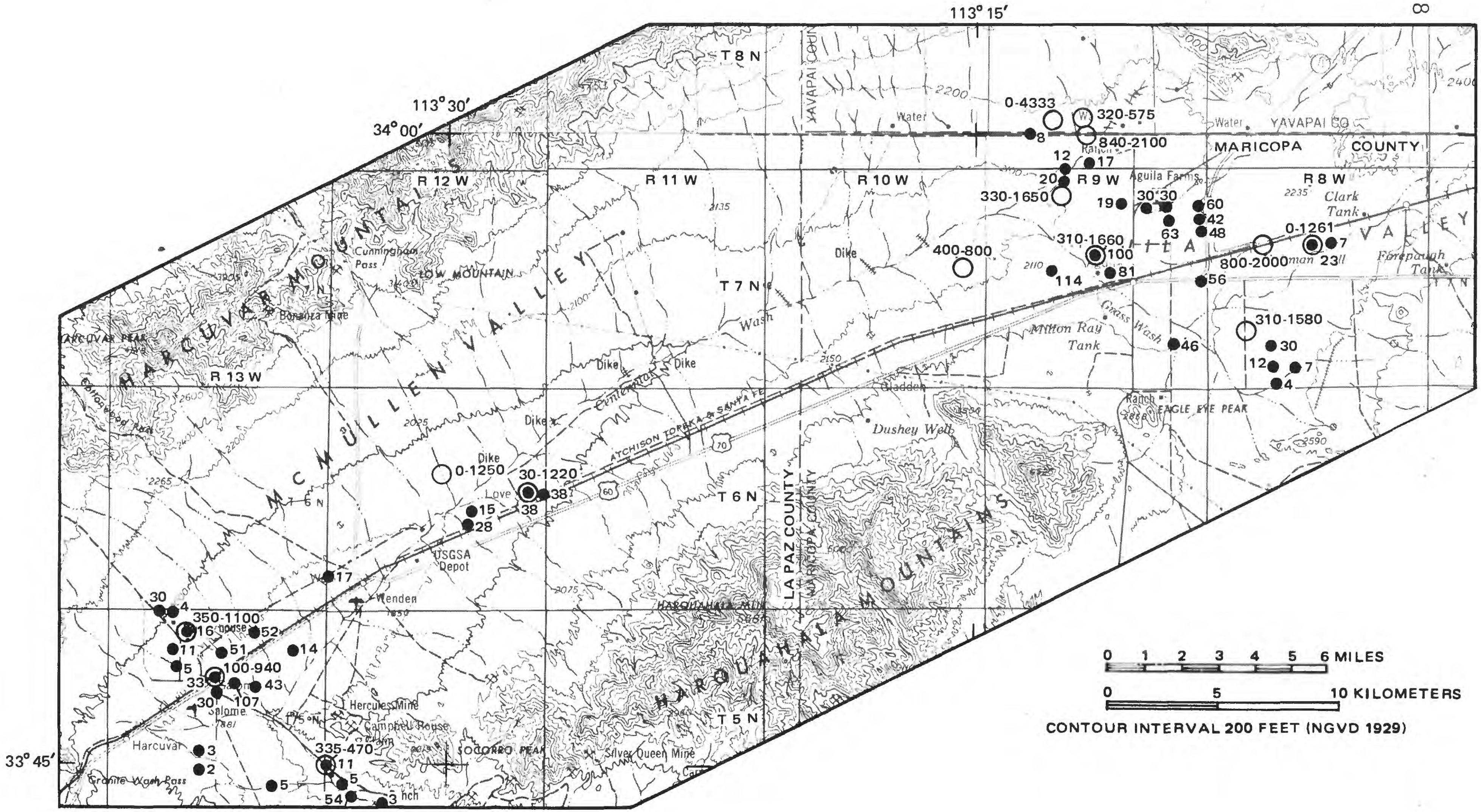


Figure 2. -- Total estimated annual pumpage and simulated annual pumpage used in the numerical model.



Base from U.S. Geological Survey, 1; 250 000
Phoenix and Prescott, 1969 and 1970

EXPLANATION

●17 WELL—Number, 17, is the specific-capacity value, in gallons per minute per foot of drawdown

○ 0-1250 WELL—Numbers, 0-1250, are the depth interval, in feet, for which lithologic logs are available

Figure 3. -- Locations of wells with specific-capacity tests and wells with lithologic logs.

The lithologic information used in this study included drillers', lithologic, and geophysical logs. Drillers' logs cannot provide detailed lithologic information; however, they were used to correlate thick intervals of fine-grained sediments and bedrock between wells. Lithologic logs describe color, mineralogic composition, and grain size of the sediments. A few good-quality lithologic logs were used in conjunction with physical inspection of well cuttings to refine correlations made from drillers' logs and to develop a more detailed description of the subsurface stratigraphy and structure. Electric logs are the only type of geophysical log available for the study area; however, most are of poor quality and could be used only in a qualitative manner. Well locations referred to in this report are described by the method shown in figure 4.

The aquifer extent and basin structure were better defined by analysis of gravity data collected at 74 gravity stations in the Wenden-Salome area and along two profiles across the basin northeast of Wenden (fig. 5). Previously collected gravity data from the University of Arizona gravity data base also were utilized. Gravity readings were made with a LaCoste and Romberg Model G gravimeter[1]. Bench marks and section corners provided altitude control for most gravity stations; accuracy was better than ±1 ft for most stations. Road-intersection altitudes were used for a few gravity stations in the Wenden-Salome area and probably are accurate to within ±2 ft. Gravity-data reductions that were applied to all readings include (1) correction for earth tides, (2) linear estimate of instrument drift, (3) free-air correction, (4) reference to the theoretical sea-level gravity (Gravity Reference Surface of 1967), (5) a Bouguer slab correction, and (6) terrain corrections for a radius of 0 to 109 mi from each station.

The gravity data along the two profiles were analyzed using a two-dimensional model (West, 1971). The model uses a variable number of vertical-density prisms that can be divided into density layers to represent an anomalous mass. The thickness of the bottom layer was allowed to vary in the iterative numerical procedure. Input to the model included thicknesses of the upper layers and density contrasts between each layer and bedrock. Sediment and bedrock densities were estimated on the basis of density information for similar materials in other basins.

A numerical model of the ground-water system was developed to analyze the hydrologic system under both steady-state and transient conditions. Two model layers, delineated on the basis of hydrologic and stratigraphic data, were used to represent the three-dimensional nature of the hydrologic system. The numerical model used a finite-difference approximation to the ground-water flow equation and simultaneously solved the equation for flow between discrete blocks of the aquifer (Trescott, 1975; Trescott and Larson, 1976; McDonald and Harbaugh, 1984). In the quasi-three-dimensional approach used in this analysis, a vertical-leakance layer that provided a control on vertical flow between layers was incorporated between the model layers.

---

[1]Use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

The well numbers used by the Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants. These quadrants are designated counterclockwise by the capital letters A. B, C, and D. All land north and east of the point of origin is in A quadrant, that north and west in B quadrant, that south and west in C quadrant, and that south and east in D quadrant. The first digit(s) of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particualr 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in counterclockwise direction, beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. In the example shown, well number (B-4-2)19caa designates the well as being in the NE¼NE¼SW¼ sec. 19, T 4 N, R 2 W. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes.

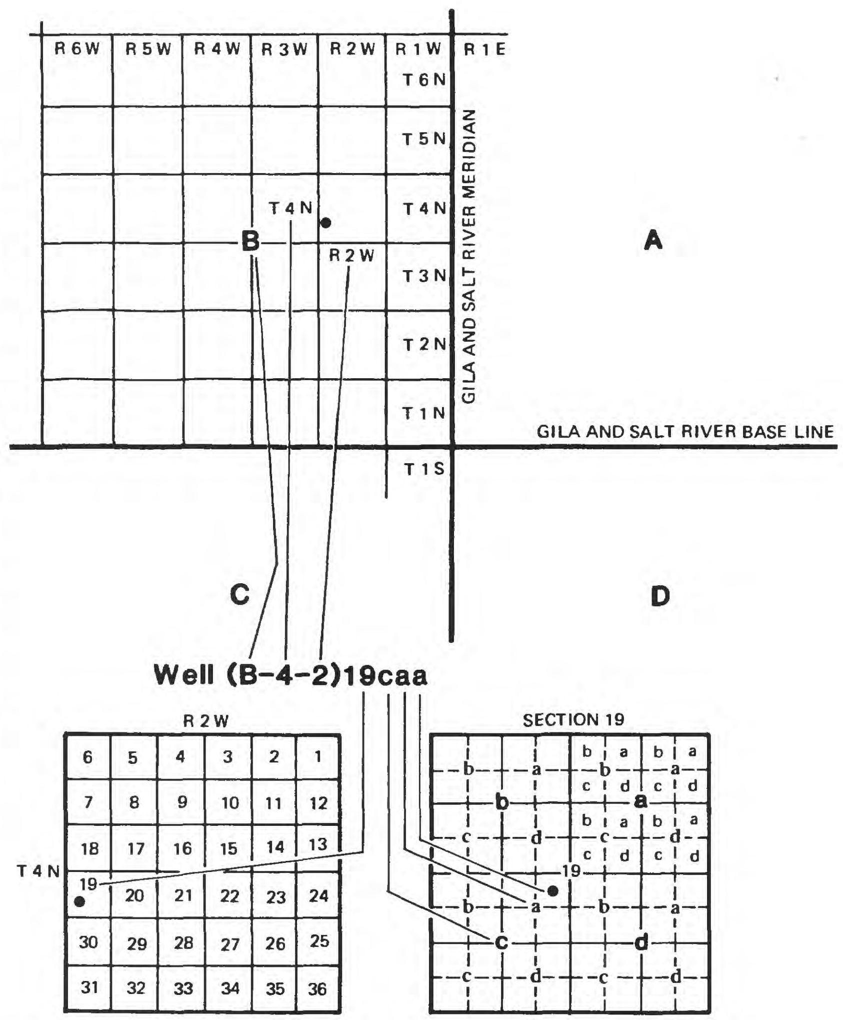


Figure 4. -- Well-numbering system in Arizona.

HYDROGEOLOGY

The hydrogeologic setting of McMullen Valley is similar to that of most of the other basins in the Basin and Range province of Arizona. Most water occurs as ground water, and surface water occurs only in response to precipitation. The main aquifer is composed of sediments—basin fill—that accumulated in structural basins which formed in response to regional extensional forces during the Basin and Range structural disturbance 15 to 10 million years (m.y.) ago (Eberley and Stanley, 1978; Scarborough and Peirce, 1978; Shafiqullah and others, 1980). Basin-fill sediments generally are porous and permeable and allow storage and movement of ground water. Older igneous, metamorphic, and sedimentary rocks generally are impermeable and are only locally important as aquifers.

McMullen Valley contains a ground-water system that is not hydraulically continuous with those of adjacent basins. The quantity and direction of ground-water movement are controlled by the volume and location of recharge and discharge. Recharge to the ground-water system occurs mainly in the upper reaches of the basin and at the base of the Harcuvar and Harquahala Mountains. Discharge from McMullen Valley occurs through Harrisburg Valley but has decreased because of ground-water pumping during postdevelopment time. Ground-water movement and storage is influenced by basin structure and by distribution of coarse-grained and fine-grained sediments within the basin fill. Most coarse-grained sediments readily transmit and yield water to wells, whereas fine-grained sediments do not. An extensive area of fine-grained sediments near Wenden and Salome significantly influences ground-water movement, water-level declines, and storage properties of the aquifer. Subsurface bedrock structures also influence water-level declines and ground-water movement in much of the basin.

Geology

The rock types in McMullen Valley range from granitic, metamorphic, and volcanic rocks to consolidated and unconsolidated sediments (fig. 5). For hydrologic purposes, the rocks are separated into two groups—pre-Basin and Range and basin fill—on the basis of age, structure, and water-bearing characteristics. Pre-Basin and Range rocks are mainly igneous and metamorphic rocks that generally are impermeable; however, some Tertiary pre-Basin and Range sediments probably serve as aquifers in local areas. Structure of the basin determines the size and shape of the basin-fill aquifer. Basin-fill stratigraphy is strongly influenced by the structural evolution of the basin. Folding of pre-Basin and Range rocks produced mainly external drainage and deposits of coarse-grained sediments. Block faulting resulted in internal drainage and fine-grained sediments in the basin center.

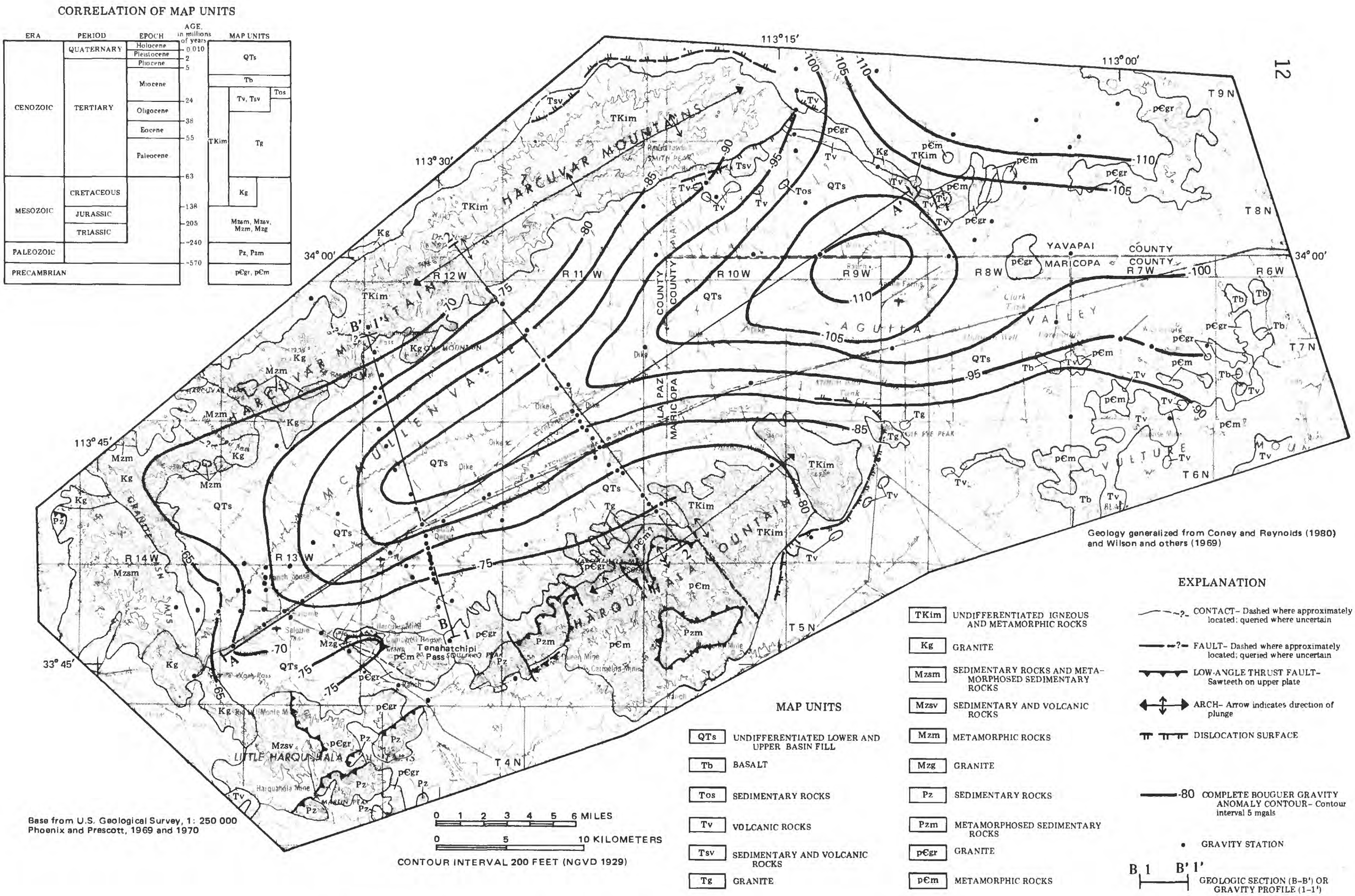


Figure 5. -- Generalized geology and distribution of gravity in McMullen Valley.

