HYDROGEOLOGICAL ANALYSIS OF GROUNDWATER FLOW IN SONOITA CREEK BASIN, SANTA CRUZ COUNTY, ARIZONA

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF GEOLOGY

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGEMENTS

The writer is most grateful to Dr. John W. Harshbarger, thesis director, for his continual guidance and enthusiasm throughout this thesis. Acknowledgement of assistance is also due to the other members of the thesis committee: Dr. W. D. Pye, and Professor J. J. Wright.

Special acknowledgement is made to Mr. Edward Davidson, U. S. Geological Survey, for his valuable help in the field and in reviewing the thesis.

In addition, acknowledgement is made to Mr. L. C. Halpenny for furnishing his reports on the area.

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ABSTRACT

The Sonoita Creek basin lies in a north trending intermontane valley in southeastern Arizona. Mature dissected mountains rise abruptly from long alluvial slopes and culminate in peaks ranging from 1000 to 1300 feet above the valley floor. The mountains surrounding the alluvial sediments are of volcanic rocks of Miocene ? age, and have been subjected to tectonic disturbance which resulted in extensive faulting, folding, and the formation of joint systems.

The alluvial sediments have been divided into five units based on their stratigraphic position, structural involvement, lithology, and permeability. The oldest unit in the basin is unit No. 5 and the youngest is unit No. 1. Groundwater supplies of the Sonoita Creek basin are developed largely from alluvial unit No. 4, and minor supplies from alluvial unit No. 1.

The groundwater originates as precipitation on the mountain areas and on the floor of the valley. The average rainfall on the valley floor is about 20 inches per year while on the mountains it is more than 50 inches per year. A minor part of the groundwater recharge is from the discharge of Monkey spring into the northern part of the

basin. Groundwater is discharged from the Sonoita Creek basin through evaporation, as effluent flow of about 7 cubic feet per second through Sonoita Creek, and by artificial discharge through pumping.

The perennial streamflow in Sonoita Creek near Patagonia is due to the impervious volcanic rocks in the subsurface, which crop out 500 feet south of the town, forcing the groundwater to discharge at the surface.

Groundwater in the basin is generally of excellent to good quality for irrigation use, and medium to good for domestic purposes. The groundwater contains high percentages of sulphate, calcium, and bicarbonates.

INTRODUCTION

Statement of the Problem

The source of the perennial stream flow, about 7 cubic feet per second, in Sonoita Creek below Patagonia, has not been clearly understood. Upstream from Patagonia there is only intermittent stream flow during the rainy season. It is believed that the flow is due to abrupt termination of the alluvial deposits which constitute the groundwater reservoir. Chemical analysis of water from wells in the Patagonia area indicates several different sources of groundwater in the alluvial deposits. These facts suggest there is a complex of geological features which control and influence the flow dynamics and chemical quality of the groundwater.

Location

The Sonoita Creek basin is in Santa Cruz County in southeastern Arizona (Figure 1). Land surface altitude ranges from 4450 feet above sea level in the northern part of the area to 4050 feet in the southern part. The basin averages about 7 miles in length and 4 miles in width, and has an area of about 30 square miles. The regional gradient of Sonoita Creek basin is 57 feet per

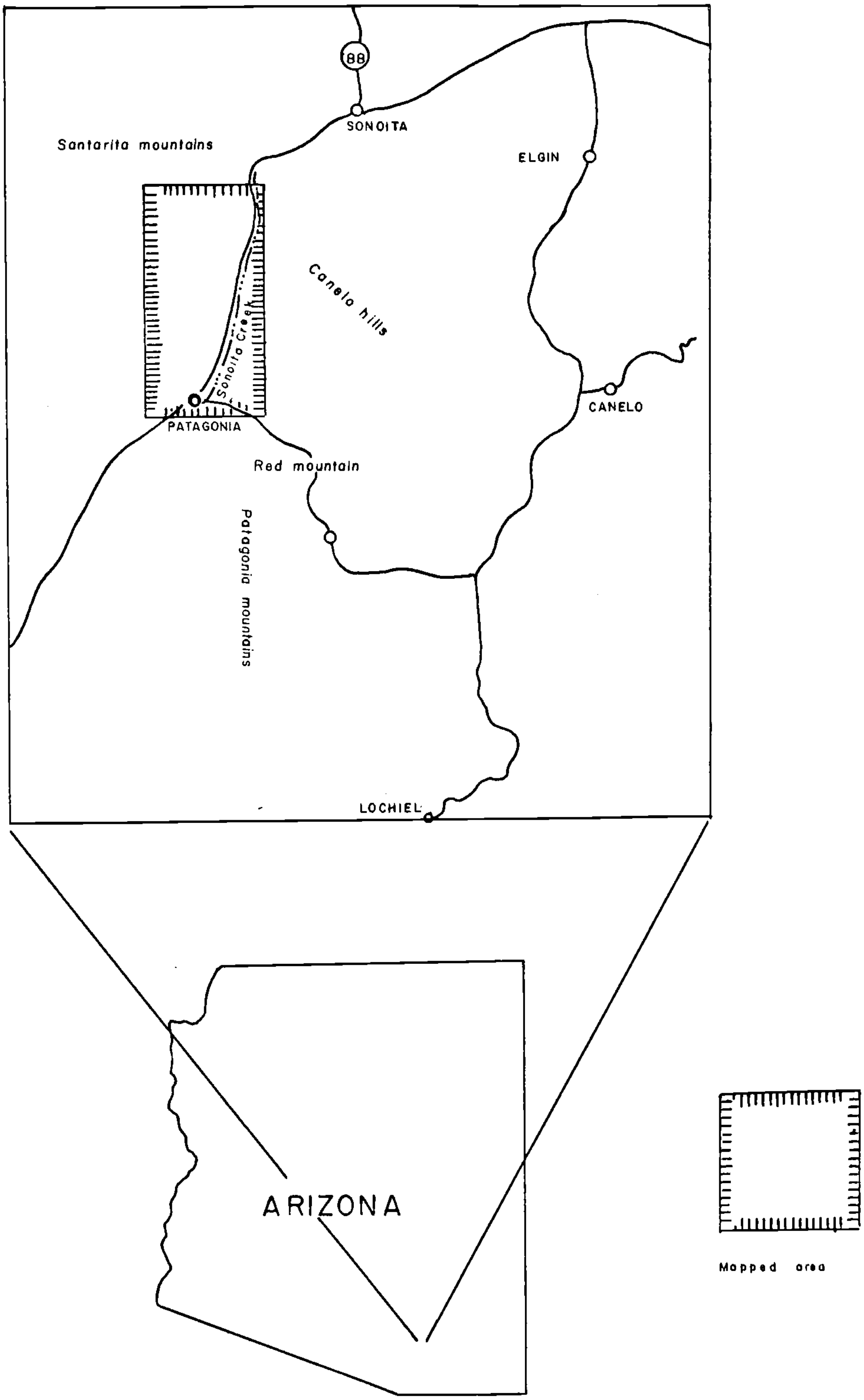

FIGURE. 1 Map showing the location of Sonoita Creek basin

mile. The highland areas that form the drainage divides of the basin are the Red, Kunde, Hugh, and Canelo Mountains to the east; Santa Cruz Mountains to the west and northwest; and Patagonia Mountains to the south.

Climate

Climatological data for the basin area were obtained from official records of the U. S. Weather Bureau. The Sonoita Creek basin has a semi-arid climate similar to that occurring at a comparable altitude in the other parts of southern Arizona. Climatic conditions in the town of Patagonia, with an altitude of 4050 feet, are considered representative of most of the basin. It has hot summers and mild winters. The mean annual rainfall, for the basin, is about 20 inches, of which 9 inches occur in the summer months. April, May and June are the driest months; January, February, August, and September are the wettest months. The average total precipitation during the dry months is about one inch. The maximum average temperature is 100°F. and the minimum average temperature is 17°F.

Previous Work

Schrader (1915) conducted a geological reconnaissance on the mineral deposits of the Santa Rita and Patagonia Mountains. This work included a detailed study of the geology of the mountains. Feth (1947) made studies of the geology of the Canelo Hills, and prepared a special report in 1954, published by the U. S. Geological Survey, on the geology and the groundwater of the Patagonia area. Rohrbacher (1963) made studies of the geology of the Temperal Gulch - Mansfield Canyon area in the west of the Sonoita Creek basin. During 1959-1964, an unpublished water supply consulting report on the hydrology of Patagonia area was prepared by Halpenny, Green, and Dausinger.

Well Numbering System

Wells and test holes shown on the accompanying map (Plate 1) are numbered according to the Federal system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and baseline, which divide the state into four quadrants. These quadrants are designated counterclockwise by the capital letters A, B, C, and D. All land north and east of the point of origin is in A quadrant, that north and west is in B quadrant, that south and west is in C quadrant, and that south and east is in D quadrant. The number shows the location of the well or test hole by township, range, section, and position within the section as illustrated in Figure 2. The first numeral of a well number indicates the township; the second, the range; and the third, the section in which the well is located. The lower case letters following the section

