AN ASSESSMENT OF RECHARGE FROM IRRIGATED AGRICULTURAL LAND IN HARQUAHALA PLAINS, ARIZONA

by

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ABSTRACT

In the current study, the Harquahala Basin was selected as an appropriate site for research into the component of recharge resulting from irrigation return flow to an aquifer system. Agriculture in this area commenced in the early 1950s, and intensive irrigation has resulted in perched water tables and zones of cascading water at various locations throughout the valley. In these areas, the quality of the perched water was significantly poorer than the regional aquifer system, leading to the hypothesis that these zones contained irrigation return flow.

Sufficient pumpage information was available to permit the development of a numerical model of the basin utilizing MODFLOW. After calibration and validation utilizing data from 1954, 1966, and 1974, it appears that, in the Harquahala area, 20 percent of the applied irrigation water eventually returns to the water table as recharge.

CHAPTER 1

INTRODUCTION

Water quantity and quality are of major concern for the future growth and development of the southwestern United States. In this predominantly semi-arid region, most streams are ephemeral and cannot be depended upon for large-scale resource development without the construction of major impoundments, delivery, and treatment systems. As a result, developing urban and agricultural areas have experienced an increased reliance upon groundwater for a dependable supply. As development increased, the demand for water gradually exceeded natural recharge, resulting in large overdrafts of the available groundwater reserves.

The most common sources of natural inflow to a groundwater reservoir include direct infiltration of precipitation along mountain fronts, recharge through stream channels, and underflow from adjacent basins. In arid and semi-arid environments, the average volume of inflow typically is small, and, in areas of extensive groundwater development, inflow normally is much less than the rate of pumping. The result is large-scale water-level declines in the host aquifer.

Basins with extensive agriculture also have an additional source of inflow to the groundwater reservoir. This source is evidenced in data from several basins in Arizona where perched water tables--a zone of saturation separated from the regional water table by an intermediate unsaturated zone--have developed. Based upon the quality of water in the perched zones and the relationship between the location of perched zones and the irrigated agricultural land, deep percolation of excess irrigation water appears to be the source.

Although evidence of perched water is not available in most areas, a decrease in the rate of water-level decline and, in some instances, an increase in water levels have been recorded in recent years, even though pumping stresses have remained uniform or increased (Graf, 1981). The changes in water level may be caused by changes in the hydrologic system such as an increase in storage coefficient with depth, the interception or change in an aquifer boundary, or the appearance of a new inflow source. Although all of the above instances are possible, it is unlikely in a southwest alluvial basin that either storage would increase with depth or that boundary conditions would change to increase the availability of water. The most logical explanation for this change in water-level decline is a new source of inflow such as that available from deep percolation of excess irrigation water to the regional water table.

Deep percolation is the quantity of applied irrigation water that passes below the root zone of crops. The amount of this water in transit through the unsaturated zone and the amount of water reaching the water table are major unknowns in the documentation of available water resources in the southwest. Previous studies attempting to quantify deep percolation have used a water budget approach (SWAB/RASA, 1978). The major limitation in this method is that the volume of the deep percolation and recharge are similar in magnitude to the possible errors in the other quantities of the water budget.

CHAPTER 2

PURPOSE AND SCOPE

The purpose of this study was to select an alluvial basin in Arizona which showed signs of deep percolation from irrigation return flow and to attempt to relate the agricultural activity in the area to the change in water-level declines. Many basins in southcentral Arizona show evidence of recharge from excess irrigation applications. Documentation of the volume of water recharged, however, is not available. As a result, it was necessary to develop a methodology for screening the alluvial basins and for selecting one basin for further study to quantify the recharge volumes and to provide suggestions for future research on this subject. The basin selected was the Harquahala Plains area, west of Phoenix.

The methodology used to select the Harquahala Basin is presented herein. The analysis emphasized the availability of data to document the modification of the natural hydrologic processes by agriculture. It required a determination of the (1) extent and nature of both the aquifer and the corresponding unsaturated zone, (2) the distribution and explanation of water quality in the aquifer, (3) the natural recharge and discharge relationships, and (4) the possible effects of agriculture on these parameters. The historical agricultural development was used to define pumpage within the basin selected. This in turn was used to develop a numerical groundwater model to assess the present quantity of water reaching the groundwater system and the possible future impacts of the percolating water.

CHAPTER 3

BASIN SELECTION METHODOLOGY

Although this study could have encompassed any of the groundwater basins in the arid or semi-arid southwest, it was decided to consider only those alluvial basins in the Basin and Range Province of Arizona. Final selection was based upon four general factors:

(1) the extent of irrigated agriculture,

(2) the availability of data,

(3) the magnitude and distribution of groundwater development within the basin, and

(4) the complexity of the hydrologic system.

There are 72 alluvial basins in southcentral Arizona. Initial review was based upon the extent of irrigated agriculture within the basins. Those areas with little or no agriculture, arbitrarily set at less than 1,000 cultivated acres as determined from the Arizona Agricultural Statistics for 1978, were not considered further. The results of this and the following analyses are listed in Table 1. Forty-two basins, including the Upper San Pedro and the Lower Verde River, were eliminated at this stage.

The remaining 30 basins were checked for background information as follows:

(1) The availability of drillers' logs or well cuttings for grain-size analysis, relative hydraulic conductivity estimates, and the

Table 1. Basin selection process

BASIN	IRRIGATED AREA LESS THAN 1000 ACRES (1980)	IRRIGATED AREA GREATER THAN 1000 ACRES: NO INFO AVAILABLE	IRRIGATED AREA GREATER THAN 1000 ACRES: STEADY STATE CONDITIONS	HYDROLOGIC SYSTEM TOO COMPLEX	TO BE CONSIDERED FURTHER
Upper Agua Fria River	X				
Aravaipa Creek	X				
Avra-Altar Valleys					X
Upper Big Chino Wash	X				
Chino Valley			X		
Big Sandy Wash			X		
Black River Basin	X				
Butler Valley	X				
Upper Bill Williams and Upper Hassayampa River	X				
Chemehuevi Valley	X				
Detrital Valley	X				
Lake Mohave	X				
La Posa Plain	X				
Mohave Valley				X	
Palo Verde Valley				X	
Vidal and Parker Valleys				X	
Yuma Wash	X				
Douglas, Sulphur Springs Valley					X
Duncan, Gila River from Redrock to Guthrie			X		
Gila Bend Plain				X	
Gila River, Palomas Plain and Sentinal Plain			X		
Gila River, San Carlos to San Carlos Reservoir	X				
Dripping Springs Wash	X				
Cuerda de Lena Wash	X				
Growler Wash	X				
King Valley, San Christobol Wash		X			
Lechuguilla Desert		X			
Mohawk Valley and Castle Dome Plain				X	
Harquahala Plains					X
Bullard Wash, Hassayampa River, Santa Maria River	X				
Hassayampa near Morristown and Wittman	X				
Hualpai Valley, Red Lake	X				
Truxton Wash	X				
Lower Hassayampa River					X
Lower Santa Cruz, Donnelly Wash	X				
Lower Santa Cruz, Eloy				X	
Lower Santa Cruz, Stanfield-Maricopa				X	
Lower Santa Cruz, Santa Rosa Valley	X				
Lower Santa Cruz, Vekol Valley	X				
Lower San Pedro			X		
Lower Verde River	X				
McMullen Valley					X
Ranegras Plain			X		
Sacramento Valley and Bill Williams River			X		
Bonita Creek and Eagle Creek	X				
San Simon Valley, Gila River to Calva		X			
Upper San Bernardino Valley	X				

Table 1--Continued

BASIN	IRRIGATED AREA LESS THAN 1000 ACRES (1980)	IRRIGATED AREA GREATER THAN 1000 ACRES		HYDROLOGIC SYSTEM TOO COMPLEX	TO BE CONSIDERED FURTHER
		NO INFO AVAILABLE	STEADY STATE CONDITIONS		
San Francisco River	X				
San Francisco River and Upper Gila River	X				
Salt River, Chandler, Queen Creek				X	
Salt River, Paradise Valley				X	
Salt River, Phoenix and Lower Agua Fria River				X	
Lower Santa Cruz, Aguirre Valley	X				
San Simon Wash	X				
Baboquivari Wash, Chutum Vaya Wash	X				
La Quitani Valley	X				
Tecalote Valley, Vamori Wash, San Luis Wash	X				
Tonto Creek, Pinto Creek, Salome Creek	X				
Upper Santa Cruz, Tucson Basin				X	
Cienaga Creek	X				
San Rafael Valley	X				
Upper San Pedro	X				
Upper San Pedro near Benson	X				
Upper Salt River	X				
Verde River		X			
Waterman Wash					X
Wilcox Basin					X
Western Mexican Drainage, LaAbra Plain	X				
Western Mexican Drainage, Sonoyta Valley	X				
Western Mexican Drainage, Tule Desert	X				
White River Basin	X				
Yuma Basin				X	

presence of fine-grained units in the unsaturated zone which might serve as perching layers;

(2) The availability of cropping history, such as length of time the area was under cultivation, past crops, water source and quality, and average water application amounts;

(3) The slope and size of fields--these factors result in variations in water application and infiltration volumes;

(4) The amount of water not used for plant growth, such as the leaching requirements, pre-irrigation water applications, or free water;

(5) The depth to water and water-table decline rates and points at which this can be monitored; and

(6) The change in groundwater quality with time at a well site and over the entire basin. Anomalously different levels of dissolved salts may indicate local areas of high recharge.

The basin selected should have as little variability in crop type, cultivation practices, and soil type as possible, and little groundwater/surface-water interaction. That is, springs, seeps, and both gaining and losing streams should not be present. The more homogeneous an area, the easier it should be to quantify the deep percolation. Surface-groundwater interaction is difficult to quantify without extensive data collection.

There were four basins for which insufficient historical data were available: (1) King Valley, San Cristobal Wash, (2) Lechuguilla Desert, (3) San Simon Valley, Gila River to Calva, and (4) Verde River. These were removed from further consideration. Nineteen more basins were eliminated as areas where agriculture was present, but the hydrologic system either was not stressed (that is, natural and culturally modified recharge equaled the discharge), or there was a complex groundwater/surface-water interrelationship. As indicated in Table 1, the basins eliminated included Douglas and Ranegras Plain which were in steady-state conditions, and the Upper Santa Cruz and the Salt River Valley which were too complex. Seven basins, Avra-Altar Valley, Douglas-Sulphur Springs, Harquahala Plains, Lower Hassayampa Valley, McMullen Valley, Waterman Wash area, and the Wilcox Basin, remained. The evaluation of these last seven basins, based on weighted parameters, is found in Tables 2 and 3. Table 2 lists the comparison of physical and hydrologic characteristics for each basin. Items considered included the year when groundwater development began, the source of irrigation water, estimated recharge and underflow, and availability of basic data such as water-level measurements and pumpage. Table 3 contains the weighting factors for each basin. Those factors judged most important for conducting an adequate analysis and in the development of a perched water table were weighted heaviest. The weighting scale is located in Table 3 as a series of 12 footnotes. The basins with the highest ratings were judged best for additional study, thus eliminating Lower Hassayampa which earned only 16 points. The six remaining basins were included in a general review of geologic and hydrologic conditions (Appendix B), which included the ease of

TABLE 2: Comparison of physical and hydrological characteristics for Basins in the deep percolation study

PHYSICAL OR HYDROLOGIC PARAMETERS	AVRA-ALTAR VALLEY	DOUGLAS-SULPHUR SPRINGS VALLEY	HARQUAHALA PLAINS	LOWER HASSAYAMPA	MCMULLEN VALLEY	WATERMAN WASH	WILLCOX BASIN
BASIN SIZE (SQ. MI.)	1,400	1.200	420	550	720	400	1,500
CULTIVATED AREA (ACRES)	37,048	34,346	33,366	32,414	26,690	14,871	61,559
CROPPED ACREAGE 1978							
COTTON (%)	22,201 (60)	5,020 (15)	16,570 (50)	16,600 (51)	12,951 (49)	7,617 (51)	14,200 (23)
GRAIN (%)	6,975 (19)	5,900 (17)	6,573 (20)	5,621 (17)	4,747 (18)	2,075 (14)	38,150 (62)
ALFALFA (%)	1,719 (5)	5,000 (15)	6,376 (19)	5,980 (18)	6,073 (2)	2,743 (18)	3,800 (6)
MISC. (%)	6,153 (16)	18,426 (53)	3,847 (11)	4,213 (14)	2,919 (10)	2,436 (17)	5,409 (5)
YEAR EXTENSIVE AGRICULTURE BEGAN	MID 1940'S	1940	1952	1950	1951	1951	MID-1940'S
IRRIGATION WATER SUPPLY (AF)							
SURFACE WATER	0	0	0	0	0	0	0
GROUND WATER	136,300	103,000	109,900	109,900	94,900	55,000	288,000
GROUND-WATER PUMPAGE (AF) (1970 NORMALIZED)							
MUNIC./INDUSTRIAL	300	13,000	100	100	100	30	2,000
EXPORT	13,400	0	0	0	0	0	0
WATER IMPORTS (AF)	0	6,000	0	15,000	0	0	0
ESTIMATE OF NATURAL RECHARGE (AF)	4,000	11,000	1,000	3,000	1,000	1,000	15,000
CULTURALLY MODIFIED RECHARGE (AF)	27,000	33,000	14,000	35,000	17,000	3,000	93,000
OVERDRAFT (AF)	119,000	64,000	95,000	57,000	77,000	51,000	182,000
ESTIMATED UNDERFLOW (AF)	—	1,400	—	—	0	0	0
MODELING EFFORTS	AWC, USGS	SCS	AWC	PRIVATE	AWC, USGS	USGS	SCS
AVERAGE DEPTH TO WATER (FT)	300	150	450	200	350	340	150
RANGE DEPTH TO WATER (FT)	250 - 450 (1974)	50 - 300 (1978)	420 - 540 (1975)	15 - 300 (1975)	150 - 550 (1973)	200 - 400 (1975)	15 - 340 (1975)
AVERAGE DECLINE (FT)	100	75	200	50	100	150	150
RANGE OF DECLINE (FT)	75 - 125	40 - 150	170 - 250	10 - 80	40 - 150	75 - 170	+20 - 260
WATER-LEVEL MAPS AVAILABLE	1940 1965 1974	1952 1966 1978	1957 1963 1966 1974 1979 1980	1970 1975	1951 1958 1973	1952 1961 1966	1952 1963 1975

FOOTNOTES:

1. Water Resources Research Center, 1980, 1978 Water Budget Analysis, SWAB/RASA Basins, Technical Appendix for the report "Regional Recharge Research for the Southwest Alluvial Basins".

2. Arizona Water Commission, 1975, Arizona State Water Plan, Inventory of Resource and Uses.

Table 3. Evaluation factors in Basin selection

FACTOR	AVRA-ALTAR VALLEY	DOUGLAS SULPHUR SPRINGS VALLEY	HARQUAHALA PLAINS	LOWER HASSAYAMPA	MCMULLEN VALLEY	WATERMAN WASH	WILLCOX BASIN
CROP UNIFORMITY - [1]	2	1	1	1	1	1	2
DURATION OF EXTENSIVE AGRICULTURE - [2]	1	1	2	2	2	2	1
ACRE UNIFORMITY - [3]	0	0	1	1	0	1	1
WATER EXPORT - [4]	0	1	1	1	1	1	1
WATER IMPORT - [4]	1	0	1	1	1	1	1
ESTIMATE OF NATURAL RECHARGE - [5]	1	1	1	1	1	1	1
ESTIMATE OF UNDERFLOW - [5]	1	1	1	0	1	1	1
EXISTING MODEL - [5]	1	1	1	0	1	1	1
AVERAGE DEPTH TO GROUND WATER - [6]	2	3	0	2	1	1	3
DEPTH VARIABILITY - [7]	1	1	3	0	0	2	0
AVERAGE WATER LEVEL DECLINE - [8]	1	2	0	2	1	1	1
UNIFORMITY - [10]	2	1	2	2	1	2	0
WATER LEVEL MAPS - [10]	2	2	3	1	2	3	2
PERCHING LAYER - [11]	0	0	2	0	2	0	2
WATER QUALITY DATA - [5]	1	1	1	1	1	1	1
AQUIFER DATA - [5]	1	1	1	1	1	1	1
WATER BUDGET - [12]	1	1	1	0	1	0	1
PUMPING UNIFORMITY - [3]	0	0	1	0	0	1	1
TOTAL	18	18	23	16	18	21	21

FOOTNOTES:

1. CROP UNIFORMITY:
   1: > 60% OF AREA IS ONE CROP
   2: < 60% OF AREA IS ONE CROP

2. DURATION OF EXTENSIVE AGRICULTURE:
   1: > 30 YEARS
   2: < 30 YEARS

Table 3--<u>Continued</u>

Footnotes: <u>Continued</u>

3. UNIFORMITY:
    0: LOW
    1: HIGH

4. EXPORT/IMPORT:
    0: YES
    1: NO

5. EXISTING INFORMATION:
    0: NO
    1: YES

6. AVERAGE DEPTH TO GROUNDWATER:
    0: > 400 FEET
    1: < 300 TO 400 FEET
    2: 200 TO 300 FEET
    3: < 200 FEET

7. VARIATION IN DEPTH TO GROUND WATER IN AGRICULTURAL AREA:
    0: RANGE > 250 FEET
    1: RANGE 200 TO 250 FEET
    2: RANGE 150 TO 200 FEET
    3: RANGE < 150 FEET

8. AVERAGE WATER LEVEL DECLINE:
    0: > 150 FEET
    1: 75 FEET TO 150 FEET
    2: < 75 FEET

9. VARIATION IN HISTORIC WATER LEVEL DECLINES IN AGRICULTURAL AREA:
    0: RANGE > 150 FEET
    1: RANGE 100 FEET TO 150 FEET
    2: RANGE 50 FEET TO 100 FEET
    3: RANGE < 50 FEET

10. NUMBER OF HISTORIC WATER LEVEL MAPS AVAILABLE:
    1: 2 MAPS
    2: 3 MAPS
    3: 4 OR MORE MAPS

11. EXISTENCE OF PERCHING LAYER:
    0: LOCALIZED
    1: MODERATELY EXTENSIVE
    2: EXTENSIVE

12. RELATIVE WORTH OF WATER BUDGET DATA
    (Based on Arizona Water Commission Study)
    0: FAIR
    1: GOOD

quantifying the water budget parameters, the uniformity of both the hydrologic system and the pumping regime, and the presence or absence of extensive perching layers.

Summary of Hydrogeologic Conditions in the Six Basins

McMullen Valley presents a complex situation because two areas of overdraft occur within one basin. The lower section, near Wendon and Salome, would be usable for the basin study, but the possible interaction of the intensively pumped areas preclude the use of a simple water budget. In addition, the extensive lakebed deposits cause a perched water table and may introduce a lateral flow component.

Willcox Basin, like McMullen Valley, has two separate areas of intensive pumping. The area north of Willcox has less of an overall water-level decline and a shallower water table, ranging between 34 feet below land surface near Willcox Playa, to 300 feet deep in the northern section. The second area, south of Willcox near Sulphur Spring School, has a much deeper water level at 150 to 400 feet. Although the overall trend in the basin has been one of decline, several wells in both sections show definite water-level rises between 5 and 10 feet.

Both McMullen Valley and Willcox Basin fulfill the basic requirements for the study, but it was concluded that they should not be used because of the two cones of depression and the complexity added by the fine-grained unit of large areal extent in the middle of the basins.

Avra-Altar Valley is a very complex system because agricultural land is being retired as water is exported to the City of Tucson. The changes in irrigated acreage make the relationship between agriculture and deep percolation difficult to derive, but the retirement of land might provide the opportunity to observe the wetting front recession. Several other advantages include the extensive work done by the U.S. Geological Survey (USGS), the University of Arizona, and the City of Tucson. These advantages, however, do not outweigh the complex stresses active in the area, so the Avra-Altar Valley was not considered further.

Douglas-Sulphur Springs Valley is different from the other five basins because a portion of the basin lies within Mexico and there is an import of about 6,000 acre-feet of water per year into the basin. Both are minor problems, but the relatively low ranking of the basin with respect to the remaining two basins, Harquahala Plains and Waterman Wash, was instrumental in the decision to remove the basin from further consideration.

Further analysis indicated that Waterman Wash did not have an extensive perching layer or perched water levels. This resulted in a lower rating than the remaining Harquahala Plains. Harquahala Plains has the advantage of being a small basin of 420 square miles, with groundwater pumpage concentrated areally (one major cone of depression) and used primarily for irrigation. It has been modeled previously. Therefore, on reviewing the entire basin selection process, the Harquahala Plains area, with a rating of 23 points, was selected for further analysis and quantification of deep percolation. The rest of this study, therefore, is restricted to the hydrology, geology, and development of agriculture within the Harquahala Plains.

CHAPTER 4

HARQUAHALA PLAINS STUDY AREA

The Harquahala Plains area is a northwest-trending, broad alluvial basin located in southwestern Arizona situated approximately midway between Phoenix and the Colorado River (Figure 1). The nearest towns include Buckeye, 30 miles east and Salome, 20 miles west.

The area of the basin is approximately 420 square miles with the basin almost three times longer (35 miles) than it is wide (12 miles). The valley is bounded on the northeast by the Big Horn Mountains, on the northwest by the Harquahala and Little Harquahala mountains, on the southwest by the Eagletail Mountains, and on the southeast by Saddle Mountain and the Gila Bend Mountains. Approximately two-thirds of the area lies in Maricopa County, with the remainder in La Paz County (Figure 2).

The Harquahala Plains basin is in the Sonoran Desert, a subdivision of the Basin and Range Province. It is characterized by a through-flowing drainage, Centennial Wash, which is a tributary to the Gila River. The 15-minute topographic quadrangle sheets which cover the area are the Hope, Lone Mountain, Big Horn Mountain, Cortez Peak, Eagletail Mountains, and Arlington Sheets.

Previous Investigations

Although extensive groundwater development and the concomitant study of the basin did not begin until the early 1950s, the geologic analysis of the Harquahala Plains began as early as 1911 with Bancroft's assessment of ore deposits in the

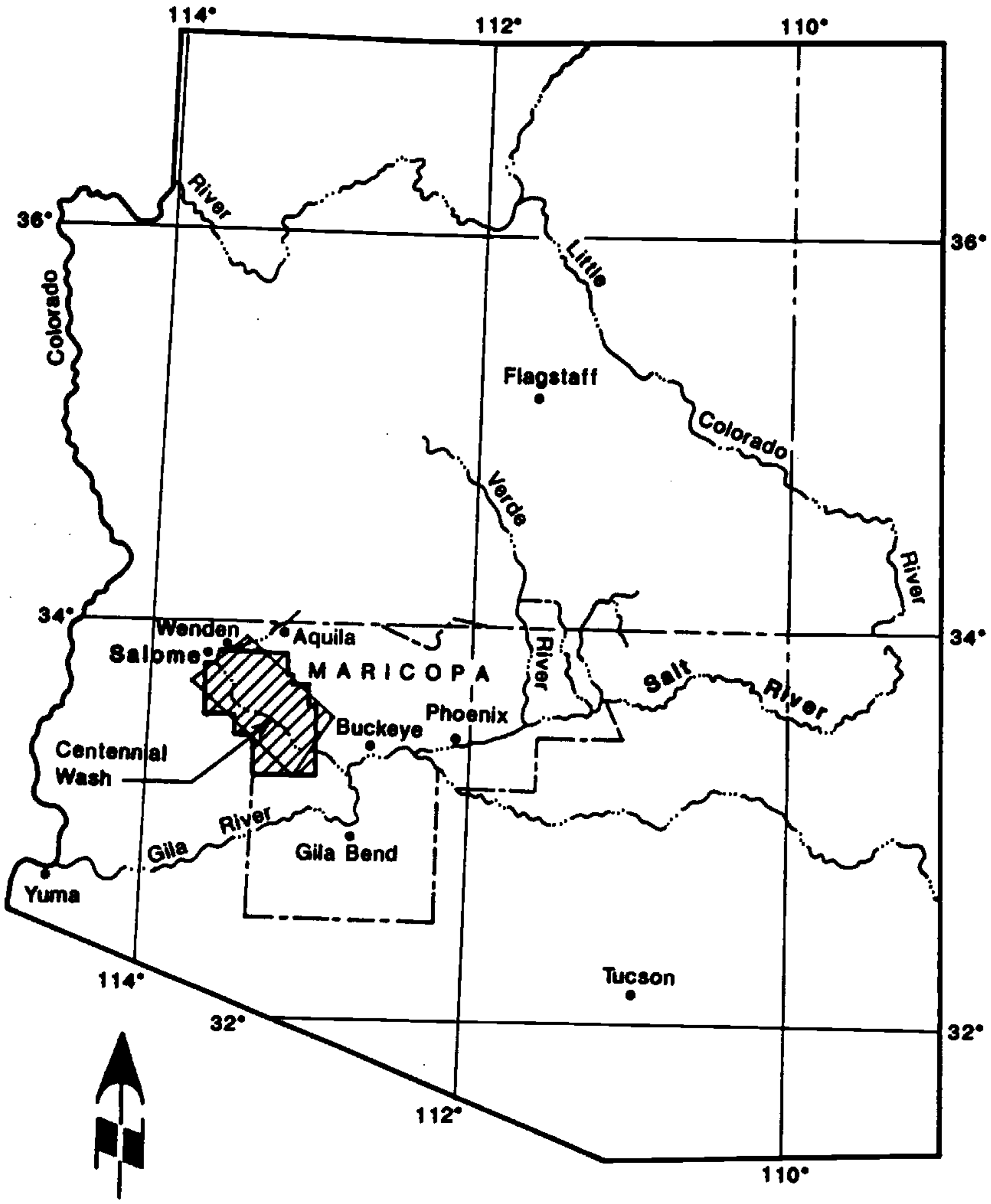


FIGURE 1:

Location of Harquahala Plains study area

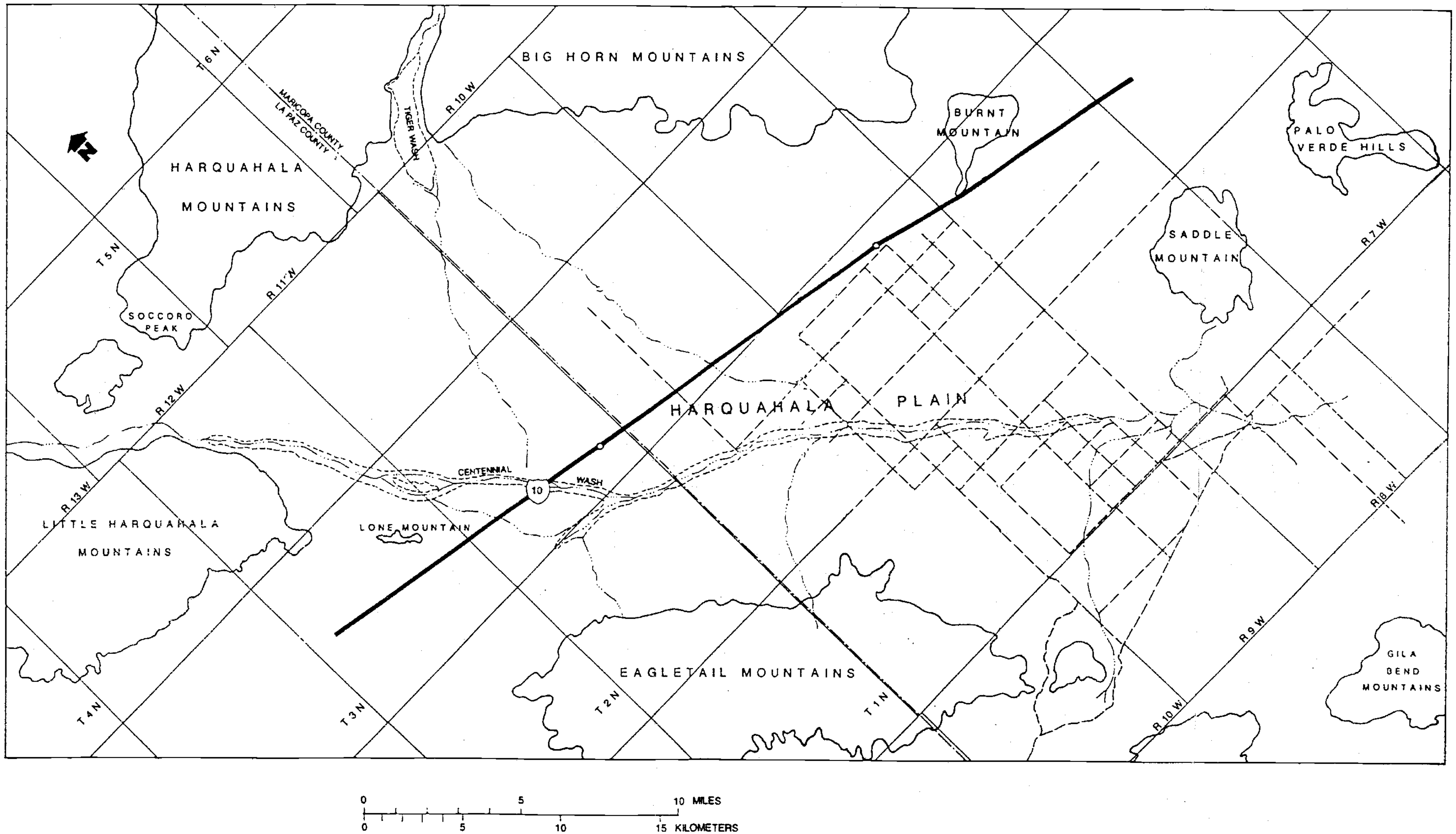


Figure 2. Base Map

Harquahala and Little Harquahala mountains. All early work was related to ore exploration and mine development and was restricted to the northwestern and southeastern mountain areas.

In his report on the desert watering places of the Lower Gila River region, Ross (1923) included the Harquahala Plains. This work represents the first hydrologic study of the area. The information provided by Ross included well logs and water quality test results. The seven wells in the area were used for domestic and livestock watering.

Little work was done in the area until 1957 when a reconnaissance study of groundwater resources was conducted by Metzger. Estimates of the original groundwater characteristics and the probable effect of extensive development were included in his study.

The existence of a perched water table was first mentioned by Stulik (1964) as the cause of anomalously high water levels in Township 2 North, Range 10 West (T2N, R10W). Several water-resources reports published by the USGS in cooperation with the Arizona State Land Department and the Arizona Water Commission (Denis, 1971 and 1976) contained assessments of groundwater conditions in the area. Results of a water-resources investigation of groundwater conditions in 1980 and the changes in the hydrologic system since 1954 were published by the Arizona Department of Water Resources (Graf, 1980a) The U.S. Bureau of Reclamation included Harquahala Plains in their Central Arizona Project Resources Report for Maricopa and Pinal counties (Bureau of Reclamation, 1976).

The first effort to delineate the perched layer, to assess its development and spatial variability, and to document the quality of the water in the perched zone was made by Graf (1980b). His paper to the Arizona Academy of Science, Nevada, Arizona Division, presented the first evidence of the definite existence of the perching layer and the mechanism for its development.

The only previous modeling of the basin, done by the Arizona Department of Water Resources (formerly the Arizona Water Commission) in 1974, was never published, but all data and results are available from the Arizona Department of Water Resources (ADWR).