Pre-Basin and Range Rocks

Pre-Basin and Range rocks are separated into two age groups—Precambrian through early Tertiary age and middle and late Tertiary age. Precambrian through lower Tertiary rocks consist of granites, gneisses, and unmetamorphosed to variably metamorphosed sedimentary and volcanic rocks. Most of the Harcuvar, Harquahala, Little Harquahala, and Granite Wash Mountains are composed of these rocks. Middle and upper Tertiary rocks are mainly volcanic rocks that are interbedded with and overlain by sedimentary rocks; these rocks crop out at the northeast end of the Harcuvar and Harquahala Mountains and also occur in the Vulture Mountains.

Precambrian through lower Tertiary rocks.--The main mass of the Harcuvar and Harquahala Mountains are gneisses and mylonitic rocks associated with the Tertiary Harcuvar metamorphic-core complex, which also includes mountain ranges to the northwest of McMullen Valley (Rehrig and Reynolds, 1977). Reynolds (1980, p. 7) describes the metamorphic-core complex as "characterized by metamorphic and mylonitic rocks whose gently dipping foliation defines broad asymmetrical arches or domes." The rocks of the metamorphic-core complex tend to grade from unmetamorphosed Precambrian through lower Tertiary rocks on the margins to amphibolite gneiss of Mesozoic and early Tertiary age in the center (Rehrig and Reynolds, 1977). An overlying dislocation surface is associated with the metamorphic-core complex (Davis and others, 1980; Rehrig and others, 1980; Rehrig and Reynolds, 1980; Shackelford, 1980). Rocks above the dislocation surface are highly faulted, tilted, and mainly Oligocene to Miocene in age; older rocks may also be present locally (Shackelford, 1980; Davis and others, 1980; Rehrig and Reynolds, 1980).

Most rocks of the Harcuvar and Harquahala Mountains are granitic and metamorphic rocks of Precambrian, Cretaceous, and Tertiary age (Rehrig and Reynolds, 1980). Precambrian rocks also are found in the Little Harquahala and Vulture Mountains and at the northeast end of the Harcuvar Mountains. Paleozoic rocks crop out mainly on the southeast side of the Harquahala and Little Harquahala Mountains. The Paleozoic rocks are highly folded and faulted metamorphosed carbonates located within thrust sheets (Reynolds and others, 1980).

Mesozoic rocks in the study area include sedimentary, igneous, and metamorphic rocks and consist of conglomerate, sandstone, quartzite, siltstone, and limestone in the Little Harquahala and Granite Wash Mountains (Rehrig and Reynolds, 1980). In the eastern part of the Granite Wash Mountains, the rocks are highly metamorphosed. In the Little Harquahala Mountains, the Mesozoic rocks include slightly metamorphosed volcanic rocks (Reynolds, 1980). Late Cretaceous plutons of granite to granodiorite composition crop out in the Granite Wash Mountains and southwest Harcuvar Mountains (Rehrig and Reynolds, 1980). A small amount of the plutonic material also crops out along the ridge at the northeast end of the Harcuvar Mountains (Reynolds, 1980).

Middle and upper Tertiary rocks.--Near Aguila and in the Forepaugh subarea, highly faulted and rotated rocks of probable late Oligocene to middle Miocene age are located above the dislocation surface and consist of a thick sequence of volcanic and interbedded sedimentary rocks overlain by sedimentary rocks. Nearly all the rocks are moderately to steeply dipping and display similar relations throughout the northern and eastern parts of the Harcuvar metamorphic-core complex. Near Aguila, the middle and upper Tertiary rocks generally dip toward the southwest; however, in the Vulture Mountains the dip is toward the northeast (Rehrig and others, 1980).

The upper Oligocene to middle Miocene rock sequence generally consists of a basal conglomerate overlain by silicic to intermediate volcanic rocks that are in turn overlain by fine- to coarse-grained clastics. The basal conglomerate is thin, less than 60 ft at the base of the ridge at the northeast end of the Harcuvar Mountains (Kam, 1964). Most of the same ridge is composed of a sequence of felsites, andesites, and tuffs that is about 400 foot thick (Kam, 1964). Similar volcanic rocks crop out in the Vulture Mountains (Rehrig and others, 1980). Basaltic andesites crop out at Bullard Peak and Eagle Eye Peak (Kam, 1964) and in the Vulture Mountains (Rehrig and others, 1980). The volcanic sequence is overlain by clastics that crop out east-southeast of Bullard Peak (Reynolds, 1980). The sediments at a butte in secs. 13 and 14, T. 8. N., R. 10 W., probably overlie the volcanic rocks and are composed of reddish-brown coarse-grained sandstone. West of the butte, the sediments consist of pink to gray sandstone, siltstone, and shale. Similar sediments were penetrated in a deep exploration well—(B-8-9)29dbc—below a depth of 700 ft before encountering basalt at a depth of 3,910 ft (Lease, 1981). Kam (1964) described several other sediments of probable early to middle Miocene age that are exposed south and east of Aguila and include limestone, fine- to coarse-grained sandstone intruded by breccia pipes and dikes, and reddish-brown sandstone and conglomerate near Eagle Eye Peak. Sediments found beneath basaltic rocks east of Aguila are probably Oligocene to middle Miocene in age because the youngest volcanic rocks in the area are flat-lying basalts thought to be contemporaneous with or closely postdate Basin and Range faulting (Eberley and Stanley, 1978; Peirce, 1976).

Basin-Fill Sediments

The stratigraphy of the basin-fill sediments in McMullen Valley is similar to that found in other basins in the Basin and Range Province of Arizona. Alluvial fans that issued from the mountains coalesced to form a bajada on the perimeter of the basin. Sedimentation was dominated by alluvial deposition on the bajada that graded into a playa or lake-depositional environment in the interior of the closed basin. The resulting basin fill contains coarse-grained sediments on the basin perimeter and fine-grained sediments in the interior. In several of the deeper basins in the Basin and Range Province, fine-grained facies include as much as a few thousand feet of evaporites (Peirce, 1976).

Time-correlative fine-grained sediments exist in much of western and southwestern Arizona but are only about 1,000 ft thick and contain only minor amounts of evaporites (Pool, 1985). The thinner deposits are similar to deposits found in McMullen Valley.

The basin fill in McMullen Valley consists of lower and upper units (fig. 6). The lower unit is the main water-bearing unit. The upper unit is thin and lies above the water table in most of the basin. Some of the upper unit may have been saturated near Aguila prior to development. Lower basin fill consists of as much as 4,000 ft of silt, sand, and gravel and contains a fine-grained silt and clay facies in the upper 1,000 ft in the southwestern part of the basin. The lower basin fill crops out extensively in washes at the base of the mountains as a fanglomerate composed of locally derived boulders in a matrix of sand, silt, and gravel. Lower basin fill does not crop out elsewhere, and lithologic information must be derived from analysis of drilling samples. The upper basin fill consists of silt, sand, and gravel and overlies the lower unit. Stream alluvium along drainage channels is included with the upper basin fill. The thickness of the upper basin fill ranges from about 100 to 200 ft near Wenden and Salome to possibly as much as 560 ft near Aguila and thins to zero toward the margins of the valley floor (Kam, 1964).

The top of the lower basin fill near Salome is found at depths of 200 ft or less. The unit is described in drillers' logs as 200 to 400 ft of silt or clay underlain by sand, gravel, conglomerate, and boulders to depths of as much as 1,100 ft. East and southeast of Salome, shallow bedrock underlies lower basin fill at depths of 300 to 1,000 ft and is probably an extension of a bedrock ridge that crops out 2 mi southeast of Salome. Drill samples and a lithologic log of well (B-5-13)4cbb indicate that the sediments are locally derived gneiss and dark-colored metamorphic clasts.

Near Wenden, the top of the lower basin fill is found from 0 to 150 ft. Drill samples and lithologic logs of two wells—(B-6-12)13dcc and (B-6-12)15bbb—indicate that the lower basin fill is 600 to 1,100 ft of fine-grained sediments underlain by sand, silty sand, and small amounts of gravel. Neither well fully penetrated the unit. The mineralogic composition of drilling samples consists of locally derived granitic and gneissic material; mica, mainly muscovite, is abundant and volcanic clasts are rare.

Near Aguila, the lower basin fill is predominantly sand with some layers of sand and gravel; no fine-grained facies is apparent. Depth to the top of the lower unit is less than 300 ft over most of the area but may be as much as 560 ft. The maximum thickness of the lower unit exceeds 1,500 ft and may be more than 3,000 ft. Volcanic rocks and probable pre-Basin and Range sediments may occur at depths of less than 1,000 ft to the south and east of Aguila. The clast composition ranges from volcanic to granite and gneiss; calcareous siltstone fragments also are common. In most intervals the main composition of the fine-grained sand fraction is clear angular quartz; dark minerals make up about 10 percent of the fine-grained sand.

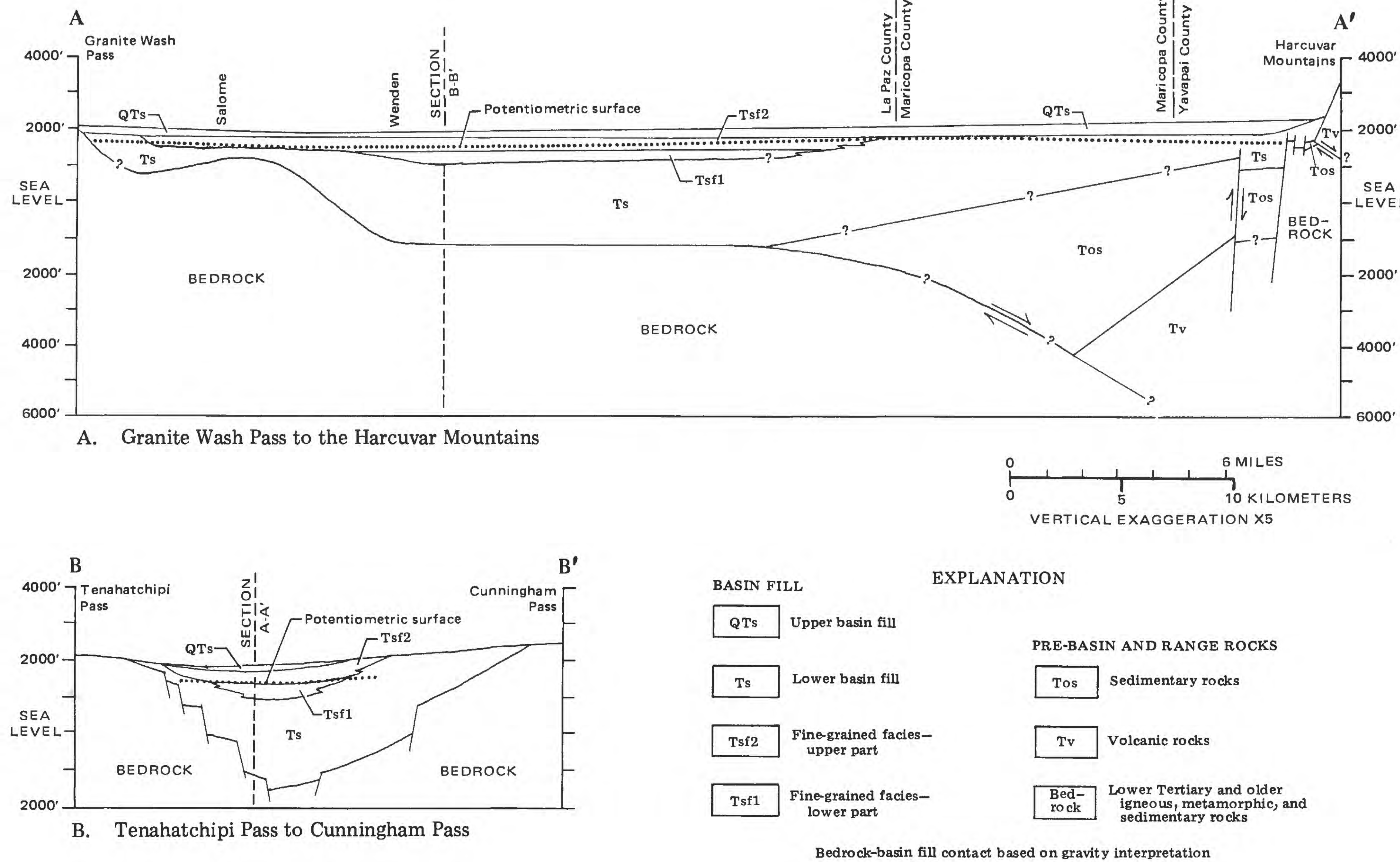


Figure 6. -- Geologic sections through McMullen Valley.

According to lithologic information and drillers' logs, the fine-grained facies of the lower basin fill has an upper part that contains sand and gravel lenses and a lower part that is homogeneous silt and clay (fig. 6). The upper part of the fine-grained facies in well (B-6-12)13dcc consists of 40 to 70 percent silt-size or smaller grains and some clay at depths of 130 to 350 ft. Sand and gravel are at depths of 180 to 210 ft and 310 to 330 ft. The lower part of the fine-grained facies is 90 percent silt-size or smaller grains at depths of 350 to 730 ft and has no sand or gravel lenses. The clay content of the lower part has not been determined but probably is greater than that of the upper part.

In well (B-6-12)15bbb the fine-grained sediments occur between depths of 100 and 1,200 ft. Kam (1964) described the interval as reddish-orange to pale-red clay and silt with some gypsum and salt. All the gypsum and salt occur below a depth of 600 ft, and most gypsum and salt are below 890 ft. Some gypsum and salt are found below the fine-grained sediments at a depth of about 1,300 ft.