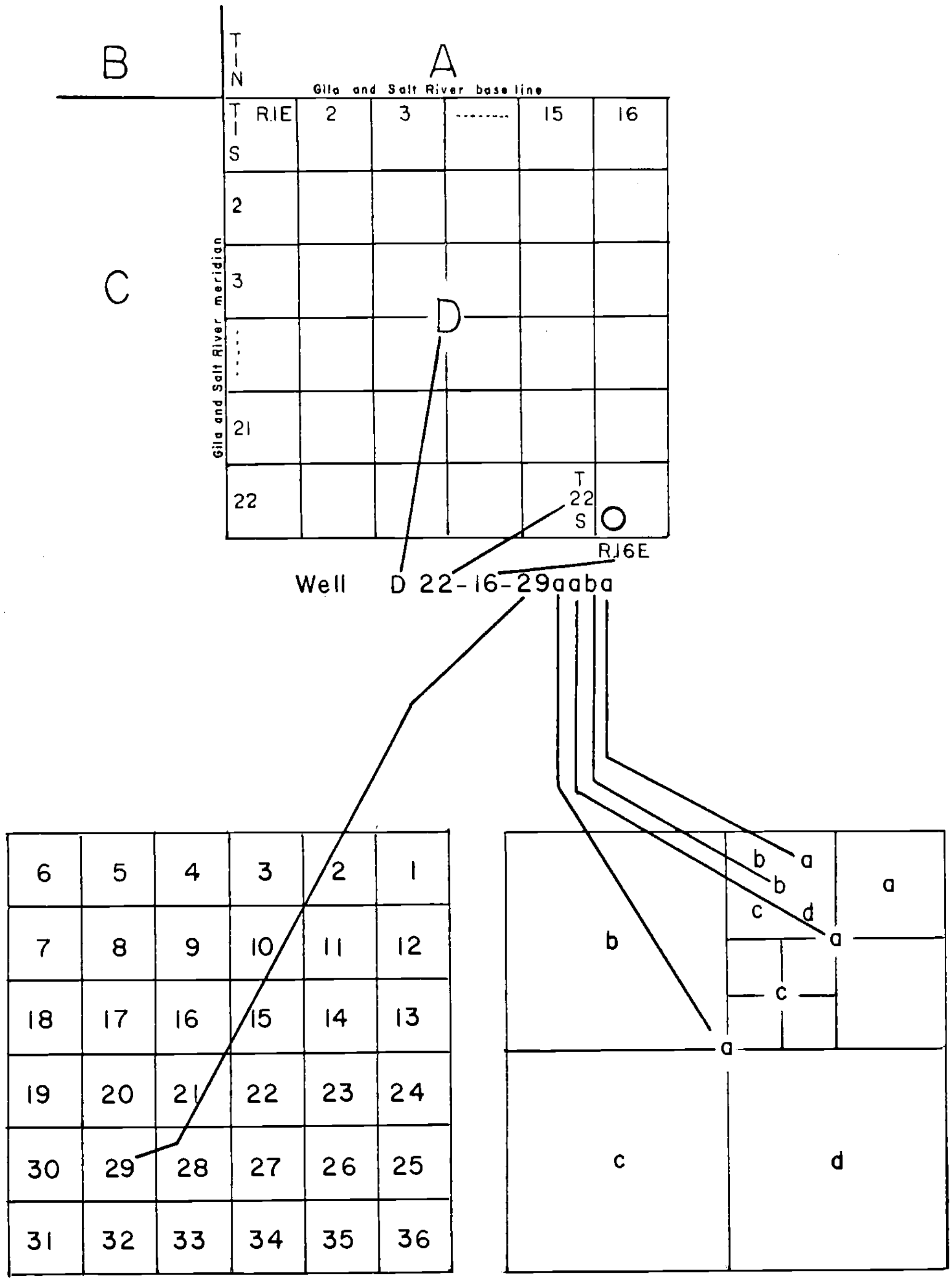

FIGURE. 2 Well numbering system in Arizona

number indicate the position of the well within the section. Each successive letter denotes a quarter of the previous subdivision, thus the first letter denotes the quarter section, the second letter the quarter-quarter section, and so forth.

GENERAL GEOLOGY

Stratigraphic Units and Water-Bearing Characteristics

The Sonoita Creek basin is underlain mainly by alluvium ranging from Tertiary to Recent age. The alluvial deposits are surrounded on the south, west, and east by volcanic rocks of Miocene ? age (Schrader 1915, pp. 71, 75). Volcanic rocks crop out on the border of the basin and culminate in peaks rising from 1000 to 1300 feet above the valley floor.

The alluvium which underlies the basin is divided into five units according to their stratigraphic and topographic positions, lithology, and relative degrees of permeability.

Alluvial unit No. 5 was deposited on the basement rocks of the Sonoita Creek basin. The unit is composed of erosion products of volcanic rocks from high hills. Following partial erosion of unit No. 5, alluvial unit No. 4 was deposited. Alluvial unit No. 4 crops out over most of the basin. Partial erosion of alluvial unit No. 4, and tilting to the northwest of units No. 5 and 4 preceded the deposition of unit No. 3. Unit No. 3 was stripped in much of the area during periods of erosion that proceeded in steps. Several terrace levels resulted and unit No. 2 is the deposit covering the terrace levels. The youngest and lowest deposit was laid down in relative deep channels under the present stream flood plain and forms alluvial unit No. 1.

There is an unconformity between the underlying volcanic rocks and the alluvium, and there are also several local unconformities between each of the alluvial units.

The volcanic rocks generally are impermeable. The alluvial units generally are permeable and their degree of permeability depends on sorting, degree of cementation and compaction, and shape and size of particles.

Volcanic rocks

The volcanic rocks in the area are predominantly andesite and rhyolite, and are of Miocene ? age (Schrader 1915).

Andesite

The andesite is dense dark grey volcanic rock that crops out in the areas surrounding the basin except in the north where the alluvium covers the bedrock, and in the southeast where the rhyolite is exposed. Andesite has a glassy groundmass, and is highly fractured in the outcrop areas (Figure 3). The average exposed thickness of the andesite in Sonoita Creek basin is approximately 500 feet.

Rhyolite

The rhyolite is a light grey, massive, siliceous rock. It is commonly highly weathered, and

Figure 3. Outcrops of the Andesite Volcanic Rocks South of Patagonia

stained reddish brown by iron oxide. Most of the exposures of rhyolite occur in the southeastern part of the Sonoita Creek basin. The approximate exposed thickness is 2000 feet. It is impregnated by a low percentage of pyrite and chalcopyrite, and has a speckled appearance, as a result of the oxidation of these minerals, to limonite and sulphuric acid (Schrader 1915, p. 75).

Andesite and rhyolite generally are considered poor water-bearing rocks because of their imperviousness, but where they are weathered and fractured, as in the eastern area of the Sonoita Creek basin, the rocks are considered to be good to medium aquifers.

Alluvium

Alluvial unit No. 5

Alluvial unit No. 5 is a consolidated brownish-red to brownish-grey conglomerate that crops out on the edge of Red Mountain, southeast of the Sonoita Creek basin. The alluvial unit No. 5 rests nonconformably on the volcanic rocks and is overlain in angular unconformity by alluvial unit No. 2 (Figure 4) where units No. 4 and 3 are eroded. The beds have been tilted to a maximum of 8°NW as the result of extensive faulting. The faults displace unit No. 5 and the volcanic rocks in the southeastern part of the area.

The rock fragments in alluvial unit No. 5 range in size from coarse sand to pebbles, cobbles and boulders as

Figure 4. Outcrops and Contacts of Units No. 2 and No. 5 Along Harshaw Road

Figure 5. Outcrop of Alluvial Unit No. 5 Along Harshaw Road

much as two feet in diameter (Folk, 1961). The pebbles, cobbles, and boulders are similar to those cropping out in Red Mountain (Figure 5). The constituent grains in this unit are so firmly cemented that in some places the rock breaks indiscriminately across cobbles and matrix.

The exposed thickness of the conglomerate is approximately 100 feet. About 400 feet of this rock type were penetrated in a well drilled in D22-16-5 acaa (Appendix 2 and Plate 3). Alluvial unit No. 5 has low to medium permeability principally due to the deposition of cementing material in the void spaces of the rock which has reduced the original high permeability of this formation. Groundwater in alluvial unit No. 5 occurs primarily in fracture and in the reduced pore space between grains.

Alluvial unit No. 4

Alluvial unit No. 4 consists of unconsolidated greyish-pink gravel which crops out in most of the Sonoita Creek basin. The unit nonconformably overlies the volcanic rocks and is unconformably overlain by alluvial unit No. 2 (Figure 6). It is generally tilted to the northwest. A dip of 25° NW was measured on this unit west of Patagonia.

Alluvial unit No. 4 is a poorly cemented, moderately sorted sandy gravel. A size analysis of a sample collected from a road cut near Rail X ranch shows 40.38

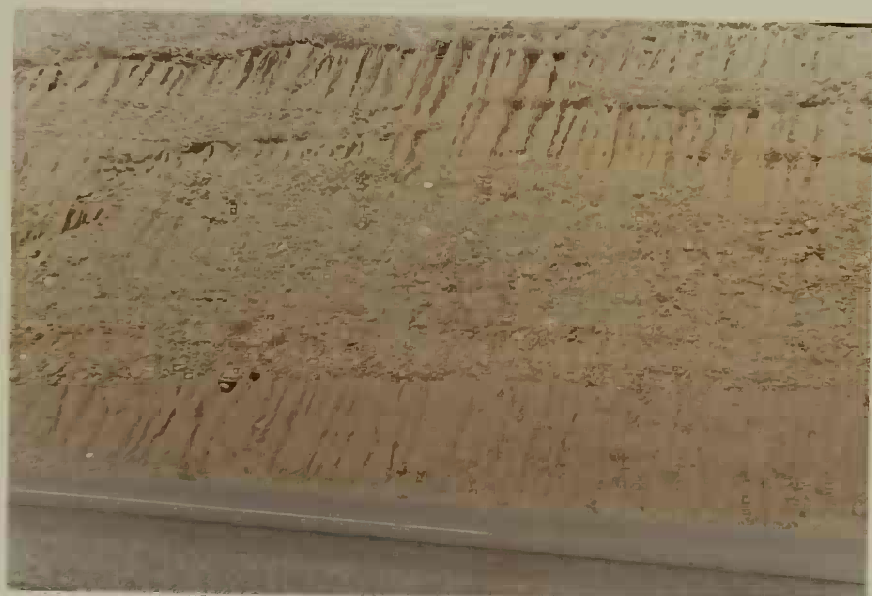

Figure 6. Outcrops of Alluvial Units No. 2 and No. 4, and Their Contact in the North Near Rail X Ranch

percent gravel, 56.46 percent sand, and 3.23 percent silt and clay (Table 2).

The average exposed thickness of the alluvial unit No. 4 is about 50 feet, but from the examination of drillers' logs (Appendix 2) the average total thickness is about 150 feet (Plate 3).