Climate

The general climate of the Harquahala Plains area is hot and semi-arid. The average rainfall, measured since 1952 at the Harquahala Plains No. 1 weather station located in section 14, T2N, R9W, is six inches per year (Sellers and Hill, 1973). As in most of southwestern Arizona, 80 per cent of the annual precipitation occurs during two periods--July through September and December through February. Each period has a mean monthly rainfall greater than 0.6 inches. The months of April, May, and June are the driest, receiving less than 0.2 inches of rain. Slightly more precipitation falls during the winter months than during the summer months.

Winter storms are regional in nature with moderate intensities and durations and tend to have lower magnitudes and longer durations of runoff. Conversely, summer storms occur as local cloudbursts or thunderstorms of short duration with high intensities and rapid runoff.

Mean daily temperatures for the Harquahala Plains average 106.3 degrees Fahrenheit (°F) for July and 66 °F for December. Summer months are hot and relatively dry, whereas the winter months are cooler and marginally more humid.

The mean annual pan evaporation ranges from 70 inches to 98 inches, with the highest evaporation period (nine inches per month) from May through August (Sellers and Hill, 1973).

Physiography

Topographic features in the Harquahala Plains are controlled by block faulting and tilting as is typical of landforms in the Sonoran section of the Basin and Range Province of Arizona. The fault blocks have been modified by erosion and sedimentation forming broad alluvial valleys bounded by steep mountains. Buried pediments are common along the perimeter of many of the valleys.

The central part of the Harquahala Plains consists of a downfaulted block filled with alluvial material eroded from the surrounding mountains. Land surface along Centennial Wash in the central part of the basin slopes 15 to 20 feet per mile towards the south.

Geology controls the physiography of the mountain systems which form the boundaries of the Harquahala Plains. The Harquahala Mountains, composed of Precambrian granites and Tertiary volcanics, have rounded crests with sharply breaking ridges. Intervening canyons are V-shaped with steep walls. The Eagletail Mountains are younger Cretaceous and Tertiary volcanics. Erosion is advanced, leaving jagged crests and gentle dip slopes. Mesas capped by Quaternary basalt also are evident.

Pediments occur extensively along the Gila Bend and Eagletail Mountains and less commonly along the Saddle Mountain and the Harquahala mountains. These comparatively smooth, hard rock surfaces are generally covered with a thin mantle of rock debris but are exposed in some locations. The pediment shape follows that of the alluvial surfaces sloping gently away from the steep mountain fronts toward the central axis of the basin.

Bedrock constrictions occur at the northwest end of the valley between the Harquahala and Little Harquahala mountains and at the southeast end between the Gila Bend Mountains and Saddle Mountain. These constrictions form the inlet and outlet for Centennial Wash, which is the major surface drainage of the area.

Centennial Wash is a through-flowing, ephemeral stream tributary to the Gila River. The position of the stream along the valley floor is controlled by the height of the mountains and the contributing drainage areas. In the northern part of the valley, the drainage areas are larger and the mountains higher than in the Eagletail Mountains to the south. Therefore, the wash has been pushed closer to the lower mountains in the south (Metzger, 1957). The stream channel is highly braided and indistinct when viewed from land surface. In the northwestern part of the basin between Harrisburg Valley and Lone Mountain, the stream is confined to one channel, and the gradient along the thalweg is steeper. The channels again coalesce, and the gradient steepens in the southeastern end of the basin between Saddle Mountain and the Gila Bend Mountains.

Elevations within the basin range from 5,720 feet at Harquahala Peak in the Harquahala Mountains to 950 feet at the basin outlet between Saddle Mountain and the Gila Bend Mountains.

Geology

The Harquahala Plains basin is enclosed on all sides by bedrock consisting of exposed granites, basalts, and metamorphics. The bedrock depth in the valley ranges from less than 100 feet deep along the mountain fronts to more than 4,000 feet deep in the basin center (U.S. Bureau of Reclamation, 1976).

Structurally, the major mountain ranges in the valley are tilted upthrust blocks of Precambrian granite, gneiss, and schist. The granite was intruded at great depth, but was exposed as the overburden was eroded in the early Cambrian period. The relief at this time was probably very low. The deposition of sandstone and slate followed with the encroachment of the Cambrian Sea. This deposition probably continued until the Permian Period as indicated by small outcrops in the area. Deposits of Triassic and Jurassic rocks are not found. Several explanations for the lack of rocks from these periods include the possibility that deposition during this time did not occur, that the units have not been identified, or that the units have since been eroded.

Intense orogeny probably followed this period of deposition because the structural characteristics of the older sedimentary rocks are quite different from those dated as Cretaceous. The tentative designation as Cretaceous of the conglomerate and fanglomerate which overlie the Cambrian sediments is made despite the absence of any fossil records. The conglomerate consists of Paleozoic rock fragments. The coarseness of the Cretaceous sedimentary deposits suggests the previously mentioned orogeny because large amounts of erosion must have occurred. Outcrops of the Cretaceous rocks are limited in extent.

Vulcanism, with minor structural movement, began in the Cretaceous and continued into the Quaternary periods. Basin and Range block faulting began in the early Tertiary period followed by erosion and deposition. The current topography is due to block faulting in the Quaternary and the erosion of the fault blocks and the development of alluvial fans and basin deposits.

The Quaternary alluvium consists of three units--Pleistocene remnant alluvial fans, basin-fill deposits, and Recent alluvium. Neither the remnant alluvial fans along the mountain fronts nor the Recent alluvium along Centennial and Rogers Washes are of any great hydrologic significance because of their limited areal extent. The Pleistocene basin-fill deposits are of importance because it is from this unit that groundwater is pumped. The basin-fill deposits, consisting of lenses of sand, silt, and clay, underlie much of the area. The heterogeneous nature of the material is due to both the change in climate during the Pleistocene period, when both arid and humid conditions were encountered, and the meandering of Centennial Wash. The alluvium is generally unconsolidated, but cementation has occurred in the central-northwestern portion of the basin as indicated by drillers' logs.

It is interesting to note that no extensive evaporite beds exist in the valley center as they do in many other southwestern alluvial basins such as McMullen

Valley or the Willcox Valley. The lack of these deposits suggests that the basin had external drainage throughout most of the depositional period.

Faint shorelines and terraces visible in the southeastern part of the area led Metzger (1957) to suggest the existence of a large lake during the late Quaternary period.

He believed that abnormally heavy rain may have formed the lake behind a lava flow that dammed the ancient Gila drainage between Buckeye and Gila Bend. The lake rose rapidly, overflowed the lava dam, and then drained rapidly. Sedimentary evidence of such an occurrence, other than the suggested high water marks, is the presence of saline-alkali soils in the eastern part of the basin.

Drillers' logs suggest a thick clay bed in the central part of the basin northeast of Centennial Wash. Although no logs are available for the area indicated, logs along the periphery show large amounts of clay interbedded with sand. At least four irrigation wells have been drilled in the area of the clay bed but abandoned because of low yields (Metzger, 1957). Clay content in the drillers' logs decreases in both the northwest and southeast portions of the area.

Surface Water

The major surface water drainage in the Harquahala Plains area is provided by Centennial Wash. The wash flows southeasterly through the basin, entering from McMullen Valley through the Harquahala and Little Harquahala mountains and leaving between Saddle Mountain and the Gila Bend Mountains. The wash is a tributary to the Gila River north of Gillespie Dam.

All washes are ephemeral, flowing only during periods of rainfall when flooding may occur. There are no groundwater contributions to flow.

Centennial Wash is not gaged within the Harquahala Plains area but is gaged near Arlington, Arizona, just before the confluence of Centennial Wash and the Gila River. Discharge records have been kept since 1965 (USGS Water Supply Papers, 1970 and 1975; Werho, 1967). Wells (1976) did a statistical analysis of streamflow data from this station. His work showed that flow in the wash occurs approximately five percent of the time and that the average discharge, 3.12 cubic feet per second (cfs), is equalled or exceeded only 2.9 percent of the time. The mean annual flood for the wash is 3,561 cfs. He concluded that even though rainfall is distributed evenly between the winter and the summer seasons, over 80 percent of the runoff is associated with the intense summer storms of short duration and that flow occurs as pulses with the hydrograph peaks occurring at the beginning of the pulse (Wells, 1976).

The Narrows Dam was originally constructed as a flood retention structure, but sinkholes developed in 1958 when the basin was filled (Kam, 1961). The area behind the dam is now a marshy area covered with trees. The appearance of these sinkholes is important in the water budget analysis used later in this report.

Groundwater in the Main Aquifer

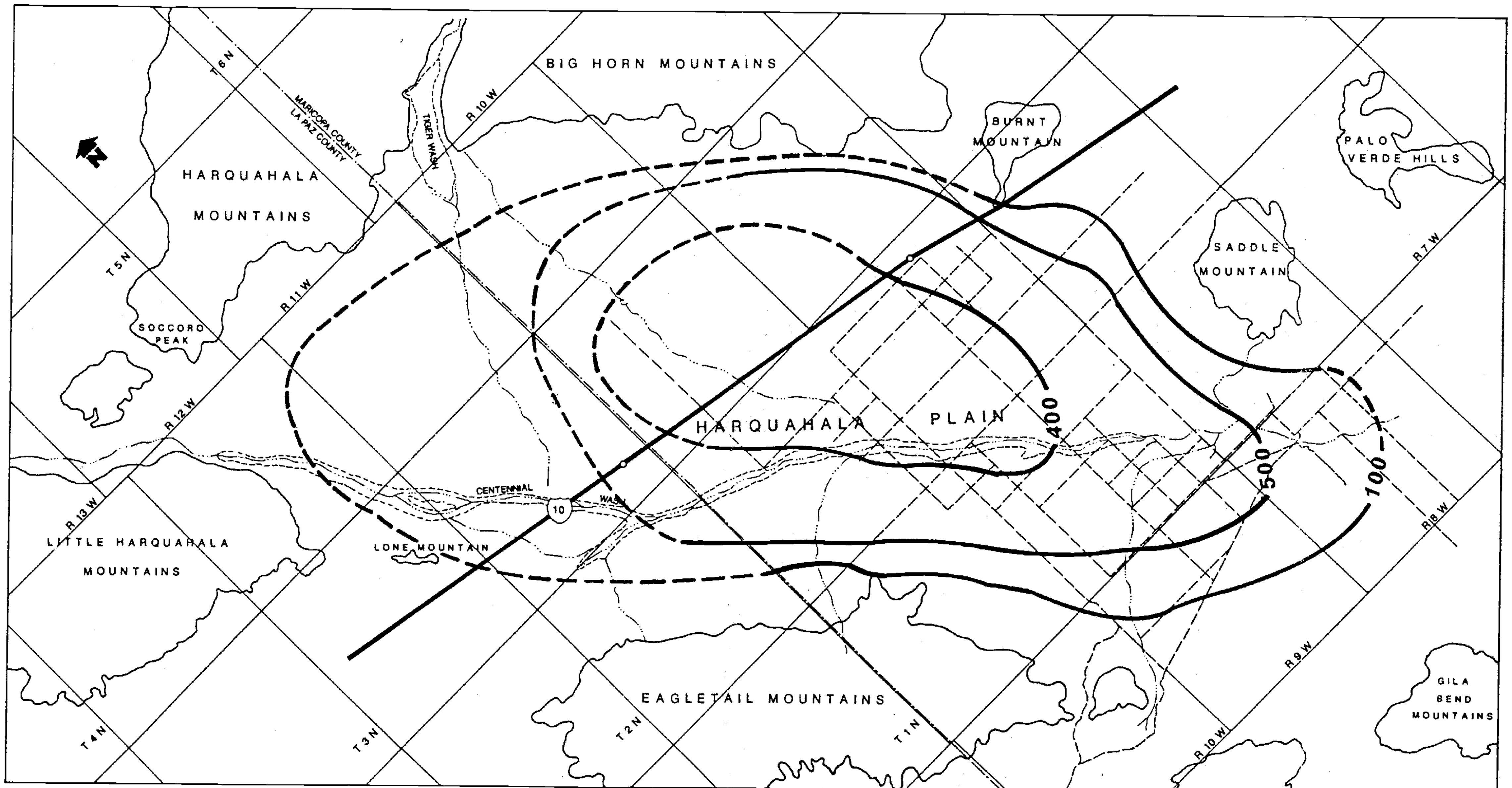
The major source of groundwater in the Harquahala Plains is the basin-fill alluvial deposits. These are a heterogeneous sequence of clay, silt, sand, and gravel which can be divided into two major alluvial units--an upper alluvium containing large amounts of fine-grained sediments and a lower, coarser alluvial unit which becomes cemented with depth. This lower coarse-grained member, described as conglomerate by the Bureau of Reclamation (1976) and as sand and gravel by Cooley (Denis, 1971) is the major source of water for irrigation. Wells tapping the lower unit produce as much as 2,500 gallons per minute (gpm) (Graf, 1980).

The upper alluvial unit, although predominantly finer grained, was the source of water for the early development (pre-1950) in the basin. It ranges in thickness from a few inches along the mountain fronts to more than 1,300 feet in the center of the basin (Figure 3).

Groundwater in the upper alluvial unit has generally been assumed to be under water-table conditions, but confined conditions may exist in some areas as a result of clay lenses. Groundwater depths in 1950, prior to major development, ranged from 17 feet along the axis of Centennial Wash to more than 424 feet near Lone Mountain (Metzger, 1957).

The lower coarse-grained unit consists of sands and gravels and conglomerate. Its thickness is not known, but a well located at Section 16, T1N, R9W, encountered 2,483 feet of interbedded clay, sand, and gravel without penetrating bedrock. In some areas, the unit rests upon basalt or lava flows (malpais), while in other areas it rests upon a red clay.

Groundwater in the lower unit probably exists under leaky confined conditions with localized areas of unconfined conditions. Leakage from the upper unit maintains hydrologic contact between the two units.



Contour Interval = 400 feet
(Dashed where inferred)

0 5 10 MILES
0 5 10 15 KILOMETERS

Figure 3. Thickness of Upper Alluvial Unit.

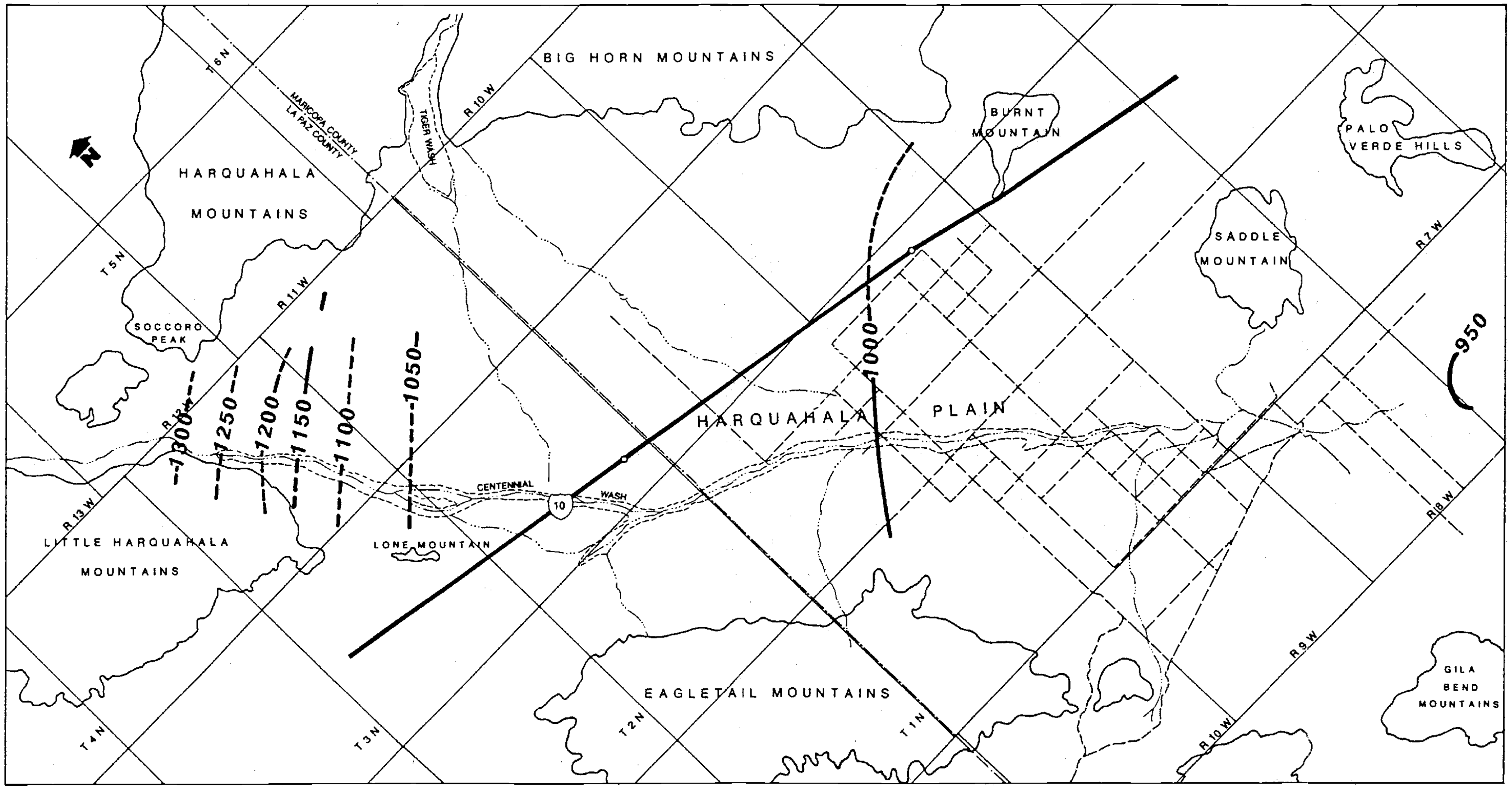
Under natural equilibrium conditions (pre-1952), the groundwater movement followed the path of surface flow. Movement was generally from northwest to southeast, entering the basin between the Harquahala and Little Harquahala mountains through Harrisburg Valley and exiting through the cut between Saddle Mountain and the Gila Bend Mountains (Figure 4). The water-table gradient was, on the average, two feet per mile.

By 1980, the natural gradient had been disrupted by two zones of heavy pumping, one south of Harrisburg Valley and the second in the southeast part of the basin centered around Harquahala Valley Road. The cones of depression developed in these areas have redefined the flow system (Figure 5). Heavy pumping in Harrisburg Valley has reversed the hydraulic gradient, reducing inflow to the valley. The hydraulic gradient at the south end of the valley has also been reversed, indicating that outflow from Harquahala is now minimal.

By 1988, hydraulic gradients in the southeast part of the valley had again changed. The importation of Central Arizona Project water in 1986 has resulted in a major decrease in the volume of water being pumped. The ADWR estimates that less than 20,000 acre-feet/year are being pumped in the area (Personal Communication, 1989).

Natural Recharge

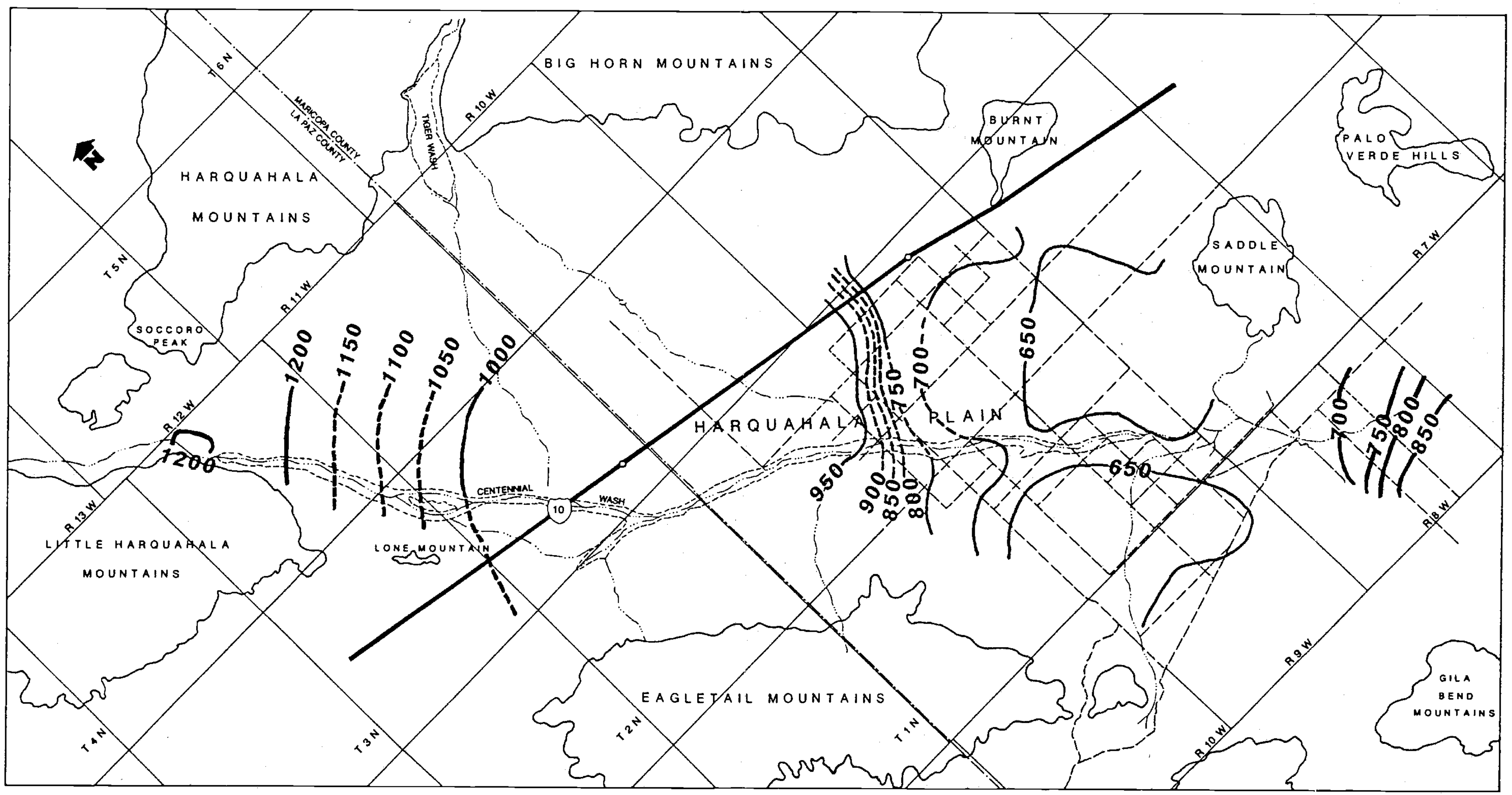
Natural recharge to southwest alluvial basins has four mechanisms, underflow from up-gradient basins, direct infiltration of precipitation, mountain front recharge, and infiltration of streamflow.



Contour Interval = 50 feet

0 5 10 MILES
0 5 10 15 KILOMETERS

Figure 4. Water level elevations, pre-1952.



Contour Interval = 50 feet

0 5 10 MILES
0 5 10 15 KILOMETERS

Figure 5. Water level elevations, 1980 (from Graf, 1980).

In the semi-arid Harquahala Plains area, direct recharge from precipitation is probably negligible. Although water does pond on the land surface during winter storms, the depth to water and presence of vegetation probably prevent infiltrated water from recharging the water table.

Under equilibrium conditions, there was underflow through the alluvium at the Narrows below Harrisburg Valley. Early estimates of underflow by Metzger (1957) indicated that the flow was negligible because the alluvial thickness is small in the Narrows area. The sinkholes that developed in 1958 behind the Narrows Dam suggest that underflow is probably higher than first believed. Graf (1980) included a hydrograph for a well downstream from the Narrows which showed a rapid rise in water levels following the draining of the reservoir. Based upon these data, underflow probably occurred not only through the alluvium, but also through folded limestone and sandstone beds as well. The estimate of the underflow used for this study is 1800 acre-feet per year for the pre-development years.

Development of groundwater in Harrisburg Valley for irrigation has created a groundwater divide just below the Narrows Dam. As a result, the natural inflow that normally would have come into Harquahala Plains area is now captured by this pumpage. However, the water that is withdrawn in the Harrisburg Valley area is imported to the Harquahala Plains area for use on irrigated fields within the basin. Although the natural underflow was reduced, a portion of the water that is imported reaches the water table as deep percolation of the irrigation water as evidenced by the increasing nitrate levels in the area (Cella Barr Associates, 1988).

The infiltration of streamflow is the major recharge mechanism in most southwest alluvial basins. Burkham (1970) studied this process in the main stream channels of the Tucson Basin and found that 70 percent of the streamflow infiltrated. Without gaging stations on Centennial Wash, it is difficult to determine not only how much water infiltrates in the stream channel, but also how much of this water actually reaches the water table. In the central part of the basin, where the channel is underlain by clay, probably very little reaches the water table before it is evapotranspired.

The Arizona Department of Water Resources (1978) concluded that natural recharge to the Harquahala basin, from all sources, was probably less than 3,000 acre-feet per year.

Natural Discharge

Natural discharge from the basin occurs as either evapotranspiration by vegetation or as underflow through the constriction between the Gila Bend Mountains and Saddle Mountain. Underflow out of the basin, like the inflow, is difficult to estimate because of the basalt flows at shallow depth. Although the channel is narrow, the thickness of the basalt flows and the extent that the flows are fractured or faulted are not known.

Evaporation and evapotranspiration probably account for the majority of water infiltrated either through the stream channel or directly as precipitation. Although this could be an important facet of the water budget in less arid areas, it has been assumed here that the volume of water infiltrated and the volume of water evaporated or evapotranspired are equal.

Two other areas of the Harquahala Plains watershed, Hubbard Plain and the area southeast of Turtleback Mountain, may contribute either to recharge or to discharge from the groundwater system. Surface runoff from these two areas drains to Centennial Wash, but there are no data available to indicate whether these areas contain significant volumes of stored groundwater or are hydraulically connected to the main basin.

For the undeveloped basin, the inflow and outflow should be equal, so that the ADWR's estimate of recharge of 3,000 acre-feet per year is also equal to the discharge. The magnitude of the natural recharge to the basin is small compared to the volume of water pumped from the aquifer. In 1950, the first year of extensive agricultural pumpage, the withdrawal was estimated to be 5,000 acre-feet. In this first year, the pumpage had already exceeded the estimated recharge and, by 1962, the pumpage was 67 times larger than the estimated recharge.

Storage Coefficient

The water pumped in the Harquahala Plains area comes from groundwater storage. The first attempt to estimate the specific yield for the alluvial material was made by Denis (1971). Using the change in water level from December 1963 to December 1966, he estimated that 3.7 million acre-feet of sediments have been dewatered. Dividing the estimated withdrawal of 560,000 acre-feet of water for the same time period by the volume of sediments dewatered, he arrived at a storage coefficient of 0.15. This value is reasonable for alluvial-filled basins under water table conditions.

The ADWR model, run in 1978, used a storage coefficient range of 0.02 near the mountain fronts, to 0.175 for the central part of the study area for the alluvial material. This model, which will be discussed later, was for the southcentral area of the basin where the greatest groundwater development had occurred.

The most recent study used a two-layer model and assumed the upper layer was water table and the lower layer was confined. Water table storage coefficients for the upper layer were modified from the ADWR model. One storage coefficient, 0.001, was used for the majority of the lower confined layer. However, in the northwestern and southeastern parts of the basin, the upper alluvial unit is missing and the lower unit is not confined. The storage coefficient was set to 0.10 in the northwestern area and ranged form 0.02 to 0.08 in the southeastern area.

Transmissivity

Aquifer tests to determine storage coefficient or transmissivity were not made in the Harquahala Plains area. Drillers ran short-term pumping tests to determine well yield and pump size when the wells were first constructed, but until 1974 no other data were available. Beginning in 1974 and continuing through 1975, the USGS calculated the specific capacity for 52 wells in the valley.

The specific capacity defines the productivity of a discharging well as the ratio of the pumping rate and the drawdown, Q/s (Walton, 1970). In general, the specific capacity can be used as an indication of the magnitude of the transmissivity. High specific capacity indicates a high transmissivity, and a low specific capacity indicates a low transmissivity. Although the general relationship is true, the specific capacity is adversely affected by partial penetration, well loss, and hydrogeologic boundaries (Walton, 1970).

The general equation used to calculate specific capacity, assuming constant discharge from a homogeneous, isotropic, non-leaky artesian aquifer of infinite areal extent, is:

$$\frac{Q}{s} = \frac{T}{264\ (\log \left(\frac{Tt}{2693r^2S}\right) - 65.5)}$$

where:

$\frac{Q}{s}$ = specific capacity (gpm/ft)

Q = discharge (gpm)

s = drawdown (feet)

T = transmissivity (gpd/ft)

S = coefficient of storage

r = nominal radius of well (feet)

t = time after pumping started (minutes)

The equation assumes that: (1) the well is uncased and penetrates the full saturated thickness, (2) the well loss is negligible, and (3) the effective radius of the well is equal to the nominal radius of the well. Although these assumptions, and those previously mentioned, are not met, the relationship of specific capacity to transmissivity is still a useful tool when no other information is available (Walton, 1970).

The specific capacities calculated by the USGS were for 2.5 weeks of pumping during the summer months. The transmissivities calculated ranged from 21,450 gallons per day per foot (gpd/ft) at a well located in Section 9, TIN, R8E, to 135,2000 gpd/ft at a second well in Section 10, T1N, R9E.

These transmissivities were used by the ADWR in the calibration of their model of the Harquahala Plains area. Large errors between the calculated and measured drawdown caused the ADWR to re-evaluate their transmissivities using the GEOLOG program.

GEOLOG Program

As previously mentioned, the aquifer parameter estimated from field measurements was the specific capacity for each of 52 wells selected by the USGS during 1973 through 1975. Long (1978) used these values to calculate transmissivities for use in the ADWR groundwater model in 1974. At the end of the 22-year verification period (1951-1973), the ADWR model using these specific capacities yielded an average error between the model predicted water levels and the measured water levels of 96 feet. About this time, the USGS contracted with the ADWR for the modification of the California Department of Water Resources computer program which estimated specific yield based upon drillers call (the driller's estimate of lithology contained in the well log). The ADWR adapted the program to calculate a relationship between the specific yield and hydraulic conductivity and the driller's call used to describe the sediments found in southern Arizona basins. These lithologic logs are readily available from drilling companies and are on file with the well registrations at the ADWR.

The program was developed in the Salt River Valley and then used by Long to modify the transmissivities estimated from specific capacity data in the Harquahala Plains model. The calibration of the model was never completed, but first runs using the modified transmissivities produced differences in predicted and measured water elevations of only 48 feet over the 22-year period modeled, cutting the error in half.

The GEOLOG program, as originally developed in California, was divided into two phases. Phase I identified the geology in terms of material so that buried physiographic features such as stream channels and faults, which could affect water movement, could be located. Phase II took the numeric values assigned in Phase I and converted the data into storage capacities and transmissivities.

The Arizona version of the program deleted Phase I, retained Phase II, and added several other features. The transmissivity values are still calculated by multiplying the hydraulic conductivity by the thickness associated with the material type, as described by the driller, but the total transmissivity section was estimated by summing the transmissivities for each interval rather than by averaging the values.