According to well-log information, the fine-grained facies of the lower unit is a lenticular body in the southwest half of the basin that extends from Salome to between 7 and 14 mi northeast of Wenden. The fine-grained facies is 2 to 3 mi wide near Salome and is more than 5 mi wide near Wenden. About 1.5 mi south of Wenden, the facies overlies bedrock at a depth of about 350 ft according to a driller's log. The fine-grained facies probably does not extend much farther south toward the Harquahala Mountains but may extend as much as 6 mi to the north of Wenden. Thickness of the fine-grained facies ranges from 200 to 400 ft near Salome and increases to about 1,100 ft northeast of Wenden. The top of the fine-grained facies appears generally flat between Granite Wash Pass to the Harcuvar Mountains and is found at an altitude of about 1,800 ft in the center of the basin (fig. 6). Between Cunningham Pass and Tenahatchipi Pass, the top of the fine-grained facies is slightly concave upward and occurs at altitudes of about 2,000 ft near the mountains (fig. 6).

The depositional history of the basin fill consists of a long period of through-flowing drainage followed by internal drainage and the re-establishment of through-flowing drainage. The coarse-grained sediments beneath the fine-grained facies in the lower basin fill probably were deposited in a subsiding basin that maintained through-flowing drainage to areas outside the present basin. The overlying fine-grained facies and evaporites represent internal drainage conditions. Through-flowing drainage probably occurred periodically during deposition of the upper part of the fine-grained facies. Upper basin fill contains no fine-grained facies and was deposited under through-flowing drainage conditions. The contact between the upper and lower basin fill may be unconformable representing a period of erosion.

Ages of the basin sediments must be determined indirectly owing to the lack of fossils or volcanic rocks that can be dated. The maximum age of the flat-lying lower basin fill is limited by the age of tilted sediments near Aguila that are between 15.8 and 13.2 m.y. (Otton, 1981; Scarborough and Wilt, 1979). Minimum age of the lower basin fill unit cannot be directly determined but can be estimated by the age of the development of external drainage in other basins on the assumption that all the basins have related geologic histories. A late Pliocene age has been determined for external drainage of basins along the lower Gila River (Shafiqullah and others, 1980). Integration of McMullen Valley drainage with the Gila River probably followed this event. The age of the lower basin fill, therefore, probably extends from late Miocene to late Pliocene. The age of the upper basin fill may be as old as late Pliocene; however, the majority of the unit is Pleistocene.

Structure

Geologic structure refers to the attitude and relation of rock units. Basin structure in a hydrologic sense refers to the size and shape of the basin and defines the geometry of the aquifer. The geologic structure of the hydrologic units influences their potential as aquifers. Units that are greatly faulted may be too discontinuous for water to flow easily between faulted segments. Recognition of the structure of rocks in outcrop aided in predicting their location in the subsurface and possible influence on ground-water flow. Gravity data were used to interpret aquifer and basin geometry. The basin shape that was determined from the gravity data influenced interpretation of the structural history of the basin.

Basin and Range Structure

Block faulting is the typical structure of basins within the Basin and Range physiographic province of Arizona. The basins contain downthrown grabens that are separated from the upthrown mountains by en echelon normal faults. Little direct evidence for basin-and-range normal faulting is found within McMullen Valley; however, some normal faulting can be inferred from geophysical and lithologic data. Steep-angled normal faulting may exist in the basin at the base of the Harquahala Mountains according to gravity modeling and drillers' logs. Data from drillers' logs south and east of Aguila indicate that the top of basalt flows tend to decrease in altitude toward the basin center. If these basalts are equivalent to flat-lying basalt flows in the area, they may be faulted in a typical basin-and-range en echelon style.

The shape of the gravity-model profiles indicate that the main structural component of the basin may be synclinal. The syncline interpretation is supported by the parallel arched structures in the Harquahala and Harcuvar Mountains and the lack of evidence of typical basin-and-range faulting in the basin. Normal faulting, however, is likely to be superimposed on the synclinal structure on the southeast side of the basin. The syncline interpretation helps to explain the orientation and stratigraphy of the basin. Most basins in the Basin and Range Province are oriented in a north or northwest direction. McMullen Valley and adjacent Butler Valley, however, are oriented northeast and parallel to the arches of the mountain ranges.

Results of Gravity Modeling

In the geophysical method used in this study, the gravitational field of the earth was measured at several locations in the study area. The acceleration of gravity at any location is related to the mass of underlying material. Differences in the mass of material across the area, which are due to differences in density and thickness of rock units, cause variations in the strength of the gravitational field. Low-density rocks, such as basin fill, cause a local decrease in the acceleration of gravity and will show as a depression in the gravitational field. The gravity values can be mathematically modeled, given an appropriate density contrast between basin fill and bedrock, to produce a generalized basin shape.

The most pronounced gravity features of the study area are a significant regional-gravity trend and the gravity low that parallels the basin axis (fig. 5). The regional complete Bouguer gravity-anomaly values decrease by 45 milligals in a northeast direction across the basin and generally decrease by about 5 milligals in a southeast direction from the Harcuvar to the Harquahala Mountains. A trend of low gravity values parallels the basin axis indicating that the thickest sediments generally lie along the axis. The gravity low and greatest thickness of low-density materials are located north of Aguila; however, the gravity low probably does not represent the largest thickness of basin fill. The regional-gravity trend and a large thickness of low-density, steeply tilted, pre-Basin and Range sedimentary and volcanic rocks both contribute to the low-gravity values near Aguila. The greatest thickness of basin fill probably lies along the basin axis between Wenden and Aguila.

Gravity modeling along profiles 1 and 2 was used to provide information on the aquifer extent and basin shape at those locations (fig. 5). Modeling requires a knowledge of bedrock densities and density stratification of the basin fill. Site-specific densities were not available; therefore, values had to be extrapolated from similar materials in other basins of Arizona. An average density of metamorphic and sedimentary rocks typical of the bedrock in McMullen Valley is about 2.67 g/cm^3 (Oppenheimer, 1980). The density of basin fill in Arizona ranges from about 1.80 to 2.60 g/cm^3 (Oppenheimer, 1980). Four density layers are found within the basin fill of McMullen Valley and consist of layer 1, unsaturated fine-grained sediments; layer 2, unsaturated coarse-grained sediments; layer 3, saturated fine-grained sediments; and layer 4, saturated coarse-grained sediments.

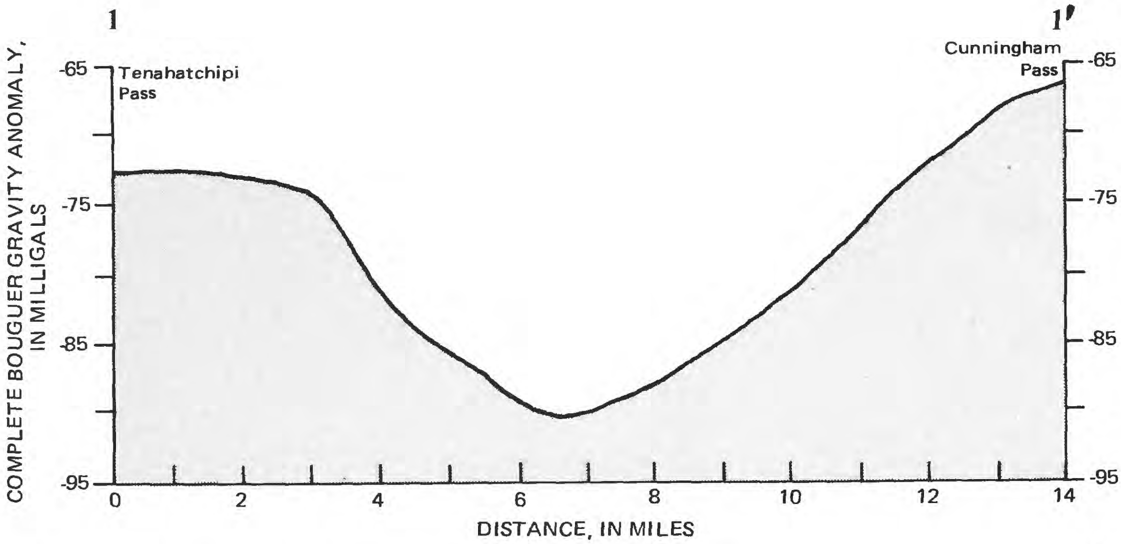
Layer 1 is near the basin center and has a density of about 2.0 g/cm^3 on the basis of bore-hole gravity studies (Tucci and others, 1982). Layer 2 is on the edge of the basin and has a density of 2.10 g/cm^3. The thicknesses of layers 1 and 2 range from 0 to 450 ft along profiles 1 and 2. Layer 3 is in the central part of the basin and ranges in thickness from 0 to about 500 ft. Densities determined from borehole-gravity measurements in fine-grained sediments that are similar to layer 3 range from about 2.05 g/cm^3 in Butler Valley to 2.20 g/cm^3 in Tucson basin (Tucci and others, 1982) and average about 2.10 g/cm^3. Density of layer 4 is difficult to determine because information on similar deposits is sparse. Borehole-gravity densities for similar sediments in south Vekol Valley averaged 2.15 g/cm^3 (Tucci and others, 1982), and this value was used for layer 4 in order to produce a conservative estimate of depth to bedrock.

Gravity-model construction consisted of 22 prisms and four density layers (fig. 7). The widths of model prisms ranged from 600 to 6,500 ft. Prism centers corresponded to the location of gravity stations. Density contrasts between bedrock and basin fill ranged from 0.67 to 0.52 g/cm^3.

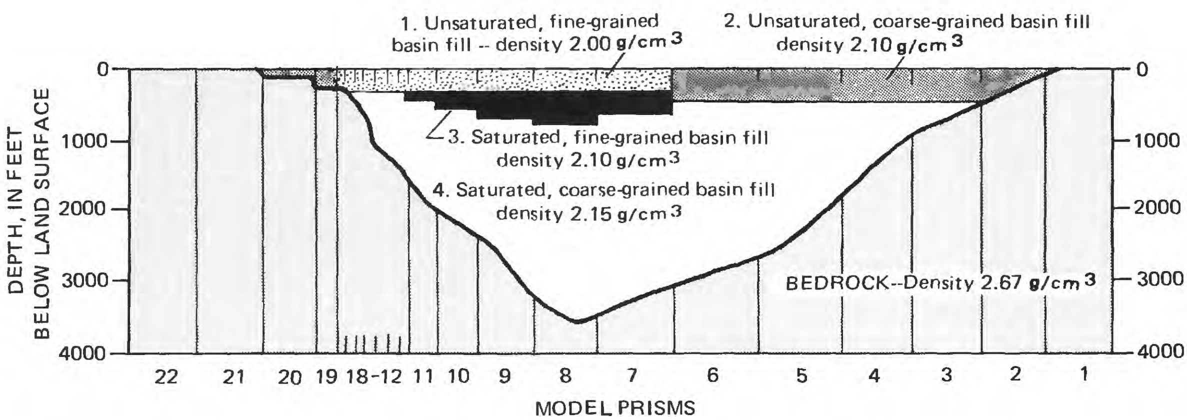
The resulting depth to bedrock along profile 1 shows an asymmetric basin with a steeper contact between bedrock and basin fill on the southeast side than on the northwest side (fig. 7). Near Tenahatchipi Pass on the southeast, shallow bedrock extends basinward for about 3 mi at which point depths increase greatly. The steepest bedrock surface corresponds to an area near the boundary of T. 5 N., and T. 6 N., where model-derived depth-to-bedrock values increase from 600 to 1,200 ft over a horizontal distance of about 1,000 ft. The northwest side of the basin has a bedrock surface that slopes gently upward from the basin center to the Harcuvar Mountains. A conservative estimate of the maximum depth to bedrock near the center of the basin is about 3,500 ft.

A similar depth-to-bedrock profile was produced by modeling the gravity values along profile 2 (fig. 5). Profile 2 lacked sufficient stratigraphic data to delineate density layers and was modeled as one layer with a density of 2.15 g/cm^3. Bedrock-gravity stations could not be established for profile 2; therefore, model results are more tenuous than results along profile 1. The depth-to-bedrock profile was similar to profile 1—a steeper contact between bedrock and basin fill was found on the southeast side than on the northwest side. A conservative estimate of maximum depth to bedrock was about 4,000 ft.

Bedrock across the profiles is assumed to be of uniform density in this modeling analysis, and bedrock structures are assumed to have a negligible effect on the bedrock density. The assumptions may not be true because there is an apparent structural change within the bedrock across the basin from stacked overthrust sheets in the Harquahala Mountains (Reynolds and others, 1980) to nonthrust faulted bedrock in the Harcuvar Mountains. A good correlation of model results to depth-to-bedrock data from drillers' logs indicates the gravity effects of the change in bedrock structure may be negligible.



A. Complete Bouguer gravity profile



B. Two-dimensional gravity model construction and depth to bedrock

Figure 7. -- Gravity profile of basin from Tenahatchipi Pass to Cunningham Pass.

The most likely structural interpretation of the gravity-model results is that the basin is a syncline that has been faulted to some extent on the southeast side. The steep contact between bedrock and basin fill on the southeast side of the basin may be due to normal faulting. The gradual increase in depth to bedrock basinward from the Harcuvar Mountains indicates no significant normal faulting.

Structural History

Most of the structural events that influenced the present hydrogeologic conditions occurred during the Tertiary Period. Events prior to this time set the framework of the bedrock geology such as overthrusting of Precambrian and Paleozoic rocks in the Harquahala and Little Harquahala Mountains and emplacement of Cretaceous plutons in the Harcuvar, Granite Wash, and Little Harquahala Mountains. Poorly understood structural events during the middle and late Tertiary Period led to the accumulation of sediments. Further structural deformation altered the distribution of these sediments and their importance as aquifers. The Basin and Range structural event subsequently created depressions in which the basin-fill sediments accumulated.

Continuity of the pre-Basin and Range and middle and upper Tertiary sediments in the study area has been restricted by complex deformation. East-northeast extension during early and middle Miocene time (Reynolds and Rehrig, 1980; Shackelford, 1980; Davis and others, 1980; Rehrig and Heidrick, 1976) caused listric faulting and rotation of the rocks above a dislocation surface that developed on the rocks of the metamorphic-core complex (Shackelford, 1980; Rehrig and Reynolds, 1980). Listric faults are normal faults that create rotation displacements on downward flattening shear planes (Rehrig and others, 1980), which results in tilting of the faulted rocks. The structural attitude of the steeply dipping volcanic and sedimentary rocks near Aguila and in the Vulture Mountains is the result of movement above the dislocation surface (Scarborough and Wilt, 1979; Rehrig and others, 1980). Scarborough and Wilt (1979) thought that the dislocation of the Bullard Peak section was synchronous with a similar event on the Rawhide and Buckskin Mountains that probably occurred between 15 and 13 m.y. ago (Davis and others, 1977). Northeast-oriented arching of the mountain ranges of the metamorphic-core complex 15 to 13 m.y. ago (Rehrig and Reynolds, 1980) was synchronous with or closely followed movement above the dislocation surface (Scarborough and Wilt, 1979).

The Basin and Range structural event is thought to have closely followed at about the same time as the arching and listric normal faulting. Initiation of the Basin and Range structural event was accompanied by basaltic volcanism around 14 m.y. ago in the Vulture Mountains (Rehrig and others, 1980). Regional ages for the beginning of the Basin and Range structural event are 15 to 13 m.y. ago (Eberly and Stanley, 1978; Scarborough and Peirce, 1978; Shafiqullah and others, 1980). Evidence of the end of the Basin and Range structural event in

McMullen Valley is scarce; however, most movement in the region probably ended by 8 m.y. ago (Shafiqullah and others, 1980).