The precise age of this unit is not known but Lance (1960, p. 156) reported the discovery of a fossil tooth of a horse Neohipparion, in the cuttings from a well near Sonoita. The tooth was found in alluvial unit No. 4 and is considered to be of Middle Pliocene age.

Alluvial unit No. 4 generally is the most permeable water-bearing unit in the Sonoita Creek basin, and yields large volumes of water for irrigation and domestic uses. Nearly all of the irrigation wells and many of the domestic wells tap alluvial units No. 1 and No. 4. High capacity wells obtain much of their water from unit No. 4, but most of these wells also obtain small amounts of additional water from unit No. 1. The average depth of wells, water levels, and discharges are listed in Table 1 and located on the map (Plate 1).

Alluvial unit No. 3

Alluvial unit No. 3 is unconsolidated brown gravel that crops out in the eastern side of the Sonoita

Creek basin. This unit rests unconformably on alluvial unit No. 4, and is unconformably overlain by alluvial unit No. 2.

Alluvial unit No. 3 ranges in size from clay and silt to pebbles and cobbles of one foot in diameter (Folk, 1961). The exposed thickness of this unit is about 100 feet.

Most of unit No. 3 lies above the zone of saturation. Locally, the unit may contain small bodies of perched water, but these are of little economic significance for irrigation purposes.

Alluvial unit No. 2

Alluvial unit No. 2 is unconsolidated gravel which forms the terraces on both sides of the Sonoita Creek. It ranges from fine clay to pebbles, cobbles and boulders up to two feet in diameter. The gravels are largely locally derived, unstratified, weakly cemented, and poorly sorted with a matrix of heterogeneous mixture of silt, sand, and gravel. The estimated porosity is about 30 percent.

A size analysis of a sample of alluvial unit No. 2, collected from a road cut in the northern part of the area, shows 30.32 percent gravel, 61.81 percent sand; and 8.97 percent silt and clay (Table 2).

Alluvial unit No. 2 unconformably overlies unit No. 4 (Figure 7) and unit No. 3. The average exposed thickness is about 60 feet, but according to the writer's interpretation of drillers' logs, its maximum thickness is about 80 feet. This unit is permeable but, unfortunately, it is also above the zone of saturation in the outcrop areas. The unit contains small bodies of perched water as indicated in well D22-16-5 acaa.

Alluvial unit No. 1

The designation alluvial unit No. 1 is used for the unconsolidated sand, silt, clay and gravel stream deposit that directly underlies the flood plains of Sonoita Creek and its tributaries. The outcrop of this unit ranges in width from less than a quarter of a mile to two miles, but averages less than a quarter of a mile. The widest exposure is in the confluence area where Harshaw Creek joins Sonoita Creek half a mile north of Patagonia.

Unit No. 1 unconformably overlies alluvial unit No. 3 and is horizontally stratified, indicating that it has not been affected by tilting. The average exposed thickness of unit No. 1 is about 20 feet, but data from drillers' logs show the average thickness of the unit to be about 80 feet. This unit is younger than unit No. 2, but topographically lower. The Sonoita Creek basin has

Figure 7. Outcrop Showing the Detailed Lithology of Units No. 2 and No. 4 and Their Contact in the North Near Rail X Ranch

gone through cycles of erosion as a result of changing the base level of the creek. After the formation of the terraces from deep erosion of alluvial unit No. 2, deposition of alluvial unit No. 1 was followed. The base level might be changed as a result of climatic fluctuations or in tilting of the sediments.

Alluvial unit No. 1 is unconsolidated poorly sorted, fine to coarse grained, and weakly cemented. A size analysis made on a sample collected from the creek near Patagonia shows 71.74 percent sand; 21.01 percent silt and clay; and 7.27 percent gravel (Table 2).

Most exposures of unit No. 1 have medium permeability which is due to the presence of fine material filling part of the pore spaces which helps in decreasing the permeability. This unit ranks second to unit No. 4 as an aquifer and constitutes a productive aquifer in the basin. Most of the wells in Sonoita Creek basin have been drilled into this unit but their discharges are not sufficient for large irrigation projects. Some wells which tap both alluvial units 1 and 4 yield sufficient water for irrigation purposes.

TABLE 1

WELL INVENTORY OF SONOITA CREEK BASIN

Well	Year Drilled	Depth (ft.)	Type of Well	Diam.	Pump	Type of Aquifer	Use	Static Water Level	Discharge	Height Above Mean Sea Level (ft.)
21-16-31 ddd	1945	110	Hand dug and drilled	8"	Wind mill	Units 1 + 3	Dom.	15	Est. 5 gpm	4180
22-16-6 abd	1950	100	Hand dug and drilled	8"	Wind mill	Units 1 + 3	Dom.	17	Est. 10 gpm	4100
22-16-6 dcb	1955	95	Hand dug and drilled	8"	Wind mill	Units 1 + 3	Aban.	28		4080
22-16-6 dcbb	1950	100	Drilled	8"	Elec.	Units 1 + 3	Dom.	27	Est. 20 gpm	4080
22-16-6 dca	1952	110	Drilled	10"	Elec.	Units 1 + 3	Dom.	11		4075
22-16-12 bba	1950	90	Hand dug and drilled	8"	Wind Mill	Units 1 + 3	Aban.	11		4070

TABLE 1 (Contd)

Well	Year Drilled	Depth (ft.)	Type of Well	Diam.	Pump	Type of Aquifer	Use	Static Water Level	Discharge	Height Above Mean Sea Level (ft.)
22-16-6 dcc	1962	100	Drilled	10"	Elec.	Units 1 + 3	Dom.	10.5	Est. 300 gpm	4070
22-16-7 bbd	1963	80	Drilled	10"	Elec.	Units 1 + 3	Dom.	12		4056
22-16-7 bbc	1960	80	Drilled	10"	Elec.	Units 1 + 3	Dom.	12		4056
22-16-7 bdb	1950	80	Drilled	8"	Elec.	Units 1 + 3	Dom.	13		4058
22-16-7 bdba	1950	90	Drilled	8"	Wind Mill	Units 1 + 3	Aban.	13		4058
22-16-7 aab	1955	120	Drilled	8"	Wind Mill	Units 1 + 3	Dom.	12		4070
22-16-7 aada	1957	100	Drilled	8"	Elec.	Units 1 + 3	Dom.	12		4070
22-16-7 aabc	1959		Drilled	16"		Units 1 + 3	Aban.	9.6	600 gpm	4075
22-16-7 aac		80	Drilled	8"	Wind Mill	Units 1 + 3	Dom.	11		4070

TABLE 1 (Contd)

Well	Year Drilled	Depth (ft.)	Type of Well	Diam.	Pump	Type of Aquifer	Use	Static Water Level	Discharge	Height Above Mean Sea Level (ft.)
22-16-7 acb	1945		Drilled	8"	Wind Mill	Unit 3	Aban.		Est. 10 gpm	4110
22-16-7 acd	1950	150	Drilled	8"	Wind Mill	Unit 3	Dom.	113	Est. 5 gpm	4150
22-16-7 ddc	1964	300	Drilled	10"		Unit 3	Aban.	198		4220
22-16-7 aadd	1952		Drilled	8"	Wind Mill	Units 1 + 3	Dom.	12		4070
22-16-7 bcd	1958		Drilled	8"	Wind Mill	Units 1 + 3	Dom.	13		4050
22-16-7 bcdd	1960		Drilled	8"	Elec.	Units 1 + 3	Dom.	13.2	Est. 50 gpm	4050
22-16-9 bac	1955	300	Drilled	8"	Wind Mill	Units 1 + 3	Dom.	43		4090
22-16-9 cdd		±150	Drilled	8"	Wind Mill	Units 1 + 3	Live-stock	23		4200
22-16-31 daa	1957	±100	Drilled	8"	Wind Mill	Units 1 + 3	Dom.	24		4250

TABLE 1 (Contd)

Well	Year Drilled	Depth (ft.)	Type of Well	Diam.	Pump	Type of Aquifer	Use	Static Water Level	Discharge	Height Above Mean Sea Level (ft.)
22-16-30 dba		+100	Drilled	8"	Wind Mill	Units 1 + 3	Live-stock	24		4400
22-16-29 aba		+100	Drilled	8"	Wind Mill	Units 1 + 3	Live-stock	48		4250
21-16-17 cac		+200	Drilled	10"	Elec.	Unit 3	Irrig.	107		4320
21-16-8 cda			Drilled		Wind Mill	Units 1 + 3	Aban.	25		4400
21-16-9 caa		150	Drilled		Wind Mill	Units 1 + 3	Dom.	45		4390
21-16-8 add	1950		Drilled	8"	Wind Mill	Units 1 + 3	Live-stock	87		4450
21-16-28 cca		+250	Drilled	8"	Wind Mill	Unit 3	Live-stock	120	5	4260
21-16-32 dab		100	Drilled	8"	Elec.	Units 1 + 3	Dom.	16.6	25	4130
21-16-32 dcd		+100	Drilled	8"	Wind Mill	Units 1 + 3	Live-stock	16		4130

TABLE 1 (Contd)

Well	Year Drilled	Depth (ft.)	Type of Well	Diam.	Pump	Type of Aquifer	Use	Static Water Level	Discharge	Height Above Mean Sea Level (ft.)
22-16-4 add	1955	80	Hand dug and drilled	8"	Wind Mill	Units 1 + 3	Dom.	15		4100
22-16-5 aca	1959	500	Drilled	8"	Elec.	Units 1 + 3	Dom.	38	10	4150
22-16-5 bdaa	1959	160	Drilled	8"	Elec.	Units 1 + 3	Dom.	12	138	4120
22-16-5 bdaab	1959	150	Drilled	16"		Units 1 + 3		11	6	4120
22-16-5 bdaba	1945	110	Drilled	16"	Elec.	Units 1 + 3	Test hde	11	15	4120
22-16-5 caca	1959	143	Drilled	12"	Elec.	Units 1 + 3	Irrig.	10	78	4105
22-16-5 cacc		97	Drilled	18"	Elec.	Units 1 + 3	Irrig.	11	1000	4090
22-16-5 caccd	1948	170	Drilled	8"	Wind Mill	Units 1 + 3		11	5	4090
22-16-5 ccad	1959	145	Drilled	16"	Elec.	Units 1 + 3	Irrig.	10	1300	4090