The program calculates total groundwater in storage for each interval and the potential well yield at varying depths of penetration based on the Theis equation (Long and Erb, 1980).

Quality of Water

In many cases, the chemical quality of groundwaters can provide an indication of the source of recharge to the aquifer system. This is true because the water carries with it a variety of chemical tags, ions held in suspension, which are not readily adsorbed onto clay particles or filtered out during percolation through the soil profile. In agricultural areas, this is particularly evident when abnormally high concentrations of nitrates and other dissolved salts are encountered in the groundwater system. These chemical constituents normally can be related directly to the farming operation as components of various fertilizers used in conjunction with crop irrigation. In unconfined aquifers, the saturated zone may actually become chemically stratified. As applied irrigation water moves through the vadose zone and reaches the water table, the velocity of vertical movement is significantly reduced, due in part to the fact that the bulk density of the irrigation return flow nearly matches the native groundwater. This results in a stratification of the aquifer system with the agricultural return flow resting on top of the older, uncontaminated supplies. If a significant clay layer exists between the land surface and the water table, then a perched aquifer may develop with the perched system exhibiting concentrations of agricultural chemicals dramatically higher than the regional groundwater body.

In this regard, the Harquahala Plains is no exception. With the expansion of agriculture in the valley, increasing pressure was placed upon the local groundwater system which contained water suitable for the irrigation of most crops. Electrical conductivity (EC) is a convenient way to estimate the salinity of a water sample.

The more ions a solution contains, the lower the resistance to the passage of an electrical current and the higher the conductivity (Drever, 1982). Although EC cannot be precisely converted to salinity unless information is available on the proportion of ions in the water, it can be used to compare the change in water quality with time. If EC increases with time, it can be concluded that the salinity of the water is also increasing.

Approximately 22 wells were sampled between 1952 and the spring of 1955. The results from these tests are tabulated in Metzger's 1957 report. At that time, total dissolved solids (TDS) ranged from 432 parts per million (ppm) to 864 ppm, and the EC varied from 691 micromhos to 1,320 micromhos. Figure 6 shows that TDS and EC tended to be lower northeast of Centennial Wash and higher south of the wash in the area mapped by Wells (1978) as saline silt and clay deposits. Figures 6, 7, and 8 show the trend in EC with time in the region of intense groundwater development in the lower Harquahala Plains.

Denis (1971) reported that in 1966, 21 wells were tested for water quality and that between 1966 and 1967 EC was measured in 49 wells. As seen in Figure 7, the range in EC was 713 micromhos to 1,300 micromhos with some wells already showing an increase in EC. The region of increased EC occurs along the axis of Centennial Wash beneath the irrigated acreage where Wells (1978) mapped the surficial deposits as eolian sand dunes and saline silt and clay. It is possible that excess irrigation water is leaking around the well casing and into the aquifer, that deep percolation has already occurred in the coarser stream channel or eolian dune

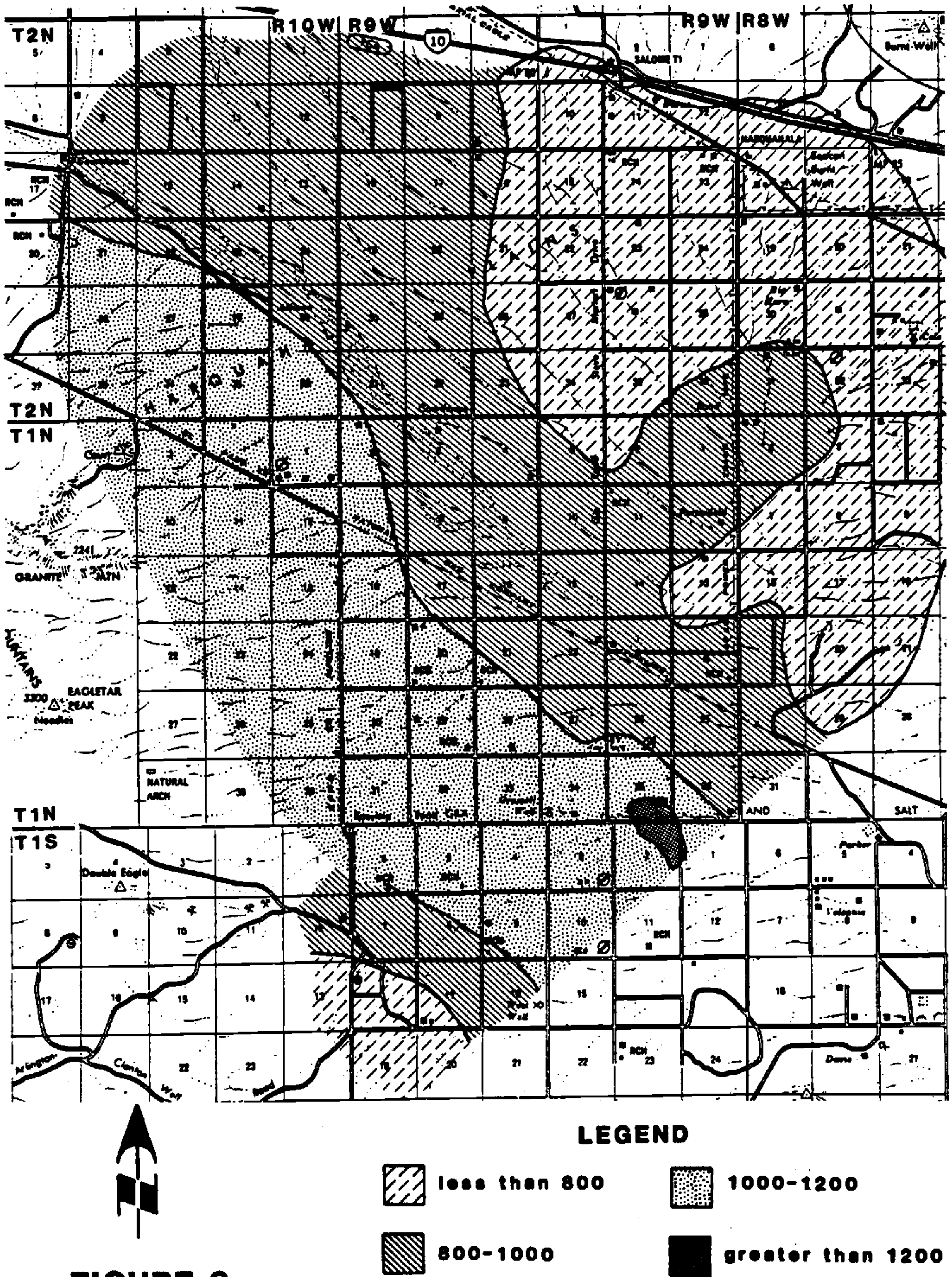


FIGURE 6:
Electrical Conductivity, Lower Harquahala Plains, 1954

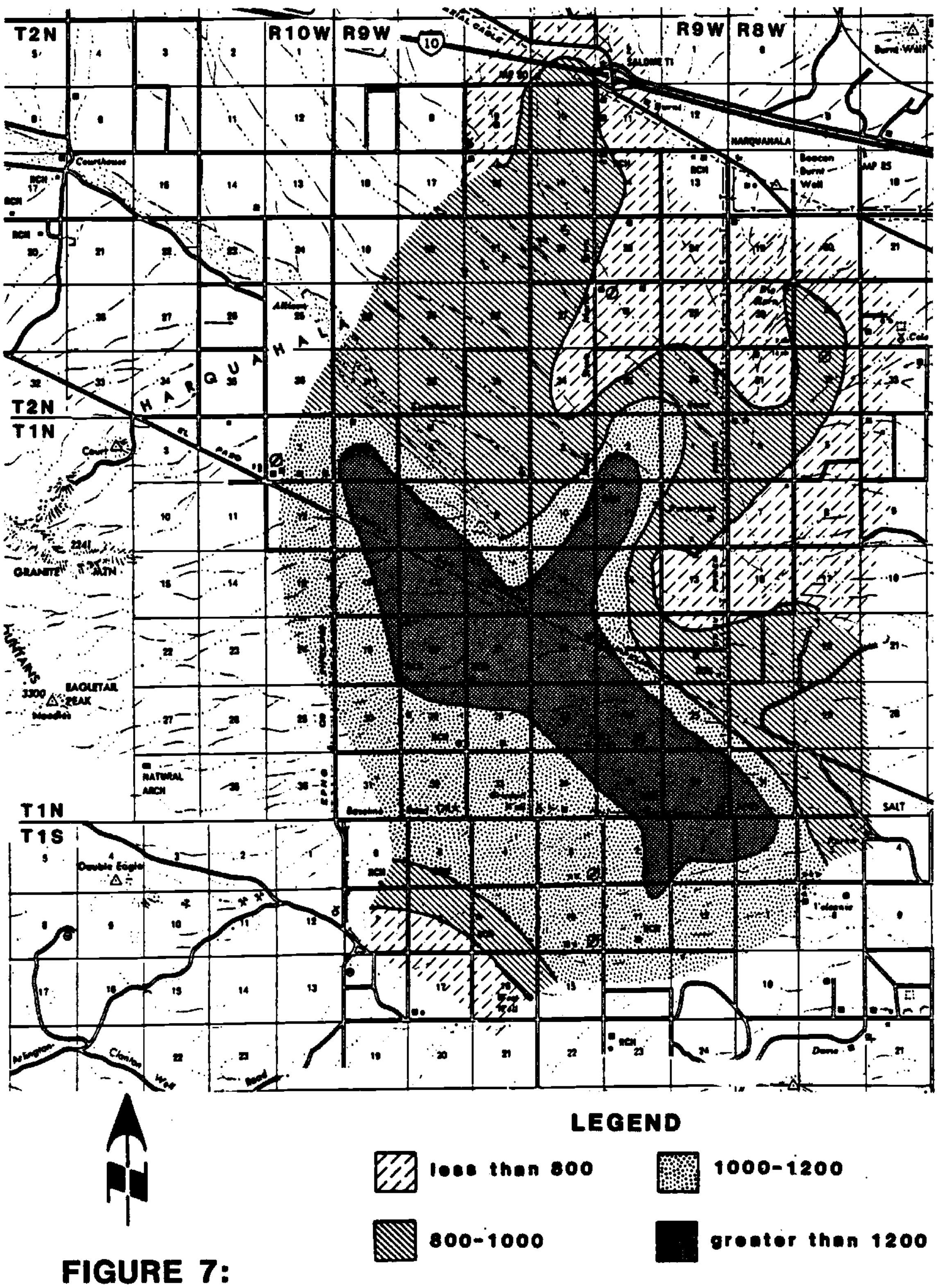


FIGURE 7:
Electrical Conductivity, Lower Harquahala Plains, 1967

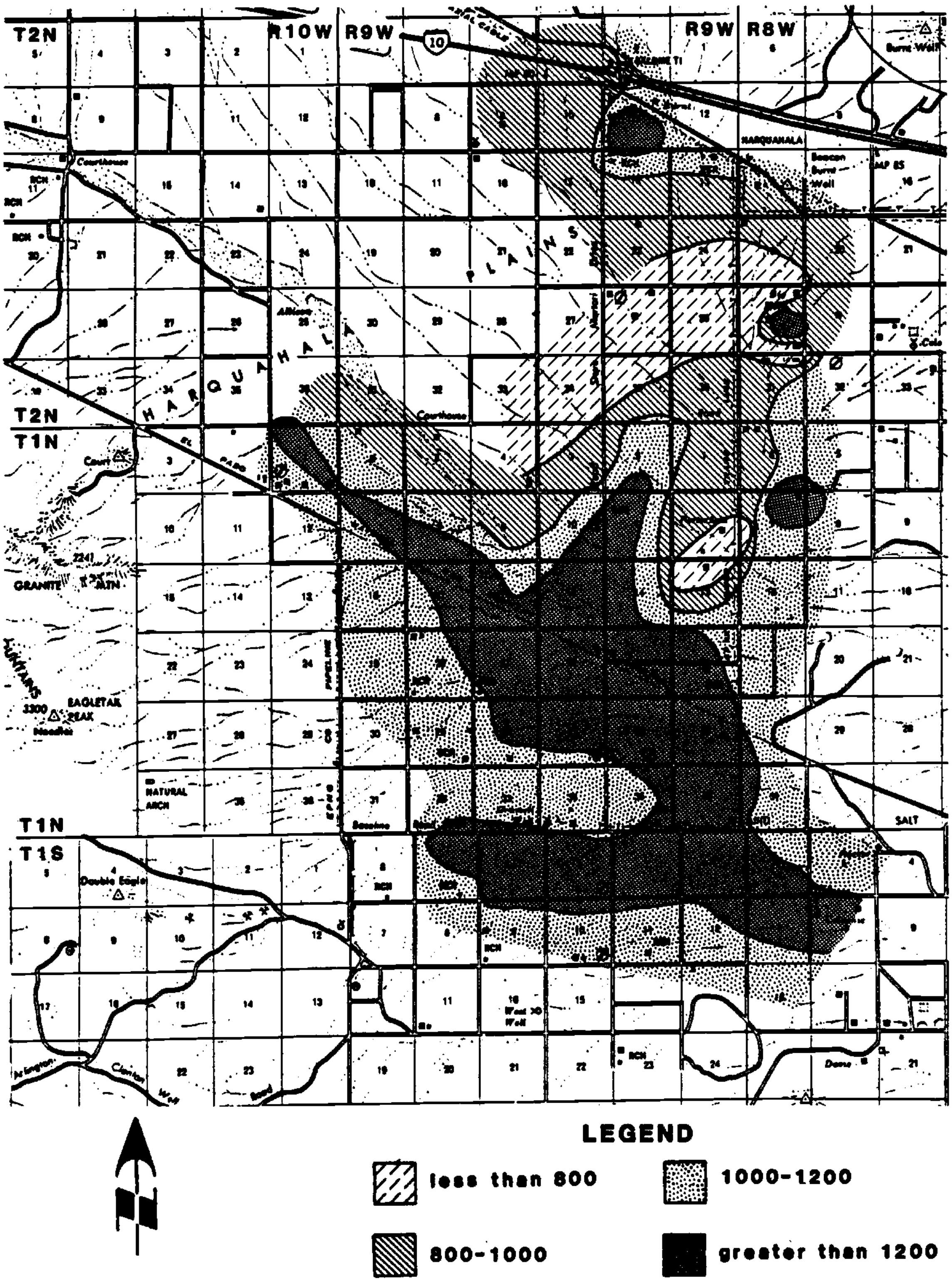


FIGURE 8:

Electrical Conductivity, Lower Harquahala Plains, 1980

deposits, or that water moving through saline sediments is transmitting poorer quality water to the aquifer.

By 1980, the EC ranged from 730 micromhos to 4,000 micromhos. The upper range of EC has almost tripled in value, while the aquifer area having an EC greater than 1,200 micromhos has almost doubled in size (Figure 8). The EC has increased in those wells having cascading water or perched water levels but also has increased in the majority of the wells measured.

The regional aquifer was sampled by Graf in 1980 and found to contain background nitrate concentrations ranging from 8 to 21 mg/l as NO_3, well within the limits (45 mg/l) established by current regulations. Similarly, the total dissolved solids concentration measured in the main water bearing unit ranged from 400 to 1000 mg/l. Although the U.S. Environmental Protection Agency lists Total Dissolved Solids (TDS) only as a secondary constituent, it does have a recommended limit for human consumption of 500 mg/l. Due predominantly to the mineralogy of local sediments,the main aquifer of the Harquahala system has fluoride concentrations ranging from 0.8 to 6.7 mg/l with an average of 3.0 mg/l (Graf, 1980). The recommended limit for fluoride is 4.0 mg/l.

Table 4, modified from Schmidt (1980), shows a comparison between water samples at seven wells in Harquahala Plains. The water samples from the main aquifer were tested in 1974; samples from the perched water table were tested in 1979. One well (B29), 14bbb, was sampled in 1974 and in 1979 and shows an example of the increase in constituents as the water in the well is contaminated by poorer quality water.

Table 4. Water Quality Data

CONSTITUENT (mg/l)	PERCHED WATER				MAIN AQUIFER			
	(B-1-9) 17abb	(B-1-9) 21bcc	(B-2-9) 14bbb	(B-2-9) 26BBB	(B-1-9) 11bbb	(B-1-9) 20ccc	(B-2-9) 14bbb	(B-2-9) 26adc
Calcium	134	66	189	13	12	16	32	17
Magnesium	88	40	21	3	2	9	14	7
Sodium	760	680	710	1140	235	204	144	143
Carbonate	0	0	0	62	0	0	0	0
Bicarbonate	173	198	102	366	165	267	140	134
Sulfate	660	440	1050	810	250	110	150	110
Chloride	796	524	630	850	81	120	120	92
Nitrate	944	522	86	151	15	15	21	15
Fluoride	3.2	4.2	4.4	17.6	1.8	2.9	1.6	2.4
pH	7.8	7.8	7.7	9.1	8	7.9	7.8	7.9
Electrical Conductivity (micromhos/cm @ 25 °C)	4000	2790	3700	0	1170	1190	1005	850
Total Dissolved Solids	3567	2423	3126	3229	738	641	589	486
Date	9/26/79	9/26/79	12/11/79	9/20/79	8/13/74	8/7/74	8/7/74	8/8/74
Lab	ADHS	ADHS	ADHS	ADHS	USGS	USGS	USGS	USGS

Graf's investigations also included an assessment of the quality of perched waters in the area. A total of six samples were extracted from wells perforated only in perched systems. Upon analysis, it was found that the nitrate concentrations exhibited by these waters were significantly higher than those in the underlying regional system, reaching a maximum of 944 mg/l in one sample and averaging 304 mg/l. Similar increases were found in the TDS levels which generally ranged from 1,402 to 3,567 mg/l. Even fluoride ions were more concentrated in the perched waters, reaching levels of 3.2 to 17.6 mg/l with an average of 6.8 mg/l.

Subsequent to Graf's work, no further sampling of the perched zones was undertaken. The regional aquifer, however, continued to display a chemistry similar to that outlined above. Given the difference in quality of the waters contained in the various aquifer systems, it appears that irrigation return flow is a major component of recharge to these systems. Quantifying the volume of this recharge, therefore, will aid in determining the useful life of potable water supplies in the Harquahala Plains.

Perched Groundwater

The occurrence of perched or cascading water was noted as early as 1964 by Stulik, who suggested that water levels in T2N, R10W represented a perched water table overlying the fine-grained material (Stulik, 1964). He suggested that perched water levels might be present because water levels in the clay unit had not declined with time. This had created a steep gradient between the clay zone and the cone of depression beneath the irrigated area. Although this is the earliest mention of a perched water table, anomalous water level rises and cascading water were not measured until 1968 in well B(1-9) 6bab. By January 1980, Graf had documented 27 wells which had either perched or cascading water; in December of that year, another four wells were measured where cascading water was present.

Figure 9 presents a comparison of the wells containing perched or cascading water and the irrigated acreage in 1954, 1958, and 1967. Twelve of the wells are located in areas irrigated since 1954. Four additional wells are in areas irrigated since 1958, and the remaining 15 are in areas irrigated since 1967.

The drilling data for 22 of the 33 wells are available in Table 5. Sixteen of these 22 wells were drilled prior to 1960. Of the 33 wells, 14 have a drilling method recorded on the well registrations; ten were drilled using a cable rig; four were drilled using a rotary rig. One of the cable tool drilled wells showing perching was drilled as recently as 1977.

All of the wells having perched or cascading water are located within the limit of the fine-grained beds. There is little or no correlation between these beds as recorded on the well logs and the elevation of the cascading water or perched water. There is also little correlation between the perforated interval of the well and the perched or cascading water. This is illustrated by the three hydrographs and associated drillers' logs and well construction data shown in Figures 10, 11, and 12. The water is cascading into well B(1-9) 21bcc1 at an elevation of 872 feet, into well B(2-9) 23aaa at 1350 feet, and into well B(1-8) 19bcc at 668 feet. It appears that no single, continuous unit is causing the cascading or perched water.

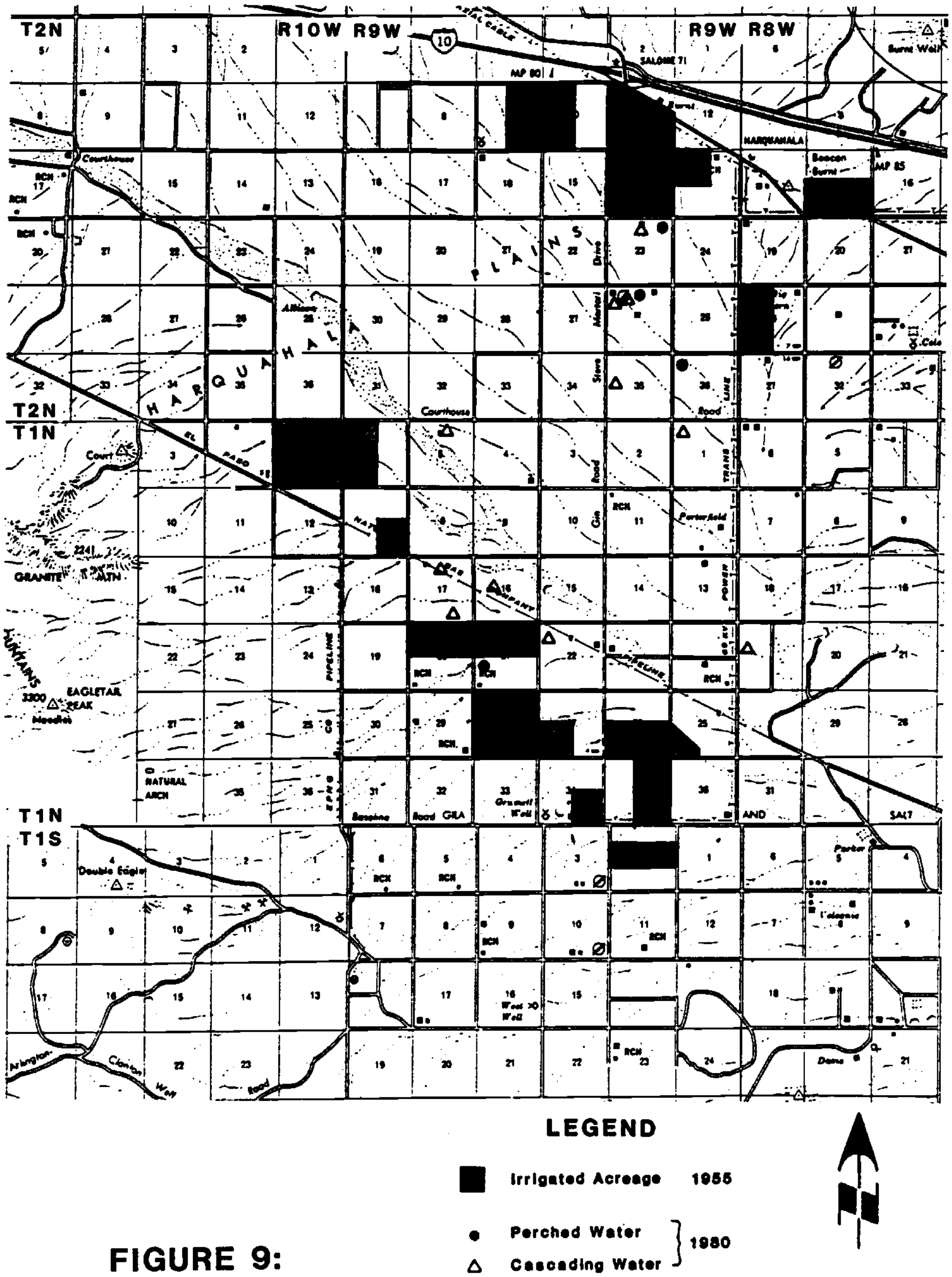


FIGURE 9:

Irrigated Acreage 1955 / Perched Water 1980

Table 5. Drilling date and method of construction for wells showing cascading or perched water

WELL LOCATION	PERCHED OR CASCADING	DEPTH TO PERCHED WATER (FEET)	PERFORATED INTERVAL (FEET)	DEPTH OF WELL (FEET)	DATE FIRST REPORTED	USE	DATE DRILLED
B(1-8) 6bba	P	122.4	425-580	605	1979	abnd	
B(1-8) 7cbb	unknown	102.7	300-600 600-899	800	1974	abnd	1958
B(1-8) 19bcc	C (1978) P (1979)	32	165-200 268-300 330-350 450-665	700	1978	abnd	1957
B(1-8) 31ccc	C	unknown	250-626	626	1979	agric.	1956
B(1-9) 1bbb	P	40	40-1536	1536	1978	stock	1957
B(1-9) 5abc	P	168.2	unknown	unknown	1978	abnd	unknown
B(1-9) 6bab	P	126	928-1385	1638	1968	abnd	1955
B(1-9) 16bdd	C	450	1306-2483	2483	1978	abnd	1965
B(1-9) 17abb	P	82	unknown	unknown	1971	abnd	unknown
B(1-9) 17dcc	P,C	250 (C) 430.9 (P)	500-1500	1505	1979	agric.	1963
B(1-9) 20bbb	P	227.2	200-930	930	1975	agric.	1952
B(1-9) 21bcc1	P,C	196 (C) 278 (P)	300-825 900-1085	1068	1973	abnd	1952
B(1-9) 22bcb	P,C	175 (C) 296 (P)	425-1005	1005	1978	agric.	1977
B(1-9) 28ddd	C	unknown	310-996	996	1978	agric.	1960
B(1-10) 1ccc	C	unknown	340-777	918	1979	agric.	1953
B(2-9) 9abb	C	465	400-1500	1540	1979	agric.	1952
B(2-9) 12abb	C	unknown	unknown	1500	1978	agric.	1957
B(2-9) 10bbb	C	385	250-1300	1300	1978	agric.	1953
B(2-9) 13baa	C	180	175-550	603	1978	gov.	1954
B(2-9) 14bab	C	unknown	490-1216	1300	1978	agric.	1976
B(2-9) 14bbb	P	173.3	294-1452	1530	1978	dom.	1951
B(2-9) 16bbb	C	unknown	unknown	unknown	1978	abnd	unknown
B(2-9) 23aaa	P,C	310 (C) 402.7 (P)	298-1550 1550-1660	1660	1978	agric.	unknown
B(2-9) 23abb	P	63	250-1506	1506	1978	agric.	unknown

Table 5--Continued

WELL LOCATION	PERCHED OR CASCADING	DEPTH TO PERCHED WATER (FEET)	PERFORATED INTERVAL (FEET)	DEPTH OF WELL (FEET)	DATE FIRST REPORTED	USE	DATE DRILLED
B(2-9) 26baa	C	unknown	unknown	unknown	1978	unknown	1977
B(2-9) 26bbb1	P	unknown	unknown	unknown	1979	abnd	unknown
B(2-9) 26bbb2	P	30	700-935	1820	1978	abnd	1958
B(2-9) 26bdd	P	46.6	unknown	unknown	1978	abnd	unknown
B(2-9) 35cbb	P	129	690-900	920	1978	abnd	1956
B(2-9) 36bbb	C	unknown	500-1100	1100	1978	unknown	1960

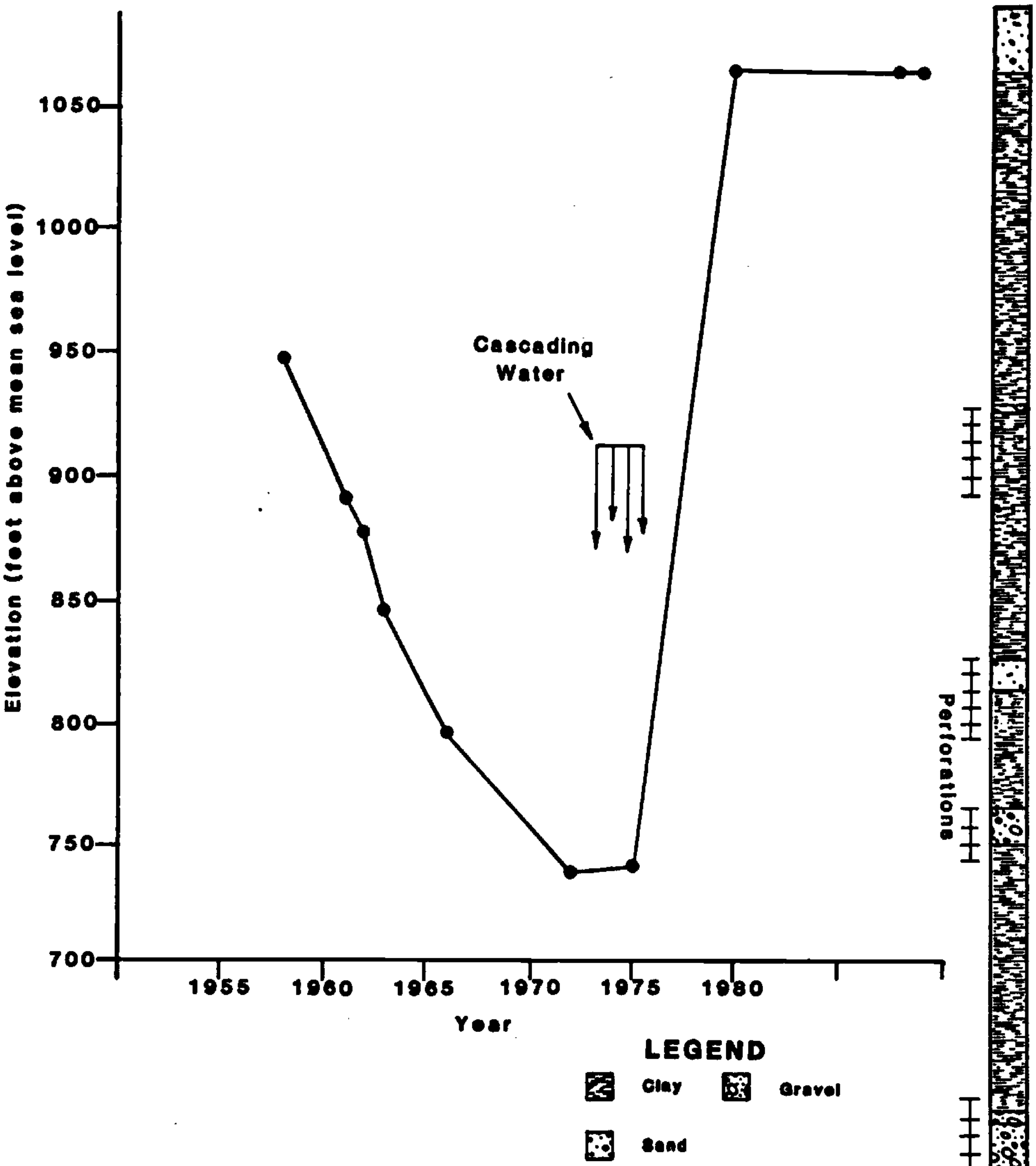


FIGURE 10:

Hydrograph, Drillers Log and location of cascading water for well B(1-8)19bcc

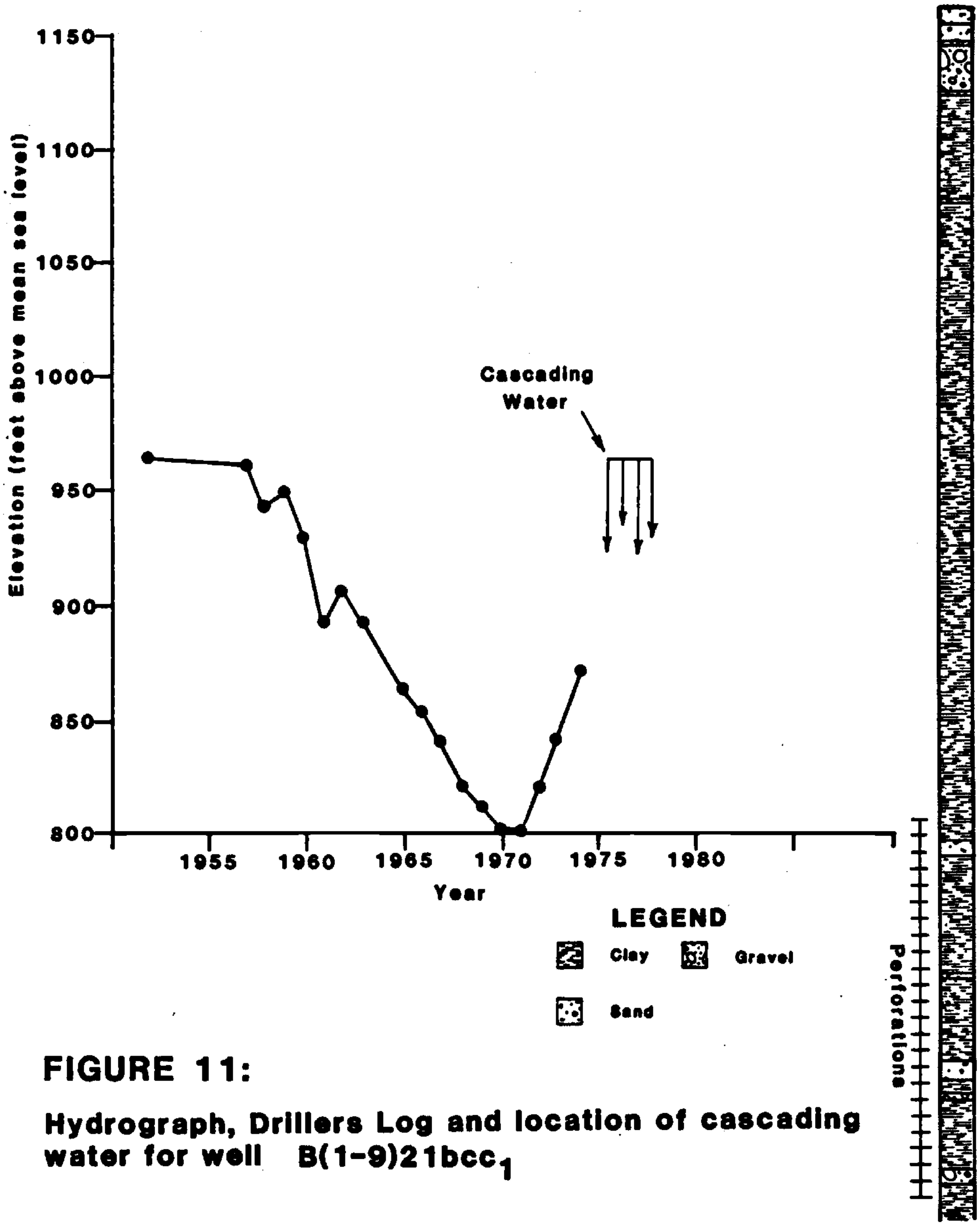


FIGURE 11:

Hydrograph, Drillers Log and location of cascading water for well B(1-9)21bcc$_1$

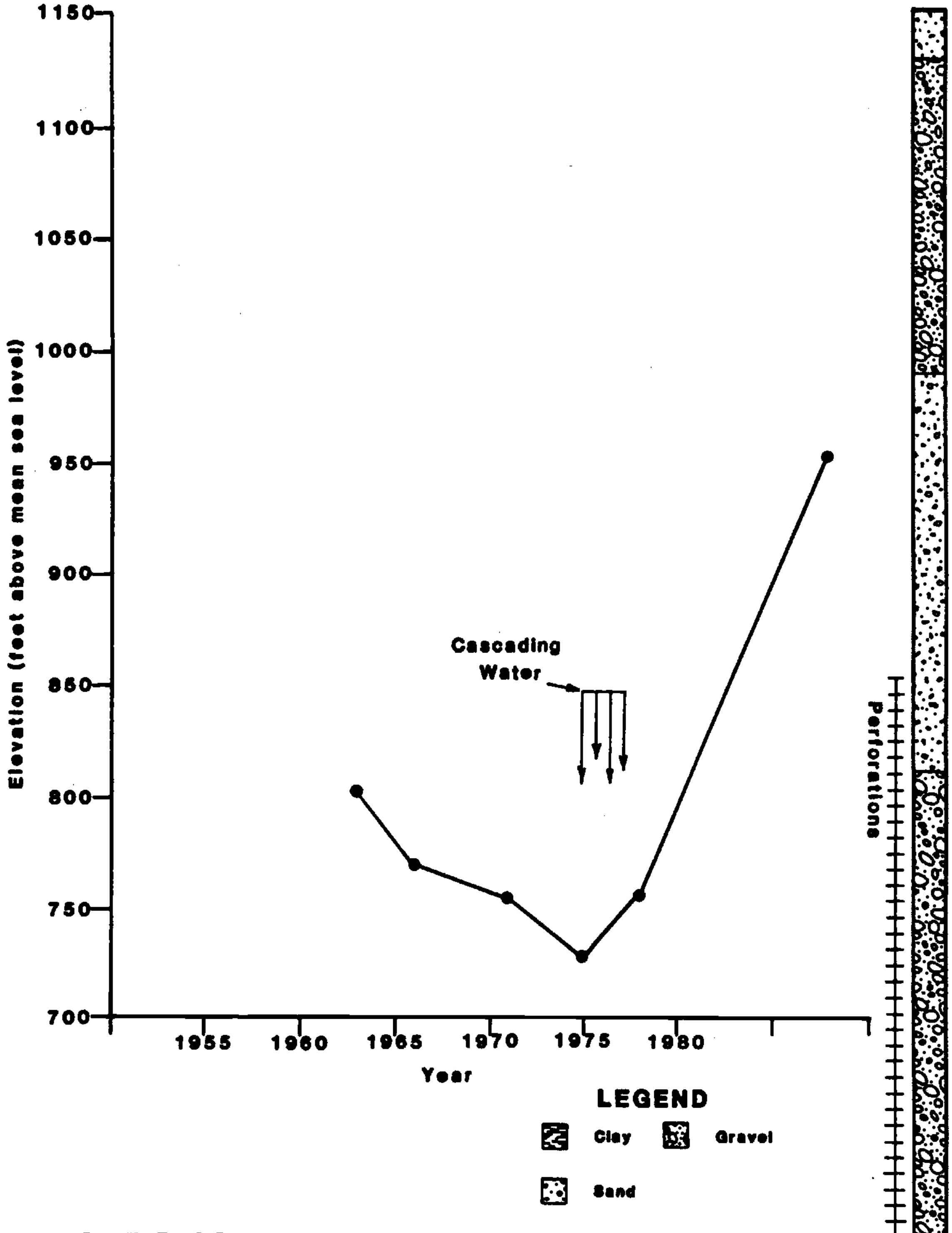


FIGURE 12:

Hydrograph, Drillers Log and location of cascading water for well B(2-9)23aaa

This may be due to the fact that the clay unit is a heterogeneous mixture of clay lenses that are not of extensive areal extent and that the entry point on the water depends more upon the casing than on the clay lenses. Based upon recent video surveys of several wells in the basin, casing which is now more than 25 years old may have deteriorated such that water previously excluded from the well bore is now gaining access.

In general, the altitude of the water level is higher than the altitude originally measured in the early 1950s. The cascading water entering the well bore will initially mix with water in the well and possibly discharge through casing perforations into the coarser-grained aquifer below. The development of the perched water table can be caused by water entering the casing faster than it can leave, either because the permeability of the main aquifer is naturally lower or has been reduced in the immediate well vicinity by entrapped air in the water. The presence of the perched water within the well could also reflect a plugged casing--whether due to casing failure and collapse or a plugging of the perforations. In the case of a plugged casing, the anomalously high water levels may not be representative of a regional perching zone. The entry point of the cascading water may not represent the elevation of the perched water because the route of travel of this water into the casing is not known. The water may short circuit along the outer casing wall until an opening in the casing is found.

Chemical Quality

As previously discussed under water quality for the main aquifer, the quality of the perched water is noticeably poorer than that of the main aquifer. Total dissolved solids are as much as three times higher than those in the main aquifer, ranging from 1.402 to 3.567 mg/l. The dissolved nitrate concentration, expressed as the nitrate ion NO_3, ranged from 1 to 944 mg/l in the perched water compared to 5.1 to 18.2 mg/l in the main aquifer. The fluoride concentration is also elevated above the main aquifer "constituents", with an average concentration more than twice that of the main aquifer, ranging from 3.2 to 17.6 mg/l. The fluoride concentrations make the water unsuitable for domestic purposes, although at least one domestic system presently withdraws water from the perched zone (Graf, 1980).

History of Cultural Development

The earliest recorded water level measurements for wells in the Harquahala Plains were made by C. P. Ross in 1917 for his summary of watering places in the lower Gila region (Ross, 1923). The seven wells cited by Ross were used mainly for stock watering by the Harquahala Livestock Company. Dry land farming was attempted between World War I and World War II and, although wells were dug for domestic and stock use, they probably were not used for irrigation. Metzger (1957) mentions the abandoned Mosher Homestead in section 31, T3N, R9W, where a hand-dug well with a depth to water of 330 feet is located. The attempts at dry land farming were unsuccessful.

The next stage in development of the groundwater was during the late 1930s, when wells were drilled for irrigation in the lower end of the basin between Saddle Mountain and the Gila Bend Mountains. Although water was pumped, it evidently was transported downstream out of the Harquahala Plains area for use along the Centennial Wash floodplain (Metzger, 1957).

The beginning of the groundwater development for irrigation came in 1951 when the well in section 14bbb, T2N, R9W, was drilled to a depth of 1,530 feet. Static water level was 200 feet below land surface, and well discharge was more than 3000 gpm (Metzger, 1957). Successful completion of this well prompted the drilling of 20 more wells in 1952 and 1953 (Metzger, 1957). By the spring of 1953, some 4,990 acres of land were being irrigated by groundwater from the Harquahala Plains alluvium (Graf, 1980).

Water level declines between 1952 and 1955 averaged between three to four feet per year within the cone of depression in the immediate vicinity of the pumping wells. The static water levels ranged from 17 to 323 feet with production ranging from 300 to 3,500 gpm. Total discharge for 1951 is estimated at 7,000 AF; by 1953, the discharge had jumped to 20,000 AF. It is interesting to note that of the 20 successfully completed irrigation wells drilled prior to 1954 in Harquahala Plains, 11 were deeper than 1,000 feet and five of the wells were deeper than 1,400 feet.

By December 1963, the number of wells had increased from 20 to approximately 100. The annual pumpage had increased to 200,000 acre-feet and was applied to 33,000 cropped acres. The depth to water ranged from 40 to more than

400 feet below land surface. Estimated pumpage was a maximum of 200,000 acre-feet per year from 1962 through 1965 (Stulik, 1964).

By December 1966, there were approximately 39,500 acres of cultivated land being irrigated by some 120 wells. About 2,000 acres of the 39,5000 acres were cultivated on the northwest part of the valley. The depth to water ranged from 30 feet below land surface between Saddle Mountain and the Gila Bend Mountains to 440 feet below land surface at a well in section 11, T2N, R9W (Denis, 1971).

By October 1977, the irrigated acreage had dropped to 36,440 acres based upon NASA color-infrared aerial photography and field verification done in 1978 and 1979. Based on field observation in 1980, the irrigated acreage had dropped to about 34,000 acres. Pumpage of 123,000 acre-feet in 1977 had decreased to approximately 87,000 acre-feet in 1979.

Many of the early irrigation wells used electrical energy and a few used diesel, but most of the wells used natural gas. Data for 1962 to 1964 show that about 75 percent of the total pumpage came from wells powered by natural gas (Bureau of Reclamation, 1976). Power records collected by the Arizona Water Commission in 1974 indicate that at least 70 of the irrigated wells were powered by electricity. The decrease in pumpage in the 1970s had several sources, the onset of the oil embargo and resulting fuel shortage increased the cost of fuel and electricity for the pumps at a time when pumping lifts were increasing. A small decrease in cropped acreage occurred as well as the increased use of sumps and pump back systems. All of these factors caused the farmers to use the pumped groundwater as efficiently as possible.

Agricultural

Cultivated land within the Harquahala Plains has been restricted largely to those areas where groundwater was available. Earliest development in 1951 was restricted to the southeast part of the valley where wells encountered good yields at moderate depths. The irrigated acreage grew from 4,990 acres in 1953 (Graf, 1980), to 39,500 acres in 1966 (Denis, 1971), and then decreased to an estimated 34,000 acres in 1980 (Figure 13).

The major crop grown in Harquahala Plains is cotton. Alfalfa and other hays are also grown and, in recent years, winter wheat has been planted. There are less than 320 acres planted in grapes and a little more than 960 acres planted in orchard. In 1980, when the crop type was estimated by driving around the valley, an attempt was being made on some fields to grow the current year's cotton from last year's stubble. This has since been discontinued because of boll weevil problems. It appears that some double cropping is occurring, but estimates of the acreage involved are not available.

The cotton, grapes, and orchard acres are all irrigated by rows, and the hay and alfalfa are flood irrigated by small basins. In the late 1960s and early 1970s, a series of sumps and pump back systems were installed near many of the fields. Although these systems increased the efficiency of water use--that is, tailwater is captured and reapplied to the field, the volume of water applied to the fields did not decrease. Irrigation efficiencies for crops in Maricopa County were estimated to be from 60 to 80 percent (USGS, 1978).

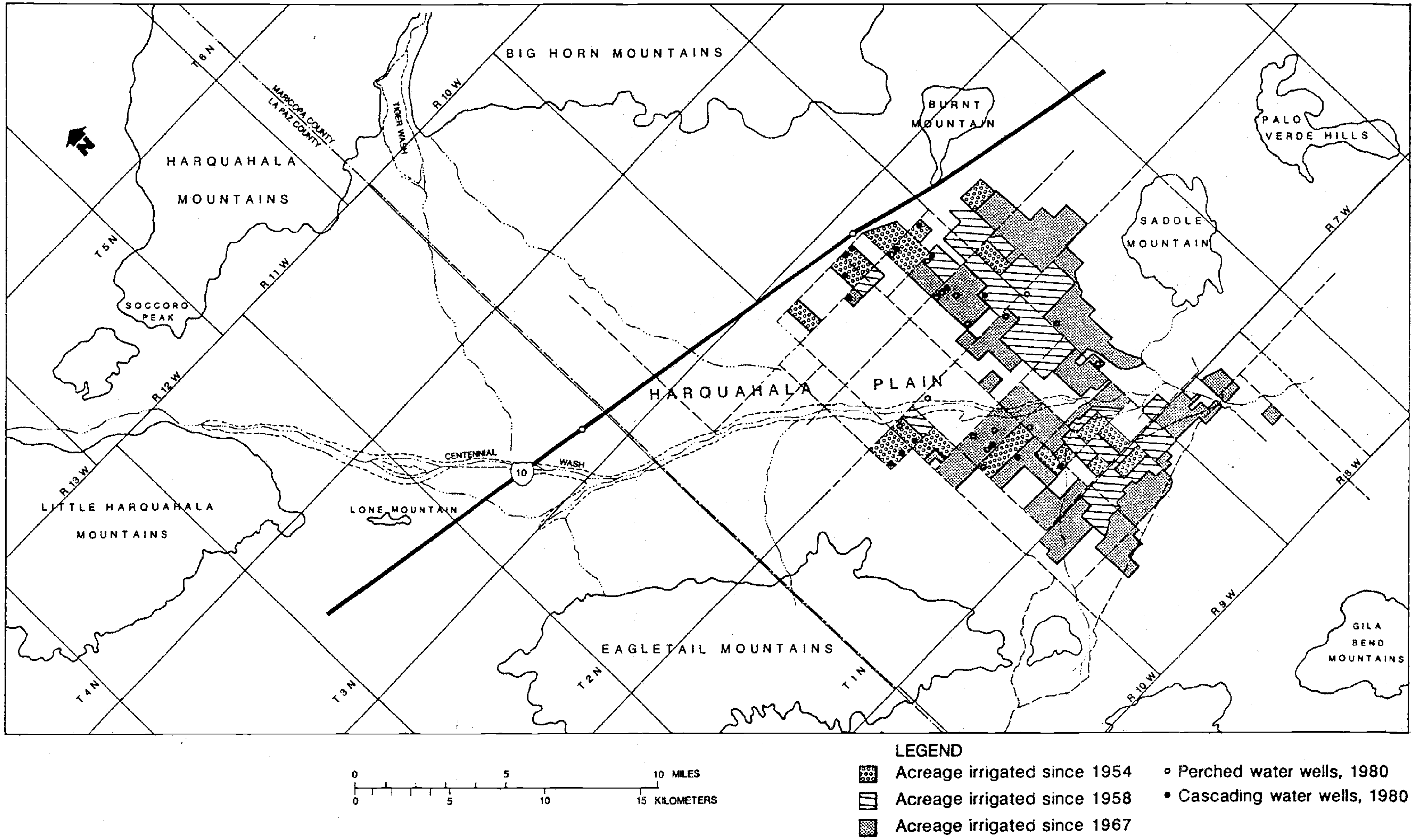


Figure 13. Irrigated Acreage in 1954, 1958, and 1967.

CHAPTER 5

GROUNDWATER MODEL DEVELOPMENT

Description of the Model

The major thrust of the Harquahala Plains study was the development of a three-dimensional groundwater model that could be used to quantify the volume of irrigation return flow that recharges the water table and, if possible, estimate the lag time between surface application and recharge.

The computer program used was the U. S. Geological Survey's (USGS) three-dimensional modular finite difference program (MODFLOW) by McDonald and Harbaugh (1988). MODFLOW was selected because it is a public domain program, is well documented,and has been in use since 1984, resulting in extensive peer review and use. The version of the program used is version 3.1 for IBM compatible microcomputers, compiled in Microsoft Fortran 77 and distributed by the International Ground Water Modeling Center at the Holcomb Reasearch Institute, Butler University. The modular design of the program enables the user to select those subroutines which best describe the physical processes important in the area to be modeled.

MODFLOW is a three-dimensional finite-difference flow simulation program which uses block-centered calculations. Aquifer layers can be water table, confined or converted from confined to water table should water levels fall below the confining layer. Flow processes simulated by the program include discharge or injection wells, areal recharge, evapotranspiration, drains, and recharge from streams. Boundary conditions can be impermeable, constant head, constant flux, or variable flux based upon the change in water levels beyond the model boundary. Two finite difference solution techniques are available, strongly implicit and slice-successive over-relaxation.

The earlier two-dimensional model of Harquahala Plains prepared by the Arizona Department of Water Resources (1975) provided a convenient starting point for the current modeling study. This earlier model used the USGS Trescott program to model the aquifer in a two-dimensional form because data availability at that time did not warrant a more complex model.

The ADWR model covered only the southcentral part of the basin in and around the cultivated area where withdrawals where concentrated. The model simulated a small portion of the groundwater flow system in the Harquahala Plains; therefore, flow across the artificially imposed boundaries had to be estimated. Transmissivities and specific yields for the modeled area were estimated using ADWR's GEOLOG program and available drillers' logs. Although their model was never completed or documented due to lack of funding, the ADWR graciously made available the data arrays and preliminary model runs. Where possible, the ADWR data were used as initial data input, but more data and a concern for the vertical component of flow--deep percolation--prompted the second modeling study and the use of the three-dimensional groundwater program.

Modeling Procedure

The Harquahala Plains basin was chosen for this model study because of the data availability and the homogeneity of water usage. The area is unusual in that it has been studied extensively by State and Federal agencies since development of groundwater began in the early 1950s. For this reason, the model for Harquahala began with a steady-state model (assumed to be pre-1953) and then used data arrays from the steady state model as input to the transient model. Model calibration was checked at selected intervals during the time from 1953 to 1985 when sufficient measured water level data were available for comparison.

Model Grid

The model grid used for this study is oriented along the axis of the Valley, trending northwest-southeast parallel to the major direction of flow (Figure 14). The grid used is variably spaced in the long direction (y axis), ranging from two miles at the northwest end to 3484 feet in the southcentral area. The grid in the short direction (x axis) is a uniform mile. The grid is 15 nodes by 36 nodes.

Model Layers

The Harquahala model is a three-dimensional simulation of the hydrologic processes. It has two layers, the unconsolidated alluvium and the lower conglomerate connected hydraulically by leakance through the middle, fine-grained unit. Where the fine-grained unit is absent, flow between the two layers is unrestricted. The upper layer is water table, the lower layer confined (except in the northwestern and southeastern parts of the valley).

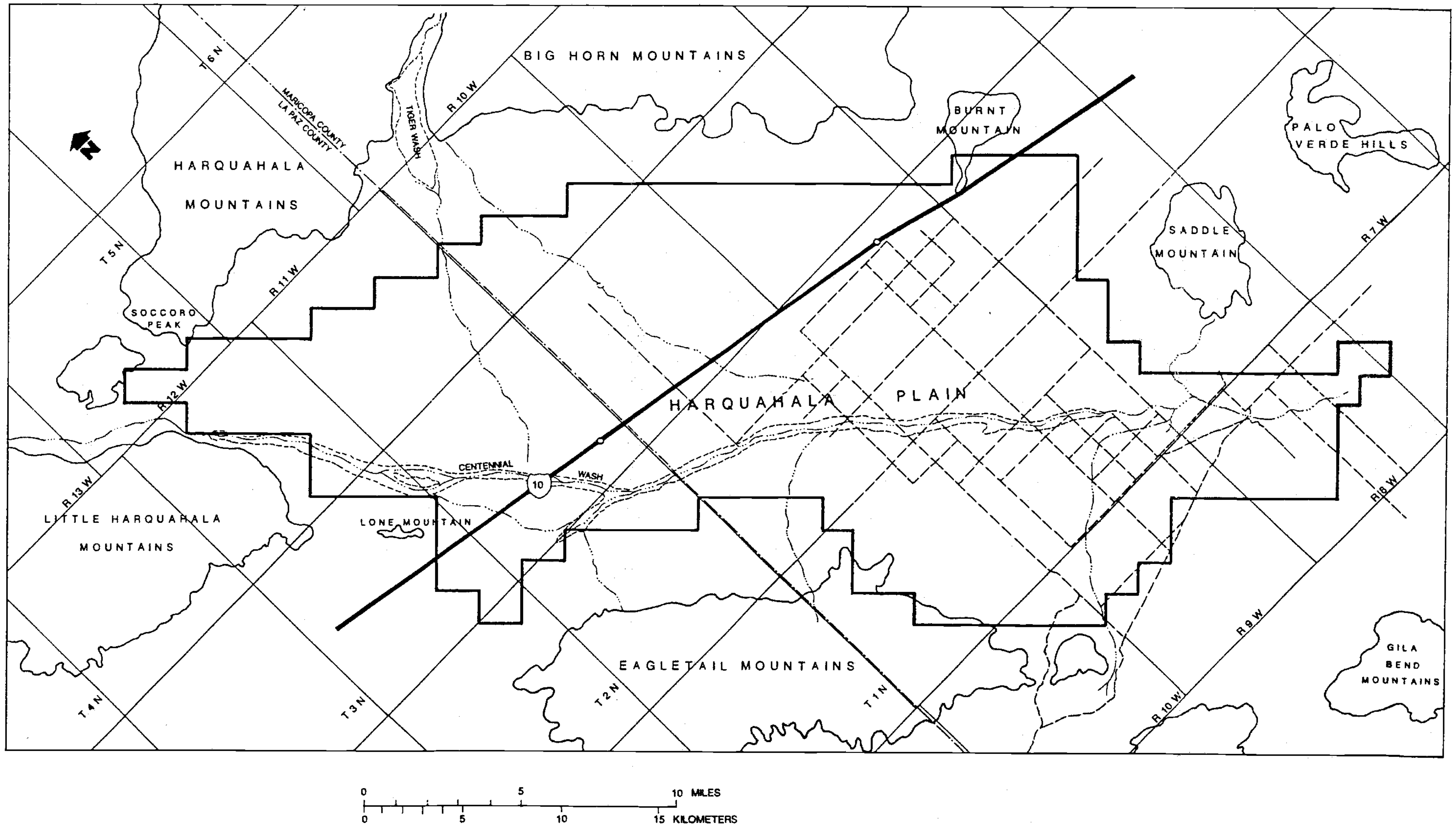


Figure 14. Model Grid.

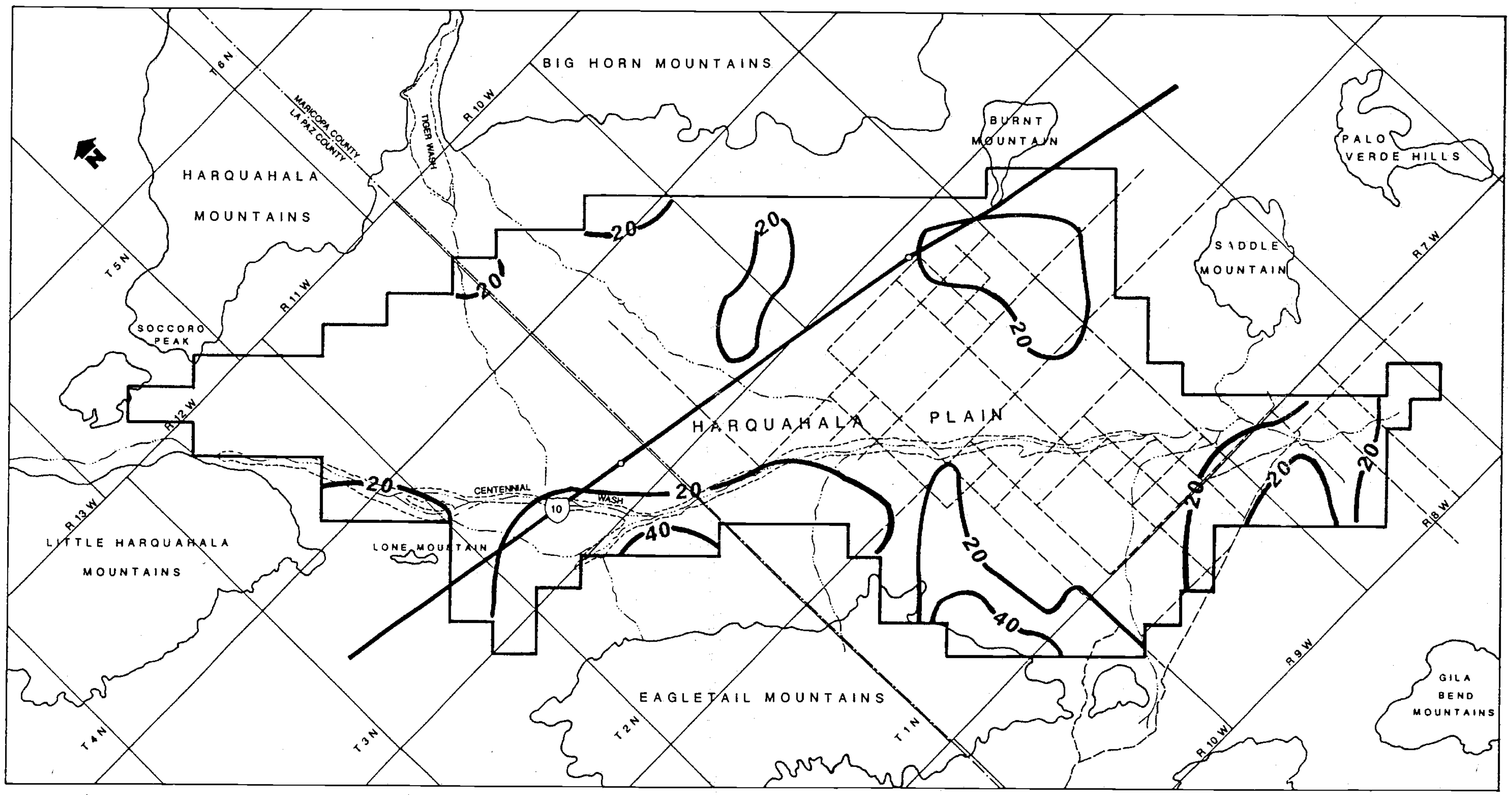
Boundary Conditions

Based upon recharge estimates, it was decided to set impermeable boundaries at the basin margins except in those areas where it was logical to expect significant inflow or outflow conditions. The steady-state model was used to estimate inflow and outflow from the basin under pre-development conditions by setting constant heads at nodes 1,8 and 36,9. Flow at these nodes was input to the transient model, but decreased with time as pumpage inside and outside the basin impacted the flow rate.

Transmissivity/Hydraulic Conductivity

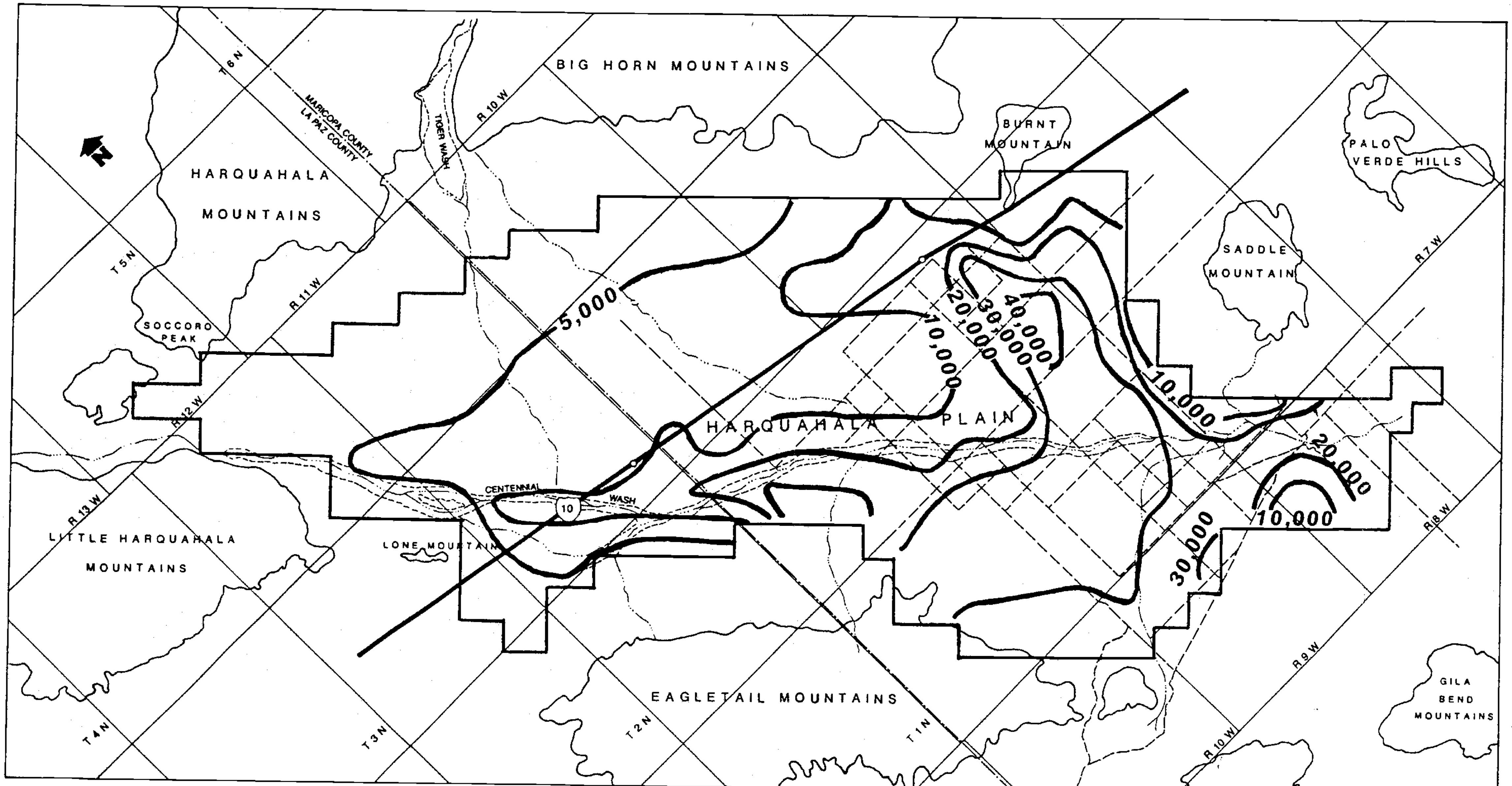
The original data arrays for transmissivity and hydraulic conductivity were based upon the 1978 ADWR model data arrays. The data were only available in the southeastern portion of the valley; therefore, the ADWR GEOLOG program was used to estimate values for the area not modeled by ADWR. The results from this effort were compared with pumping test data in the Fullmer ranch area (Cella Barr Associates, 1988) in the northwestern part of the valley and found to be in good agreement.