Most basins were drained internally after the start of the Basin and Range structural event, resulting in the accumulation of fine-grained sediments and evaporites in the subsiding centers of the basins. McMullen Valley has a fine-grained facies in the upper 1,000 ft of lower basin fill, which is underlain by coarse-grained sediments that probably are more than 2,000 ft in thickness. External drainage must have existed for an extended period of time during the early stages of basin formation in order to accumulate the large thickness of coarse-grained sediments. The development of a syncline rather than block faulting would support through-flowing drainage during the early stages of basin formation. Basin-and-range faulting that would have resulted in the deposition of the evaporites and fine-grained facies near the top of the lower basin fill may have developed later.

Hydrology

Prior to the withdrawal of ground water for irrigation, the hydrologic system in McMullen Valley was in a state of equilibrium—inflow was equal to ouflow. The hydrologic system underwent significant changes as a result of development of the ground-water supply for irrigation. Definition of the hydrologic system under predevelopment conditions is poor because of a paucity of data. Information is more abundant for the postdevelopment conditions. The principal changes in the system during postdevelopment are water-level declines and changes in flow direction associated with the withdrawal of ground water.

Most ground-water movement occurs in the basin-fill sediments. Some water can be found in older rocks; however, they are of minor importance to the hydrologic system because the individual units are areally discontinuous. Only small quantities of water can be withdrawn by wells in the rocks of Precambrian through early Tertiary age; however, wells that intercept fractures may produce several gallons per minute. The generally impermeable nature of these rocks was pointed out by Metzger and others (1973) who noted the lack of springs on the south side of the Granite Wash Mountains at altitudes that are much lower than water-level altitudes in McMullen Valley. Solution cavities in Paleozoic carbonate rocks (Kam, 1964) may locally serve as conduits for ground-water flow from McMullen Valley to Harquahala Plains at the southeast end of Harrisburg Valley. Some water may be derived locally from the coarse-grained Oligocene to middle Miocene sediments near Aguila.

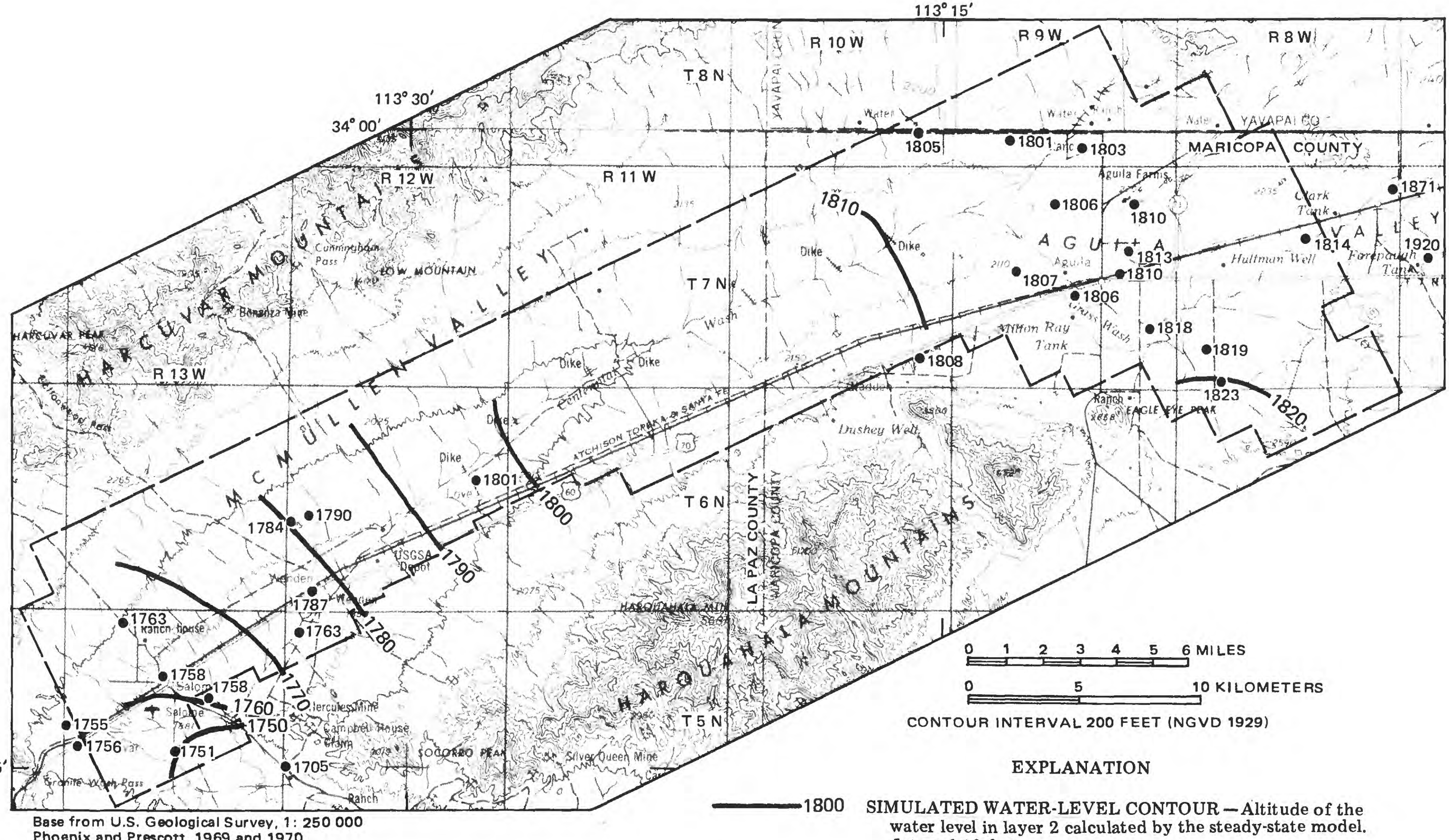
The lower basin fill is the main aquifer in the basin. The upper basin fill is above the water table in most of the area and is not significant as an aquifer. The quantity of water that is stored and the ease with which water flows through the basin-fill sediments depend on the pore space and degree of interconnection. Fine-grained sediments—silt and clay—have small pore spaces and do not easily transmit water. Coarse-grained sediments—sand and gravel—have large pore spaces that can easily transmit water. Both fine- and coarse-grained sediments occur as layers within the basin fill and strongly influence the movement of water through the aquifer.

Predevelopment Conditions

Prior to 1952, the hydrologic system in McMullen Valley was in a state of equilibrium. Ross (1923) conducted an early reconaissance of the area and collected water-level information, which gives an indication of the natural conditions in 1917. Ground-water conditions in the areas of Wenden, Salome, and Harrisburg Valley changed little between 1917 and 1951, according to 1951 conditions described by Kam (1964). Significant development of the ground-water resources near Wenden, Salome, and Harrisburg Valley began in 1952, and development of the water supply near Aguila began about 1955.

The predevelopment water-level contours are based on pre-1952 data for Wenden, Salome, and Harrisburg Valley and on pre-1955 data for Aguila (fig. 8). Data are limited to the area along the central axis of the basin where the valley floor is best suited for agriculture and depth to water is least. Water levels near the mountains are unknown because of a lack of data. The general direction of ground-water movement is toward the southwest along the axis of the basin then southeast through Harrisburg Valley. This flow direction is evidence that some recharge occurs in the northeastern part of the basin and that discharge occurs in Harrisburg Valley. Hydraulic gradients range from about 0.6 ft/mi in the area between Aguila and Wenden to about 10 ft/mi in Harrisburg Valley. The shallow gradients between Wenden and Aguila may be the result of recharge from the Harquahala and Harcuvar Mountains or higher transmissivities in the area. In Harrisburg Valley, gradients probably are steep because of the restricted cross-sectional area of aquifer.

Recharge to the ground-water system probably occurs at the base of the Harcuvar and Harquahala Mountains and in the Forepaugh subarea. Two wells—one near the base of the Harcuvar Mountains and one near the base of the Harquahala Mountains—have water-level altitudes nearly 600 and 250 ft higher, respectively, than wells in the basin (Remick, 1981). The water levels indicate some mountain-front recharge but may not represent the regional ground-water system. Geochemical data indicate little downgradient chemical evolution of the ground water and the presence of recharge from the Harcuvar and Harquahala Mountains (F. N. Robertson, U.S. Geological Survey, written commun., 1986). A steep hydraulic gradient between the Forepaugh and central subareas is evidence that water enters the central subarea as underflow through the Forepaugh subarea. The hydrologic systems in the two subareas may be poorly connected. Estimates of total recharge to the ground-water system have been 2,000 acre-ft/yr (Arizona Water Commission, 1975). Recharge estimates based on precipitation are 1,000 to 2,000 acre-ft/yr (Freethey and Anderson, 1986).



EXPLANATION

1800 SIMULATED WATER-LEVEL CONTOUR — Altitude of the water level in layer 2 calculated by the steady-state model. Interval 10 feet

BOUNDARY OF LAYER 2 OF STEADY-STATE MODEL

• 1807 WELL — Number, 1807, is field-measured water level

Figure 8. -- Field-measured and simulated water levels, predevelopment .onditions.

Some recharge probably occurs through infiltration of surface flow in Centennial Wash. One shallow well—(B-5-12)6cab—south of Wenden and close to Centennial Wash has water levels that have fluctuated more than 10 ft between yearly measurements, probably in response to the percolation of infiltrating streamflow (Kam, 1964; Remick, 1981).

The only known area of ground-water discharge under steady-state conditions was in Harrisburg Valley where discharge occurred as underflow and evapotranspiration (Kam, 1964). Underflow through the basin fill at the outflow point in the southeast end of Harrisburg Valley probably is limited by a restricted cross-sectional area of aquifer. Outflow may be increased by flow through solution cavities in Paleozoic limestone (Kam, 1964). Some ground water is lost to evapotranspiration because of phreatophytes and shallow water levels near the outflow point.

Data from several wells near Wenden and Salome indicate that the lower part of the fine-grained facies is of low permeability and separates the aquifer into shallow and deep systems. Many of the early stock and domestic wells obtained water from the shallow system where water is found in coarse-grained sediments within or above the upper part of the fine-grained facies. The deep system is encountered where wells penetrate the lower part of the fine-grained facies and tap water in underlying coarse-grained sediments. Low permeabilities between the shallow and deep systems are indicated by the following:

- Several drillers reported water from the deep system rising to a level close to that in the shallow system.
- Water levels in one system do not respond to changes in water levels in the other system.
- Water from shallow wells has a higher total dissolved-solids content than water in the deeper wells (Ross, 1923; Kam, 1964).

Water-level maps in this report represent the deep system. The lack of water-level data prohibits a good delineation of the water-table configuration in the shallow system.

The general distribution of aquifer transmissivity was estimated using specific-capacity data (fig. 4) and a flow-net analysis. Specific-capacity values near Wenden and Salome range from 1 to 150 (gal/min)/ft of drawdown and average about 25 (gal/min)/ft. Near Aguila, values range from 8 to 105 (gal/min)/ft of drawdown and average about 40 (gal/min)/ft with values tending to decrease to the northwest and southeast of Aguila. Flow nets were constructed using predevelopment water-level contours near Aguila, Wenden, and Salome. Transmissivities then were calculated on the basis of an estimated ground-water flow rate of 1,000 acre-ft/yr. The transmissivity distributions from the specific-capacity data and the flow-net analysis compared favorably.

Transmissivity near Aguila is about 10,000 ft^2/d according to the flow-net calculation and decreases toward the northwest and southeast. Transmissivity values are about 6,000 ft^2/d near Wenden and Salome and tend to decrease toward the northwest. South of Salome near the northern part of Harrisburg Valley, transmissivity is about 700 ft^2/d.

The hydraulic-property values of the aquifer tend to decrease with the presence of fine-grained sediments and age of the deposit. In the southwest half of the basin, the main aquifer is composed of coarse-grained and fine-grained facies of lower basin fill. The fine-grained facies has poor hydraulic properties, and most ground-water flow probably occurs in coarse-grained sediments adjacent to and beneath the fine-grained facies. Near Aguila, high transmissivities probably are due to the greater thickness of coarse-grained lower basin fill and some overlying saturated upper basin fill. In the areas northwest and southeast of Aguila, lower transmissivity values are due to a lack of saturated upper basin fill, thin deposits of coarse-grained lower basin fill, and the presence of shallow pre-Basin and Range sediments of lesser hydraulic conductivity.

The hydraulic conductivity of the sediments is difficult to estimate because no aquifer tests have been conducted and the thickness of the aquifer is not known. If the assumption is made that most ground-water flow occurs in a thickness close to that penetrated by wells—1,000 to 1,500 ft—hydraulic conductivities should be in the range of 5 to 10 ft/d. Hydraulic conductivities of 5 to 10 ft/d are comparable to those found in similar sediments in other basins (T. W. Anderson, U.S. Geological Survey, written commun., 1986). The hydraulic-conductivity values vary with the aquifer stratigraphy across the basin. Stratigraphy and hydraulic gradients indicate that slightly lower hydraulic conductivities are more likely to occur in the southwestern part of the basin than in the northeastern part. Previous ground-water models used hydraulic conductivities of 1 ft/d or less and transmissivities of less than 1,000 ft^2/d to represent similar fine-grained sediments (G. W. Freethey, U.S. Geological Survey, written commun., 1986).

Postdevelopment Conditions

Ground-water withdrawals after 1952 altered the natural ground-water flow system. Pumpage of nearly 200 times the rate of recharge to the system disrupted the previously existing equilibrium of inflow and outflow. Water drawn from storage resulted in water-level declines and changes in the direction of ground-water movement. Storage depletion is the main hydrologic process occurring in the postdevelopment system because nearly all water is drawn from aquifer storage.

Two major areas of water-level decline developed near Wenden and Salome and near Aguila, which are the main agricultural centers. Near Wenden and Salome, a large elongated cone of depression had developed by 1965 and extended from southwest of Salome to about 8 mi northeast of Wenden (fig. 9). Maximum declines since 1952 were about 50 ft near Salome and more than 100 ft northeast of Wenden. The cone of depression is asymmetric; higher water levels and steeper hydraulic gradients exist on the northwest side than on the southeast side. A large oblong cone of depression had developed northeast of Aguila by 1965 with maximum declines of about 90 ft. Nearly all the water-level data for 1965 show declines from the steady-state water levels. These data indicate that ground-water declines were areally extensive across the aquifer and probably had reached the impermeable boundaries in most of the basin.

The same general trends persisted from 1965 to 1980 as shown by water-level contours for December 1980 (fig. 10). By 1980, the asymmetric cone of depression near Wenden and Salome had deepened significantly and the center had shifted southwest toward Salome. Maximum declines of more than 250 ft had occurred since predevelopment in an area that extended from Salome to several miles northeast of Wenden. Water-level gradients in the center of the cone were shallow as compared to those at the aquifer boundaries where gradients are about 50 ft/mi. Near Aguila, the center of the cone had shifted eastward and declines of more than 150 ft had occurred since predevelopment. The shape of the cone was nearly circular, and shallow hydraulic gradients extended radially. Nearly all water-level data in 1980 indicated that declines were more than 100 ft from predevelopment conditions. Large declines probably are common near the aquifer boundaries, although sparse data exist near the aquifer boundaries.