TABLE 1 (Contd)

Well	Year Drilled	Depth (ft.)	Type of Well	Diam.	Pump	Type of Aquifer	Use	Static Water Level	Discharge	Height Above Mean Sea Level (ft.)
22-16-5 cccd	1963	105	Drilled	16"		Units 1 + 3		13	338	4086
21-16-16 acb	1963		Drilled	18"	Elec.	Units 1 + 3	Irrig.			4300

TABLE 2

SIZE ANALYSIS FOR ALLUVIAL UNITS NO. 1, 2, AND 4

Alluvial Unit No.	Particle Size	Raw Weight	Cumulative Weight	Cumulative Percent	Individual Percent
No. 1	-2.0Ø	3.50	3.5	4.45	4.45
	-1.0Ø	2.20	5.70	7.26	2.86
	0.0Ø	8.60	14.30	18.21	10.95
	1.0Ø	13.42	27.72	35.31	17.09
	2.0Ø	12.82	40.54	51.31	16.33
	3.0Ø	11.82	52.36	66.70	15.05
	4.0Ø	9.64	61.00	77.70	12.22
	Pan	16.50	78.50	100.00	21.07
	Total	78.50			

TABLE 2 (Contd)

Alluvial Unit No.	Particle Size	Raw Weight	Cumulative Weight	Cumulative Percent	Individual Percent
No. 2	-4.0Ø	21.90	21.90	23.10	23.10
	-3.0Ø	6.75	28.65	30.22	7.12
	-2.0Ø	0.65	29.30	30.90	00.68
	-1.0Ø	00.80	30.10	31.75	.84
	0.0Ø	4.60	34.10	35.97	4.21
	1.0Ø	12.60	46.70	49.26	13.29
	2.0Ø	20.40	67.10	70.78	21.51
	3.0Ø	13.90	81.00	87.44	14.55
	4.0Ø	5.35	85.45	91.08	05.64
	Pan	8.45	94.80	100	08.91
	Total	94.80			

TABLE 2 (Contd)

Alluvial Unit No.	Particle Size	Raw Weight	Cumulative Weight	Cumulative Percent	Individual Percent
No. 4	-2.00ø	18.65	18.65	26.24	26.24
	-1.00ø	10.05	28.70	40.38	14.14
	0.00ø	9.00	37.70	53.04	12.10
	1.00ø	10.00	47.70	67.10	14.16
	2.00ø	9.60	57.30	80.62	13.50
	3.00ø	9.45	66.75	93.92	13.29
	4.00ø	3.02	69.77	98.17	4.24
	Pan	2.30	71.07	100.00	3.23
	Total	71.07			

Structural Features

The Sonoita Creek basin and the surrounding areas have been subjected to several periods of tectonic activity during Tertiary and Quaternary ages. As a result of this activity several systems of faults, folds and joints have been created.

Folding

The area west of the Sonoita Creek basin has been effected by intense folding (Rohrbacher, 1963). The major fold is trending northwest-southeast in the same direction as the basin trend. Another fold was discussed by Feth (1947) in his study of the north Canelo Hills. This fold is also trending northwest-southeast. It seems that these two major folds have played an important role in establishing the trend of the Sonoita Creek basin.

Faulting

The Sonoita Creek basin is a tectonic basin of the Basin and Range province. The alignment of the northwesterly mountain and valley areas has resulted from major movements along faults. The depth to which the rock floor of the valley has been down-faulted in relation to the volcanic mountains can be deduced from previous investigations in areas adjacent to the basin, and from recent drilling in the area. On the western side of the basin, Rohrbacher (1963, p. 62) indicated several faults trending N20°W. These faults were dated as Pliocene-Eocene age. Along the central part of the Sonoita Creek basin occur northwest dipping volcanic dikes (Figure 8) that might be a result of pre-existing fault zones.

A water well (D22-16-5acaa) penetrated 500 feet of alluvial sediments and bottomed in volcanic rocks. The volcanic strata are structurally more than 1000 feet lower than matching beds in the adjacent mountains to the east, so the rock floor of the Sonoita Creek basin has probably been displaced downward at least 1000 feet.

Jointing

A general east-west trending joint system prevails on the west side of the Sonoita Creek basin (Rohrbacher, 1963, p. 61).

Generally, structure plays an important role in controlling groundwater movement and in changing the degree of permeability of the rocks. Usually, the groundwater movement follows the dip of the strata, especially where the strata have moderate to low permeability, and where cementation has caused a decrease in pore space in the consolidated rocks. The presence of faults in certain cases provides secondary permeability. The writer believes that faulting in the alluvial units has been in part a

Figure 8. Exposure of the Volcanic Dike East of Patagonia

contribution toward the development of permeable zones, and influences the yields of two wells in the Sonoita Creek basin. Wells 5caccc and 5ccad penetrate units No. 1 and No. 4, and yield more than 1000 gpm. This yield is five times more than that supplied by other wells in the Sonoita Creek basin that tap the same alluvial units.

GENERAL HYDROLOGY

Occurrence of Groundwater

Groundwater may be defined as the water that is available to wells or is discharged through streams or springs. The ultimate source of most of groundwater is from precipitation in the form of rain or snow. Part of the precipitation runs off from the surface of the ground directly into streams, and part is returned to the atmosphere by evapotranspiration and the remainder infiltrates into the subsurface reservoir as potential recharge to the aquifers.

Groundwater occurs under water table condition in areas where water infiltrates downward through pore spaces in the ground to the zone of saturation. The upper surface of the zone of saturation is the water table.

Artesian confined conditions exist where the water-bearing formation (aquifer) is overlain by a less permeable formation (aquiclude) and the water in the aquifer is under sufficient hydrostatic pressure to produce a water level which will rise above the interface between the aquiclude and the aquifer.

In the Sonoita Creek basin the water in the principal aquifer, alluvial unit No. 4, is locally under artesian hydrostatic pressure (semi artesian), and thus the wells in those areas are considered semi-artesian wells.

Recharge

The major source of recharge to the basin aquifers is from precipitation. Rain water on land surface is absorbed by the soil, unless the rate of precipitation exceeds the rate at which the soil will accept it. The precipitation rejected by the soil becomes runoff and flows into gullies and rills, then into the main creek. Water that infiltrates the soil in excess of the ability of the soil to hold it as soil moisture continues to move downward to the zone of saturation and becomes groundwater.

In addition to the precipitation, the basin receives water from the springs on the margin of the basin. Monkey spring, located one-half a mile northeast of the mapped area, is the largest of these. The yield of Monkey spring is 450 gpm (Feth, 1947, p. 134). Most of the water is used for irrigation in that area and probably seeps into the alluvium in the basin and reaches the shallow groundwater.

Discharge

Groundwater leaves the basin sediments by artificial and natural discharges.

Artificial recharge is represented by the pumping of water wells. Most of the groundwater pumped from the basin is through irrigation wells. Minor amounts are pumped from the wells of the town of Patagonia for domestic purposes. The yield of irrigation wells ranges from 100 to 1300 gpm. They are constructed of 8" to 18' diameter pipes and depths vary from 80-200 feet (Table 1). The estimated average discharge through pumping is about 338 acre feet per year from about 45 wells (Halpenny and others, 1964, p. 11).

Natural discharge includes the stream flow to Sonoita Creek and the loss through evapotranspiration.

Sonoita Creek below Patagonia is the only perennial stream in the area. The measurements of the streamflow two miles downstream from Patagonia which were made by the U. S. Geological Survey indicate that a year-round average of 5085 acre feet per year rises to the surface downstream from Patagonia (Halpenny and others, 1964). The writer measured the stream flow at the same section during August, 1966, and the yield was 15,300 acre feet per year. Another section, 200 feet downstream from Patagonia, was measured at the same time and the yield was

4050 acre feet per year. The downstream increase in flow is due to the contribution of groundwater to the surface flow of the stream (Figures 9 and 10).

The loss of groundwater through evapotranspiration in the Sonoita Creek basin varies over the area. The amount of evapotranspiration a mile north of Patagonia is believed to be negligible due to the deep water table in that area, but the amount of evapotranspiration south of this area is believed to be high due to shallow water table. Evapotranspiration plays an important role in the discharge of groundwater in the basin from the phreatophytes which occur over most of the basin. The amount of groundwater that may be utilized by phreatophytes and vegetation is conditioned by the species of the plant, the depth of the roots, the density of the plant growth on the surface, the length of the growing season, the depth to the water table, and the climate. The varieties of the phreatophytes in the basin are alfalfa, mesquite, and saltbush. Most of the area is covered by mesquite which is capable of sending its roots to more than 30 feet below the land surface. The area of the mesquite covers is about two square miles (1280 acres), and its density is about 50 percent surface covered. Mesquite of 100 percent covered surface in Safford Valley, 80 miles northeast of Tucson, Arizona, where depth to water is 10 feet, used a total of

Figure 9. Point of Effluent Flow in Sonoita Creek, 200 Feet Downstream from Patagonia

Figure 10. Sonoita Creek Stream Flow Two Miles Downstream from Patagonia

more than 3 acre-feet of water per acre in 1943-44 (Gatewood and others, 1950, p. 203). But due to lower density and deeper water table in the Sonoita Creek basin, one or less acre-feet of water is used. The area of the phreatophytes is 1280 acres, so the estimated discharge through evapotranspiration in the Sonoita Creek basin is about 1280 acre feet. Therefore, the total estimated yearly discharge from the basin is 6700 acre feet which is the summation of the discharge from pumping, from the Sonoita Creek stream outflow, and from the evapotranspiration.

Water Level Fluctuations

The water level in the Sonoita Creek basin fluctuates primarily in response to variations in recharge and discharge. These fluctuations are reflected by water level changes in wells which provide information on the change in groundwater storage. The water table of 1966 in the town of Patagonia is slightly above the level of the stream flow, but upstream the water table is deeper.