Hydraulic conductivity (Figure 15) was used for the upper layer because transmissivity is calculated by the program based upon saturated thickness at each time step. Transmissivity (Figure 16) was used for the lower layer because it was assumed to be confined (or unchanged) during the entire simulation period. These arrays were used as input to the steady-state model and to the transient model.



Contour Interval = 20 ft/day

Figure 15. Hydraulic Conductivity Distribution for the Upper Layer.



Contour Interval = ft²/day

0 5 10 MILES
0 5 10 15 KILOMETERS

Figure 16. Transmissivity Distribution for the Lower Layer.

Storage Coefficient/Specific Yield

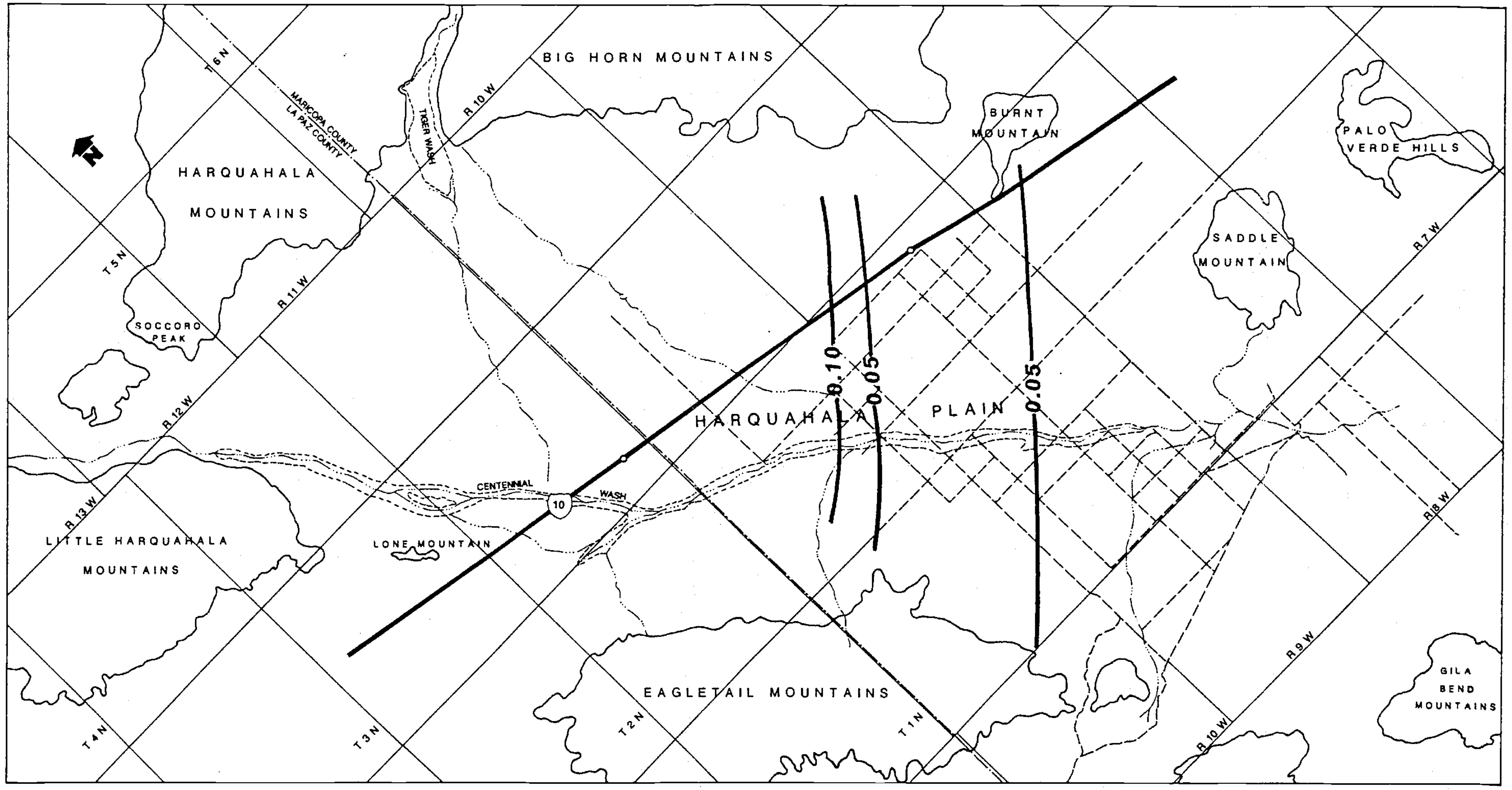
These two arrays are not used in the steady-state model because the assumption of steady state means that there is no change in storage in the aquifer. However, two arrays were used in the transient model, a heterogeneous specific yield array (Figure 17) for the water table upper layer and a storage coefficient array of 0.001 in the central portion of the basin with 0.10 in the northwestern area and a range of 0.02 to 0.08 in the southwestern area, for the lower layer.

Starting Water Levels

A starting water level map (Figure 4) was developed using pre-1953 water levels. The pre-1953 water level map was input to the steady-state model for starting heads. Water levels in Layers 1 and 2 were assumed equal. Changes of less than five feet in the water level elevations of the originally drawn map were made during the steady-state model runs to achieve a good mass balance.

Pumping

Under steady-state conditions, it was assumed that there was minor pumping for domestic and irrigation use, but that this pumping was insufficient to change the steady-state condition. Extensive pumping began in 1953 and continued through 1985. The total volume of water pumped in the basin from 1911 through 1984 was estimated by the USGS in 1986 (Table 6). Photographs of cropped acreage, electrical records, and well registration records were used to distribute the pumpage within the basin. In many cases, the pumping rates for several wells had to be



Contour Interval = 0.05

Figure 17. Specific Yield Distribution for the Upper Layer.

TABLE 6. Estimated annual pumpage, in thousands of acre-feet, in the Harquahala Plains

YEAR	PUMPAGE
1940	1
1941	1
1942	1
1943	1
1944	1
1945	1
1946	1
1947	1
1948	1
1949	1
1950	5
1951	7
1952	10
1953	20
1954	33
1955	30
1956	40
1957	50
1958	60
1959	95
1960	125
1961	100
1962	200
1963	200
1964	200
1965	200
1966	160
1967	170
1968	165
1969	145
1970	111
1971	99
1972	108
1973	109
1974	137
1975	130
1976	129
1977	123
1978	100
1979	93
1980	108
1981	129
1982	79
1983	56
1984	72

lumped in a single model node because the wells were all located within the same nodal area. This was caused by the size of the model grid and its orientation within the basin.

The time period 1953 to 1985 was divided into five pumping periods based upon availability of water level measurements and the homogeneity of assumed pumping rates within that time period. The pumping periods are:

Pumping Period 1	1953-1956
Pumping Period 2	1957-1965
Pumping Period 3	1966-1973
Pumping Period 4	1974-1979
Pumping Period 5	1980-1985

Leakage

The hydraulic conductivity and thickness of the middle, fine-grained unit are used by the model to calculate vertical flow between the two layers. These data are input as a vertical conductivity array, which is calculated by the user from the vertical conductivity of the confining layer divided by the thickness of the confining layer. This is a simplification of the calculation offered by McDonald and Harbaugh (1988) for a confining layer having a much lower conductivity than adjacent layers.

CHAPTER 6

MODEL RESULTS

Steady-State Model

The steady-state model used four MODFLOW modules, the basic package (Unit 1), the block-centered flow package (Unit 11), the strongly implicit solution package (Unit 19), and the output control package. The data arrays used are starting water levels, hydraulic conductivity for Layer 1, transmissivity for Layer 2, and the vertical conductivity for the confining layer.

The steady-state model was run for three time steps for a total time of two years. The results from the steady-state model are inflow and outflow and drawdown. The objective of the steady-state model is to fine tune the input data arrays so that the model can maintain the starting water levels given the inflow and outflow in the aquifer. In general, changes are made to the data array considered least accurate until model calculated drawdowns are minimized and the mass balance is close to zero. In the Harquahala model, minor changes in water levels, less than five feet, produced the desired result. The steady-state model drawdowns were less than two feet; the mass balance error was 1.09 percent. Inflow and outflow were both calculated as 1800 AF/yr. At this point, the model was accepted as adequately representing the Harquahala basin under steady-state conditions given the existing data base; the data arrays from the final steady-state run were input to the transient model.

Transient Model

The five pumping periods of the transient model were used in an attempt to calibrate and verify the model parameters. This procedure compares actual water level measurements with the model calculated water levels at select intervals of time. If the trend and magnitude of the model calculated data reasonably match the actual data, the model is accepted as calibrated. In this study, the first four pumping periods (1953-1956, 1957-1966, 1957-1974, and 1975-1979) were used to calibrate the model. The data arrays needed for the transient runs are those developed in the steady-state model, starting water levels, inflow and outflow, hydraulic conductivity and thickness for Layer 1, transmissivity for Layer 2, and the confining layer leakage array. In addition, the specific yield and storage coefficient arrays for Layers 1 and 2, respectively, are needed to calculate changes in storage as pumping occurs. To assess the calibration of the model, it was necessary to compare the actual to calculated water levels. This was done by comparing water level hydrographs of the data for selected wells across the basin. The criteria for selecting the hydrographs were the number of measured data points, the time span of the data, and the location of the well within the basin. Seventeen wells, shown in Figure 18, were selected. The physical characteristics of each well, such as well depth, use, screened interval, and presence or absence of perched water, are listed in Appendix C. The hydrographs of the actual data are shown in Figures 19 through 35.

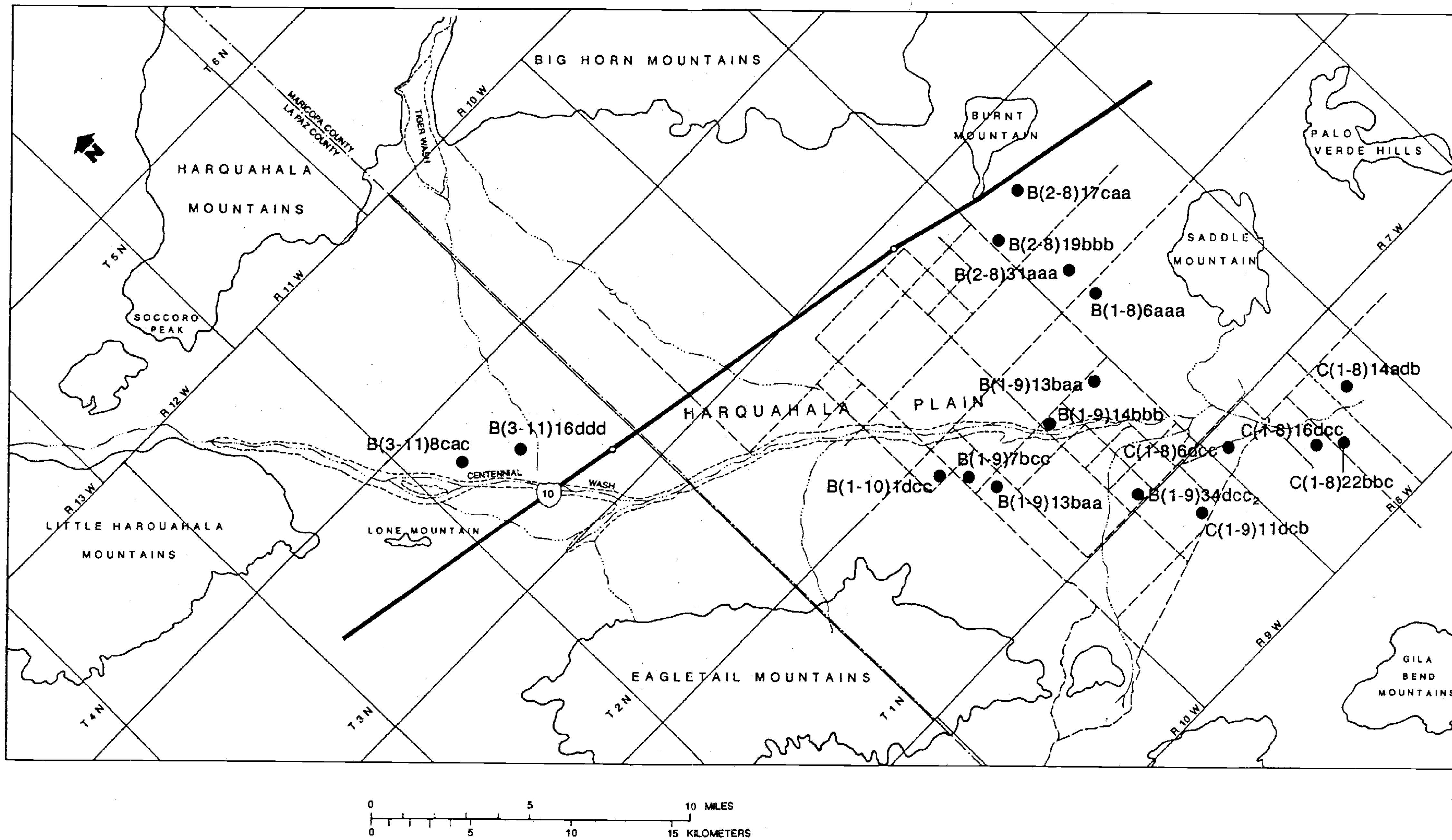


Figure 18. Location of Wells Used in Model Calibration.

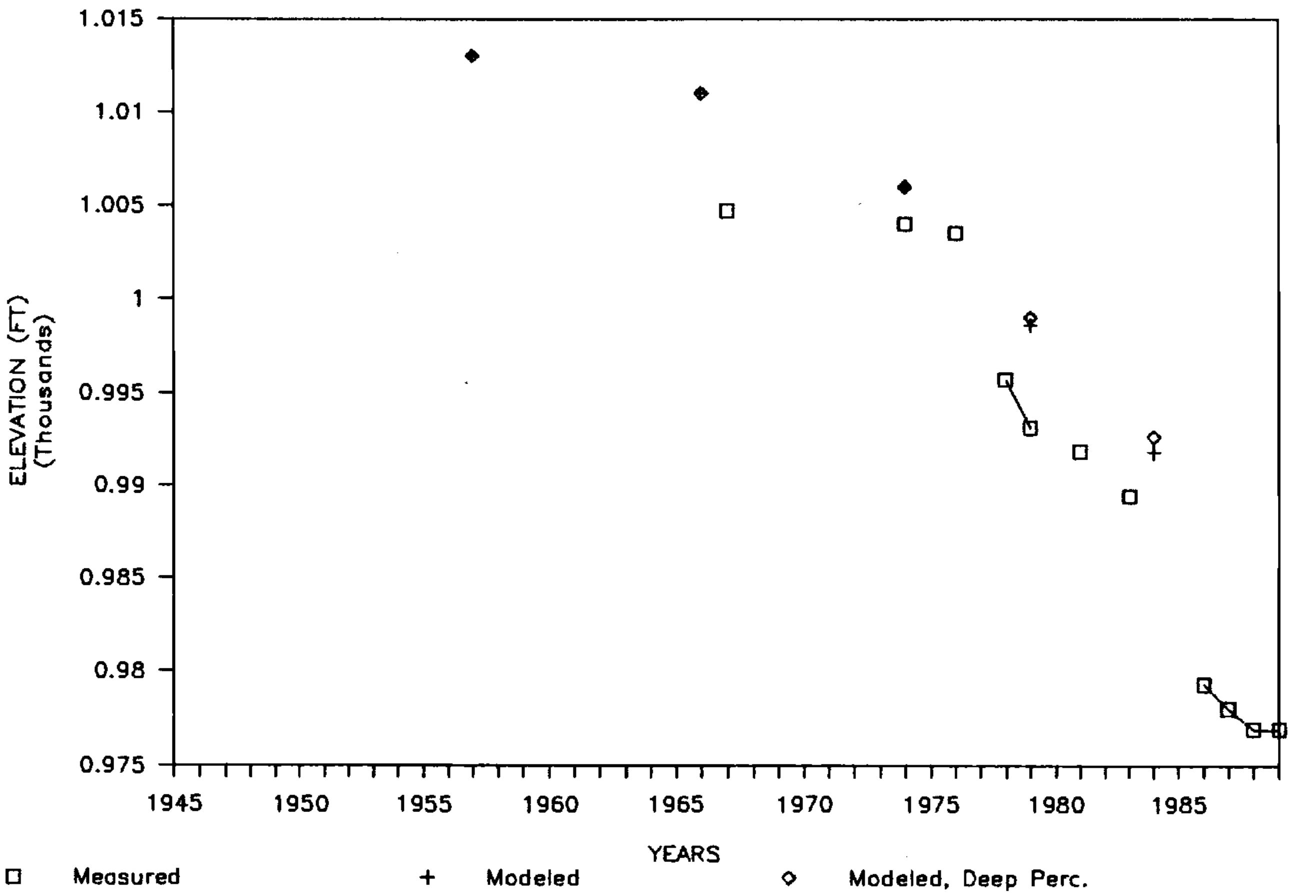


FIGURE 19: Hydrograph of Well B(3-11)8cac (6,6)

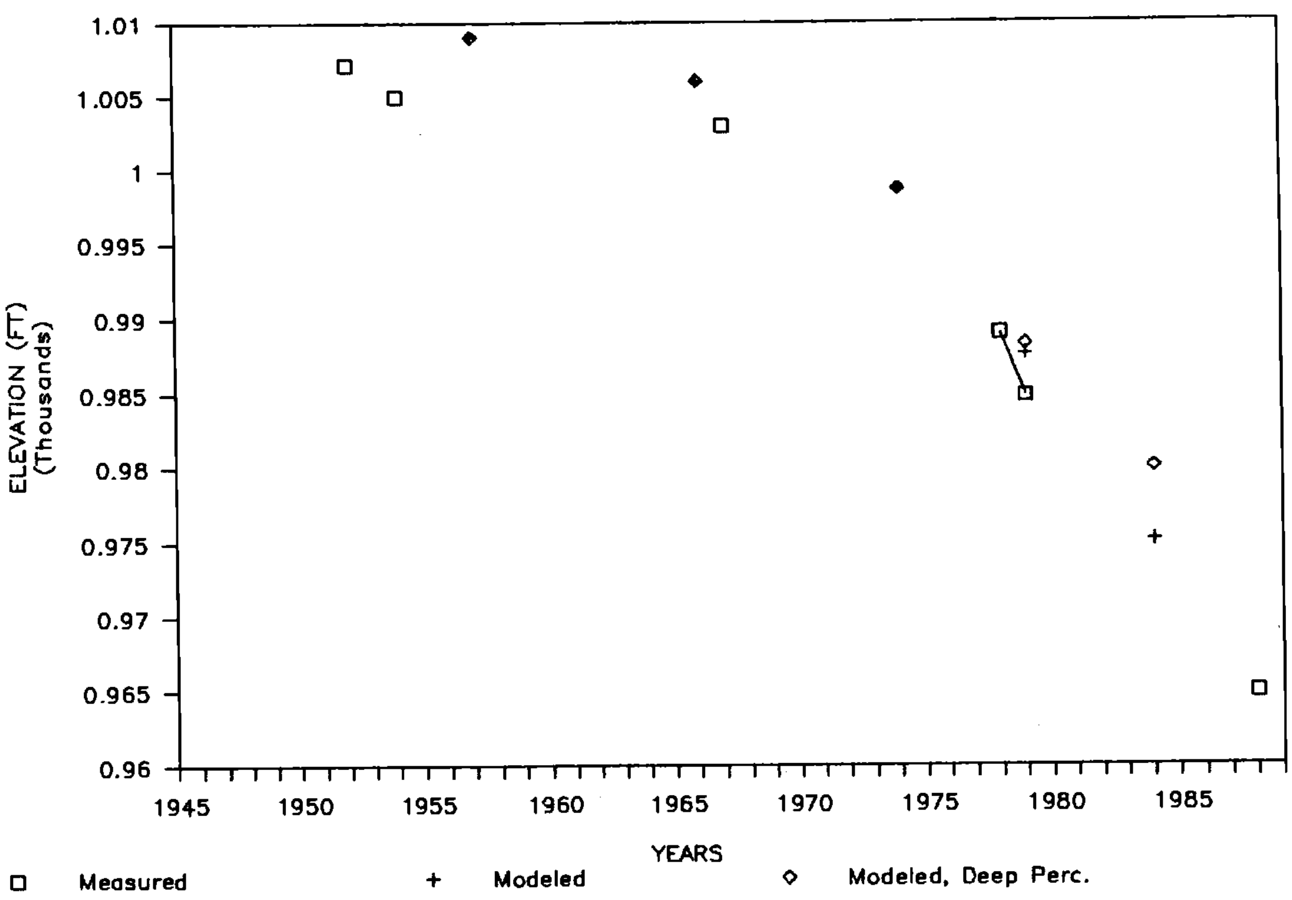


FIGURE 20: Hydrograph of Well B(3-11)16ddd (7,7)

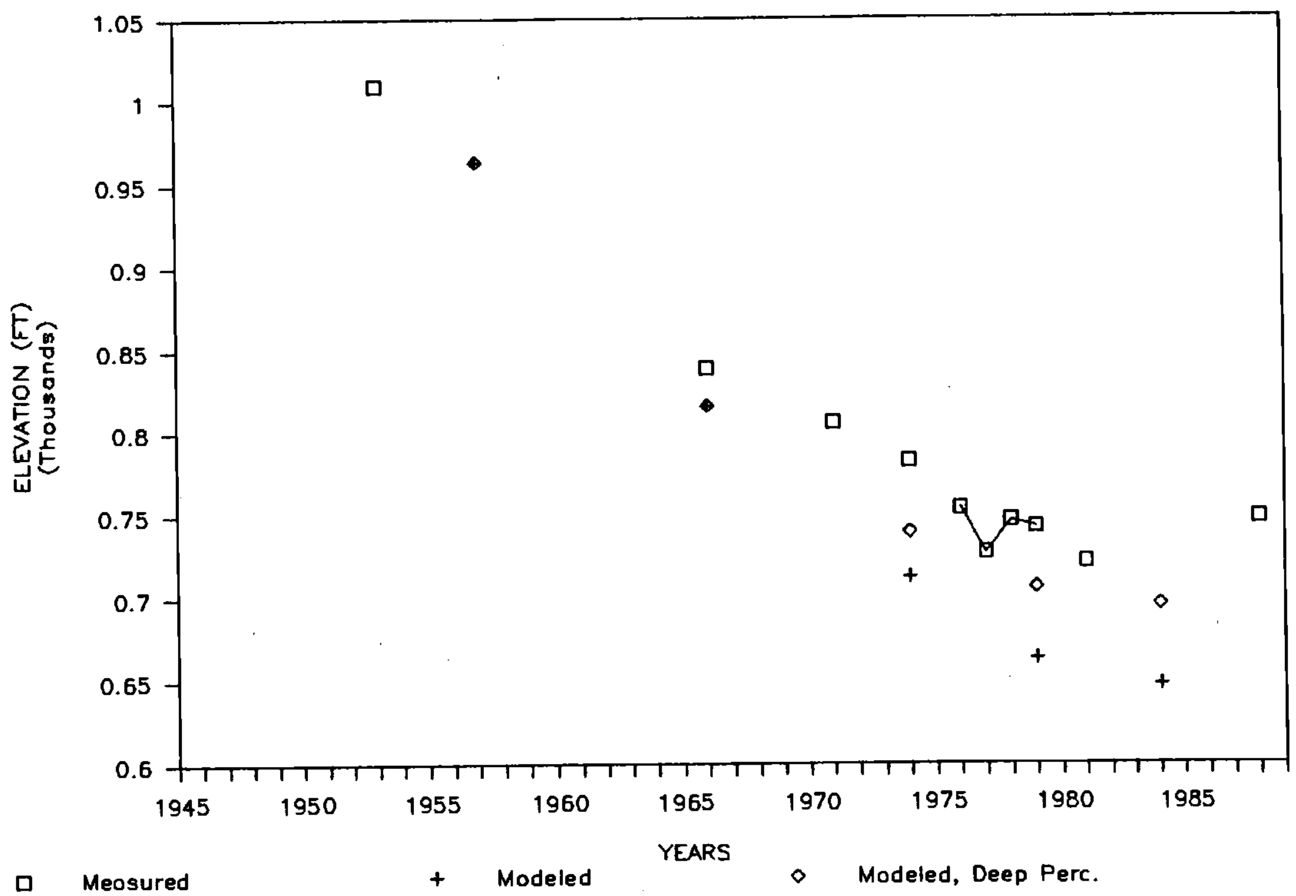


FIGURE 21: Hydrograph of Well B(1-10)1dcc (19,6)

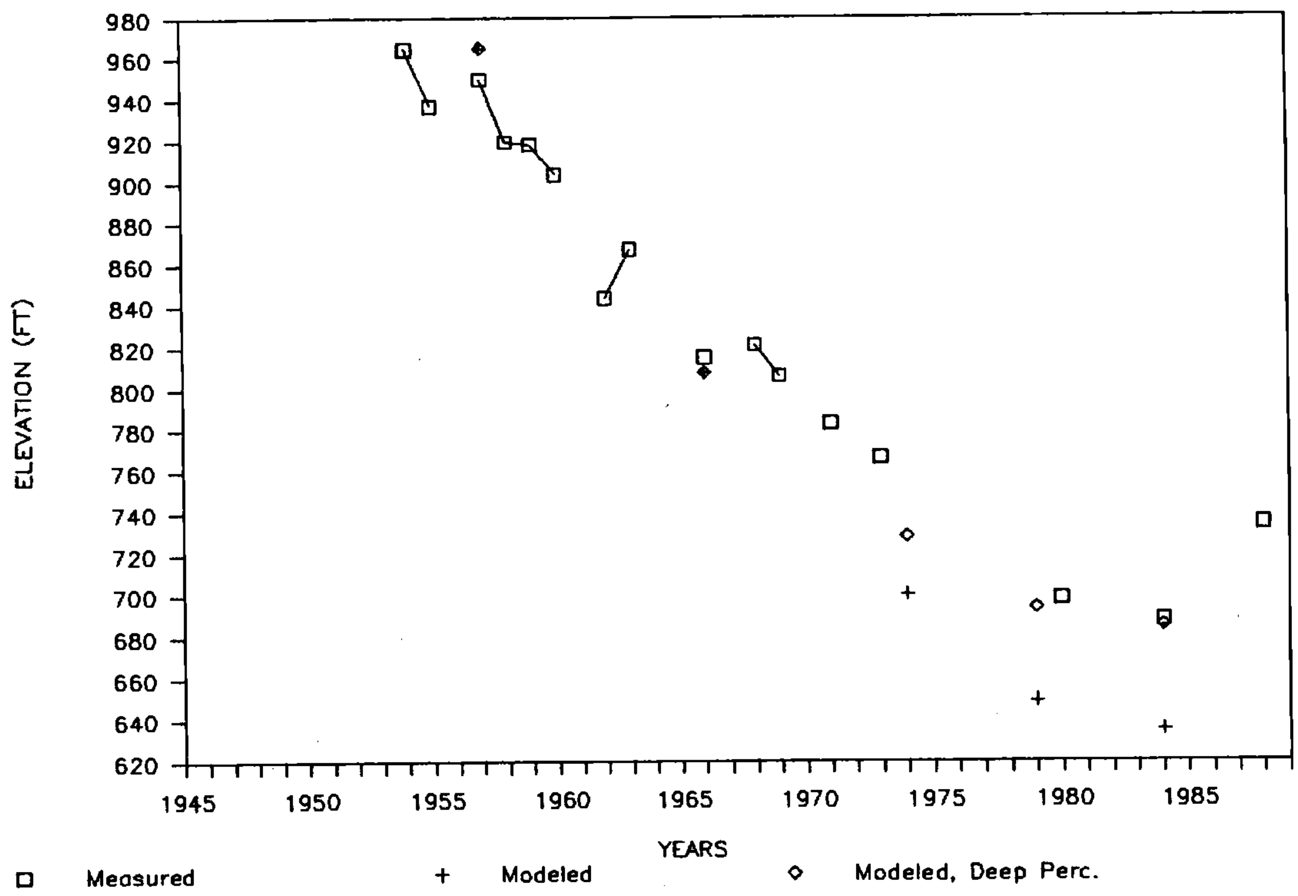


FIGURE 22: Hydrograph of Well B(1-9)7bcc (20,6)