Hydrographs of two wells—one near Wenden and Salome and one near Aguila—are representative of water-level decline in the two areas (fig. 11). Decline rates have been about 10 to 13 ft/yr near Wenden and Salome and 6 to 10 ft/yr near Aguila.

The low hydraulic conductivity of the fine-grained facies of lower basin fill may be restricting the downward movement of water from overlying materials during postdevelopment time. A few shallow wells near Wenden show little decline in water levels since the beginning of development. The lack of response in the water levels of the shallow system to declines in the deep system indicates poor hydraulic connection between the two systems. The areal extent of these conditions is not known because of the lack of water-level data in the shallow system.

Storage properties of the aquifer are a controlling factor in the storage-depletion system and determine rates and magnitudes of water-level decline; however, no aquifer-test data are available from which storage properties can be determined. An average specific yield of the dewatered zone was estimated from water-level declines and total

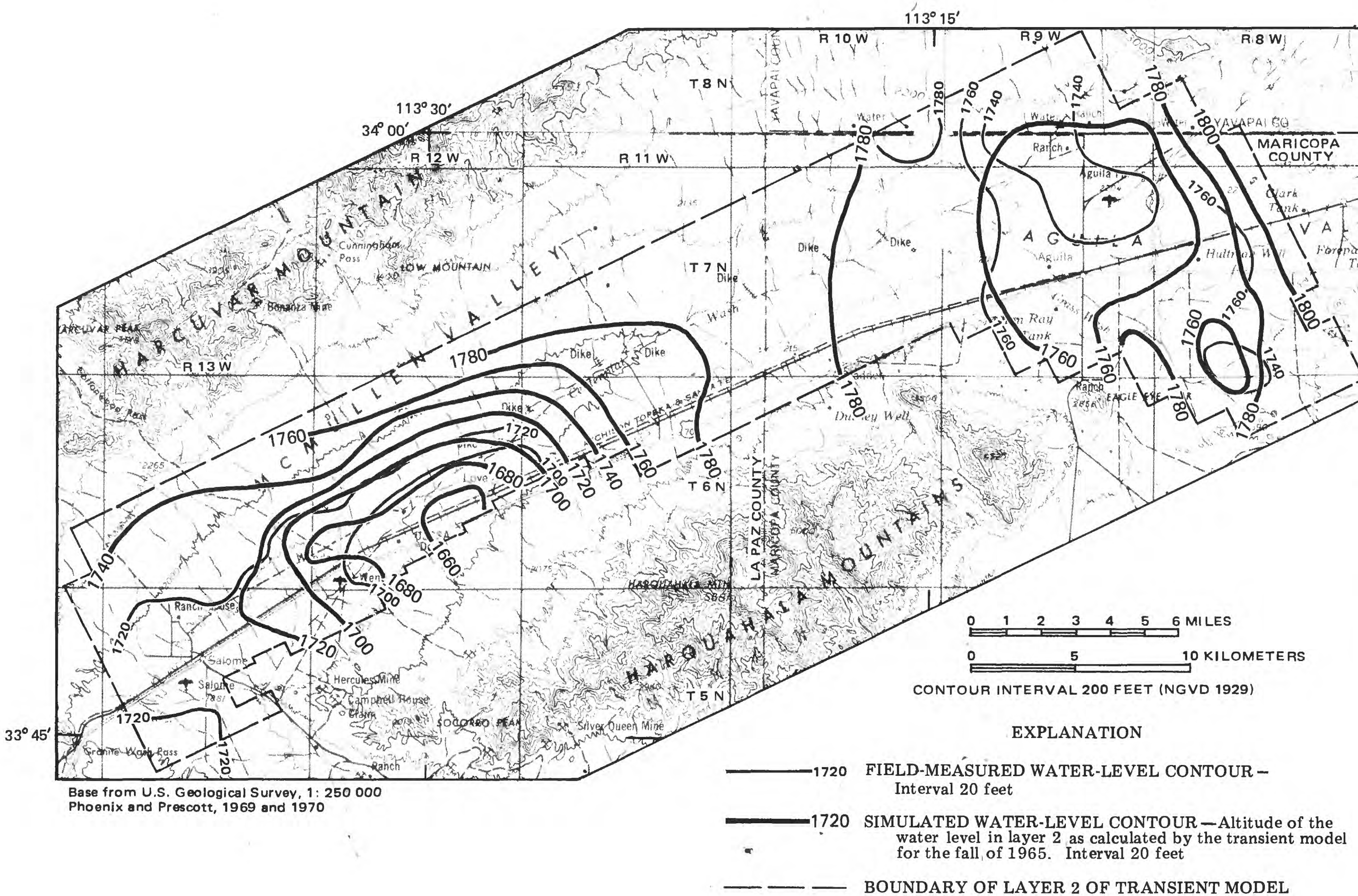
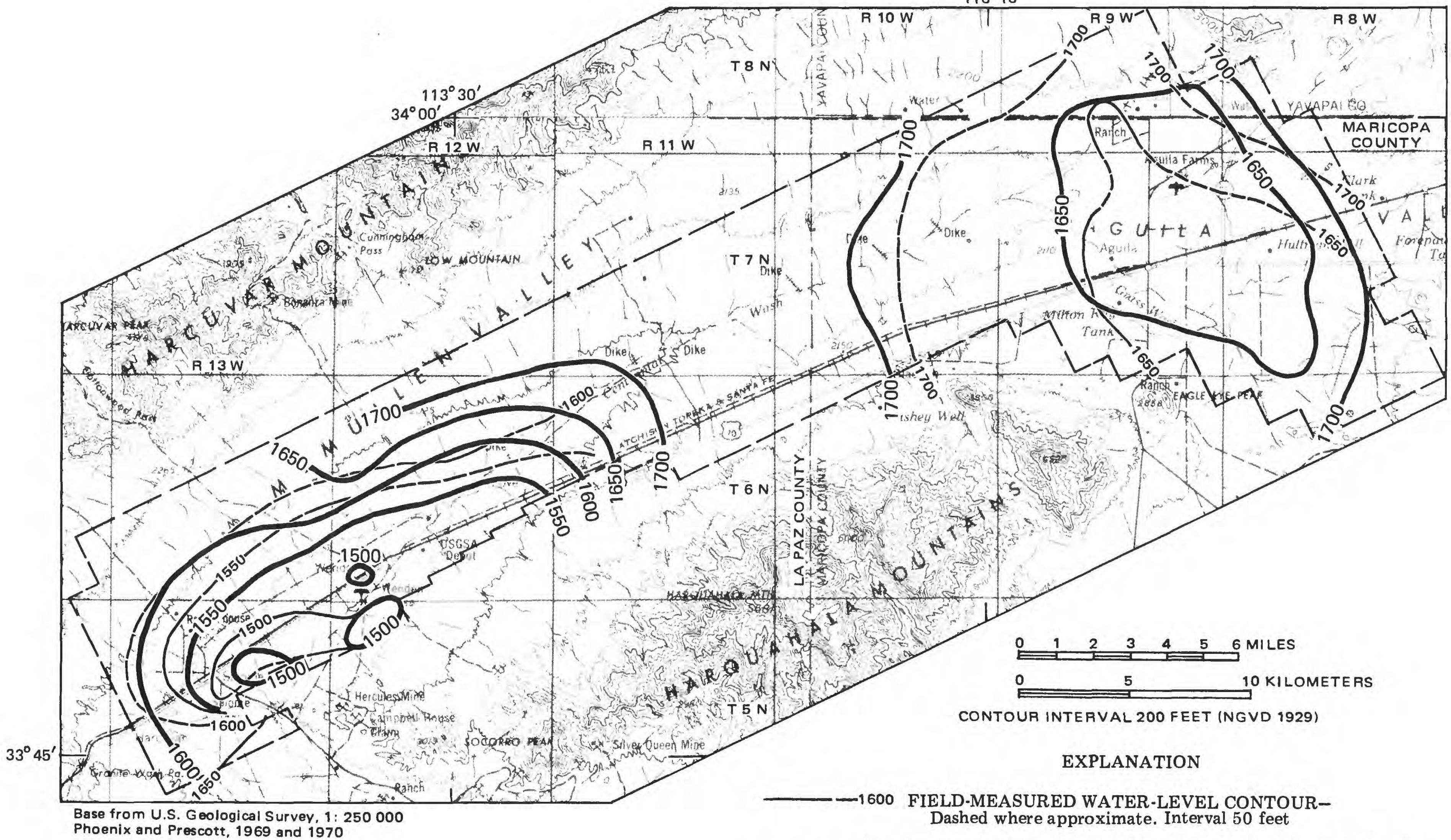


Figure 9. -- Field-measured and simulated water levels, fall 1965.



EXPLANATION

1600 FIELD-MEASURED WATER-LEVEL CONTOUR— Dashed where approximate. Interval 50 feet

1600 SIMULATED WATER-LEVEL CONTOUR— Altitude of the water level in layer 2 as calculated by the transient model for December 1980. Interval 50 feet

BOUNDARY OF LAYER 2 OF TRANSIENT MODEL

Figure 10.-- Field-measured and simulated water levels, December 1980.

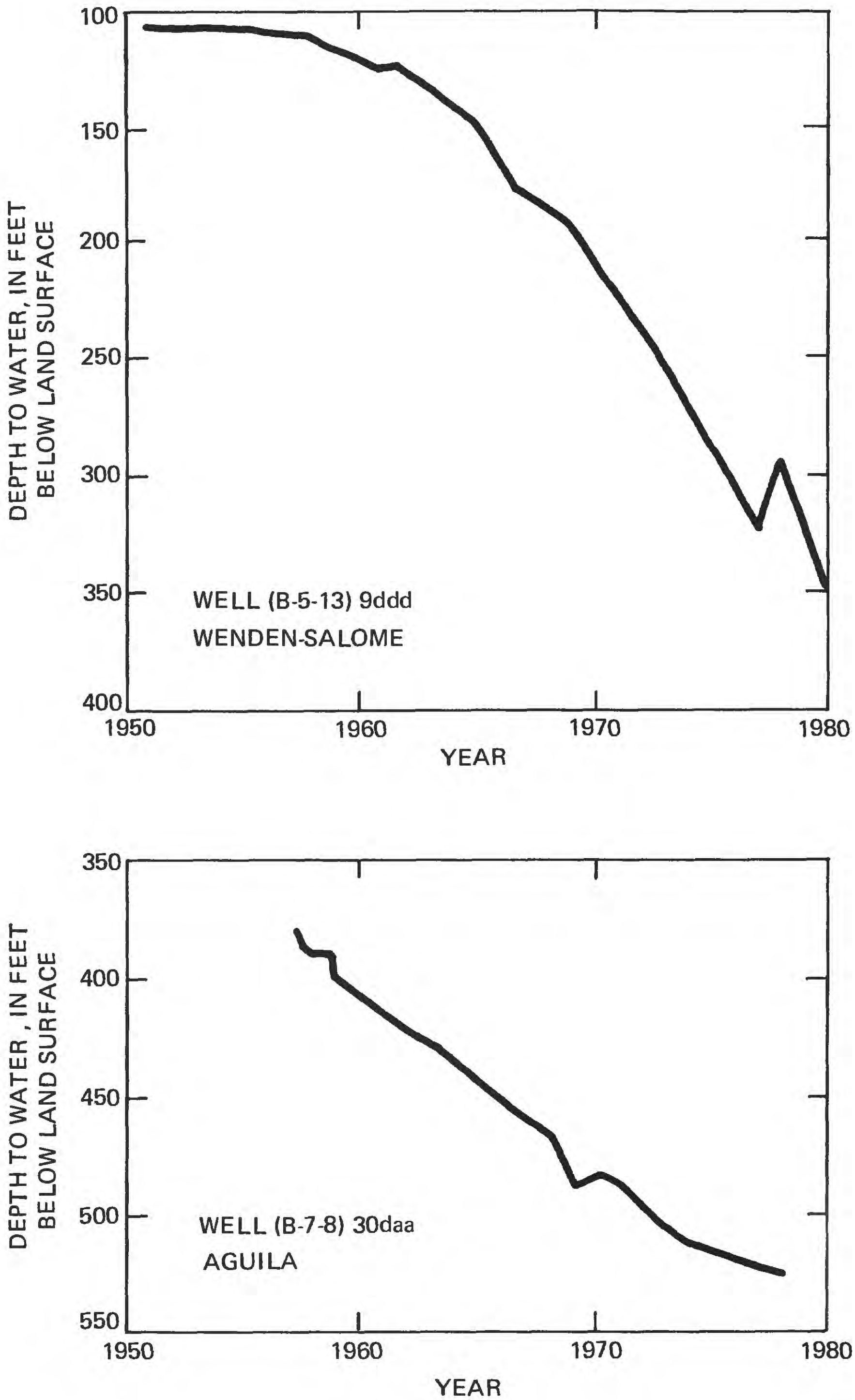


Figure 11. -- Water levels in selected wells near Wenden and Salome and near Aguila.

ground-water withdrawals for 1958-80. Average specific yields of 0.09 near Wenden and Salome and 0.10 near Aguila were determined. Knowledge of the areal extent of the aquifer, water-level declines, and pumpage affect the reliability of these estimates. Lack of information on aquifer boundaries and water-level declines outside the pumping centers are the main sources of error. In addition, the extent of water-level declines in the shallow system are unknown. Actual local values of specific yield may be considerably different from the estimate because of the wide range of sediment types being dewatered.

MODELS OF THE HYDROLOGIC SYSTEM

Numerical models of the steady-state (predevelopment) and transient (postdevelopment) ground-water conditions in McMullen Valley were constructed using the quasi-three-dimensional approach of Trescott (1975), Trescott and Larson (1976), and McDonald and Harbaugh (1984). The steady-state model was used to analyze the hydraulic-property distribution in the aquifer and the volume and location of recharge and discharge. The transient model was used to analyze the response of the ground-water system to pumping stress. Sensitivity analysis aided in evaluating the controls on the hydrologic system under steady-state and transient conditions.

The numerical models consisted of two model layers and an intervening vertical-leakance layer. Areal extent of each layer is slightly different and corresponds to the extent of the hydrogeologic units (fig. 12). Near Aguila, the lower layer—layer 2—represents pre-Basin and Range sediments and the upper layer—layer 1—represents upper and lower basin fill. Layer 1 does not extend to the southeast of Aguila because only the pre-Basin and Range sediments are thought to be saturated in that area. Near Wenden and Salome, all sediments below the upper part of the fine-grained facies of the lower basin fill are represented by layer 2; all overlying saturated sediments are represented by layer 1. Layer 1 is more extensive than layer 2 near Wenden and Salome because layer 2 is limited in extent by shallow bedrock.