The water level in 1966 has risen 25 feet from the water level of 1965 (Figure 11) which indicates that the recharge to the basin is much higher than the total discharge out of it. Usually, the water level rises in February, declines in April, and continues declining until the middle of August when it again rises. The area

FIGURE. 11 Water level fluctuations for six years in well (22-16-5cccd) in Sonoita Creek basin

receives high quantities of rainfall in January-February and August-September. During 1966 the seasonal water level fluctuations were different from the other years in that the water level started rising in January and continued rising until September of the same year (Figure 12).

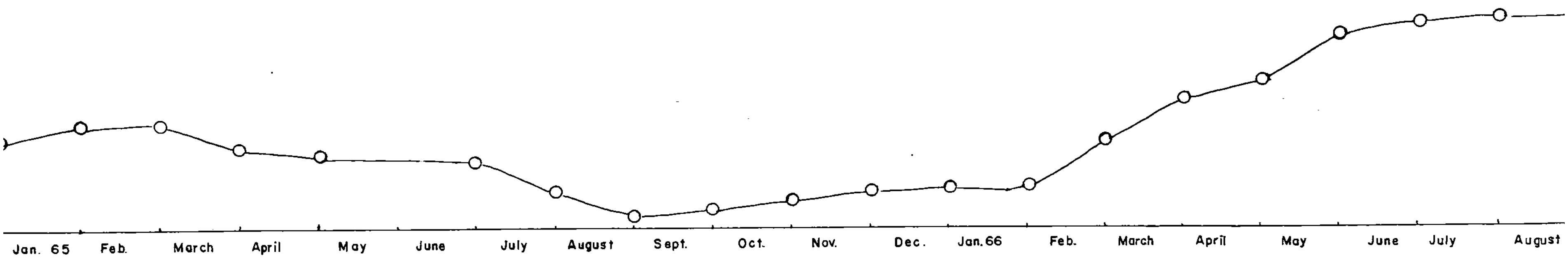

FIGURE. 12 Seasonal fluctuations of the water level in well 5caccd in Sonoita Creek basin

MOVEMENT OF GROUNDWATER

The general movement of groundwater in the Sonoita Creek basin is shown by the water contour map (Plate 2). A flow net constitutes a graphical solution of the pattern of groundwater movement in the aquifer. It is composed of two sets of lines: equipotential lines represent contours of equal head in the aquifer and stream lines or flow lines represent the path a droplet of water follows as it moves through the aquifer in the direction of decreasing head. Equipotential lines and flow lines intersect at right angles. The equipotential lines indicate that recharge occurs at the mountain fronts and that groundwater moves toward the central part of the valley, where it moves through the alluvial unit No. 1, with a slight angle to the south, and follows the channel fill.

The elevation of the water table at Rail X ranch in the north is about 4450 feet above sea level, while at Patagonia in the south, the water table elevation is 4050 feet. The distance between the two locations is 7 miles. Therefore, the average hydraulic gradient is 57 feet per mile which is relatively steep.

The groundwater in the Sonoita Creek basin moves towards the south as an influent flow all over the basin. The influent flow becomes effluent flow, 200 feet downstream from Patagonia, as a result of the impervious outcrops of volcanic rocks which cause the groundwater to discharge into the stream channel as perennial stream flow. The volcanic rocks which forced the groundwater to discharge on the surface outcrop are located one-half a mile southwest of Patagonia (Plate 1).

QUANTITATIVE CHARACTERISTICS

The amount of water that a material can hold is a direct function of its porosity. Where the pore spaces are large and interconnected, as they commonly are in sand and gravel, water is transmitted freely and the material is said to be permeable. But when the pores are small, as in clay, water is transmitted slowly and the material is considered to have low permeability.

A measure of the ability of a material to transmit water is given by the coefficient of permeability, P, which is defined as the rate of flow of water in gallons per day through a cross-sectional area of one square foot under hydraulic gradient of 100 percent at a temperature of 60°F. Theis (1935) introduced the term coefficient of transmissibility, T, which is usually determined in the field by pumping tests and may be defined as the number of gallons of water transmitted in one day through a vertical strip of the aquifer one foot wide having a height equal to the saturated thickness of the aquifer under a hydraulic gradient of 100 percent at prevailing groundwater temperature. The permeability multiplied by the thickness of the aquifer, in feet, is equal to coefficient of transmissibility. The volume of water released from storage or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to the surface is representing the coefficient of storage. The coefficients of storage and transmissibility are the principal hydraulic characteristics of an aquifer used in computations used in groundwater flow.

In order to determine water resources of the Sonoita Creek basin it is essential to estimate the aquifer characteristics by water level measurements, pumping tests, construction of flow nets, and by interpretation of the geological data available. All the quantitative characteristics of the area have been calculated from the data collected by Halpenny, Green, and Dausinger and by construction of flow net for the basin. The data available are incomplete but the writer has used the following techniques to estimate the quantitative characteristics of the alluvial units:

1. Theis matching curve method for estimating the coefficient of transmissibility and coefficient of storage.

2. Determination of the coefficient of transmissibility using the specific capacities of pumping tests.

3. The flow net method.

Theis, utilizing an analogy of the flow of groundwater to the flow of heat by conduction, developed the non-equilibrium formula for computing the coefficients of storage and transmissibility.

$$s = \frac{Q}{4\pi T} \int_{r^2 s / 4T_o}^{\infty} \frac{e^{-u}}{u} \, du \qquad (1)$$

Using the ordinary survey units, equation (1) may be written as

$$s = \frac{114.6Q}{T} \int_{\frac{1.87r^2S}{T_t}}^{\infty} \frac{e^{-u}}{u} \, du \qquad (2)$$

Equation (2) is changed to

$$s = \frac{114.6Q\ W(u)}{T} \qquad (3)$$

and

$$u = \frac{1.87\ r^2S}{T_t} \qquad (4)$$

But under steady state condition, equation (1) reduces to

$$s = \frac{Q}{4\pi T} [-.5772\ \text{In}\ u] \qquad (5)$$

which is equal to

$$s = \frac{Q}{4\pi T} [-.5772 \log_e \frac{4T_t}{r^2S}] \qquad (6)$$

$$s = \frac{Q}{4\pi T} \log_e \frac{2.25\ T_t}{r^2S} \qquad (7)$$

Writing drawdown for two different wells at distances r_1 and r_2 and substitution from equation (7)

$$s_1 - s_2 = \Delta s = \frac{Q}{4\pi T} \text{In } r_2/r_1 \qquad (8)$$

In survey field units,

$$T = \frac{527.7 \ Q \log r_2/r_1}{\Delta s} \qquad (9)$$

$$= 527.7 \frac{Q}{\Delta s} \log r_2/r_1 \qquad (10)$$

and if $\frac{Q}{\Delta s}$ = specific capacity, equation (10) reduces to the form

$$T = 527.7 \ C_s \log r_2/r_1 \qquad (11)$$

If the pumping well has a radius of one foot and the distance (r_2) is 10,000 feet, then

$$T = 527.7 \times C_s \times 4.0$$

$$T \approx 2000 \ C_s.$$

And if r_2 = 50,000, then

$$T = 527.7 \times C_s \times 4.29$$

$$T \approx 2000 \ C_s \qquad (12)$$

where s = drawdown, in feet, at observation well

Q = discharge, in gallons, per minute

T = coefficient of transmissibility

r = distance, in feet, from observation well to pumped well

S = coefficient of storage

t = time, in days, since pumping started

$u = 1.87\ r^2/S/T_t$

(1) Application of Theis matching curve method in the field by using pumping tests

Theis matching curve method has been applied for two pumping wells (5caccc and 5bdaaa) of 100 and 160 feet depths. The first well has tapped alluvial Units No. 1 and No. 3 and the second well has tapped units No. 1, No. 3 and No. 4 (Plate 3). As only one observation well was used to measure drawdown in each pumping test, the data of both the observation wells (Appendix I) was plotted (Figures 13 and 14) on log/log paper and, by matching it with the Theis type curve, the apparent parameters were obtained (Table 3).