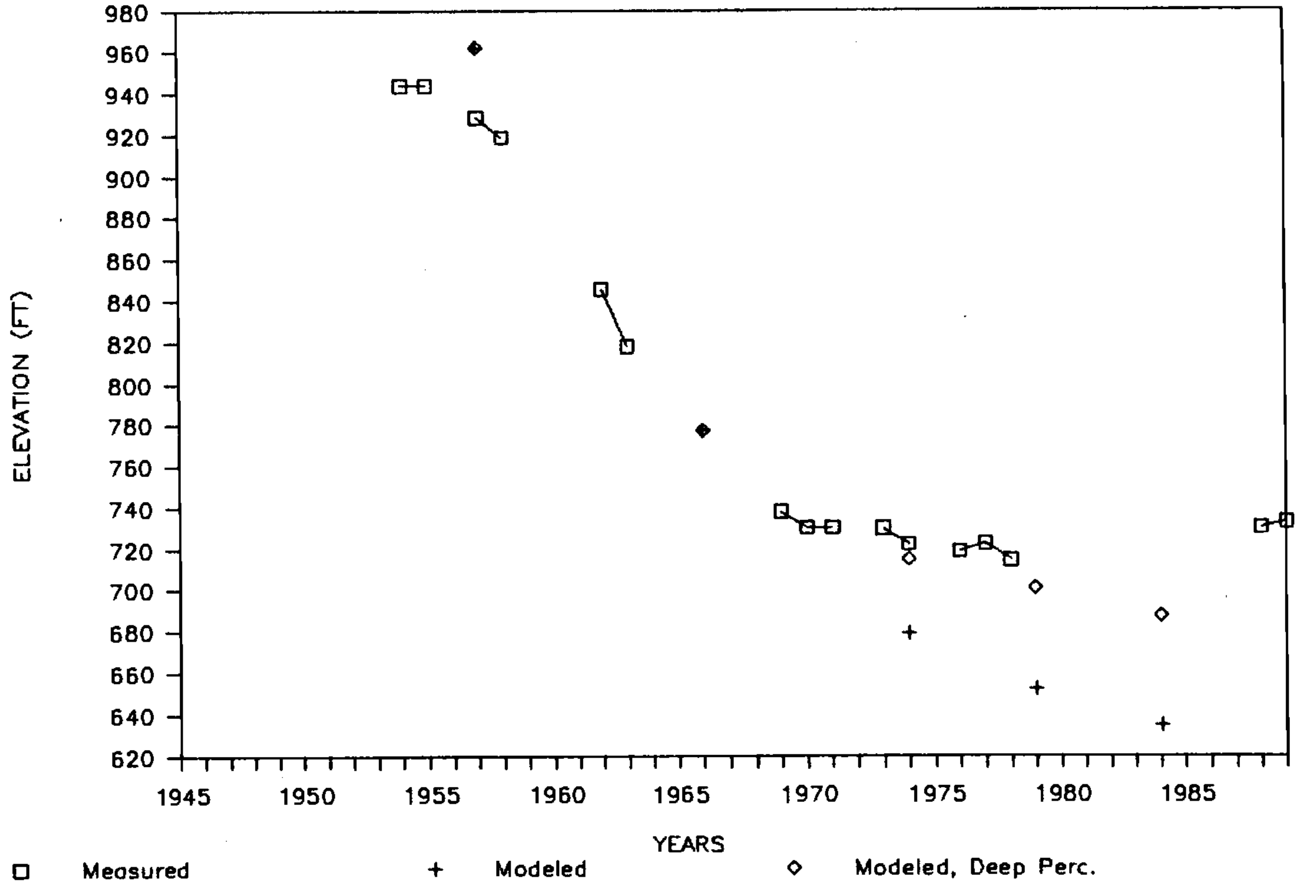


FIGURE 23: Hydrograph of Well B(2-9)13baa (20,13)

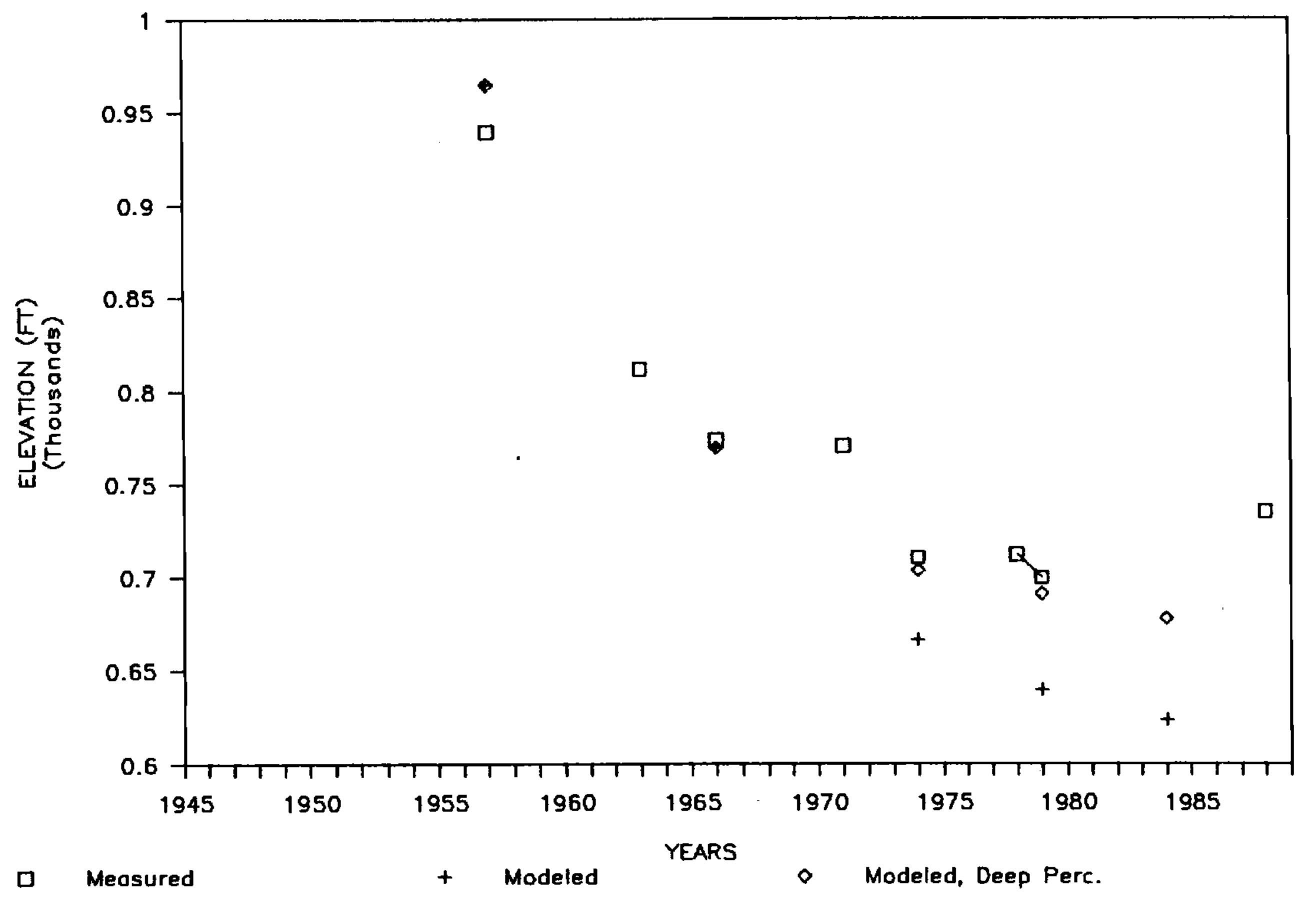


FIGURE 24: Hydrograph of Well B(2-8)19bbb (21,13)

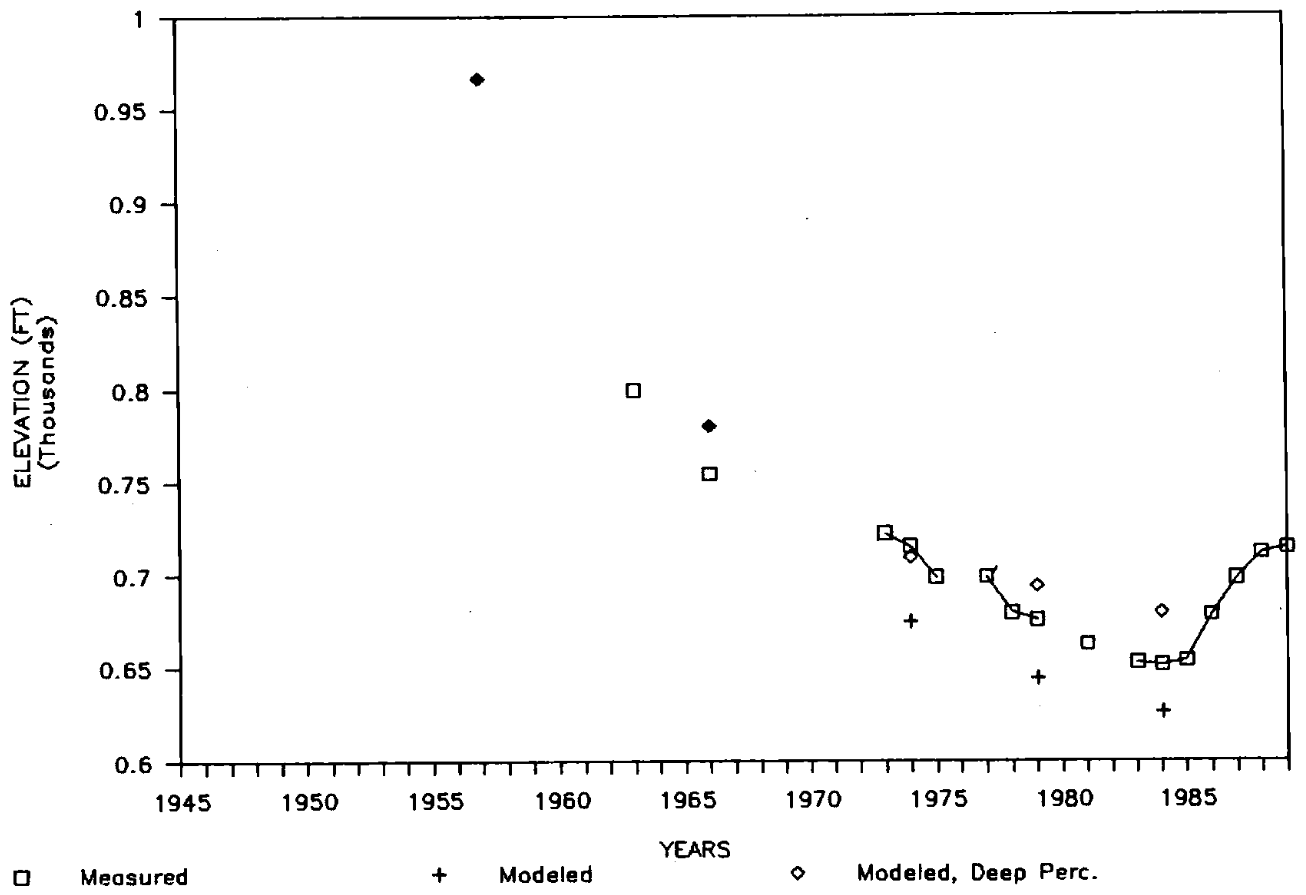


FIGURE 25: Hydrograph of Well B(2-8)17caa (21,14)

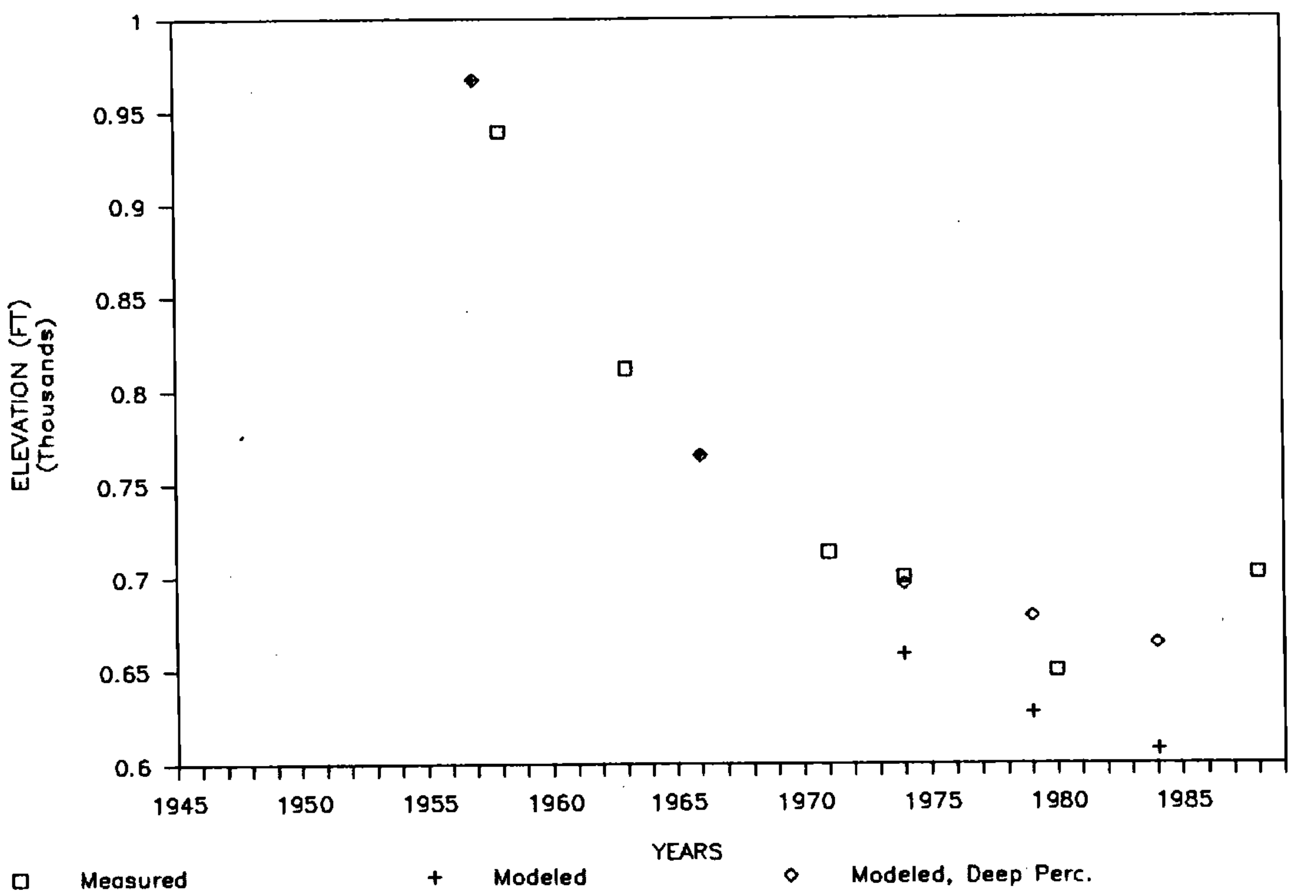


FIGURE 26: Hydrograph of Well B(2-8)31aaa (23,12)

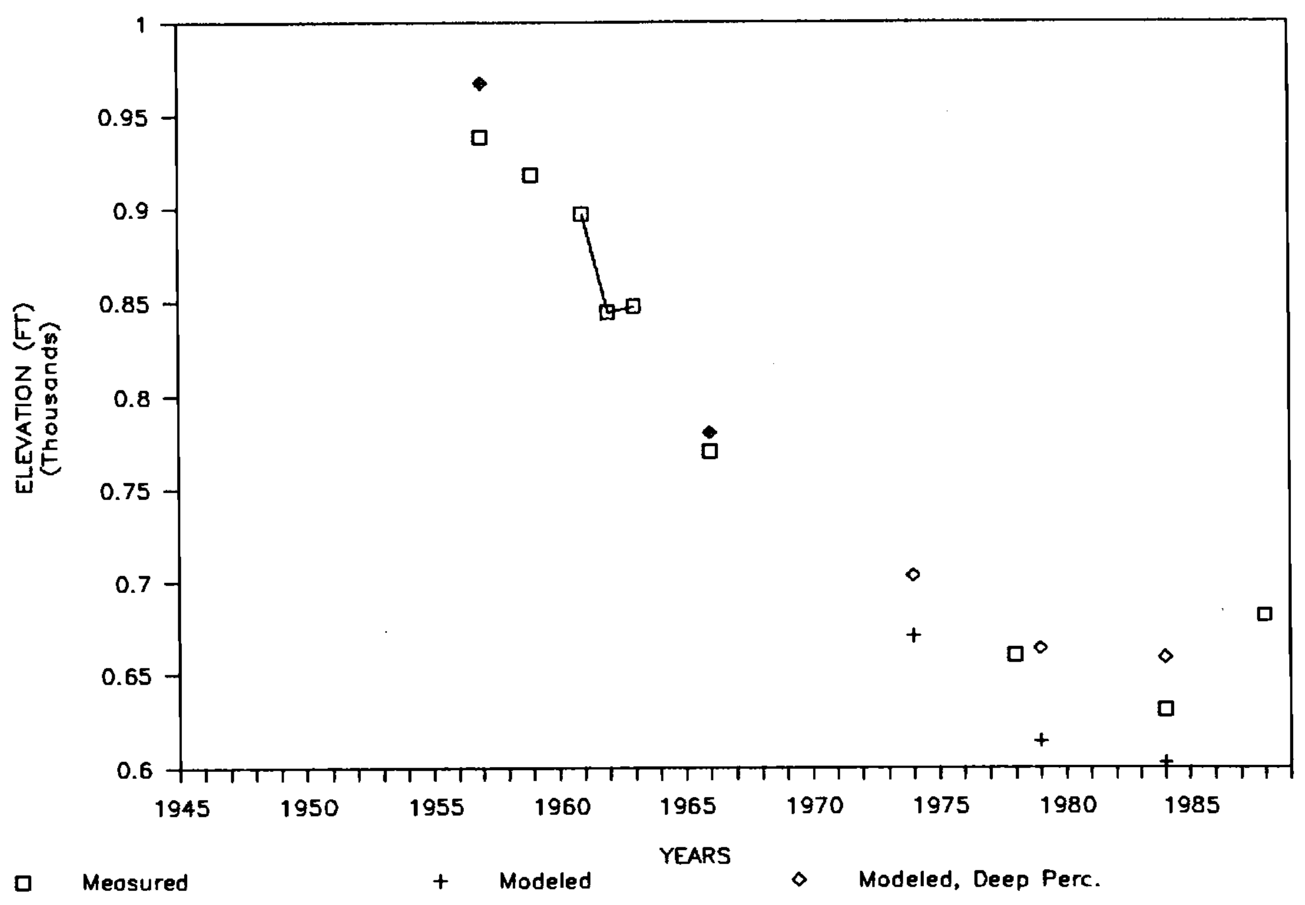


FIGURE 27: Hydrograph of Well B(1-9)14bbb (23,8)

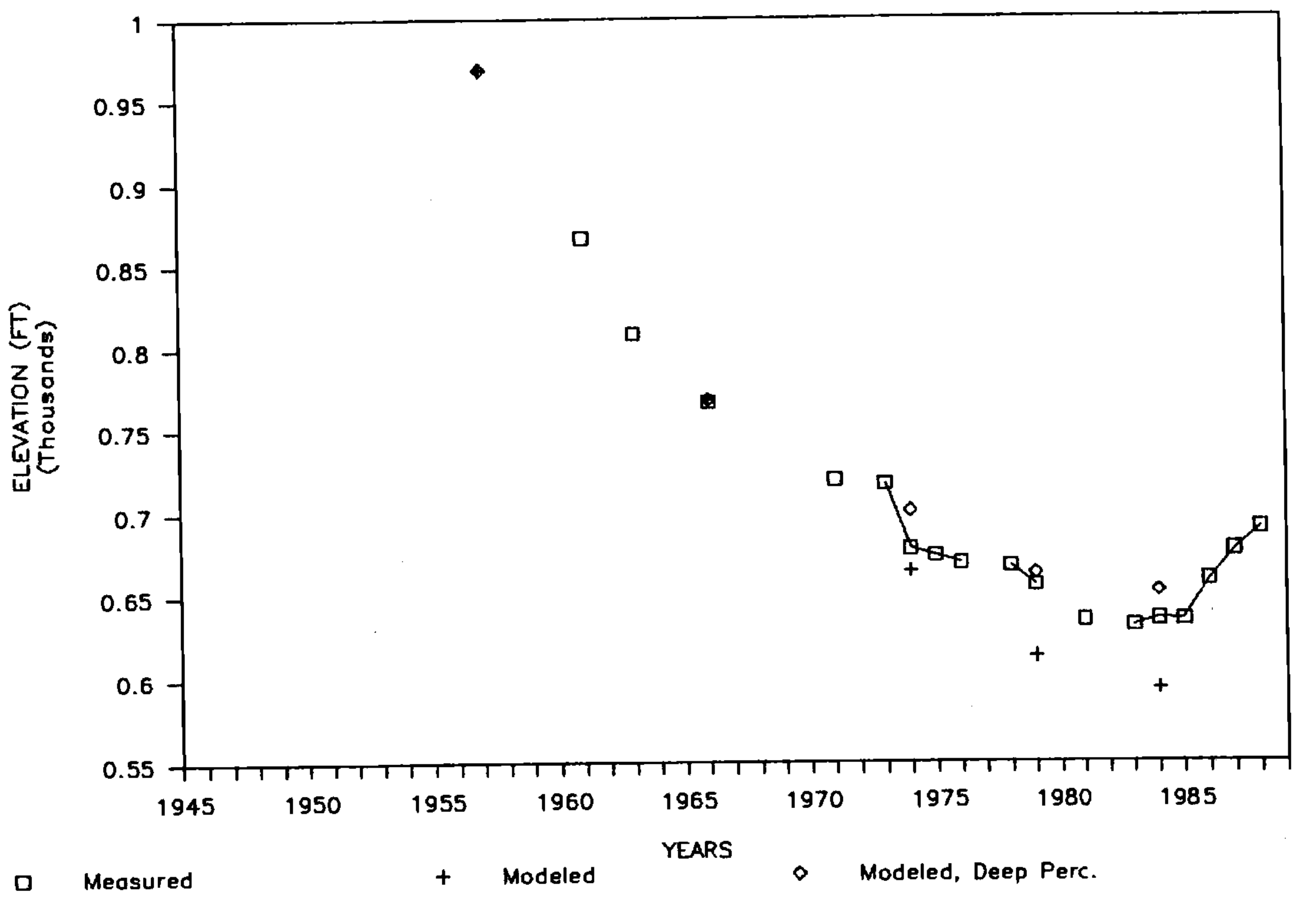


FIGURE 28: Hydrograph of Well B(1-8)6aaa (24,11)

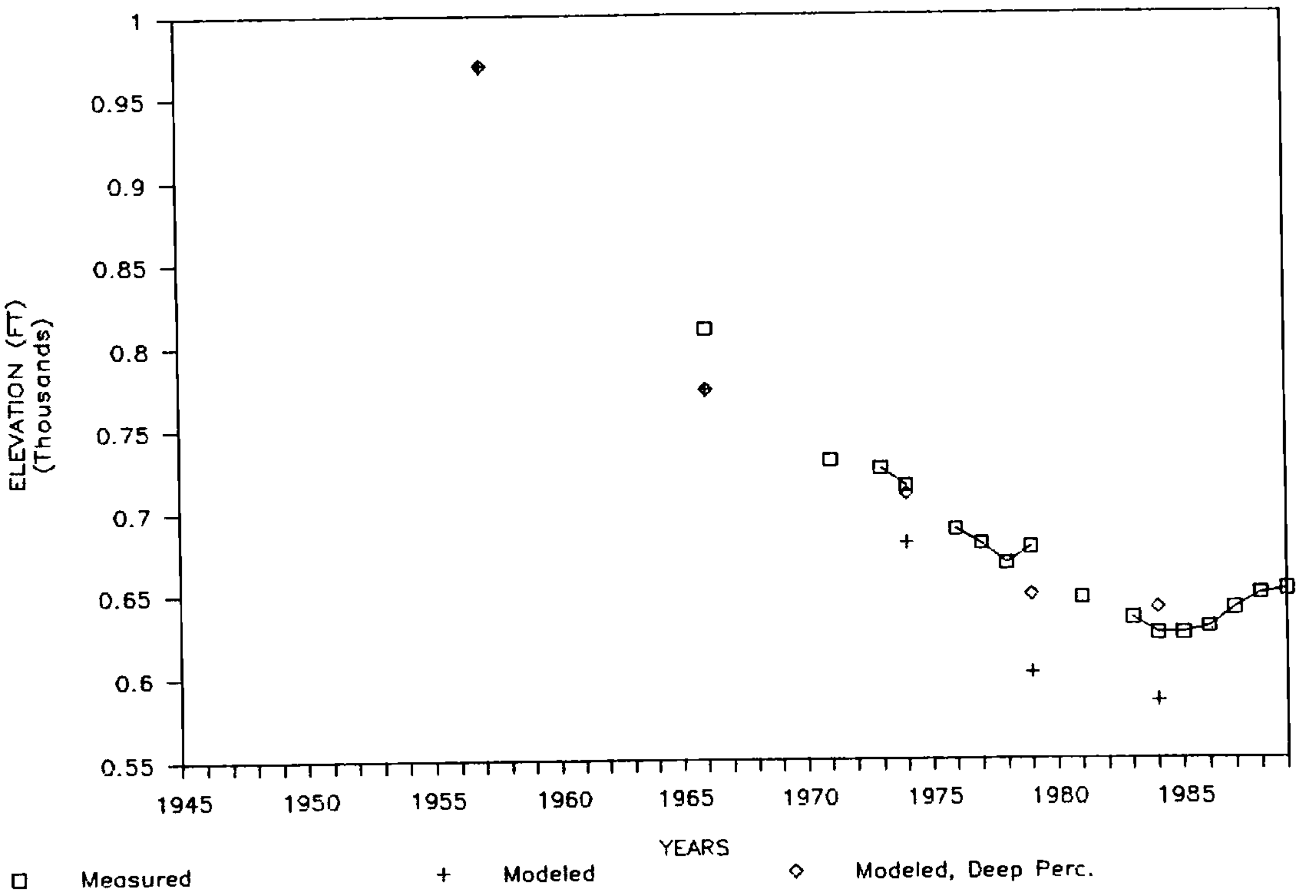


FIGURE 29: Hydrograph of Well B(1-9)18acb (25,1)

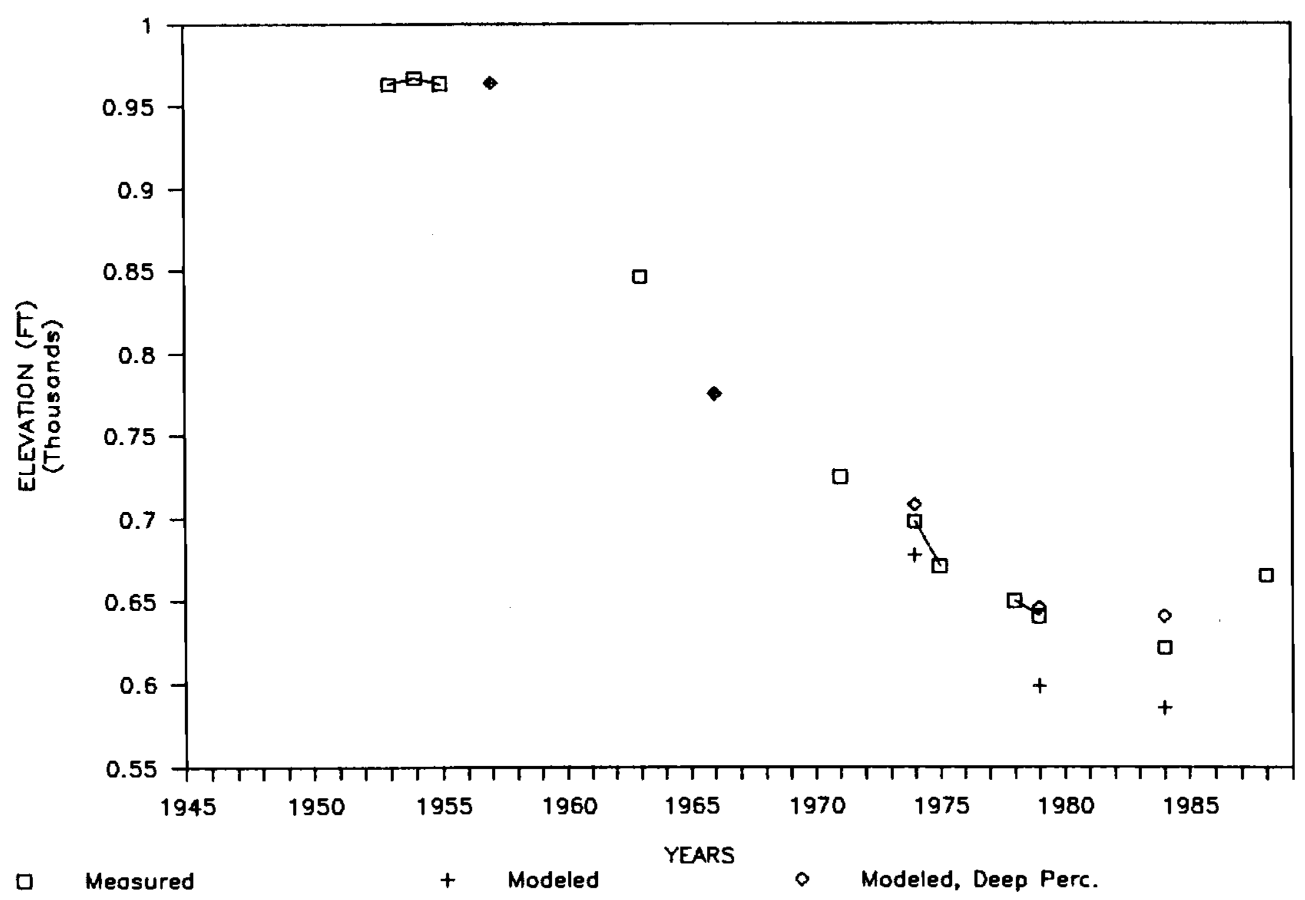


FIGURE 30: Hydrograph of Well B(1-9)34dcc2 (25,5)

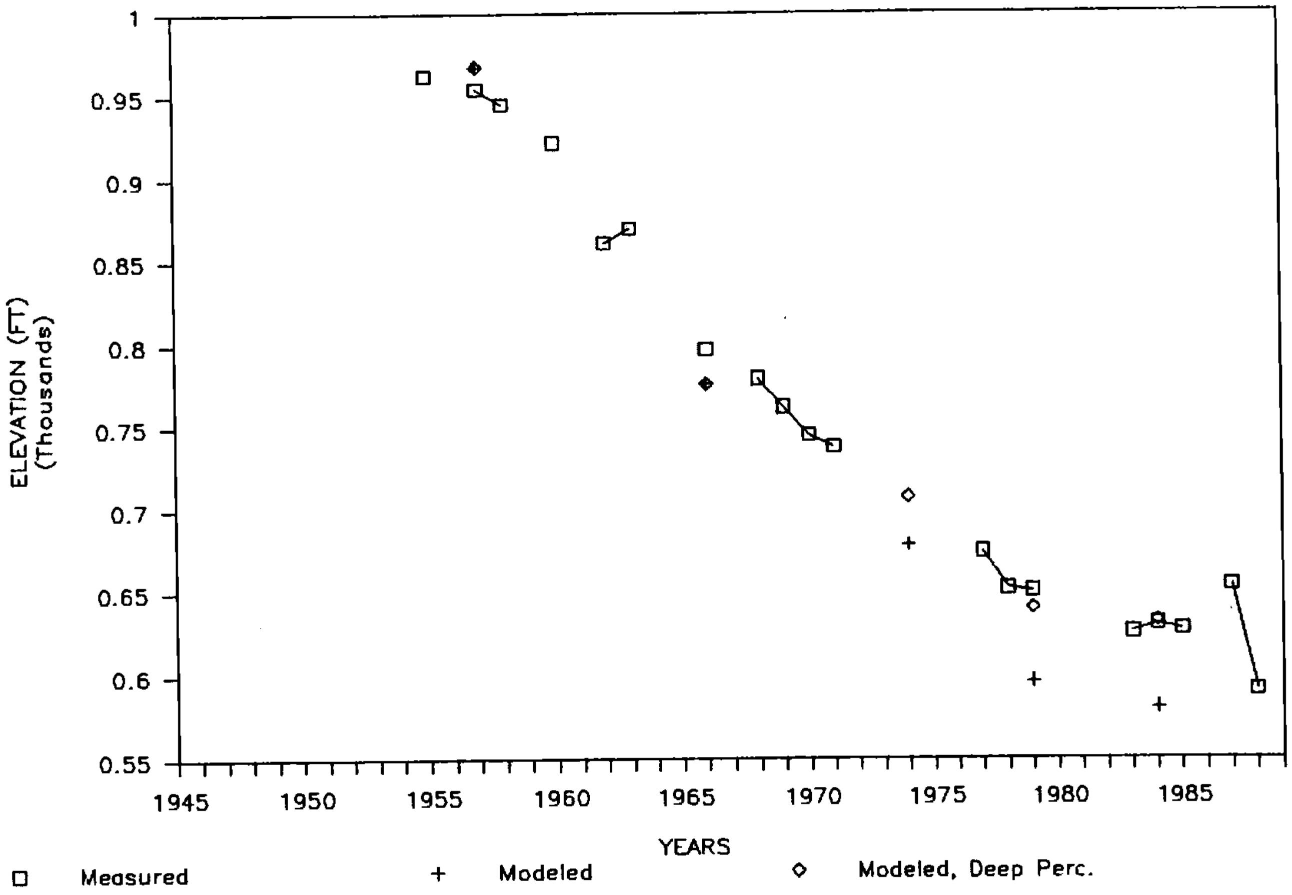


FIGURE 31: Hydrograph of Well C(1-9)11dcb (27,4)