Areally, the aquifer is divided into finite-difference blocks by a grid of 37 rows and 29 columns (fig. 12). A variable-spaced grid was used to provide more detail where it was needed. Row spacing was 1 mi over most of the basin. Larger row spacing of 2 mi in the center of the basin corresponds to areas of low data density. Column widths ranged from 1,000 ft near Wenden-Salome and Aguila to 2 mi at the base of the Harcuvar Mountains. The small spacing allowed for more accurate simulation of steep gradients, more precise pumping locations, and better analysis of boundary effects.

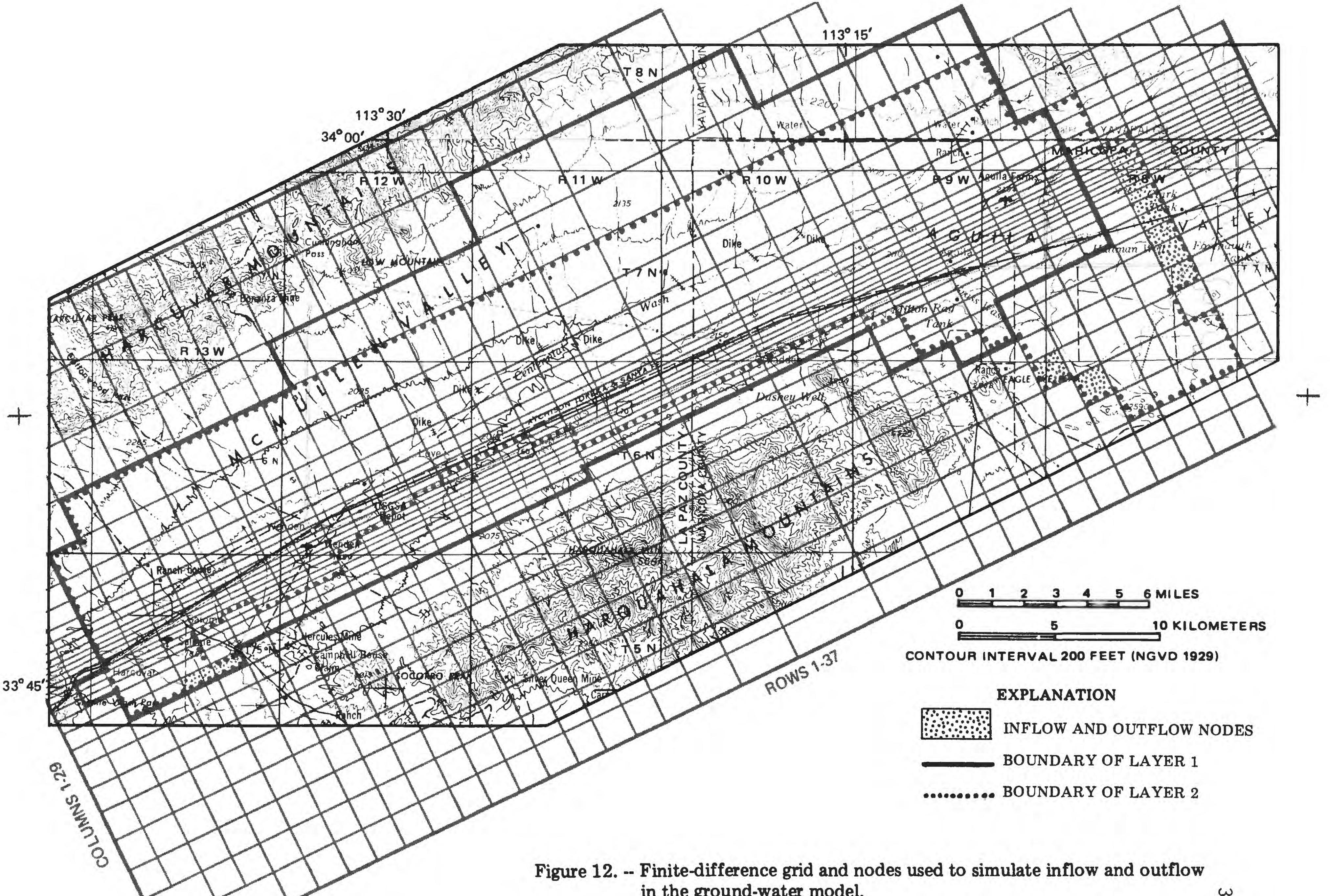


Figure 12. -- Finite-difference grid and nodes used to simulate inflow and outflow in the ground-water model.

The locations of flow boundaries were approximated using drillers' logs, lithologic logs, gravity data, and surface geologic information. Few wells encountered bedrock materials, so most boundaries were located using gravity data and surface geologic information. Gravity stations are sparse in most of the valley except for the area of the two gravity profiles (fig. 5). A more dense coverage of gravity stations is needed in the rest of the valley in order for gravity methods to be a useful tool for accurately locating boundaries in those areas. The gravity data were particularly useful in locating the boundary southeast of Wenden. Results of gravity modeling indicated that the boundary is much closer to the pumping centers than is implied by surface geologic information.

Model-input components include altitudes of the steady-state water levels, hydraulic properties, and the altitude of the bottom of layer 1. Steady-state water-level altitudes are assigned to each active node in layers 1 and 2. Average hydraulic properties input to each node of each layer consist of transmissivity for layer 2 and hydraulic conductivity for layer 1. The saturated thickness of layer 1 is calculated by the model on the basis of the altitude of the bottom of layer 1 and the water level. Vertical-leakance values were assigned to each node between layers.

The type of inflow or outflow nodes were varied from the steady-state model to the transient model. Inflow and outflow areas were modeled as constant-head nodes for the steady-state analysis. In the transient model the inflow and outflow areas were modeled as constant-flux nodes because of large water-level declines in those areas. Constant-flux values were derived from the steady-state model. The effects of using constant-head or constant-flux flow boundaries were analyzed as a sensitivity analysis and are discussed in the section on sensitivity analysis.

Simulation of Predevelopment Conditions

The steady-state model was used to simulate predevelopment water-level conditions (fig. 7). The purpose of the simulation was to calibrate the hydraulic properties and flow components used in the steady-state model. The calibration procedure consisted of adjusting the hydraulic properties and flow components in the steady-state model so that the predevelopment water levels were closely simulated. Accuracy of the simulation depended on the adequacy of water-level, recharge, and hydraulic-property data; however, these data in McMullen Valley are minimal. The predevelopment simulation, therefore, can be considered only an approximation of the system.

Model Characteristics

The hydraulic properties assigned to each node were based on the flow-net analysis. The hydraulic conductivity for the fine-grained facies of layer 1, however, was set at 1 ft/d. Estimated total transmissivity was apportioned between layers 1 and 2. Near Wenden and Salome, the transmissivity of the fine-grained facies in layer 1 was subtracted from the total estimated transmissivity to produce a value for the transmissivity of layer 2 (fig. 13). Flow-net transmissivities were assigned to layer 2 southeast of Aguila where layer 1 is absent. Similar values then were used in layer 2 in the remainder of the area near Aguila. Hydraulic conductivities for layer 1 near Aguila were calculated by subtracting the transmissivity for layer 2 from the flow-net transmissivity and dividing by the thickness of layer 1. Hydraulic conductivity for layer 1 in Harrisburg Valley was determined by dividing the flow-net transmissivity by the aquifer thickness. Vertical-leakance values were 10^{-11} (ft/sec)/ft in the region of the fine-grained facies and 10^{-6} (ft/sec)/ft outside the fine-grained facies.

Inflow was represented by constant-head cells at the boundary with the Forepaugh subarea and at the boundary with the Hassayampa area. Outflow was represented by one constant-head cell in Harrisburg Valley. No other recharge or discharge areas were originally modeled. Mountain-front recharge of 413 acre-ft/yr was distributed equally among 38 nodes at the base of the Harcuvar and Harquahala Mountains. Most of the phreatophytes that use shallow ground water are downgradient from the modeled area in Harrisburg Valley. Recharge along Centennial Wash was assumed to be small and was not modeled.

Model Results

The calibration procedure resulted in a good comparison of simulated and field-measured water-level contours in the areas of Wenden, Salome, and Harrisburg Valley (fig. 7). The location of the 1,800-foot water-level contour was the least known and also the least well simulated. Simulated gradients near Aguila are about half the observed gradients; the difference could be because of a lack of water-level and transmissivity data at the inflow points. The water budget that resulted from the final calibration indicated about 650 acre-ft/yr of inflow and outflow.

The general distribution of hydraulic properties in most of the aquifer was changed little during calibration. Hydraulic-property values for nodes near inflow and outflow areas were subject to the greatest change because of the lack of water-level and transmissivity data (fig. 13A-C). Hydraulic conductivity of layer 1 ranged from 1 ft/d in the fine-grained facies to 10 ft/d near the outflow area. The transmissivity of layer 2 ranged from 100 to 30,000 ft^2/d; the highest

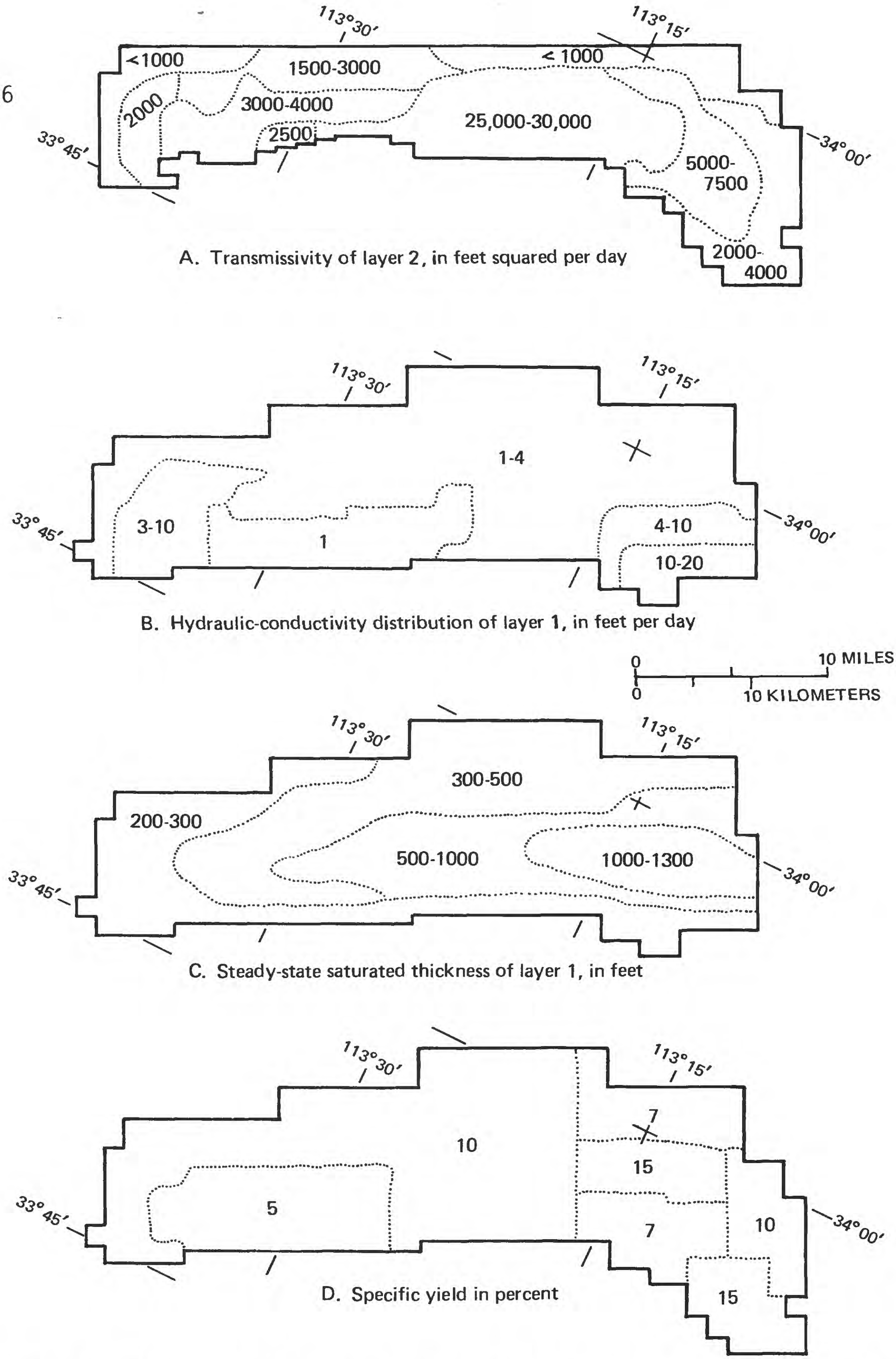


Figure 13. – Distribution of hydraulic properties in the steady-state and transient models.

values were near Aguila. Total transmissivity values ranged from less than 500 ft^2/d at the edges of the basin to as much as 35,000 ft^2/d near Aguila.

Inflow through the constant-head nodes totaled 235 acre-ft/yr. Inflow from mountain-front recharge was 413 acre-ft/yr. Outflow from the constant-head nodes at Harrisburg Valley was 646 acre-ft/yr. Total difference between inflow and outflow in the model was less than 1 percent.

Simulation of Postdevelopment Conditions

A transient simulation of the ground-water system for 1951-80 was developed to analyze the response of the hydrologic system to the stress of ground-water pumping. The effects of the various hydrologic properties—storage, transmissivity, vertical leakance, and boundary location—on the transient response were also analyzed. The hydraulic components used in the steady-state model were used in the transient model; in addition, storage components and pumpage were added. Water-level changes for 1951-65 and 1966-80 were simulated during the calibration procedure.

Model Characteristics

Inflow and outflow areas were modeled as constant-flow boundaries. Outflow from Harrisburg Valley was maintained at the steady-state model flow rate of 646 acre-ft/yr. Inflow was simulated as 413 acre-ft/yr of mountain-front recharge and 235 acre-ft/yr of underflow. Inflow and outflow areas were modeled as constant-head boundaries in a sensitivity analysis.

Pumpage was simulated in four time periods—(1) 1951-57, (2) 1958-65, (3) 1966-72, and (4) 1973-80—that were selected to simulate the changes in pumping trends (fig. 2). Period 1 represents the initial stages of development when withdrawals were small. Increasing withdrawals are represented in period 2, and the end of the period coincides with the water levels for fall 1965. Withdrawals further increased during periods 3 and 4. The end of period 4 coincides with water levels for December 1980. Total pumpage and individual node pumpage in the model were constant during each period. The pumpage could have been divided into smaller time periods that would have more closely approximated the pumping trends; however, the cost of model calibration would have increased significantly.

Pumpage was distributed on the basis of available pumpage and irrigated-acreage data. Pumpage for period 1 was based on estimates by Kam (1964) and was distributed equally among the wells in the two major pumping centers. The total pumpage for periods 2 and 3 was divided between the two pumping centers on the basis of the proportion of irrigated acreage in each area and was then distributed equally among the wells within each area. Pumpage for period 4 was determined from individual power records for each well and is considered to be more accurate than pumpage for the previous periods.