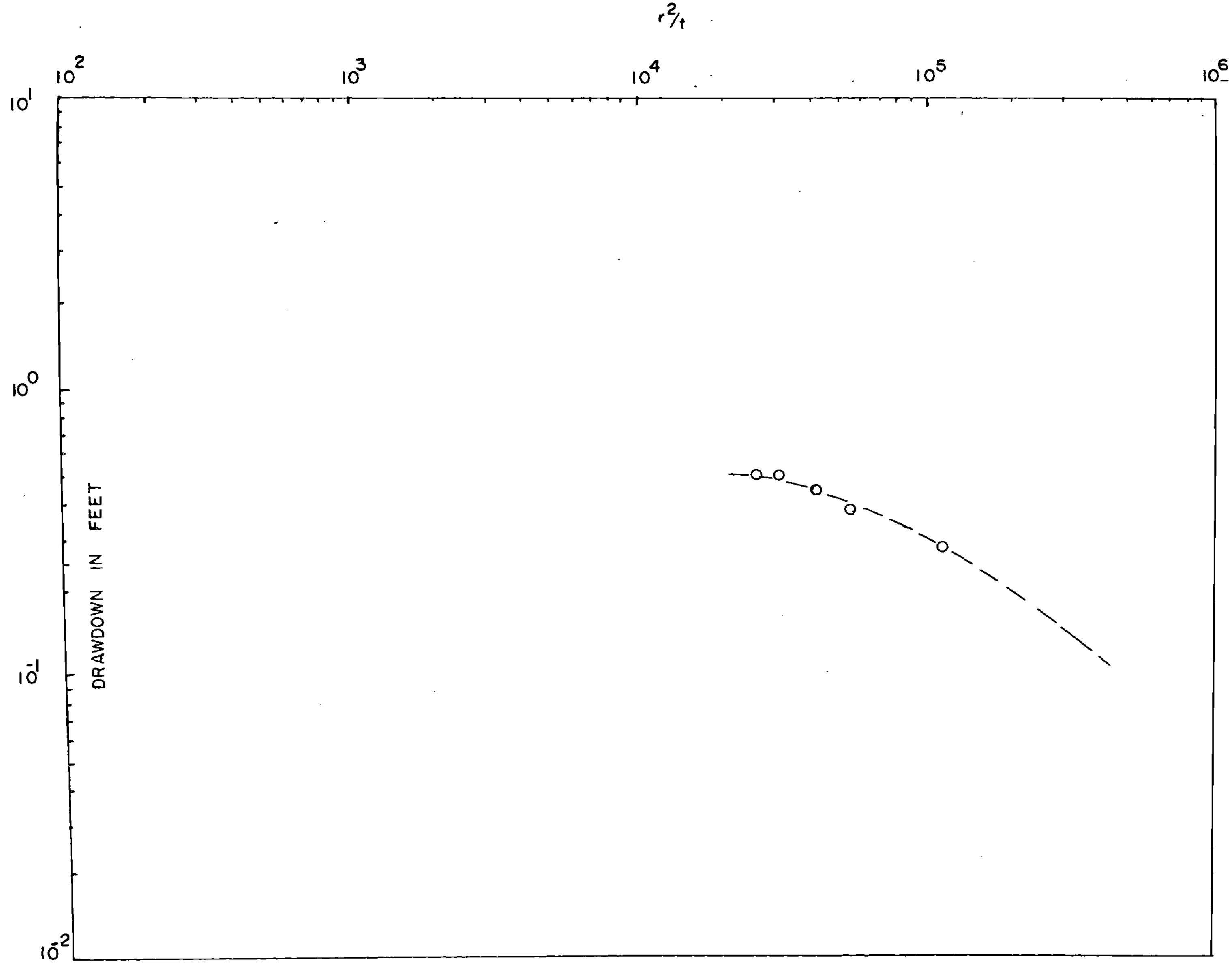

FIGURE. 13 Hydrograph of results obtained from a pumping test in well 5caccc in Sonoita Creek basin

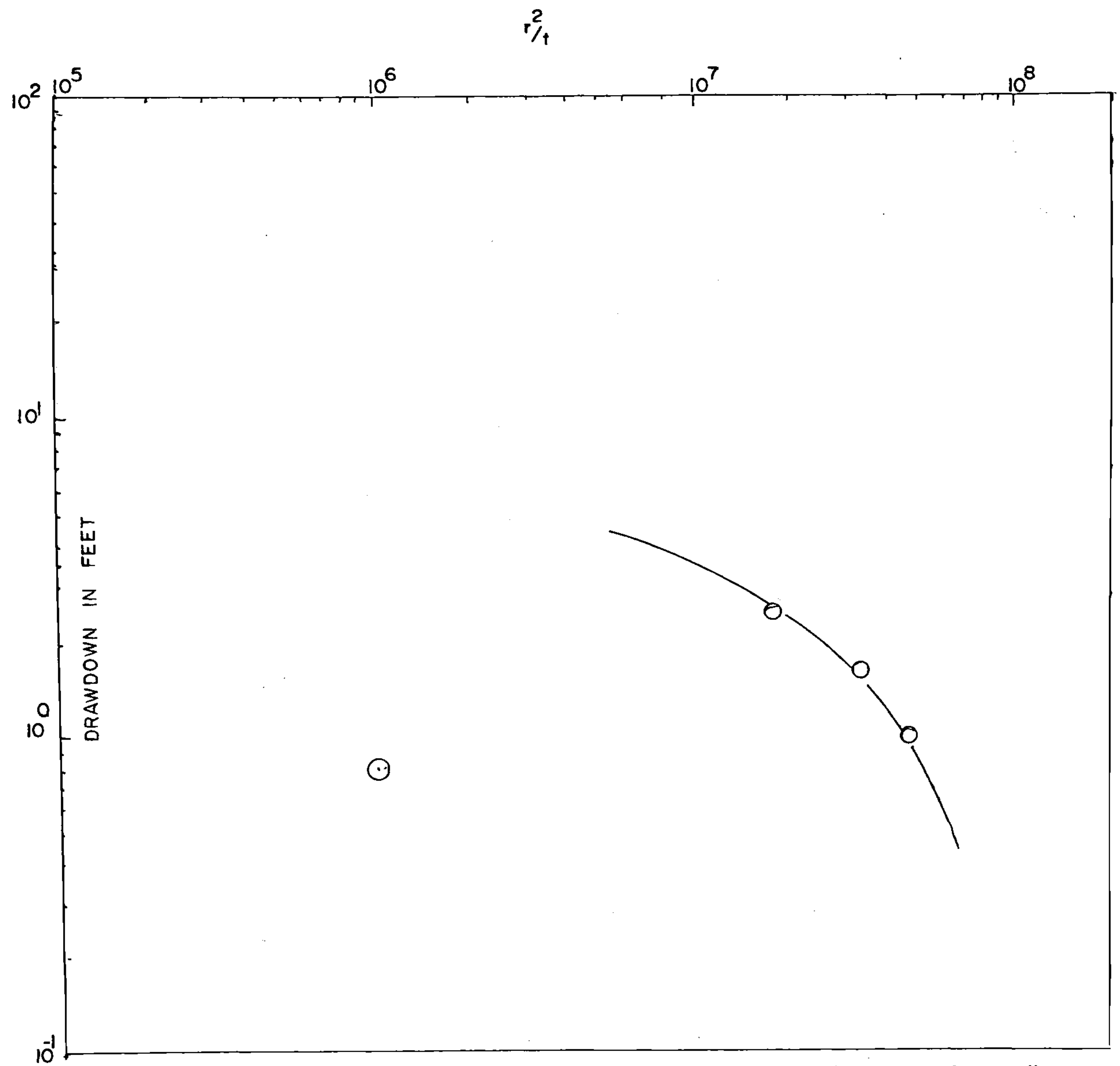

FIGURE. 14 Hydrograph of results obtained from a pumping test in well 5bdaaa in Sonoita Creek basin

TABLE 3

PUMPING TEST DATA FOR OBSERVATION WELLS 5caccc AND 5bdaaa AND THEIR CONSEQUENTS u AND W(u)

Pumping well	Drawdown	r^2/t	u	W(u)	Discharge in gallons per minute
5caccc	$9x10^{-2}$	10^4	$4.9x10^{-3}$	.80	192
5bdaaa	$8.0x10^{-1}$	10^6	$1.2x10^{-2}$	$4.4x10^{-1}$	150

From these parameters, the values of coefficients of storage and transmissibility have been calculated by equations (3) and (4).

(1) $$T = \frac{114.6 \text{ x } Q \text{ x } (Wu)}{s}$$

$$= \frac{114.6 \text{ x } 192 \text{ x } .80}{9 \text{ x } 10^{-2}}$$

$$= \frac{1.146x10^2x1.92x10^2x8x10^{-1}x10^2}{9}$$

$$= 1.95 \text{ x } 10^5 \text{ gallon/day/foot}$$

$$S = \frac{uT}{1.87 \; r^2/T}$$

$$= \frac{4.9 \text{ x } 10^{-2} \text{ x } 1.95 \text{ x } \not{10}^{\not{5}}}{1.87 \text{ x } \not{10}^{\not{4}}} = .0517$$

(2) $$T = \frac{114.6 \times 150 \times 4.4 \times 10^{-1}}{8 \times 10^{-1}}$$

$$= 9500 \text{ gallons/day/foot}$$

$$S = \frac{1.2 \times 10^{-2} \times 10^{-6} \times 9.5 \times 10^{3}}{1.87}$$

$$= 6.09 \times 10^{-5}$$

(2) Determining the coefficient of transmissibility by using the specific capacities of pumping wells.

Specific capacity of 5caccc well was calculated by plotting drawdown vs. discharge of the well (Figure 15).

$$C_s = \frac{\Delta Q}{\Delta s} = \frac{345 - 245}{2.5-1.7} = \frac{100}{0.8} = 125 \text{ gallons/foot}$$

A table of specific capacities of wells was prepared by using the above method (Table 4) and corresponding values of coefficient of transmissibility were calculated.