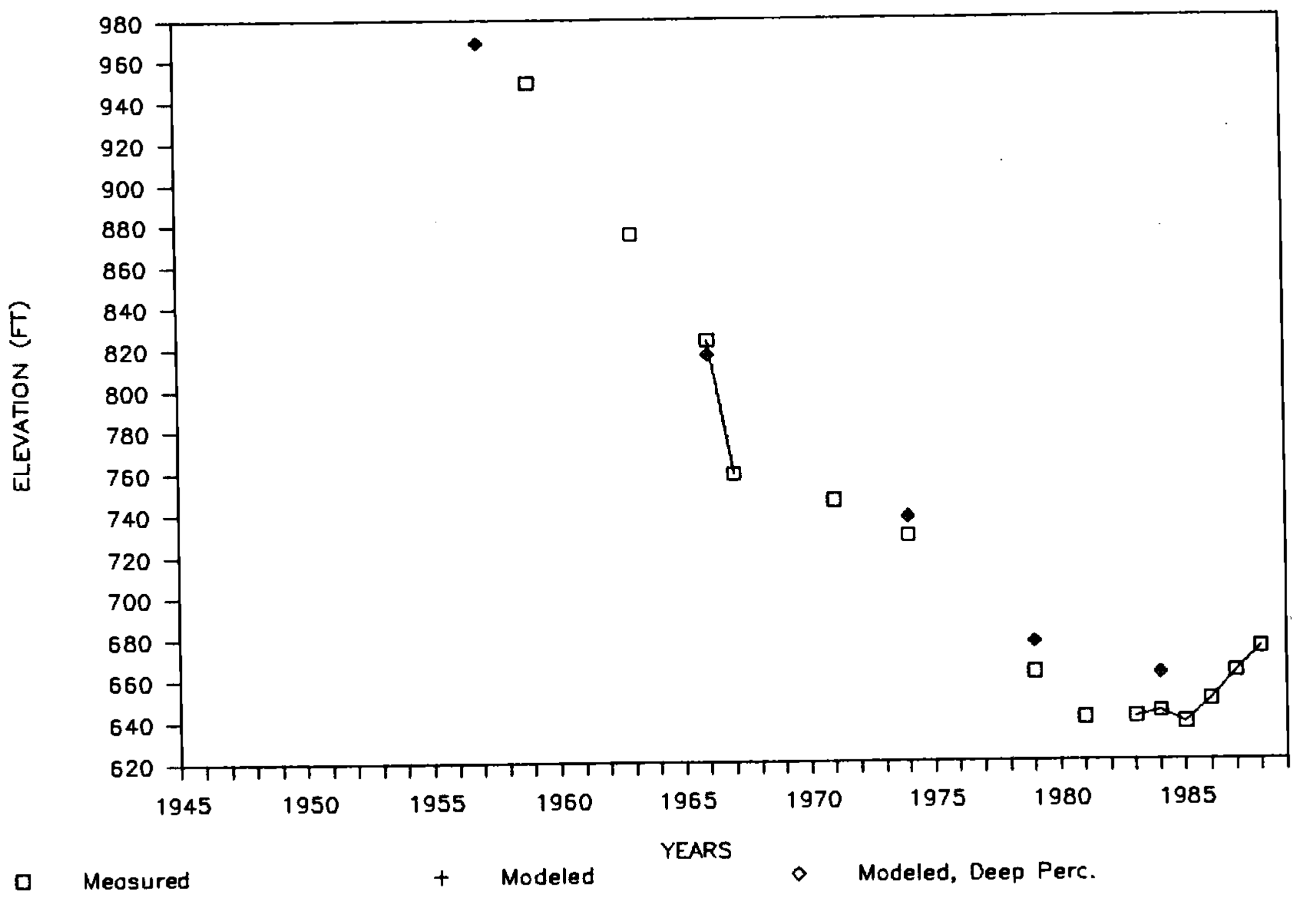


FIGURE 32: Hydrograph of Well C(1-8)6dcc (28,6)

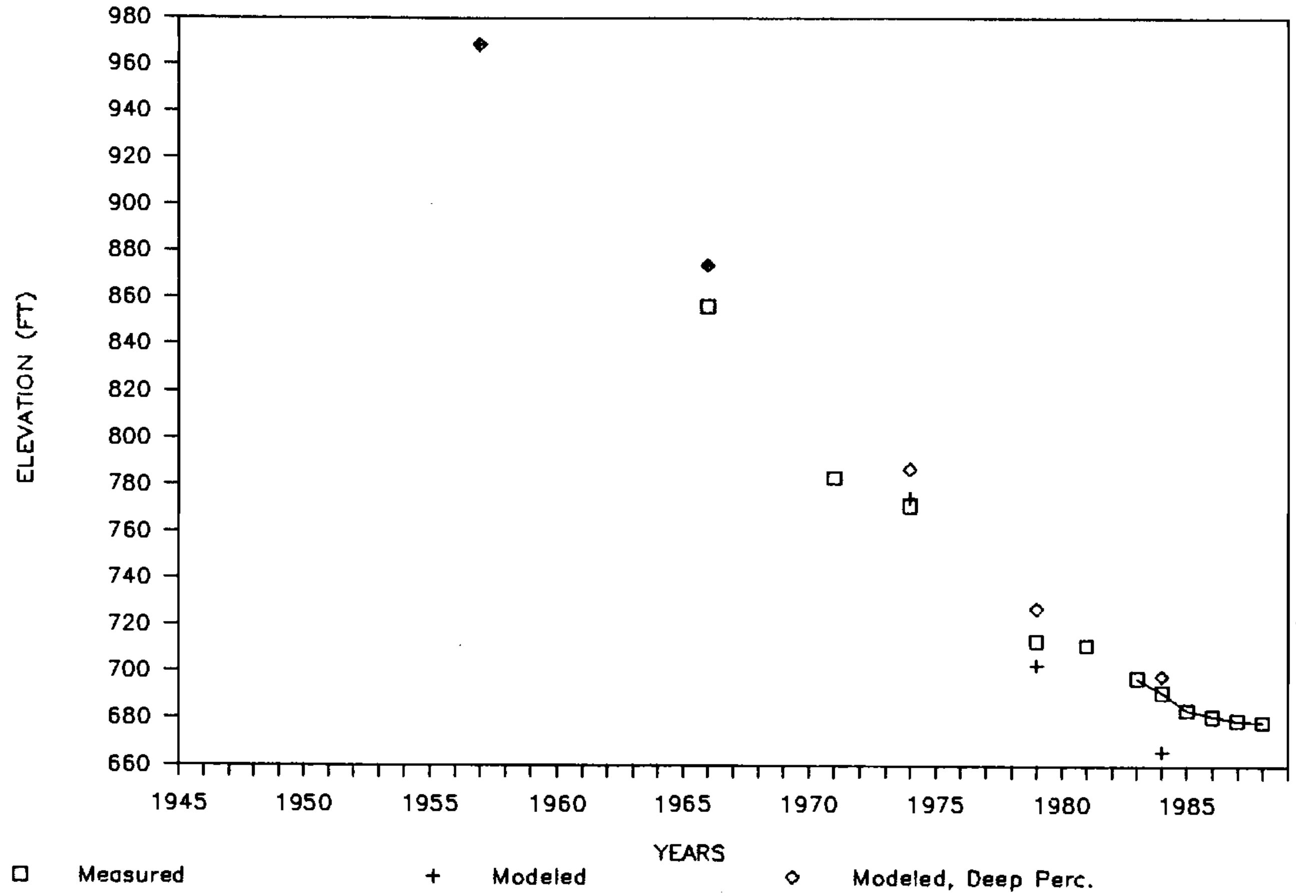


FIGURE 33: Hydrograph of Well C(1-8)16dcc (31,6)

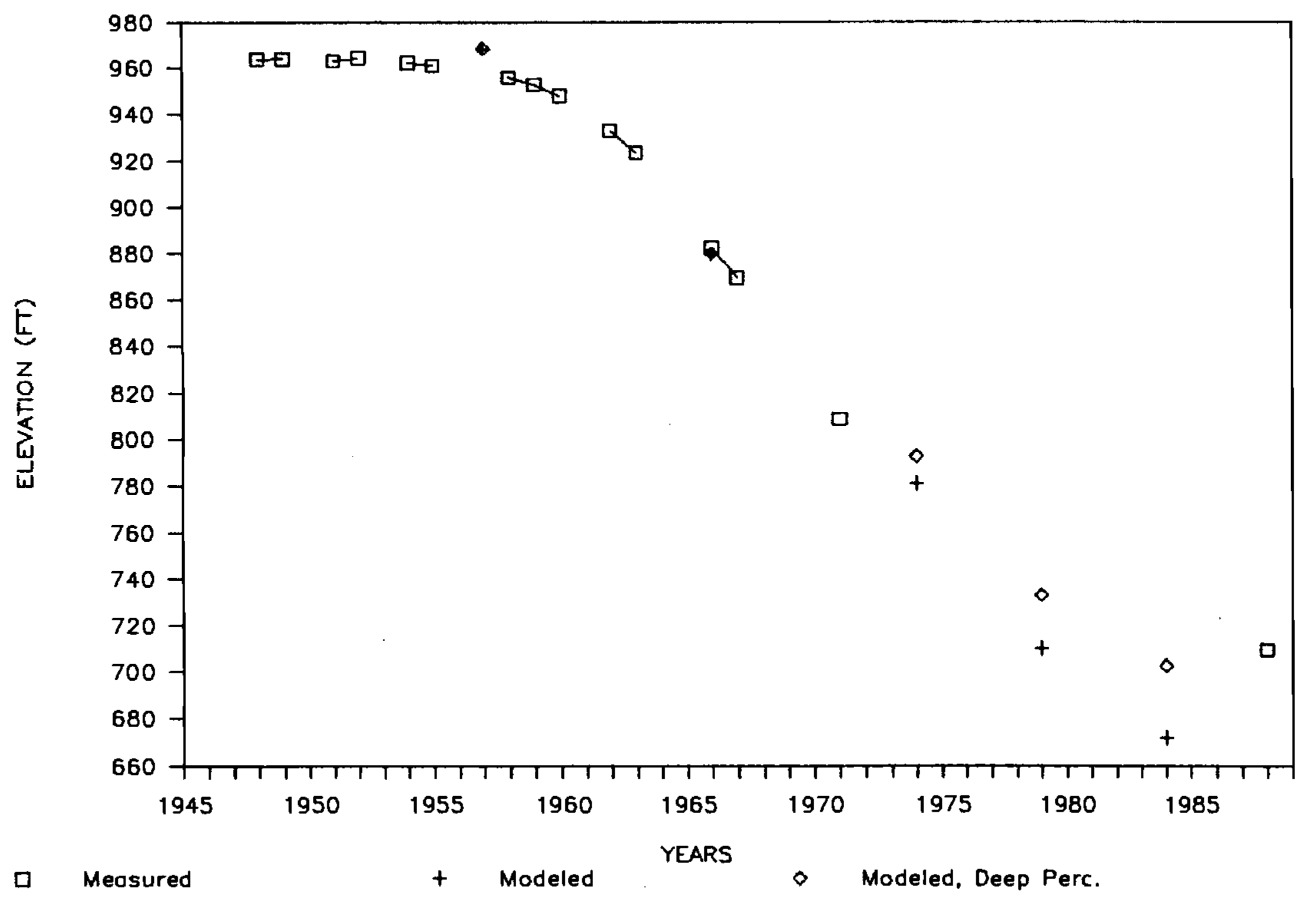


FIGURE 34: Hydrograph of Well C(1-8)22bbc (32,6)

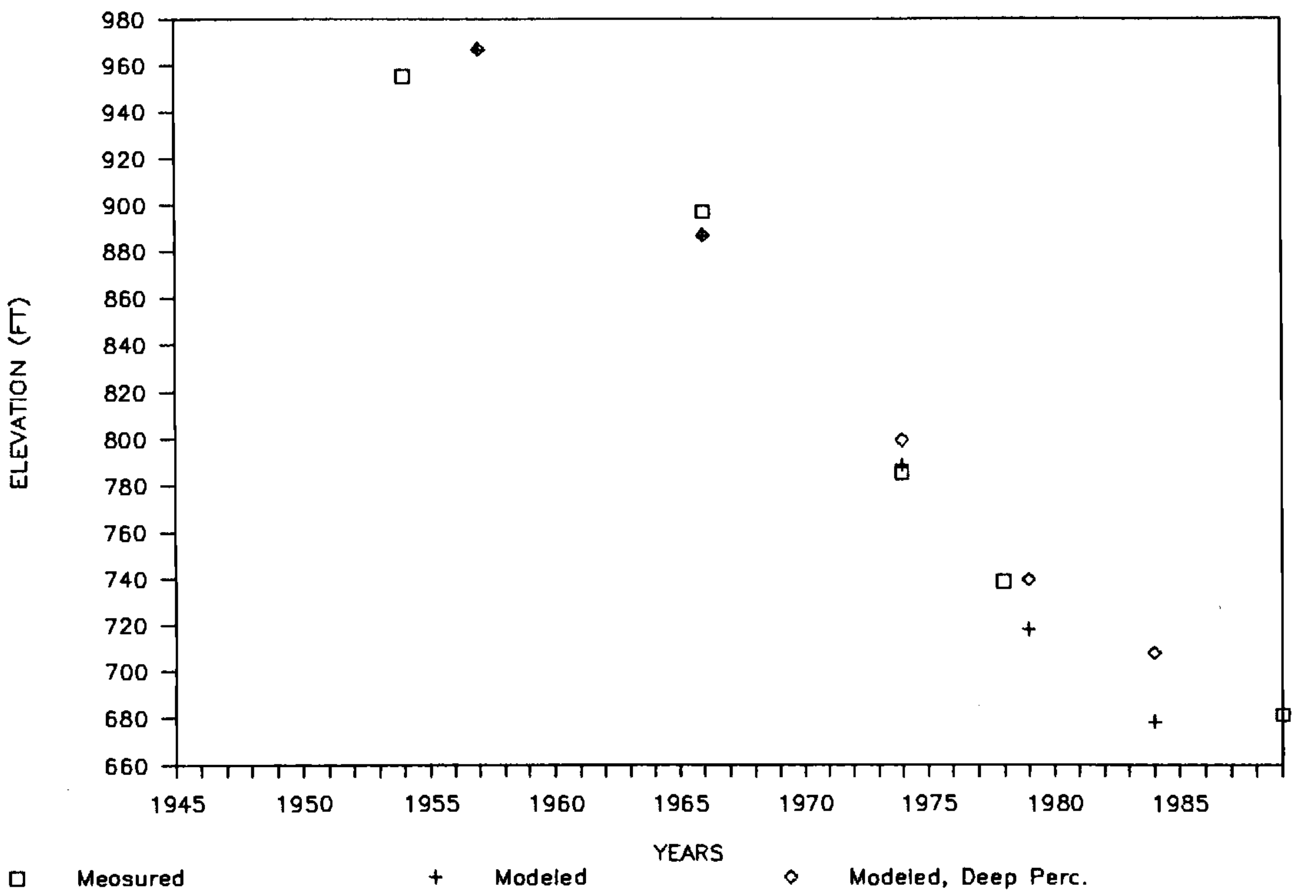


FIGURE 35: Hydrograph of Well C(1-8)14adb (33,8)

Calibration

Calibrating the model proved difficult. The initial efforts assumed that the steady-state generated data arrays were reasonably correct and changed the storage coefficient array in the lower aquifer. Water levels in the lower aquifer never fell below the confining layer in the heavily pumped central portion of the basin; therefore, it was decided to leave that layer as confined throughout the entire simulation. However, several storage coefficients were tested to determine the most reasonable magnitude of the storage coefficient. The study began with a homogeneous storage coefficient array of 0.001 for the entire basin. A sensitivity analysis was run during this preliminary stage to determine the probable range of values in the lower aquifer. This was done by changing the storage coefficient uniformly over the entire basin. Two values, 0.05 and 0.0001, were tested. Neither array produced water-level declines and decline rates that compared well with the measured data over the entire watershed. However, the water table storage coefficient produced better results in the northwestern and southeastern portions of the basin. Review of existing water levels in the northwestern and southeastern parts of the valley indicated that these areas were not confined but were in fact under water table conditions. The storage coefficient array was then modified to show 0.001 in the center of the basin and water table coefficients of 0.10 and 0.02 to 0.08 in the northwestern and southeastern parts of the basin. This array produced the best agreement in the first two pumping periods for all the wells, a good agreement (less than 20 feet difference) for the first three pumping periods in nodes 25,6; and good agreement during the entire simulation for nodes 6,6; 7,7; 15,8; 28,6; 32,6; and 33,8.

The results from this first model are shown in Figures 19 through 35 which are hydrographs for the 17 wells selected for calibration.

The next step at this point was to determine what mechanism resulted in the lower water level declines in the heavily-pumped central portion of the basin. It was already known that deep percolation is occurring. Cascading water or perched water was reported in the wells listed in Table 5 as early as the mid-1960s, and a perched layer was mapped by Graf in 1980. The next step was to see if percolating water from the land surface could have resulted in the change in water level decline rates. The pumping module of MODFLOW was used to input water (positive wells or a reduction in the pumping rate) in Layer 2 during the third pumping period, 1966-1974, and continued through the subsequent periods. The magnitude and areal extent of the "recharge" was modified during the fourth and fifth pumping periods as pumping and irrigated acreage changed. A first cut at estimating the long-term rate of recharge was made by multiplying the pumpage from the previous time period by 0.20 and adjusting the pumpage in the current time period by that amount or by inputting that rate as a positive well. By using the pumping rates from the previous time period, 1957-1966, a rough lag time of about ten years was assumed. If there was no pumpage at the node during 1957-1966, it was assumed that there was no recharge.

The results from this model run are shown in Figures 17 through 35 as the diamond shape. This simulation reproduced the water declines in the center of the basin much better than the model runs without "recharge". Differences between measured water levels and calculated water levels were less than 20 feet in nodes

19,6; 20,6; 20,13; 21,13; 21,14; 24,11; 25,1; 25,5; 31,6; 32,6; and 33,8. Water levels changed less than five feet in nodes 6,6 and 7,7, which were matched in the earlier run without recharge.

The mass balance errors for both transient runs were -0.59 and -0.62 for the pumpage only run and the pumpage plus deep percolation run, respectively. Based upon the mass balances and the comparison of the measured and calculated water level hydrographs, the transient model was accepted as reasonably representing the Harquahala Plains hydrologic system.

The total volume of water entered into the model as deep percolation was:

1974-1979	208295 AF
1980-1984	139674 AF
Total	347969 AF

The average deep percolation during the fourth pumping period, six years, is 34,716 acre-feet/yr; during the fifth pumping period, five years, it is 27,935 acre-feet/yr. The USGS estimated that the deep percolation for Harquahala Plains during 1978 was 38,410 AF. This value was calculated using a water budget analysis of irrigated area, water application rate, crop consumptive use rate, and an estimated irrigation efficiency. The model calculated deep percolation volume is within ten percent of the water budget calculated deep percolation volume for 1978.

CHAPTER 7

RECOMMENDATIONS AND CONCLUSIONS

The groundwater model, given the available data, is a reasonable representation of the Harquahala Plains hydrologic system. As the modeling study progressed, it became apparent that the existing data base was not as complete as had been hoped. The first problem was the storage coefficient/specific yield arrays and transmissivity/hydraulic conductivity arrays. There have been no long-term aquifer tests made in the central part of the basin. A 180-day test run by Cella Barr Associates in the northwestern part of the valley yielded a storage coefficient of 12 percent and a transmissivity of 60,000 gpd/ft. Even after 180 days, the well still showed signs of delayed drainage (Cella Barr Assoc., 1988) This type of information is not available in the central portion of the basin.

A second weakness in the model is the water level data available. Many of these water levels, particularly in 1957 and 1966, were flash statics--the pump was turned off, the well was allowed to recover for a short period of time, and the water level was measured. These values are not representative of regional water levels but rather represent one point in time at a specific location within the basin. The model, because of the finite difference solution technique, averages pumpage and water levels over an area, the model node. A comparison of point water levels to average water levels is a source of error within the model.

A third problem is the pumpage estimates. The USGS estimated pumpage by power consumption records and cropped acreage. There were no metered measurements of pumpage. In 1985, well owners registered an estimate of their groundwater pumpage with the ADWR. The total pumpage registered in Harquahala was 55531.7 AF. This is 17,000 acre feet less than the USGS estimated as pumpage for 1984. The USGS pumpage estimates are lumped by section. These had to be further divided between model nodes because the model nodes do not correspond to sections. Pumpage for individual wells is not available.

The last major problem is the inability to model the movement of the applied irrigation water through the vadose zone to the water table. There is insufficient data to characterize the vadose zone parameters; therefore, a saturated-unsaturated flow model is not warranted. However, the use of such a model would provide a much better estimate of deep percolation.

Despite these problems, the MODFLOW groundwater model of the Harquahala Plains area predicts the changes in water levels in the aquifer with a reasonable error. The model was used to estimate deep percolation to the lower aquifer at an average rate of 34,000 acre-feet/yr. This value agrees with the volume calculated by the USGS and is supported by the poor chemical of both the cascading water and the perched water. Based upon this model, poorer quality water is in transit through the vadose zone and began reaching the main water table during the mid-1970s. As water levels recover and pumpage decreases, the better quality water in the main aquifer will mix with the poorer quality water in transit, resulting in a downgrading of the water quality in the main aquifer.

APPENDIX A

SOUTHWEST ALLUVIAL BASINS

SOUTHWEST ALLUVIAL BASINS

Basin Abbreviation	Basin Name
AGF	Upper Agua Fria River
ARA	Aravaipa Creek
AVRALT	Avra-Altar Valleys and part of Lower Santa Cruz
BIC	Upper Big Chino Wash
BICLIC	Chino Valley
BIS	Big Sandy Basin
BRB	Black River Basin
BUT	Buttler Valley
BWMHAS	Upper Bill Williams Drainage and Upper Hassayampa River
CHICHE	Colorado River, Chemehuevi Valley
CHIDET	Colorado River, Detrital Valley
CHILMO	Colorado River, Lake Mohave
CHILPP	La Posa Plain
CHIMOH	Colorado River, Mohave Valley
CHIPVV	Colorado River, Palo Verde Valley
CHIVPK	Colorado River, Vidal and Parker Valleys
CHIYUM	Colorado River, Yuma Wash
DOU	Douglas, Sulphur Springs Valley
DUN	Duncan, Gila River from Redrock to Guthrie
GIL	Gila Bend Plain
GRD	Gila River, Palomas Plain, Sentinel Plain
GSK	Gila, San Carlos-San Carlos Reservoir
GSKDSW	Gila River, Dripping Springs Wash
GTDCDL	Cuerda de Lena Wash
GTDGRL	Growler Wash
GTDKVG	King Valley, San Cristobal Wash
GIDLEC	Lechuguilla Desert
GIDMHV	Mohawk Valley and Castle Dome Plain
HAR	Harquahala Plains
HASBWM	Bullard Wash, Hassayampa River, Santa Maria River
HASSRV	Hassayampa near Morristown and Wittman
HUA	Hualpai Valley, Red Lake
HUATRX	Truxton Wash
LHA	Lower Hassayampa
LSCDON	Lower Santa Cruz, Donnelly Wash
LSCELY	Lower Santa Cruz, Eloy
LSCSTA	Lower Santa Cruz, Stanfield-Maricopa
LSCSTR	Lower Santa Cruz, Santa Rosa Valley

LSCVEK	Lower Santa Cruz, Vekol Valley
LSPGSK	Lower San Pedro
LVR	Lower Verde River
MMU	McMullen Valley
RAN	Ranegras Plain
SACBWM	Sacramento Valley and Bill Williams River
SAFBON	Bonita Creek and Eagle Creek
SAFSSI	San Simon Valley, Gila River to Calva
SBV	Upper San Bernardino Valley
SFR	San Francisco River
SFRUGL	San Francisco River and Upper Gila River
SRVCHA	Salt River, Chandler, Queen Creek
SRVPAR	Salt River, Paradise Valley
SRVPHO	Salt River, Phoenix and Lower Agua Fria River
SSCARR	Lower Santa Cruz, Aguirre Valley
SSW	San Simon Wash
SSWBAB	Baboquivari Wash, Chutum Vaya Wash
SSWLQV	LaQuitani Valley
SSWTEC	Tecalote Valley, Vamori Wash, San Luis Wash
TONUSR	Tonto Creek, Pinto Creek, Salome Creek
USC	Upper Santa Cruz, Tucson Basin
USCCNG	Cienega Creek
USCSRF	San Rafael Valley
USP	Upper San Pedro
USPBEN	Upper San Pedro near Benson
USR	Upper Salt River
VER	Verde River
WAT	Waterman Wash
WIL	Willcox Basin
WMDLAP	Western Mexican Drainage, LaAbra Plain
WMDSON	Western Mexican Drainage, Sonoyta Valley
WMDTUD	Western Mexican Drainage, Tule Desert
WRB	White River Basin
YUM	Yuma Basin

APPENDIX B

GENERAL DESCRIPTION OF BASINS

GENERAL DESCRIPTION OF BASINS

Geology

The seven basins selected for further study were all within the Basin and Range Physiographic Province of southern Arizona, a region characterized by broad alluvial valleys bounded by high mountain ranges. Generally, the basins were formed by large-scale movement along northwest-trending faults during middle and late Tertiary time. Later erosion and sedimentation filled the valleys with alluvial sediments. The lowermost sedimentary unit is normally a low permeability, indurated, coarse conglomerate which interfingers with more permeable lava beds in many areas.

Through drainage occurred in most basins throughout the depositional history, but several closed basins were formed where drainage was restricted. This resulted in the deposition of fine-grained sediments in the playas that were formed. Salts, such as gypsum, were deposited along the margins. Continued cycles of erosion, volcanism, and uplift supplied both alluvial debris and lava beds.

These unconsolidated sediments of middle Tertiary to late Quaternary age, plus the more recent channel-fill deposits, are several thousand feet thick. The oldest alluvium is interbedded sands and gravels with lenses of impermeable silts and clays. The younger, more permeable, alluvium is composed of stream channel deposits such as sand and gravel point bars. Sediments grade from coarse textures near the mountain slopes to finer deposits in the basin center. Heterogeneities exist as lenses of coarse sand and gravel introduced as the stream meandered across the valley floor during the depositional history.

Hydrology

The alluvial fill deposits comprising the major aquifer consist of several thousand feet of interfingered sand, gravel, and silt-clay beds. Although the lenses of impermeable silts and clays may be locally extensive, in general, the aquifers in the alluvial fill are hydraulically connected to form a single water table aquifer with small areas exhibiting confined conditions.

Water levels are widely variable from basin to basin and within individual basins. Water levels range from at surface, near effluent streams, to more than 700 feet below land surface in heavily pumped areas. All basins considered here show a disruption of the natural hydraulic gradient so that flow is toward centers of pumping. These basins are in a state of overdraft--withdrawals exceed recharge--both culturally modified and natural recharge. Water level declines during the past 20 years vary from basin to basin, but range from no decline to more than 150 feet near areas of heaviest pumpage.

Recharge to the aquifers is from four possible sources: (1) the infiltration of precipitation in the valley floor and along the mountain fronts, (2) the infiltration of surface flow in the streams draining the basin, (3) the infiltration of applied irrigation water, and (4) the infiltration of sewage effluent and industrial wastewater. Direct infiltration of precipitation in semi-arid areas is considered negligible. Mountain front recharge and streamflow infiltration are the major natural recharge components, even though most streams flow intermittently. The culturally modified component--particularly that due to agriculture--is the subject of this thesis because, in agriculturally developed basins, it may represent the major source of recharge.

All of the basins considered, with the exception of the Willcox Basin, have external drainage. A basic description of each basin follows. For more complete information, consult the partial reference list.

Characteristics of Individual Basins

Avra-Altar Valley

Agricultural development in Avra-Altar Valley began before 1950, with more than 90 irrigation wells providing water for 30,000 acres of farmland by 1951. Land currently cultivated (1975) has only increased to 36,000 acres, but the annual water use has almost doubled. In 1951, 80,000 acre-feet were pumped; by 1970, the estimated pumpage was 136,300 acre-feet. This increase is attributed to double cropping.

The alluvial deposits which fill the structural depression and make up the major aquifer system are comprised of interfingered lenses of silt, sand, and gravel. These deposits, as thick as 2,000 feet in the valley center, are generally unconsolidated. The basal unit of the sequence is a firmly cemented red mudstone. The water table is a single unit above 700 feet, but a second aquifer under confined conditions may occur below 1,100 feet.

Water levels declined as much as 152 feet between 1952 and 1974. These declines occurred in the central part of the basin but may include interference from pumping centers north of Red Rock. Depth to water in the spring of 1974 ranged from 147 feet near Three Points to 780 feet in the bajada region of the Sierrita Mountains.

Douglas-Sulphur Springs Valley

The first irrigation wells in the Douglas-Sulphur Springs Valley were drilled in 1910, but intensive development did not begin until 1940 when approximately 3,000 acres were under cultivation. From 1940 to 1951, the acreage increased to 14,000 acres with approximately 75 percent of this area devoted to cotton. By 1978, the acreage had more than doubled with 34,346 acres under cultivation. Emphasis has shifted from cotton, in 1951, to miscellaneous crops such as vegetables.