The model of transient conditions required the input of storage components for layers 1 and 2. A storage coefficient of 0.0001 was assigned to most of layer 2 because water is derived through the compressibility of the aquifer material and expansion of water. East of Aguila where layer 2 is not overlain by layer 1, layer 2 was assigned a specific yield that ranged from 0.07 to 0.15 (fig. 13D). Specific-yield values were assigned to layer 1 on the basis of the previous discussion in the section entitled "Postdevelopment Conditions." Near Wenden and Salome, specific-yield values ranged from 0.05 in the fine-grained facies to 0.10 in the surrounding coarse-grained sediments. The specific yield of layer 1 near Aguila ranged from 0.07 to 0.15. Specific-yield values and their areal distribution were adjusted slightly during the calibration procedures to simulate observed drawdowns and to estimate the model sensitivity to storage values.

Model Results

Calibration of the transient model required adjusting the location of low vertical-leakance values and specific-yield values. All other components including pumpage were considered fixed and were not adjusted during calibration. The extent of low vertical-leakance values was considered the least known of the variable components. Specific yield was considered to be variable within only a few percent.

The model-generated water levels were compared to the water levels for fall of 1965 and December 1980 corresponding to the end of the model pumping periods 2 and 4, respectively (figs. 8 and 9). The model-generated water levels from layer 2 were used for comparison with field-measured data. More calibration emphasis was placed on the final pumping period because of the more abundant water-level data and more accurate pumping data.

The results of the transient model indicate two different types of responses of the ground-water system to pumping stress in the two pumping centers of Wenden-Salome and Aguila. The response in the Wenden-Salome vicinity is largely influenced by the areal extent of the fine-grained facies that is represented by low vertical-leakance values and by the close proximity of the hydrologic boundary to pumpage. At Aguila, the response can be interpreted as a simple storage-depletion system where model response is controlled mainly by pumpage and specific-yield distributions.

Hydrologic data from Wenden-Salome also provide evidence that the ground-water system is different from that of Aguila: (1) The cone of depression is asymmetrical, (2) the shape of the cone is not closely correlated with pumpage distribution, (3) rates of decline are greater than at Aguila, and (4) anomalously high water levels exist in some shallow wells. The most likely reason for the difference is that the hydraulic properties of the fine-grained facies of the lower basin fill have a strong influence on the ground-water system near Wenden and Salome. Most pumpage is from the underlying coarse-grained sediments, and drawdown patterns duplicate the areal extent of the fine-grained facies. The anomalously high water levels and shallow wells are found in an area overlying the fine-grained sediments.

Water-level contours from data collected during the fall of 1965 and model-generated water-level contours at the end of pumping period 2 are shown in figure 8. The model-generated contours are shown for all of layer 2; observed water levels are shown only where data were sufficient in number to draw a contour. Declines were more than 10 ft throughout most of the model. The general shape of the declines near Wenden and Salome was also simulated. Model-generated gradients on the northwest side of the cone were similar to field-measured gradients; however, gradients between Wenden and Salome were about twice as steep as field-measured gradients. The shape of the declines near Aguila generally was well simulated with two main centers of decline—one to the north of Aguila and the other to the southeast near the boundary of the Hassayampa area. Maximum model-generated declines however were about 10 to 20 ft less than the observed declines of 60 to 70 ft.

The general shape and magnitude of the model-generated and field-measured drawdown patterns for December 1980 are similar (fig. 9). Drawdowns were over 50 ft in layers 1 and 2 throughout most of the model. Water levels were similar in both layers except for the area of low vertical-leakance values where differences of as much as 150 ft occurred. Simulated water levels in layer 2 were within 25 ft of observed water levels throughout most of the modeled area. Water-level gradients within the drawdown cones of each area were also similar. The largest difference occurs northeast of Wenden where field measurements indicate that the cone of depression extended farther to the northeast than that simulated by the model.

Model Reliability and Sensitivity

The ground-water model was used to help understand the hydrologic system and generally simulate the actual field conditions. The reliability of the model-input components is gaged by how well the model represents the general hydrologic conditions rather than how closely specific water levels are simulated at particular locations. The model cannot precisely simulate actual conditions because the aquifer is represented by discrete model blocks that are assigned average values of hydraulic components. The actual hydraulic properties within a part of aquifer represented by a block may be heterogeneous. Water levels calculated by the model represent values calculated for the center of each model block.

Model sensitivity is expressed by describing how the numerical solution changes as the hydrologic components are varied. Components that have the greatest effect on the model are those that also have the greatest control on the actual hydrologic system. Hydraulic and storage properties, pumpage, and boundary locations were systematically varied—one at a time—as a means of evaluating the effect of the variations on model response.

The values of hydraulic conductivity and transmissivity were systematically altered in the steady-state model by plus or minus an order of magnitude. Significantly different results indicated that the steady-state model is sensitive to changes in these properties. Changing the hydraulic conductivity and transmissivity values resulted in changes of the hydraulic gradients through the basin and changes in the quantity of flow at the inflow and outflow nodes. An acceptable solution may be attained through recalibration at lower or higher values; however, the small flow components at the lower transmissivity range would be unacceptable.

The transient model is more sensitive to decreasing the transmissivity values than increasing the transmissivity values. Lower transmissivity values produced steeper gradients, decreased the areal extent of the cones of depression, and increased drawdowns by 50 percent in the pumping node. Higher transmissivities produced shallower gradients, increased the areal extent of the cones of depression, and decreased drawdowns by 50 percent in the pumping node. The change in water levels however was much less significant than at the lower values. The transient model, like the steady-state model, could be calibrated using a higher range of transmissivities.

Calibration of the transient model indicated that low leakance values of 10^{-10} (ft/sec)/ft or less were needed between the two model layers to simulate the low vertical hydraulic conductivity of the fine-grained facies and hydraulic head differences of 150 ft between layers. Leakance values equal to or greater than 10^{-9} (ft/sec)/ft in the region of the fine-grained facies produced results that were greatly different from the calibrated model. The results were:

— Drawdowns in layer 2 were reduced by nearly 50 percent.

— The cone of depression became circular and did not spread as far areally.

— The hydraulic connection between layers was greatly increased as the hydraulic-head difference between layers decreased to about 30 ft.

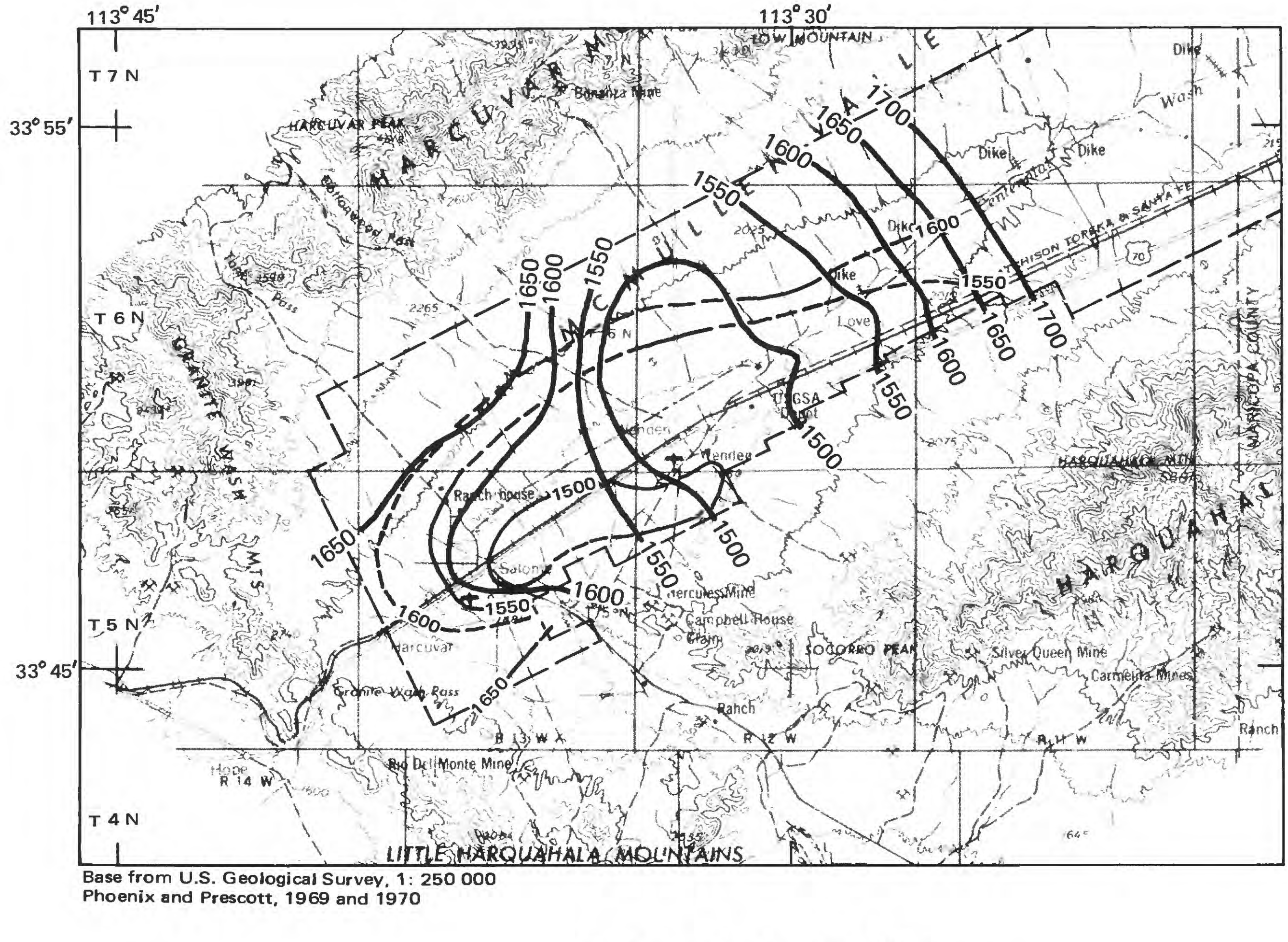
Similar results were produced when leakance values of 10^{-10} or 10^{-11} (ft/sec)/ft were used, although the lower value produced drawdowns that were slightly greater in layer 2 and less in layer 1. Model results at values lower than 10^{-11} (ft/sec)/ft could not be evaluated because the transient model would not converge to a solution. Variations of the leakance values from 10^{-9} to 10^{-11} (ft/sec)/ft produced no significant change in the steady-state model results.

The shape of the cone of depression in layer 2 conformed to the areal distribution of low leakance values. Steep water-level gradients appear at the edges of the area of low leakance values because water can be readily withdrawn from storage in layer 1 by vertical leakage. Steep water-level gradients are found at the northwest and northeast edges of the fine-grained facies as a result of this boundary effect. The location of observed steep water-level gradients was easily simulated by changing the areal distribution of low leakance values.

Model results indicated that the lower part of the fine-grained sediments and low vertical-leakance values do not extend to the northwest across the entire width of the basin near Wenden and Salome. A simulation that included a basinwide fine-grained facies produced a cone of depression that was much greater in areal extent than the observed cone of depression (fig. 14).

Errors in the modeling analysis may result from incorrect pumpage distributions. The most accurate method by which pumpage is estimated is through use of power-consumption data. Another reasonably accurate method is through consumptive use by crops, irrigation application, and efficiency estimates. Power-consumption data were available for the final pumping period of the transient simulation. Pumpage for previous time periods was estimated using irrigated area and irrigation efficiency and was distributed as an average pumpage per well. The pumpage distributions from the two methods appear to be consistent on the basis of the small amount of information available. A more accurate estimate probably was not necessary for this general investigation but may be needed if more detailed information is to be gained from modeling.

In order to evaluate the possible effects of inadequate simulation of the pumpage distribution, pumpage for one pumping period near Wenden-Salome was distributed by two methods—an average rate per well and an average rate per irrigated area—and the results were compared. Resulting cones of depression for both methods were similar in extent and magnitude. No significant differences in the interpretation of the hydrologic system would result from using one method rather than the other in McMullen Valley. In other basins, different pumpage-distribution methods may not provide similar results because irrigation practices may vary greatly across the area. Also, in some areas wells may be close to a boundary and the boundary effects are a significant influence on the response of the system.



EXPLANATION

———1600 FIELD-MEASURED WATER-LEVEL CONTOUR – Dashed where approximate; Interval 50 feet

———1600 SIMULATED WATER-LEVEL CONTOUR – Altitude of the water level in layer 2 in the Wenden-Salome area on the basis of an assumed basinwide fine-grained facies. Interval 50 feet

— — — BOUNDARY OF TRANSIENT MODEL

Figure 14. -- Simulated water-level configuration near Wenden and Salome assuming a basinwide fine-grained facies.

Specific yield was a major controlling factor in the response of the system to stress near Aguila. Specific-yield values were varied between 0.05 and 0.20, but the final areal distribution of 0.07 to 0.15 produced the most reasonable areal patterns and magnitude of declines. A marked variation in specific yield with depth probably exists in the upper few hundred feet of sediment and was not accounted for in the model. More accurate assignment of areal and vertical specific-yield values would require more detailed knowledge of the stratigraphy and storage properties of the sediments.

Specific yield of the aquifer outside the area of the lower part of the fine-grained facies near Wenden and Salome partially controls the magnitude of declines. The influence of the vertical flow in the fine-grained facies on the extent and magnitude of the cone of depression, however, overshadows the influence of specific yield. Variation of the specific-yield values between 0.01 and 0.15 throughout the area near Wenden and Salome produced different amounts of water-level decline but did not alter the overall pattern. Specific-yield values used in this model—0.05 for the upper part of the fine-grained facies and 0.10 for coarse-grained sediments—are those that are thought to best represent the system. Better calibration of specific yield through modeling analysis would require more accurate knowledge of the areal extent and hydraulic properties of the fine-grained facies and delineation of impermeable boundaries.

Locations of impermeable boundaries limit the extent of the aquifer and volume of sediments from which water can be withdrawn. In aquifers where declines have not reached impermeable boundaries, their accurate locations are generally unimportant. In McMullen Valley, water-level data and ground-water modeling indicate that declines are areally extensive throughout the valley; therefore, the size of the aquifer is an important consideration. The general locations of basin-fill and bedrock boundaries in McMullen Valley can only be estimated from surface geology, well-log information, and geophysical data.

Modeling of gravity data located the boundary near Wenden along the northwest side of the Harquahala Mountains. The transient model was used to analyze the effect of the boundary location on model results by varying the boundary location between 500 and 12,000 ft from the nearest pumping node (fig. 15). The maximum drawdown in the pumping node through pumping period 4 increased by more than 35 percent—from 220 to 299 ft—as the boundary is moved from a distance of about 12,000 ft to 500 ft. Drawdowns increased greatly as the boundary was moved within 7,000 ft of the pumping node, and increased drawdowns became significant within 5,000 ft. Results indicated that boundaries within about 5,000 ft of the major pumping center have significant control on drawdowns.