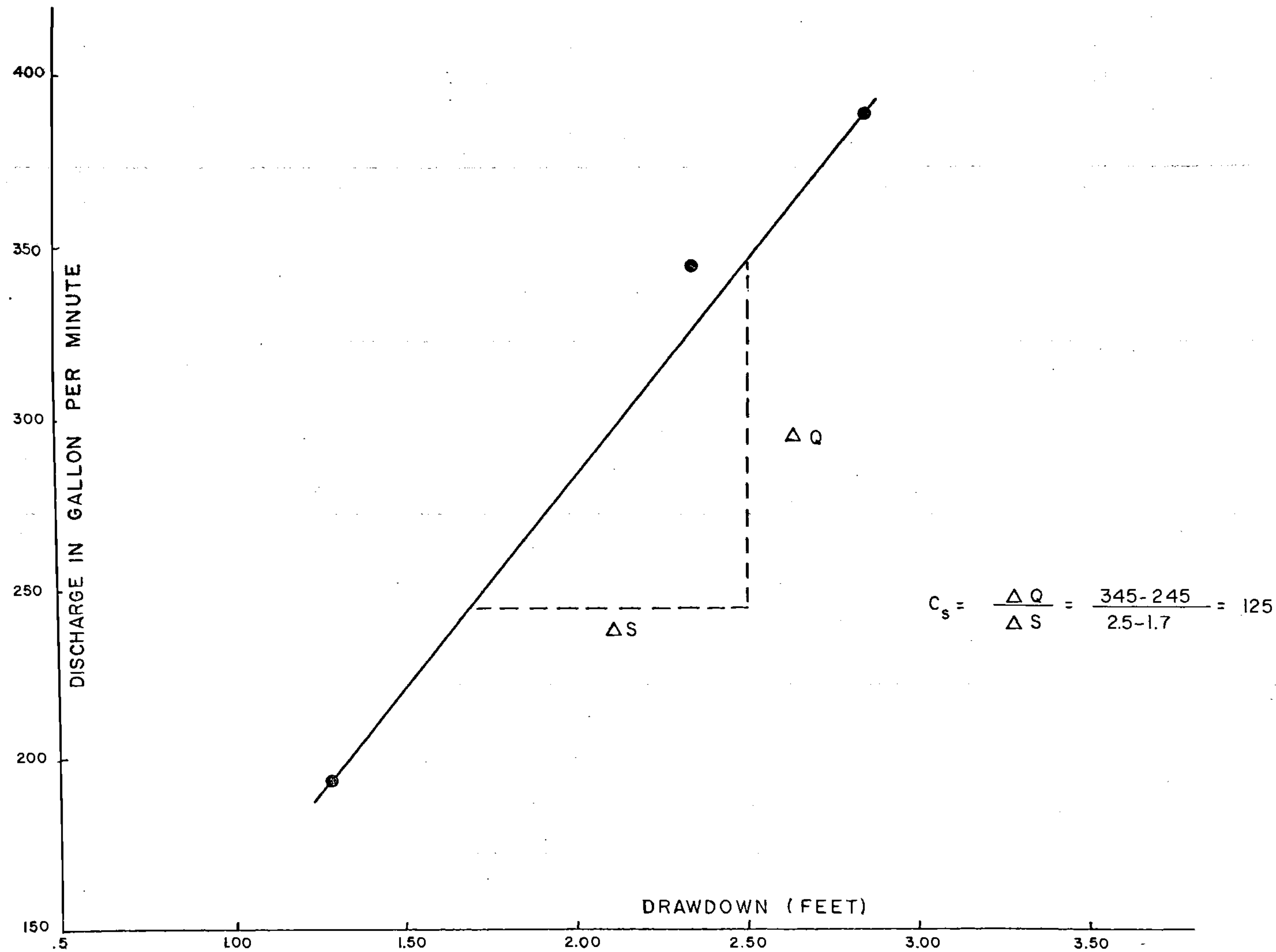

FIGURE. 15 Graph for determining the specific capacity of 5caccc well

TABLE 4

TRANSMISSIBILITIES FOR SELECTED WELLS IN THE SONOITA CREEK BASIN DETERMINED BY THEIR SPECIFIC CAPACITIES

Well	Depth in feet	Discharge in gallon/ ft	Specific cap. in gal/ft	Coefficient of Transmissibility gallons/day/ft $T = C_s \times 2000$
5bdaaa	160	138	4.5	9000
5bdaba	110	15	10	20000
5caccc	97	1000	125	250000
5ccad	145	1300	130	260000
5cccd	105	338	9	18000

Transmissibilities for selected wells were determined by using the equation (12) T (transmissibility) = C_s (specific capacity) x 2000. Various values of transmissibility were obtained either with high values as in wells (5caccc and 5ccad) or low values as in wells (5bdaaa and 5cccd), and are located within one-half a mile of each other along the flood plain of Sonoita Creek. The values obtained show that there are reasons for their discrepancies. The area west of the basin was exposed to tectonic activities during Quaternary age (Rohrbacher, 1963). The writer believes that this activity has created faulted zones in the basin, on which the high productive wells are located.

(3) Flow net method

A useful form of Darcy's law (Ferris, 1962) is given by

$$Q = TIL$$

where Q = discharge in gallons per minute

T = transmissibility in gallons per day per foot

I = hydraulic gradient

L = width of the aquifer

By construction of the flow net diagram for the Sonoita Creek basin (Plate 2), the transmissibility can be determined. By considering the portion of the flow net diagram shown on the plate south of the basin, it is possible to determine the hydraulic gradient, I, feet per mile, and width, L, in miles.

From the portion of the flow net diagram, I is equal to contour interval, 50 ft., over the distance between the two equipotential lines, 2110 ft., and the width, L, is equal to the distance between the two flow lines, 1500 ft. The discharge, Q, is measured at that area and is equal to 3,000,000 gallons per day.

Then by using equation (12)

$$T = \frac{Q}{IL}$$

$$= \frac{3,000,000 \times 2110}{50 \times 1500} = 124,000 \text{ gal per day per ft}$$

From the preceding methods, it is concluded that the average conservative figure for the transmissibility of the basin is about 100,000 gal/day/ft.

WATER QUALITY

Chemical analysis of 24 groundwater and surface samples collected in the Sonoita Creek basin are shown in Table 7. All of these wells were drilled in alluvial unit No. 1, and have penetrated alluvial unit No. 4. Water of the Sonoita Creek basin is of calcium bicarbonate, sulphate type, hard, and of moderate to high dissolved solids content. Concentrations of fluoride range between 0.3 and 0.8 ppm. The table shows that the samples contain from 215 to 1113 ppm of dissolved solids which consist mostly of sulphate, bicarbonate and calcium. The source of most of the dissolved solids in groundwater of the basin is the minerals of the weathered rocks material of the surrounding rocks. The sulphate content in the basin groundwater is variable from 6 ppm in the west of Sonoita Creek to 680 ppm in the east. The percentage of the sulphate increases from west to east approaching the rhyolite volcanic rocks which are impregnated with pyrite, chalcopyrite, and chalcocite. The pyrite is oxidized into hematite and sulphuric acid

$$4\,FeS_2 + 15O_2 + 8H_2O \rightarrow 2Fe_2O_3 + 8H_2SO_4$$

Hardness is an undesirable characteristic of water used for domestic purposes. The water of the basin is very hard exceeding 144 ppm and reaches as high as 800 ppm (Hem, 1959). This quality analysis is given in Table 5.

TABLE 5

CHEMICAL ANALYSIS OF WATER SAMPLES FROM WELLS IN THE SONOITA CREEK BASIN

Well	Analyzed by	Date of Collection	Temperature	Specific Conductivity	Calcium	Magn.	Sodium and Potassium	Bicarbonate	Sulphate	Chloride	Fluoride	Nitrate	Total Dis-solved Solids	Hardness
5bdaaa	Health Dept.	7/9/61	73°F	1050	156	24	12	202	330	6	0.5	7	635	490
5bdaab	Wadevco	9/3/59		700										
5bdbaba	U. of A.	9/26/59	66°F	875	92	9	66	178	240	8	0.8			
5bdabd	Wadevco	10/7/59	68°F	860										
5caca	Health Dept.	8/9/63		1650	76	12	29	172	136	8	.4	7	354	240
5caccc	U. of A.	8/10/59	66°F	810	155	17	35	265	285	18			636	458
5caccd	Geol. Survey	6/17/49	69°F	829	132	27	15	240	243	8	.5	11	554	438

Table 23. Anion analyses of Rose Canyon Lake water. Concentrations are expressed as mg/l.

Date	Situation	Total PO_4	NH_4-N	NO_3-N
26 August 1966	Surface	-	0.55	0.75
8 September 1966	Surface	0.29	0.81	0
23 September 1966	Surface	0.95	0.90	0.70
"	Hypolimnion	2.80	2.60	0.90
18 November 1966	Surface	0.17	0.71	0.40
2 February 1967	Surface	1.00	4.20	-
17 April 1967	Surface	1.17	Turbid	0.90

Table 24. Anion analyses of Rose Canyon inflow water. Concentrations are expressed as mg/l.

Date	Estimated flow (cfs)	Total PO_4	NH_4-N	NO_3-N	Si	SO_4
12 August 1966	20.0	0.10	0.90	1.10	0	4.0
14 August 1966	0.5					
22 August 1966	0.5	-	0.30	1.00	-	-
26 August 1966	0.5					
8 September 1966	0.5	2.29	0.30	0	-	-
23 September 1966	0.5	0.81	0.45	0.65	-	-
18 November 1966	0.5	0.21	0.20	0.10	-	-
2 February 1967	No inflow					
17 April 1967	1.0	0.65	Turbid	0.45	-	-

TABLE 5 (Contd)

Well	Analyzed by	Date of Collection	Temperature	Specific Conductivity	Calcium	Magn.	Sodium and Potassium	Bicarbonate	Sulphate	Chloride	Fluoride	Nitrate	Total Dis-solved Solids	Hardness
7bacd	U. of A.	7/9/63			140	29	23	278	300	12	.8	10	627	470
7bbcc	The Writer	8/11/66		950					300	20	0.5			350
7bcdd	The Writer	8/11/66							320	25	.5			450
7bbdd	The Writer	8/11/66							180	10	.2			320
8baca	U. of A.	9/30/61		1,150	124	71	72	258	468	26	.8	2	881	600
8bacd	U. of A.	7/9/63				52	31	248	540	13	1.3	1	966	730

CONCLUSIONS

1. The groundwater flow in Sonoita Creek basin issues on the surface as stream flow due to the impervious outcrops of volcanic rocks, 200 feet south of Patagonia.
2. Pumping tests data analyses were made to determine the qualitative characteristics of the alluvial sediment, and the average transmissibility in the area is about 100,000 gpd/ft.
3. Water supplies in the Sonoita Creek basin are obtained mainly from alluvial unit No. 4 and partly from alluvial unit No. 1.
4. The water quality, in general, is satisfactory in spite of the high concentration of sulphate which comes from the oxidation of pyrites contained in the rhyolite rocks.