The major water-bearing stratum in the basin is the unconsolidated alluvium. This alluvium, from 750 to 2,000 feet thick, consists of poorly-sorted clay, silt, sand and gravel with occasional areas of large boulders. A statistical analysis of well logs for the Central Valley Region indicates that clay and silt may make up greater than 80 percent of the fill. These fine-grained deposits are particularly abundant in the southern half of the basin. The presence of a Pleistocene Lake, possibly indicating a closed basin, is evidenced by laminated clays and marls with gypsum deposits. These beds have been dated by fossil snail associations. Quaternary age basalt flows are interbedded with the alluvium along the eastern margin of the valley, but the extent is too small to have any major effect on the water table.

Water in the basin occurs under water table conditions, although localized areas of confined conditions and small perching zones are evident. Water table contours for 1975 show a reversal of flow near Elfrida. The contours originally followed the surface water drainage pattern, but flow is now toward sites of heavy pumpage. Between Elfrida and the international border, there has been little change in the contour pattern or the depth to water. Maximum water level decline from

1952 to 1975 has been on the order of 90 feet; some wells have not declined but have shown a rise in water level. Depth to water ranges from 300 feet to less than 100 feet below land surface in the valley center.

Harquahala

Extensive agricultural development began in the Harquahala Valley in the early 1950s with pumpage in 1954 estimated at 33,000 acre-feet per year. The major aquifer is the interbedded sand and gravel alluvium which underlies most of the plains area. It varies in thickness from less than 300 feet near the mountain fronts to more than 1,200 feet in the valley center. The water generally occurs under water-table conditions, although some local areas of confined conditions exist. Before development, the groundwater contours trended from the northwest to the southeast. By 1957, the gradient had been reversed with flow moving toward three cones of depression. These zones had coalesced into one major depression in the southeastern part of the basin by 1966. Water levels have declined more than 200 feet between 1957 and 1975 with the depth to water averaging about 450 feet below land surface in 1975.

Lower Hassayampa

Alluvial fill deposits form the major aquifer in the Lower Hassayampa Basin. These deposits are composed of weakly consolidated sand, silt, and clay with small amounts of gravel and minor basalt flows. They may be as thick as 1,200 feet in the central part of the basin and, in some areas, are capped by as much as 50 feet of caliche-cemented gravels and terrace deposits.

The alluvium forms a single water-table aquifer with depths to water ranging from 20 feet near the washes to more than 400 feet below land surface in the northwest part of the basin. Estimated pumpage for 1974 was 89,000 acre-feet. No estimates for 1950 pumpage were available because the Hassayampa pumpage was included in that of the Salt River Valley. Water level changes since 1956 have ranged from a rise of two feet to a decline of more than 84 feet.

McMullen Valley

Agricultural use of groundwater began in 1917 at the extreme southwest end of McMullen Valley, but no extensive irrigation use developed until the first deep well was drilled in April of 1954.

Four stratigraphic units have been identified in the alluvial fill. In ascending order, these are: (1) a cemented coarse sand and gravel conglomerate, (2) poorly-sorted alluvial fan deposits, (3) extensive lakebed deposits composed of clay, silt, and fine-grained sand with interbedded deposits of gypsum and other salts, and (4) an unconsolidated alluvium of lenticular gravels, sands, and silts of the same approximate age as the lakebed deposits. Generally, the units are hydraulically interconnected and water is under water-table conditions except in areas near lakebed deposits. These deposits have created both an extensive perched water table and localized confined conditions. The deposits are estimated to cover at least 30 square miles. Wells tapping the alluvial fan deposits produce water in excess of 2,000 gallons per minute.

Heavy pumping in the Aguila and Salome-Wenden areas has created two distinct cones of depression. Water-level contours in 1973 show a depth to water ranging from less than 100 feet, south of Salome, to greater than 550 feet below land surface southeast of Aguila. Declines from 1958 to 1973 ranged from 40 to 150 feet southeast of Aguila and from 40 to 110 feet near Salome.

Waterman Wash

Agricultural development in the Waterman Wash area is recent. In 1952, 3,500 acres of land were cultivated but, by 1978, this had increased to 14,871 acres. The stratigraphic record in Waterman Wash indicates two probable cycles of deposition and erosion. Below 600 to 800 feet, the alluvial material is well indurated and contains little clay. This implies a well-developed drainage system which predates basin and range activity (the Laramide Orogeny). Above this layer lies a second section consisting predominantly of poorly-consolidated, poorly-sorted, lenticular beds of gravel, sand, sil,t and clay. No extensive clay layers are present. The full sequence of deposits, to about 1,500 feet deep, probably forms one, hydraulically interconnected, water-table aquifer. Localized areas of confined conditions and perched water are evident, but neither is extensive.

Current water-table elevation contours (1975) show a localized cone of depression in the northern part of the basin around the extensively irrigated areas. The depth to water ranges from less than eight feet near the edges of the area to nearly 172 feet in the most heavily-pumped areas. The depth to water ranges from less than 200 feet below land surface to slightly over 400 feet. The 1974 estimate of pumpage in the basin was 69,000 acre-feet.

Willcox

Willcox is the only closed basin studied. Unconsolidated alluvium consisting of two major facies--streambed deposits and lakebed deposits--underlies most of the area. The stream deposits are unconsolidated, weakly-cemented, interbedded lenses of gravel, sand, silt, and clay. These deposits are not continuous but rather thin and highly lenticular. The lakebed deposits are uniform layers of black clay indicative of a quiet, lacustrine environment. These deposits, probably thicker than 140 feet in the basin center, act as a confining layer in and near the present Willcox Playa. The principal aquifer is the streambed deposits where water-table conditions predominate. At depth, however, moderately extensive clays may create perched conditions near the playa where some confined conditions exist.

Before development, groundwater movement was from the sides toward Willcox Playa. Development of two pumping centers within the basin, north and south of the playa, have forced groundwater movement toward these centers. Aquifer response to recharge and pumping between 1954 and 1975 has varied. Declines of more than 200 feet have been measured in 20 wells, while rises of almost eight feet have occurred in others. Depth to water varies from less than 100 feet near the playa to more than 300 feet along basin margins.

APPENDIX C

WELL CHARACTERISTICS

WELL LOCATION	LAND SURFACE	Y LOCATION	X LOCATION	REG. NO	REMARKS	PUMP 1983	GPM	OTHER REG	YIELD (gpm)	WELL DEPTH	CASE DIAM	DATE DRILLED	USE
				640740		96	59.52						
B-01-08 4bbb	1142	24	12	802143					2350	1000	16	May-10-1960	Dom/Munic
B-01-08 6aaa	1117	24	11	612565		1973	1223.		2143	759	20	Jun-23-1958	Irrig.
B-01-08 6add	1115	24	11	612567	6daa?			612565	1430	1200	20		Irrig.
B-01-08 6bba	1115	23	11	801366	6bab?				600	1100	16		Irrig.
B-01-08 6bbb	1117	23	11										
B-01-08 6bdb	1112	23	11	801365	6bdc?				1280	1038	16		Irrig.
B-01-08 7aaa	1111	24	11	619502					20	775	20		Domestic
B-01-08 7aab	1110	24	10	619500					2450	800	18		Irrig.
B-01-08 7adc	1102	24	10	619501					1980	1013	20		Irrig.
B-01-08 7cbb	1100	24	10	85118		3561.	2208.		1600	1007	16	Jan-14-1981	Irrig.
B-01-08 7ccb	1100	24	9										
B-01-08 19abb1	1086	25	9	624599									Dom/Stock
B-01-08 19abb2	1086	25	9	624581									Irrig.
B-01-08 19bbb	1100	25	9	600201					3000	1200	20		Irrig.
B-01-08 19bcc	1095	25	8	600200					700	600			Irrig.
B-01-08 19cbc	1088	26	8	600202					3000	1200	20		Irrig.
B-01-08 31ccc	1080	27	7	511460									
B-01-09 1bbb	1123	22	10	612564						1536	20	Oct-26-1957	Irrig.
B-01-09 2abb1	1130	22	10	635441				614407	2500				Irrig.
B-01-09 2abb2	1130	22	10										
B-01-09 2baa	1132	22	10	614408				614407	1800	1510	18		Irrig.
B-01-09 2caa	1130	22	9	614407		1188.	736.8			1228	20		Irrig.
B-01-09 2cdd		22	9	635442				614407	2500				
B-01-09 4dda	1150	21	8	617068		111	68.82						
B-01-09 5abc	1172	20	7										
B-01-09 6bab	1190	19	7	624942					900	1500	16	Feb-9-1955	Irrig.
B-01-09 6ccc	1196	19	6	624941					1600	1420	16	Nov-3-1953	Irrig.
B-01-09 6ccc2	1196	19	6	624938				624935		1265	18		
B-01-09 6cdc	1187	19	6	624943	6dcc?				1850	1700	16	Jul-3-1977	Irrig.
B-01-09 7bcc	1201	20	5	635435					1800				Irrig.
B-01-09 7ccc	1205	20	5	635434		123	76.26		2300				Irrig.
B-01-09 7dcc	1187	20	5	635429					20				Domestic
B-01-09 10bbb	1148	22	8	800152	10add?								
B-01-09 11bbb	1130	22	9	635430		148	91.76		400	800	16		Irr/Dom
B-01-09 11bbb2	1132	22	9	635431				635430	2200				Irr/Dom
B-01-09 12cbb	1115	23	9	635433		1039.	644.7		2500	1000	20		Irr/Dom
B-01-09 12cbb2	1115	23	9										
B-01-09 12cbb3	1115	23	9										
B-01-09 13abb	1111	24	9	610759				85118		1007	16	May-1-1960	Irr/Dom
B-01-09 13bbb	1113	24	9	610760				85118		1300	16	Jan-1-1964	Irrig.
B-01-09 13bcd	1108	24	8	610761				85118	16		1015	Jul-26-1973	Irrig.
B-01-09 13cad	1103	24	8										
B-01-09 14bbb	1125	23	8	628438						1100	20		Irr/Dom
B-01-09 15abc1	1128	23	7	609321						2000	20		Irrig.
B-01-09 15abc2	1128	23	7										
B-01-09 16bdd	1140	22	7	804057	16bdb?						20		Stock
B-01-09 17abb	1157	21	6										
B-01-09 17bba1	1165	21	6	616570					2250	1973	20	Feb-A3-1973	Irrig.
B-01-09 17bba2	1165	21	6										

WELL LOCATION	LAND SURFACE	Y LOCATION	X LOCATION	REG. NO	REMARKS	PUMP 1985	GPM	OTHER REG	YIELD (gpm)	WELL DEPTH	CASE DIAM	DATE DRILLED	USE
B-01-09 17cbb	1173	21	6	616569					1000	1500	20	Jun-10-1958	Irrig.
B-01-09 17ccb	1173	21	5	616573	17ccc?				2250	1524	24	Dec-5-1980	Irrig.
B-01-09 17dbb	1158	21	6	627796		362.3	224.6		2000	1580	20	Apr-13-1966	Irrig.
B-01-09 17dcc	1158	22	6	627797				627796	800	1500	20	Mar-4-1963	Irrig.
B-01-09 18bcc	1212	20	5	605716	18ccb?				2185	1500	20	Jul-25-1958	Irrig.
B-01-09 18ccc	1215	21	5	600112					2700	1500	20		Irrig.
B-01-09 19bcc	1216	21	4	635428					2500				Irrig.
B-01-09 19ccc	1218	21	4	635432		309	191.5		2500				Irrig.
B-01-09 20bbb	1175	22	5	616571					1600	1400	20	Jun-10-1952	Irrig.
B-01-09 20bdc	1167	22	5	616572					2500	1500	20	Jun-22-1977	Irrig.
B-01-09 20ccc	1179	22	5	635436				621123	2500	1200	20		Irr/Dom
B-01-09 21bcc1	1146	22	6	616574					15	1500	20	Oct-6-1952	Irrig.
B-01-09 21bcc2	1147	22	6										
B-01-09 21bcc3	1147	22	6										
B-01-09 21ccc	1152	23	5	635443		354.5	219.8		2300	1000	18		Irr/Dom
B-01-09 22ada	1112	24	7	621123		740.3	459.0				6		
B-01-09 22bcb	1124	23	6										
B-01-09 23bcc1	1110	24	7	635440		87	53.94		2500	1000	18	Sep-1-1976	Irrig.
B-01-09 23bcc2	1112	24	7										
B-01-09 24caa	1103	25	8	635439				635438	2500	1000	20		Irr/Dom
B-01-09 24cbb	1103	25	8	635438		516.9	320.5		2500	1000	18		Irr/Dom
B-01-09 25bab	1090	25	7	635437		56	34.72		2500	1000	18		Irrig.
B-01-09 26acb	1103	25	7										
B-01-09 26bcb	1112	24	6										
B-01-09 26cbc	1115	25	6										
B-01-09 26ccb1	1115	25	6	501885					12	800	8	Feb-23-1982	Domestic
B-01-09 26ccc	1118	25	6	926949					2000	1100	24		Irr/Dom
B-01-09 28bcc	1160	23	5	621127				621124	1800	1030	20		Irrig.
B-01-09 28ccc	1171	23	5	621129				621124	2500	1000	20		Irrig.
B-01-09 28cdc	1162	24	5	621126				621124	2000	1090	20		Irrig.
B-01-09 28dbb	1149	24	5	621130				621124	2000	1000	20		Irrig.
B-01-09 28dcc	1158	24	5	621124		4037.	2503.		1800	1120	20		Irrig.
B-01-09 28ddd	1145	24	5	621125				621124	1200	1180	20		Irrig.
B-01-09 29bcc	1183	22	4	603852					3000	720	22		Irrig.
B-01-09 31ccc		23	2	626950				614409	1600	800	20		Irrig.
B-01-09 32ccc	1216	23	3	626952		891.4	552.7	614409	1800	1200	24		Irrig.
B-01-09 32ccc		23	3	614409		7196.	4461.		3100	986	20		Irrig.
B-01-09 34add	1127	25	5	627798		3235.	2005.		2300	1000	18	Mar-10-1977	Irrig.
B-01-09 34ccc	1163	25	5										
B-01-09 34dcc2	1153	25	5	627799				627798	2350	1000	18	Mar-30-1978	Irrig.
B-01-09 35dcd	1117	26	6	605181	35dcc?	1132	701.8		2650	780	20	Feb-2-1953	Irr/Dom
B-01-09 36ccc		26	6	626951				614409	1600	800	20		Irr/Dom
B-01-09 36ccc	1114	26	6	614410		1162.	720.6	614409	2900	1190	18		Irr/Dom
B-01-10 1bbb	1223	18	6	624940					2000	1238	18	Jun-18-1978	Irr/Dom
B-01-10 1bdd		18	6	624939					1800	1220	18	Mar-17-1978	Irrig.
B-01-10 1ccc	1236	18	5	624935		1659.	1028.		1702	917	12	Jan-21-1953	Irr/Dom
B-01-10 1dcc	1215	19	6	624937				624935	2196	1494	12	May-14-1953	Irr/Dom
B-01-10 1ddc	1205	19	6	624936				624935	2200	2005	16	Mar-25-1963	Irr/Dom
B-01-10 12bcc	1242	19	5										
B-02-08 15bbd	1263	out											

WELL LOCATION	LAND SURFACE	Y LOCATION	X LOCATION	REG. NO	REMARKS	PUMP 1985	GPM	OTHER REG	YIELD (gpm)	WELL DEPTH	CASE DIAM	DATE DRILLED	USE
B-02-08 15bcd	1240	out		636532					7	830	8		
B-02-08 17caa	1180	21	14										
B-02-08 17daa	1193	22	15										
B-02-08 18caa	1186	21	13	608006					80	600	20		Irrig.
B-02-08 19aaa	1164	21	13	608459					35	640	20		Domestic
B-02-08 19bbb	1163	21	13	608458					35	700	20		Domestic
B-02-08 19cbb	1147	21	12	608454				608451	1600	1080	20		Irrig.
B-02-08 19ccc		21	12	608455				608451	2000	1000	20		Irrig.
B-02-08 19daa	1153	22	13	608451		4140.	2571.		800	1050	20		Irrig.
B-02-08 20bcb	1158	22	13										
B-02-08 20ccc	1145	22	13										
B-02-08 23baa	1260	out											
B-02-08 23bba	1260	out											
B-02-08 27bba	1204	24	14	643347						1125	16		Domestic
B-02-08 28caa	1165	24	13	603487					500	1200	16		Domestic
B-02-08 28ccb	1152	24	13	603489					1000	1100	16		Irr/Dom
B-02-08 28cdb	1158	24	13	603488					800	1100	16		Domestic
B-02-08 28dcc	1158	24	13	633436					35		8		Stock
B-02-08 29abb	1155	23	13										
B-02-08 29baa		23	13	606841					300	1100	20		Irrig.
B-02-08 29bdd	1147	23	13	606839					1500	800	20		Irrig.
B-02-08 29cbb	1137	23	13	606836	29ccb?				1500	800	20		Irrig.
B-02-08 30aaa1	1144	22	13	608452				608451	2400	1180	20		Irrig.
B-02-08 30aaa2	1144	22	13										
B-02-08 30acc	1131	22	12	608453				608451	1800	1200	20		Irrig.
B-02-08 31aaa	1127	23	12	612556				612555	1440	1200	20		Irrig.
B-02-08 31baa	1123	23	12	612555		1721.	1067.		1836	1200	20	Jul-23-1958	Irrig.
B-02-08 31daa	1120	23	12	612560				612555	2524	1200	20		Irrig.
B-02-08 32baa	1137	23	12	612558				612557	620	1200	20		Irrig.
B-02-08 32bba	1133	23	12	614430				612557	2000	1720	20		Irrig.
B-02-08 32bba		23	12	612557		86	53.32		1439	1200	20		Irrig.
B-02-08 32ddd	1140	24	12										
B-02-08 33aad	1165	24	13	612561				612559		1605	10	May-19-1959	Irrig.
B-02-08 33cbb	1143	24	13	612559	33bcc?	174.1	107.9		1260	1600	20		Irrig.
B-02-08 33dbb	1153	24	13										
B-02-09 3bbb	1260	17	13										
B-02-09 7abb	1260	16	10										
B-02-09 9abb	1233	17	12	611123		5477.	3396.		1365	1540	20	Jul-25-1952	Irrig.
B-02-09 9dbb	1219	17	11	611127				611123	1610	1510	20	May-31-1955	Irrig.
B-02-09 10abb	1223	18	12	611125				611123	1930	1398		Feb-17-1957	Irrig.
B-02-09 10bbb	1227	17	12	611124				611123	1390	1300	20	Mar-17-1953	Irrig.
B-02-09 11acc	1205	19	13										
B-02-09 11adb	1210	19	13										
B-02-09 11bbb	1220	18	13	611126				611123	2500	1355	20	Jan-01-1952	Irrig.
B-02-09 11bdd		18	13	611130				611123	2290				Irrig.
B-02-09 11cbb	1206	18	13	611128				611123	1960	1505	20	May-20-1960	Irrig.
B-02-09 13baa	1197	20	13	630292					2025	603	18		Irrig.
B-02-09 14bab	1193	19	12	611129				611123	1970	1300	18	Feb-5-1976	Irrig.
B-02-09 14bbb	1192	19	12	611134								May-1-1955	Irrig.
B-02-09 16bbb	1215	17	11	629624					2700	1400	20	May-1-1955	Irrig.
B-02-09 18abb	1235	16	10										

WELL LOCATION	LAND SURFACE	Y LOCATION	X LOCATION	REG. NO	REMARKS	PUMP 1985	GPM	OTHER REG	YIELD (gpm)	WELL DEPTH	CASE DIAM	DATE DRILLED	USE
B-02-09 23aaa	1167	20	12	611132				611123					Irrig.
B-02-09 23abb	1169	20	12	611131				611123		1000	20		Irrig.
B-02-09 24bba	1164	20	12	611133				611123	1540	1200	18	Apr-5-1977	Irrig.
B-02-09 26aba	1148	21	11	619265				619265		1400	20		
B-02-09 26acd	1140	21	11	619263		2964	1837.		1850	1645	18	Oct-1-1965	Irr/Stock
B-02-09 26adc	na	21	11										
B-02-09 26baa	1150	20	11	619264					1800	1200	18	Apr-1-1977	Irr/Stock
B-02-09 26bbb	1153	20	11	619266				619266		1820	20	Dec-1-1958	Irr/Stock
B-02-09 26bcb	1148	20	11	619262	26bbc?				1850	1455	20	Jul-1-1962	Irr/Dom
B-02-09 26bcc	na	20	10										
B-02-09 26bdd	1143	21	11	619267						1337	20		
B-02-09 30baa	1138	22	12	608456				608451	1600	1150	20		Irrig.
B-02-09 34dbb	1149	21	9										
B-02-09 35cbb	1142	21	10										
B-02-09 36bbb	1132	22	11	608457				608451	1800	1100	20		Irrig.
B-02-10 5abb	1330	11	8										
B-02-10 8ddd	1276	13	7										
B-02-10 14dca	1246	15	8										
B-02-10 16bbb	1278	13	7	614431						494	6		Stock
B-02-10 17dca	1296	13	6										
B-02-10 20abb	1303	13	5	803947						410	6	Mar-13-1982	Domestic
B-02-10 23bba	1248	15	7										
B-02-10 26dbb	1230	17	7	607664						755	14	Sep-20-1981	Irrig.
B-02-10 26dcc	1232	17	6	86190						800	16		
B-02-11 22bcc	1535	out											
B-02-11 2bbb	1346	9	5	603419		0.3	0.186		3300	850	20		Irrig.
B-02-12 1cbc	1440	7	1										
B-02-12 1ccb	1443	7	1	611598					10	579	11	Jan-9-1969	Ind/Dom
B-02-12 2dda	1440	7	1	611584					52	702	11	Feb-12-1969	Ind/Dom
B-03-09 31aad	1315	14	12										
B-03-10 31cbb	1348	10	7	603422		1097.	680.7		2840	835	20		
B-03-10 33cbb	1349	11	8	86183					26	600	8		
B-03-11 1bcb	1490	7	10										
B-03-11 8cac	1444	6	6	610071	8cab?				200	560	16	Apr-12-1958	Irr/Dom
B-03-11 13ccc	1415	8	8	86813					28	554	8		Domestic
B-03-11 13cda1	1418	8	8										
B-03-11 13cda2	1418	8	8										
B-03-11 16ddd	1405	7	7	633434					35		8	Jan-1-1952	Stock
B-03-11 17bdc	1432	6	6	614437						130	6		
B-03-11 22ccb	1388	7	6	617026	23ccb?				1500	879	16	Dec-16-1975	Industrial
B-03-11 34aba	1366	9	6	603424				603420		850	12		Irrig.
B-03-11 34baa	1368	8	5										
B-03-11 34bbb	1373	8	5	603423		1745.	1081.	603420	2740	850	20	Dec-22-1975	Irrig.
B-03-11 34bcc	1366	8	5	603420		750.9	465.5		2480	855	20	Sep-16-1976	Irrig.
B-03-11 34daa1	1355	9	5	603425					180	590	10	Sep-20-1975	Domestic
B-03-11 34daa2	1355	9	5	633431					35				Stock
B-03-11 36baa	1364	9	7	603426	36abb?			603421	1535	860	20	Sep-1-1976	Irrig.
B-03-11 36bbb	1364	9	6	603427				603421	3000	912	20	Aug-1-1975	Irrig.
B-03-11 36cbb	1352	10	6	603421		3838.	2380.		3370	875	20	Feb-1-1976	Irrig.
B-03-12 19aaa	1410	out		603144						588	10		Stock
B-03-13 23bbb	1373	out											

WELL LOCATION	LAND SURFACE	Y LOCATION	X LOCATION	REG. NO	REMARKS	PUMP 1985	GPM	OTHER REG	YIELD (gpm)	WELL DEPTH	CASE DIAM	DATE DRILLED	USE
B-03-13 28adc	1338	out											
B-04-09 30aac	1767	out		612687					35	500	6	Jun-20-1960	Stock
B-04-11 15adc	1655	out		612688					35	650	6	Jun-22-1960	Stock
B-04-12 4cca	1640	2	8	603141				602987	800	1018	18		Irrig.
B-04-12 5ada	1664	1	8	510352									
B-04-12 5daa	1643	1	8	510353									
B-04-12 9acc	1615	2	7	602987	9bda?	266.2	165.0		480	1340	8		Irrig.
B-04-12 10ccc	1600	2	7	603142						900	16		Domestic
B-04-12 14cbb	1582	3	8	603143				602987		1059	18		Irrig.
B-04-12 23abc	1559	3	7										
B-04-12 25aca	1530	4	7										
B-05-09 25dcc	na	out											
B-05-12 32add	1697	1	8										
B-05-12 33cbd	1670	1	8										
C-01-07 12cca		out		622913					2000	1000	20		Irrig.
C-01-07 13add		out		86710					2500	660	1	Feb-4-1981	Irrig.
C-01-07 13baa		out		603637					2000	915	20	Nov-10-1974	Irrig.
C-01-07 14add	919	out											
C-01-07 14bbb		out		604464					600	500	18		Irrig.
C-01-07 15bbb	949	out		605710					300	1200	20		Dom/Stock
C-01-07 19baa	960	36	9	624597					35				Stock
C-01-07 19bad	949	36	9										
C-01-07 19bbb	960	35	9										
C-01-07 24aab		out		628648					1500	960	18		Irrig.
C-01-07 24bbd		out		628647					1600	980	18	Feb-1-1980	Irrig.
C-01-07 24dc	875	out											
C-01-07 32ac	965	out											Stock
C-01-08 4bbd	1060	29	8	606844	4bc?				380	672	20		Irrig.
C-01-08 4bda	1060	29	8										
C-01-08 5bdd	1050	28	7	640723						486	8		Dom/Stock
C-01-08 6ccc1	1090	28	6	606835					1600	800	20		Irrig.
C-01-08 6ccc2	1090	28	6										
C-01-08 6dcc	1086	28	6	606843					1800	1150	20		Irrig.
C-01-08 8bb	1062	29	6	606842					1800	800	20		Irrig.
C-01-08 8bcb	1067	29	6	606838	8bcc?				1800	1150	20		Irrig.
C-01-08 9bbb	1043	29	7	606837					1800	800	20		Irrig.
C-01-08 13bdb	990	33	8										
C-01-08 13cbb	982	33	8										
C-01-08 13dcb	975	35	8										
C-01-08 13dcd	975	35	8										
C-01-08 14abb1	1008	33	8										
C-01-08 14abb2	1008	33	8										
C-01-08 14abc2	998	33	8										
C-01-08 14adb	992	33	8										
C-01-08 14add	990	33	8										
C-01-08 14bbb	1010	32	8										
C-01-08 14ddd	990	34	8										
C-01-08 15ddd	1000	33	7	611112					100	451	8		Irr/Dom
C-01-08 16cbc	1055	30	6	800031					1140	600	24	Mar-26-1969	Irrig.
C-01-08 16ccc	1055	31	6										
C-01-08 16dcc	1035	31	6	800034					1650	585	18	Dec-3-1956	Irr/Stock

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C-01-08 17abc	1062	30	6										
C-01-08 17acc1	1074	30	6	622244					1100	1800	16		Irrig.
C-01-08 17acc2	1065	30	6	622235						800	8		Domestic
C-01-08 17dcc	1074	30	6	622243					1620	1050	16		Irrig.
C-01-08 20adb	1061	21	5										Irr/Stock
C-01-08 20adc	1061	21	5										
C-01-08 21bab	1040	31	6										Irr/Stock
C-01-08 22bbb	1020	32	6										Irr/Stock
C-01-08 22bbc	1020	32	6										
C-01-08 22bcc	1020	32	6										
C-01-08 22cdc	1016	33	6										
C-01-08 22dcc	1012	33	6										
C-01-08 23ccd	1016	34	7										
C-01-08 27bbb	1020	33	6										
C-01-08 27bbc	1023	33	6										
C-01-08 27bcc	1030	34	6										
C-01-08 27ccc	1041	34	5										
C-01-08 28aad	1025	33	6										
C-01-08 28dbb	1040	33	5										
C-01-08 32add	1073	out											Stock
C-01-08 34bcd	1054	out											Stock
C-01-09 1ccc	1126	27	5	626955				614409	1500	950	20		Irrig.
C-01-09 2bcc	1151	26	5	626953				614409	1100	1000	20		Irrig.
C-01-09 2ccc	1160	26	4	626957				614409	1340	1100	24		Irrig.
C-01-09 2dcc	1143	27	5	626956				614409	2000	900	20		Irrig.
C-01-09 3ccc	1190	26	4	626959				614409	1350	900	24		Irrig.
C-01-09 3dcc	1175	26	4	626958				614409	1400	1120	20		Irrig.
C-01-09 4ccc	1220	25	3	626961				614409	1500	1000	24		Irrig.
C-01-09 4dcc	1206	25	3	626960				614409	1480	900	24		Irrig.
C-01-09 5acc	1215	24	3	626954				614409	1400	1200	24		Irrig.
C-01-09 5ccc	1248	24	2	602826					500	1140	8		Irr/Stock/Munic.
C-01-09 5dcd	1230	25	3	626962	5dcc?			614409	1520	1100	24		Irr/Dom
C-01-09 6dcc	1259	24	2	602920		228.3	141.5		1200	1179	12		Irr/Dom/Indust.
C-01-09 7dcc	1296	25	1	602917					800	800	16		Irr/Stock/Dom
C-01-09 8dcc	1265	25	2	602823					1000		20		Irr/Stock/Dom
C-01-09 9bcc	1236	25	3										
C-01-09 9ccc	1247	26	2	602825					2500	1425	20	May-1-1980	Irr/Mun./Ind.
C-01-09 10acb	1180	26	4	627801	10aac?				1100	1000	20	Feb-11-1972	Irrig.
C-01-09 10dcc	1200	27	3	627804					35	775	20	Nov-8-1958	Domestic
C-01-09 11ccc	1180	27	4	627800					1300	690	20	Apr-20-1959	Irrig.
C-01-09 11dbc	1158	27	4	610097	11dc?	2706.	1678.		3500	1000	20		Irr/Dom
C-01-09 11dcb	1158	27	4	610098				610097	1100	1000	20		Irr/Dom
C-01-09 14ccc	1198	27	3										
C-01-09 16cbb	1267	26	2	630049	16cbc?	3.27	2.027		95	1200	16		Irr/Dom
C-01-09 17dcb	1288	out		610441		585	362.7		1100	1150	20		Irrig.
C-01-09 17dcc	1290	out		610442				610441	1200	601	20		Irrig.
C-01-09 18acb	1305	25	1	625970					3500	985	20		Irrig.
C-01-09 18cbb	1328	25	1										
C-01-09 18ccc	1340	out											
C-01-09 22bcc	1245	out											
C-01-09 23bdb	1197	out											

WELL LOCATION	LAND SURFACE	Y LOCATION	X LOCATION	REG. NO	REMARKS	PUMP 1985	GPM	OTHER REG	YIELD (gpm)	WELL DEPTH	CASE DIAM	DATE DRILLED	USE
C-01-09 25ccc	1190	out		605831					35	300	12		Stock
C-01-10 9ccc		out		606840					1500	800	20		Irrig.
C-01-10 12ada	1270	24	1	601285					34				Stock
C-02-07 26aba	1126	out											
C-02-07 27aab	1144	out											
C-02-07 28aaa	1162	out											
C-02-07 29aaa	1176	out											
						55775							

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