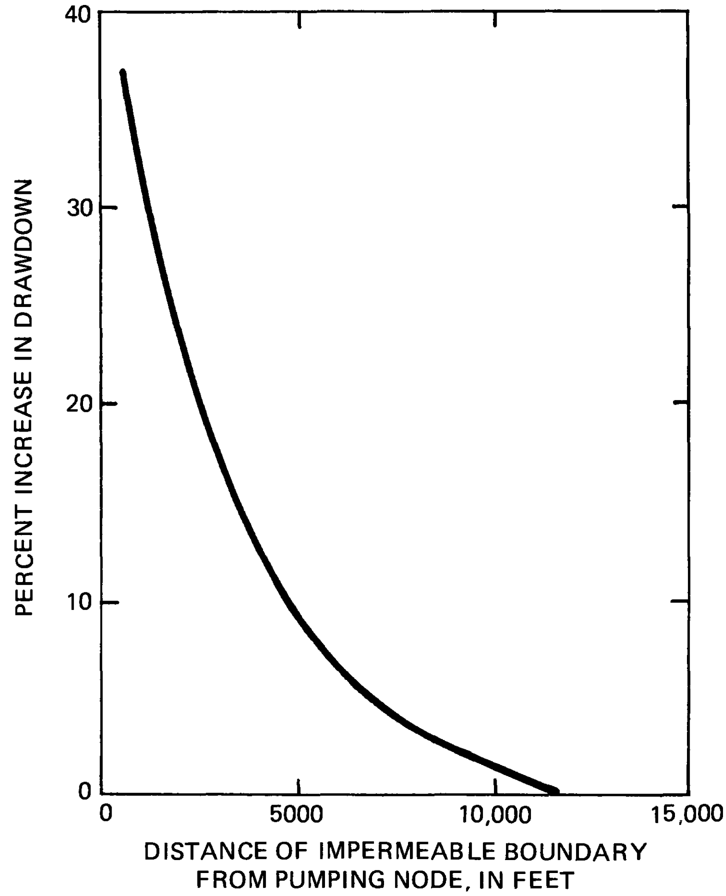


Figure 15. -- Relation between model-generated drawdown and the location of the impermeable boundary near Wenden.

ADDITIONAL DATA REQUIREMENTS FOR GROUND-WATER MODELS

Study of the hydrogeology of McMullen Valley has resulted in a better conceptual model of the hydrologic system. The area however is lacking in some important hydrologic data. The hydrologic system could be better understood and a more representative numerical model of the system could be developed if the following hydrologic information were better known:

— Hydraulic conductivity and transmissivity.

— Hydraulic properties and areal extent of the fine-grained facies.

— Storage properties.

— Location of impermeable boundaries.

— Pumpage distribution.

The hydraulic properties and areal extent of the fine-grained facies are not well known, although they are a significant influence on the response of the hydrologic system to pumping stress. Present data indicate that the fine-grained facies consists of a lower part that is more than 90 percent silt and clay and an upper part that is 40 to 70 percent silt and clay and contains interbedded sand and gravel lenses. Hydraulic properties of the two fine-grained layers are significantly different according to evidence from model results, lithologic descriptions, and hydrologic data. The lower part of the fine-grained facies separates the aquifer into upper and lower units that are poorly connected. The numerical model could be used to determine the vertical hydraulic properties of the fine-grained facies if the hydraulic-head difference between the upper and lower hydrologic units were better understood. Few known data points are available from which to determine the vertical difference in hydraulic head. Some shallow wells may exist in which water-level measurements can be made, or several shallow observation wells may be drilled.

Results of ground-water modeling also indicate that the areal extent of the fine-grained facies exerts a strong influence on the shape of the cones of depression. More accurate mapping of the fine-grained facies would allow better model representation of the hydrogeology and could eliminate the uncertainty of areal extent of low leakance values as a variable. Mapping of fine-grained sediments would allow other components to be better analyzed through modeling techniques. Differences in electrical properties between fine- and coarse-grained sediments offer a means of mapping the fine-grained facies by use of electrical-geophysical techniques.

The storage properties of the aquifer are poorly known. Estimates of specific yield are more reliable near Aguila than near Wenden and Salome. The large influence of the fine-grained facies near Wenden and Salome prevented a good evaluation of specific yield in that area. Further analysis of specific yield is needed before a more accurate model can be constructed. Analysis may be conducted through borehole-geophysical logging or laboratory measurement of water yield from core samples. The methods require collection of extensive field data.

The location of the impermeable boundary influences drawdowns that extend to the aquifer boundary. In McMullen Valley drawdowns have occurred throughout the aquifer and the location of the impermeable boundaries does influence drawdowns. Geophysical techniques are the logical tools for locating impermeable boundaries.

The proper pumpage distribution is needed for accurate modeling of the response of a ground-water system to stress. Pumpage distribution is assumed to be accurate for those years for which individual power-use records were available. Pumpage distributions prior to the 1970's however are tenuous. Continued efforts to document the magnitude and areal distribution of pumpage are essential for future modeling efforts.

The existence of recharge from excess applied irrigation water in the area was not analyzed in this investigation because of a lack of field observations and the uncertainty in other components. Monitoring of the water content and water quality of the unsaturated zone may help to document the existence or nonexistence of recharge from excess irrigation water.

SUMMARY

The hydrogeology of McMullen Valley was investigated using geologic, geophysical, and hydrologic data and a numerical model of the ground-water system. Integration of information from these techniques has aided in understanding the response of the ground-water system to pumping stress. Concepts developed through the study of this basin may be applicable to other basins that have a similar hydrogeologic setting.

The geologic setting of McMullen Valley is within a metamorphic core complex structure that encompasses a much larger area than the valley and surrounding mountains. Hydrologically significant structures in the area are listric normal faulting and associated rotation of middle to late Tertiary rocks and broad northeast-oriented arches. Analysis of gravity data indicates that the basin may be an intervening syncline between two of the arches. The basin is asymmetric in cross section with a steep bedrock-basin fill contact on the southeast side that may represent normal faulting superimposed on the syncline. Other basins in Arizona may exhibit similar structure.

The basin fill, which is the major aquifer in the area, consists of a lower unit and an upper unit. The lower unit includes sediments of two different depositional phases. The first phase or lowermost part consists of more than 2,000 ft of coarse-grained sediments that probably were deposited during a period of through-flowing drainage. Northeast-oriented arching of the mountain ranges and syncline formation may have been occurring at this time. The second phase of lower basin-fill deposition was a period of internal drainage that resulted in the deposition of a fine-grained sedimentary facies in the basin center. The fine-grained sediments are about 1,000 ft thick and include two parts. The lower part is mainly silt and clay and includes evaporites. The upper part contains no evaporites, is coarser grained, includes sand and gravel lenses, and is less consolidated than the lower part. The lower part of the fine-grained facies does not yield water to wells and separates the aquifer into shallow and deep systems. The upper basin fill is a relatively thin layer of coarse-grained sediments that was laid down after the redevelopment of integrated drainage. The upper basin fill is unsaturated in most of the basin; a small thickness was saturated near Aguila prior to extensive development and has since been dewatered.

A ground-water model of the predevelopment ground-water system was developed to aid in understanding the workings of the system under equilibrium conditions. The model calculated a total water budget for the basin of about 650 acre-ft/yr. The model is not sufficiently sensitive and field data are inadequate to determine if the main area of recharge is along the major mountain fronts, in the Forepaugh subarea, or a combination of the two. Transmissivities for the aquifer ranged from 3,000 to 10,000 ft^2/d near Wenden and Salome to about 35,000 ft^2/d near Aguila.

The ground-water model was further used to analyze the system response to pumping stress during 1951-80. The transient system near Aguila represents a simple storage-depletion process. The process near Wenden and Salome is also one of storage depletion, but the presence of the lower part of fine-grained facies affects the size and shape of the cone of depression. The fine-grained facies inhibits the downward movement of water to the underlying coarse-grained material, and the system has responded in the manner of a confined ground-water system. Drawdowns have extended to impermeable boundaries throughout the basin. Pumping near Wenden is close to the impermeable bedrock boundary of the aquifer, and drawdowns are greater than elsewhere because of boundary effects. Gravity modeling was used to estimate the location of the boundary in this area.

Information on several important hydrologic components is lacking in McMullen Valley. Hydraulic properties and areal extent of the fine-grained facies are the controlling components of the system near Wenden and Salome; however, they are poorly known. Storage properties and aquifer-boundary locations are also not well known. Accurate pumpage data are needed for the simulation of the storage-depletion process.

Despite the lack of detailed hydrogeologic information in McMullen Valley, the ground-water model helped to evaluate hydrologic properties that control the hydrologic system response to stress. The calibrated model generally simulated the transient system and may be used to predict the general system response and magnitude of future water-level decline. Adequacy of predictions will depend on the adequacy of the simulated hydrologic conditions in representing the hydrologic system.

REFERENCES CITED

Anderson, T.W., 1980, Study plan for the regional aquifer-system analysis of alluvial basins in south-central Arizona and adjacent states: U.S. Geological Survey Open-File Report 80-1197, 22 p.

Arizona Water Commission, 1975, Inventory of resource and uses—Phase 1, Arizona state water plan: Arizona Water Commission report, 224 p.

Briggs, P.C., 1969, Ground-water conditions in McMullen Valley, Maricopa, Yuma, and Yavapai Counties, Arizona: Arizona State Land Department Water-Resources Report 40, 31 p.

Coney, P.J., and Reynolds, S.J., 1980, Cordilleran metamorphic core complexes and their uranium favorability: U.S. Department of Energy Open-File Report GJBX-258 (80), 627 p.

Davis, G.A., Anderson, J.L., Frost, E.G., and Shackelford, T.J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountain terrain, southeast California and western Arizona: Geological Society of America Memoir 153, p. 79-129.

Eberly, L.D., and Stanley, T.B., Jr., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, p. 921-940.

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

Kam, William, 1964, Geology and ground-water resources of McMullen Valley, Maricopa, Yavapai, and Yuma Counties, Arizona: U.S. Geological Survey Water-Supply Paper 1665, 64 p.

Laskey, S.G., and Webber, B.N., 1949, Manganese resources of the Artillery Mountains region, Mohave County, Arizona: U.S. Geological Survey Bulletin 961, 86 p.

Lease, L.W., 1981, Summary geologic report on drilling in western Prescott and Williams quadrangles, Mohave, Yavapai, and Yuma Counties, Arizona: Bendix Field Engineering Corporation, GJBX-243 (81), 82 p.

McDonald, M.G., and Harbaugh, A.W., 1984, A module three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83-875, 528 p.

Metzger, D.G., 1951, Geology and ground-water resources of the northern part of the Ranegras Plain area, Yuma County, Arizona: U.S. Geological Survey open-file report, 31 p.

Metzger, D.G., Loeltz, O.J., and Irelan, Burdge, 1973, Geohydrology of the Parker-Blythe-Cibola area, Arizona and California: U.S. Geological Survey Professional Paper 486-G, 130 p.

Oppenheimer, J.M., 1980, Gravity modeling of the alluvial basins, southern Arizona: Tucson, Arizona, University of Arizona, unpublished M.S. thesis, 81 p.

Otton, J.K., 1981, Geology and genesis of the Anderson Mine, a carbonaceous lacustrine uranium deposit, western Arizona—A summary report: U.S. Geological Survey Open-File Report 81-780, 25 p.

Peirce, H.W., 1976, Tectonic significance of Basin and Range thick evaporite deposits: Arizona Geological Society Digest 10, p. 325-339.

Pool, D.R., 1985, Aquifer geology of alluvial basins of Arizona, in Anderson, T.W., and Johnson, A. Ivan, Eds., Regional Aquifer Systems of the United States, Southwest Alluvial Basins of Arizona: American Water Resources Association Monograph Series No. 7, 116 p.

Rehrig, W.A., and Reynolds, S.J., 1977, A northwest zone of metamorphic core complexes in Arizona: Geological Society of America, Abstracts with Programs, v. 9, p. 1139.

__________ 1980, Geologic and geochronologic reconnaissance of a northwest-trending zone of metamorphic core complexes in southern and western Arizona: Geological Society of America Memoir 153, p. 131-157.

Rehrig, W.A., Shafiqullah, M., and Damon, P.E., 1980, Geochronology, geology, and listric normal faulting of the Vulture Mountains, Maricopa County, Arizona: Arizona Geological Society Digest, v. 12, p. 89-110.

Remick, W.H., 1981, Maps showing ground-water conditions in the McMullen Valley area, Maricopa, Yavapai, and Yuma Counties, Arizona—1981: Arizona Department of Water Resources Hydrologic Map Series Report Number 6, 3 sheets, scale 1:125,000.

Reyner, M.L., Ashwill, W.R., and Robison, R.L., 1956, Geology of uranium deposits in Tertiary lake sediments of southwestern Yavapai County, Arizona: U.S. Atomic Energy Commission, RME-2057, 43 p.

Reynolds, S.J., 1980, Geologic framework of west-central Arizona: Arizona Geological Society Digest, v. 12, p. 1-16.

Reynolds, S.J., Keith, S.B., and Coney, P.J., 1980, Stacked overthrusts of Precambrian crystalline basement and inverted Paleozoic sections emplaced over Mesozoic strata, west-central Arizona: Arizona Geological Society Digest, v. 12, p. 45-52.

Ross, C.P., 1923, The lower Gila region, Arizona, a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places: U.S. Geological Survey Water-Supply Paper 498, 237 p.

Scarborough, R.B., and Peirce, H.W., 1978, Late Cenozoic basins of Arizona, in Callender, J.F., Wilt, J.C., and Clemons, R.E., eds, The Land of Cochise: New Mexico Geological Society Guidebook, 29th Field Conference, p. 253-259.

Scarborough, R.B., and Wilt, J.C., 1979, A study of uranium favorability of Cenozoic sedimentary rocks, Basin and Range province, Arizona, Part 1, General geology and chronology of pre-late Miocene Cenozoic sedimentary rocks: U.S. Geological Survey Open-File Report 79-1429, 102 p.

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

Shackelford, T.J., 1980, Tertiary tectonic denudation of a Mesozoic-early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona: Geology, v. 8, p. 190-194.

Shafiqullah, M., Damon, P.E., Lynch, D.J., Reynolds, S.J., Rehrig, W.A., and Raymond, R.H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, p. 201-260.

Sherborne, J.E., Jr., Buckovic, W.A., DeWitt, D.B., Hellinger, T.S., and Pavlak, S.J., 1979, Major uranium discovery in volcaniclastic sediments, Basin and Range Province, Yavapai County, Arizona: American Association of Petroleum Geologists Bulletin, v. 63, p. 621-646.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 103 p.

Trescott, P.C., and Larson, S.P., 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76-591, 21 p. [Supplement to Open-File Report 75-438.]

Tucci, Patrick, Schmoker, J.W., and Robbins, S.L., 1982, Borehole gravity data and basin-fill densities in Arizona: U.S. Geological Survey Open-File Report 82-473, 23 p.

U.S. Geological Survey, 1982, Annual summary of ground-water conditions in Arizona, spring 1980 to spring 1981: U.S. Geological Survey Open-File Report 82-368, scale 1:1,000,000.

West, R.E., 1971, Iterative two-dimensional gravity modeling program: Tucson, University of Arizona, Department of Geosciences, unpublished laboratory report.

Wilson, E.D., Moore, R.T., and Cooper, J.R., 1969, Geologic map of Arizona: Arizona Bureau of Mines map, scale 1:500,000.