APPENDIX 1

CALCULATED DATA OF OBSERVATION WELLS 5cacaa AND 5caccd

Pumping well 5bdaaa

Q = 150 gallon/minute

Observation well 5cacaa

Distance from pumping well is 1100 feet

Drawdown in feet	Time	Time in Minutes	Time in days	r^2/T
0	11.25	22	1.63×10^{-2}	7.44×10^{7}
1	11.41	38	2.64×10^{-2}	4.6×10^{7}
1.85	12.04	61	4.27×10^{-2}	3.87×10^{7}
2.55	12.43	100	6.95×10^{-2}	1.74×10^{7}

Pumping well 5caccc

Q = 192 gallon/minute

Observation well 5caccd

Distance from pumping well is 32 feet

0.29	10.17	19	1.32×10^{-2}	1.15×10^{5}
0.38	10.37	39	2.70×10^{-2}	5.65×10^{4}
0.44	10.52	54	3.75×10^{-2}	4.10×10^{4}
0.50	11.09	71	4.92×10^{-2}	3.12×10^{4}
0.51	11.23	85	5.90×10^{-2}	2.58×10^{4}

APPENDIX 2

LOGS OF WELLS IN THE SONOITA CREEK BASIN

Material	Thickness	Depth
5acaa		
Sandy soil	10	10
Soft clay, gravel	15	25
Hard clay, gravel, water	28	53
Soft clay	22	75
Layers of clay and sandstone	50	125
Soft clay and gravel	160	285
Sticky clay	10	295
Clay and gravel	20	315
Sticky clay	110	425
Clay, gravel	60	485
Soft clay, gravel	10	495
Rhyolite	5	500

APPENDIX 2 (Contd)

Material	Thickness	Depth
5bdaaa		
Dirt	10	10
Red clay	16	26
Clay, gravel	9	35
Loose gravel, seep at 45'	10	45
Tight gravel, clay	10	55
Tight conglomerate	50	105
Tight sandy clay	10	115
Tight clay, gravel	45	160
5bdba		
Sand	4	4
Gravel	10	14
Light clay, gravel	6	20
Red clay	17	37
Tight clay, gravel	14	51
5caca		
Dirt	25	25
Gravel, clay	22	47
Loose gravel and water	18	65
Red clay, gravel	40	105
Tight clay, gravel	38	143

APPENDIX 2 (Contd)

Material	Thickness	Depth
5ccad		
Dirt	9	9
Red clay	26	35
Tight gravel, clay	7	42
Gravel and water	32	74
Light clay, sand	64	138
Tight clay, gravel	7	145
5cccd		
Soil	15	15
Conglomerate	30	45
Sand and gravel, water	10	55
Muddy sand and gravel	30	85
Yellow clay with gravel	5	90
Yellow clay	5	95
Red clay with gravel	5	100
Yellow clay	5	105

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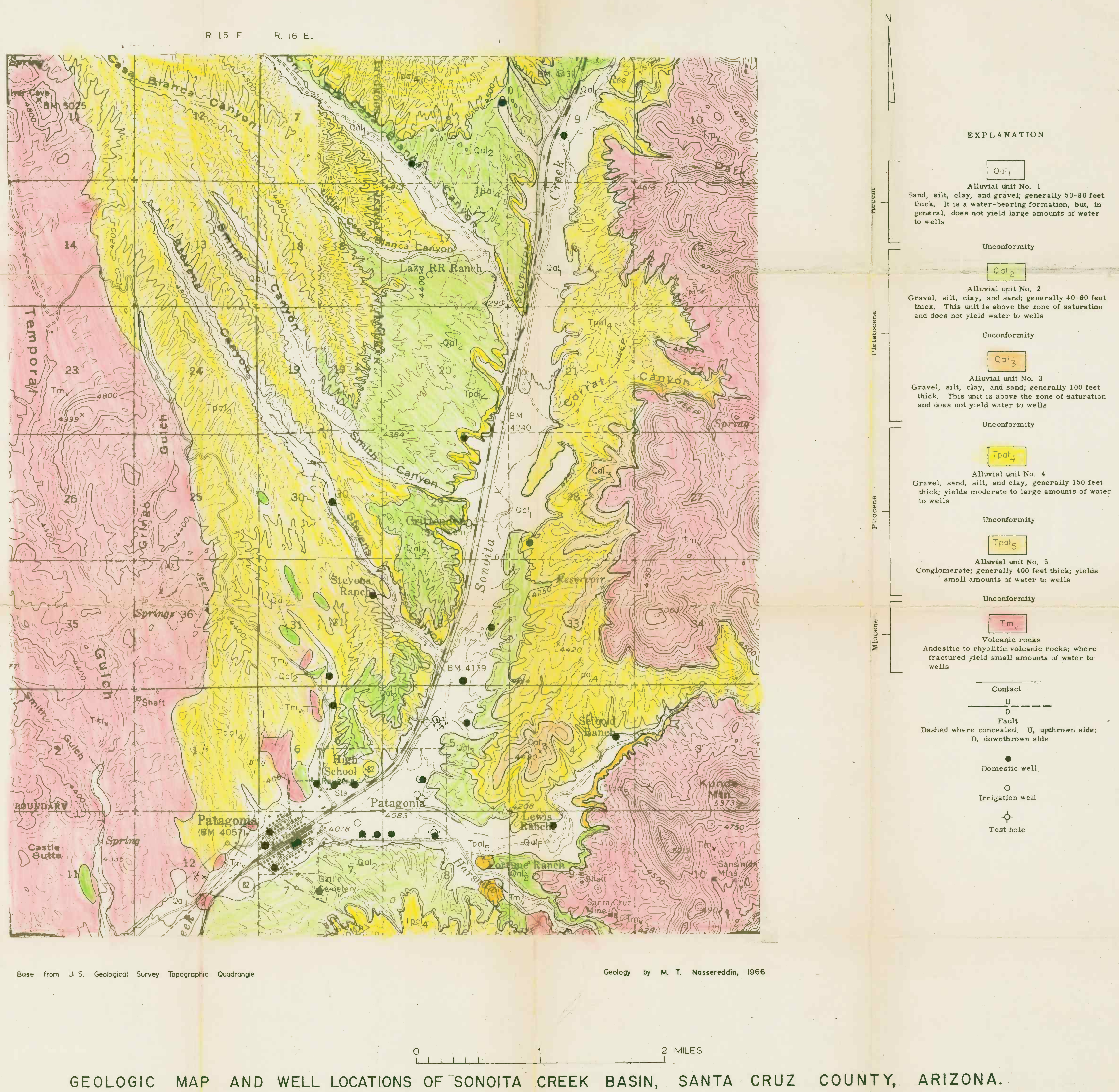
PLATE I



Base from U. S. Geological Survey Topographic Quadrangle

Geology by M. T. Nassereddin, 1966

GEOLOGIC MAP AND WELL LOCATIONS OF SONOITA CREEK BASIN, SANTA CRUZ COUNTY, ARIZONA.

PLATE 2

R. 15 E. R. 16 E.

T. 21 S.

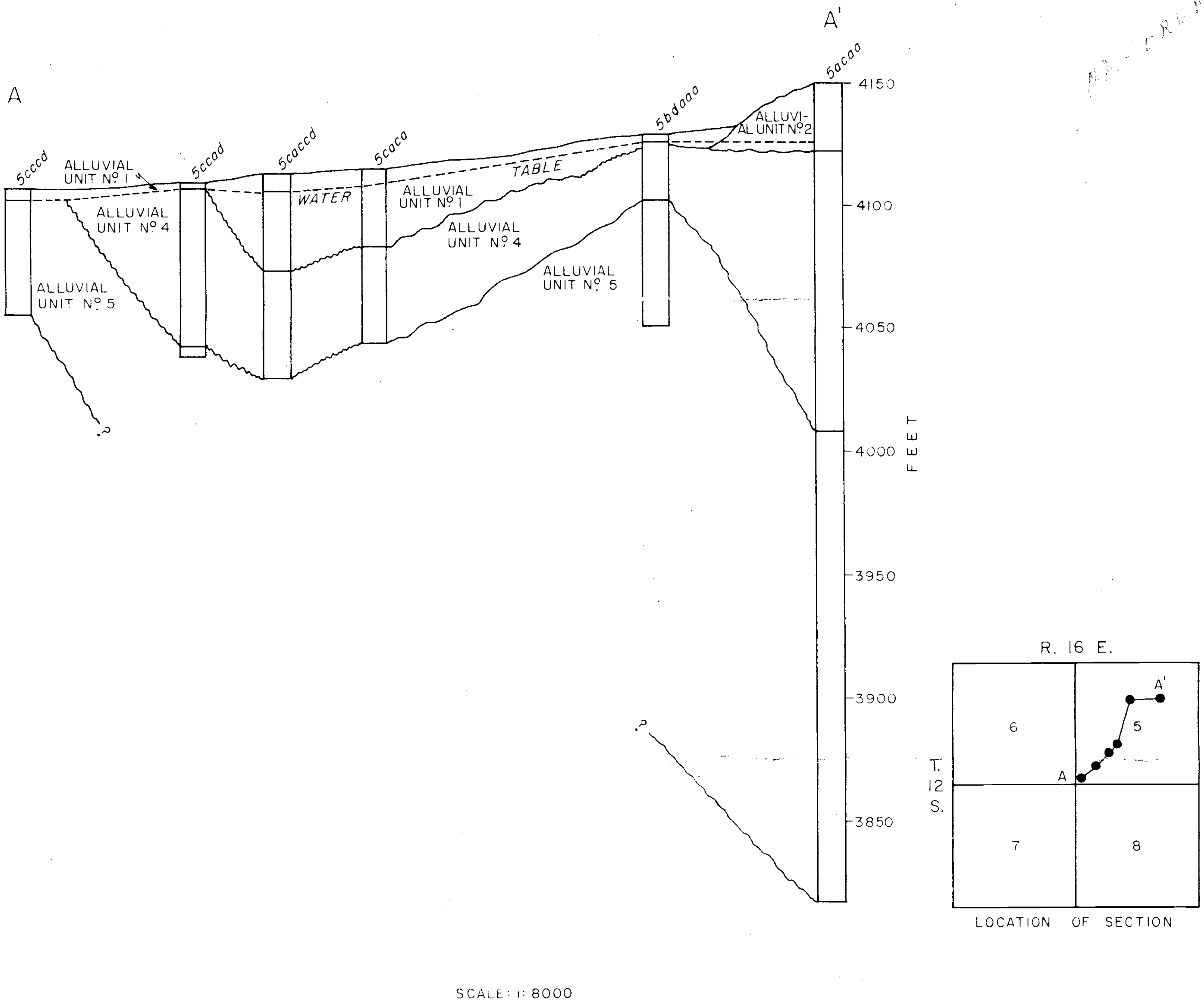
T. 22 S.

SCALE 1:24,000

GENERALIZED GROUND WATER FLOW NET DIAGRAM BASED ON 1966 WATER LEVEL CONTOURS.

E9791
1967
43

PLATE 3



HYDROLOGICAL CROSS SECTION IN SONOITA CREEK BASIN.