HYDROGEOLOGY AND AQUIFER TEST OF THE SAN ANDRES-GLORIETA AQUIFER ON THE SOUTHWEST PART OF THE ZUNI INDIAN RESERVATION, CIBOLA COUNTY, NEW MEXICO

By Thomas M. Crouch

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CONTENTS

FIGURES

FIGURES--Concluded

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
square foot	0.09290	square meter
square mile	2.590	square kilometer
acre-foot	1,233	cubic meter
gallon per minute	0.06309	liter per second
gallon per day	0.003785	cubic meter per day
cubic foot per second	28.32	liter per second
cubic foot per day	0.02832	cubic meter per day
acre-foot per year	0.001233	cubic hectometer per year
gallon per minute per foot	0.2070	liter per second per meter
gallon per cubic foot	0.10719	liter per cubic meter
foot per mile	0.1894	meter per kilometer
foot per minute	0.3048	meter per minute
foot per day	0.3048	meter per day
foot squared per day	0.0929	meter squared per day

Temperature in degrees Fahrenheit (°F) or degrees Celsius (°C) can be converted as follows:

$$°F = (1.8 \times °C) + 32$$

$$°C = 5/9(°F - 32)$$

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

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ABSTRACT

A large-yield aquifer test of the confined San Andres-Glorieta aquifer was conducted in 1988 by pumping from a cave-fracture system on the southwest part of the Zuni Indian Reservation to evaluate aquifer properties, the effects of a large-yield aquifer test, and the chemical quality of water from selected wells and a spring. The productive cave-fracture system occurs along a northeast-southwest lineament that is parallel to major lineaments in New Mexico and Colorado. The San Andres-Glorieta aquifer is part of the only regional aquifer in much of the area capable of yielding large amounts of water to wells.

Test-production well ZS-3 was constructed in 1988, along with additional observation wells ZS-101 and ZS-102, to perform the test and to monitor aquifer response over a larger area than that monitored for previous aquifer tests. Well ZS-3 was pumped at about 2,580 gallons per minute for more than 10 days. Pumping produced almost instantaneous drawdown in all observation wells at the aquifer-test site except well ZS-1, which does not penetrate caves, and produced drawdowns after delays of about 15 minutes to 4 days at more distant wells and Rainbow Spring. Drawdown after 9 days varied from about 4 feet at the pumped well to about 0.2 foot at the most distant observation well and Rainbow Spring.

Time-drawdown data for two wells were analyzed using the Jacob method to estimate transmissivity and storage coefficient. Estimated transmissivities ranged from 640,000 to 750,000 feet squared per day and storage coefficients ranged from 0.00048 to 0.07. If pumping were to continue at the same rate as for the first 9 days of the test and aquifer response remained constant, Rainbow Spring would have about 2 feet of drawdown after 30 years. Two feet of drawdown at Rainbow Spring probably would be accompanied by a reduction in springflow of about 65 percent, to about 210 gallons per minute.

Water quality remained generally unchanged throughout the aquifer test. The temperature of pumped water remained constant at about 27 degrees Celsius. Dissolved-solids concentration averaged about 750 milligrams per liter. The concentrations of all constituents except barium and iron remained about constant for four samples taken during the test. The water quality is practically the same as that of samples taken at well ZS-1 in 1984 and Rainbow Spring in 1979. This consistency of water quality may indicate that water moving through the San Andres-Glorieta aquifer might be expected to continue unchanged in future years.

INTRODUCTION

The scarce ground-water resources of the Zuni Indian Reservation and surrounding areas in New Mexico and Arizona increasingly are being used by power companies, agriculture, and municipalities. Although minimally developed, the San Andres-Glorieta aquifer of west-central New Mexico, together with its equivalent, the contiguous Coconino aquifer of Arizona (Crouch, 1991, p. 19 and 28), is the only regional aquifer capable of yielding large quantities of water to wells. The scarcity of surface-water resources in most of the region has resulted in increased development of the San Andres-Glorieta aquifer, which is expected to continue as various needs arise.

Power companies are the largest water users in the region, followed by agriculture. A powerplant near St. Johns, Arizona, has two well fields located north and west of St. Johns, about 32 and 40 miles southwest of Ojo Caliente (fig. 1). A powerplant near Springerville, Arizona, has a well field located about 42 miles south-southwest of Ojo Caliente between St. Johns and Springerville. All water for these two plants is pumped from the Coconino aquifer, and the total withdrawal from the two powerplants averaged about 10,500 acre-feet per year during 1979 through 1983 and about 15,100 acre-feet per year during 1984 through 1989. These rates are equivalent to continuous withdrawal rates of about 6,500 and 9,400 gallons per minute, or about 8 to 12 times the combined flow of the springs at Ojo Caliente (discussed below under "Spring Discharge"). During 1979 through 1983 the water used by the two powerplants accounted for about 55 percent of ground water used in the St. Johns-Springerville area of Arizona and during 1984 through 1988 their combined use was about 79 percent of ground water used. Withdrawals for agriculture accounted for most of the remaining water used. Crouch (1991, p. 28) discussed earlier use of water from the Coconino aquifer in the St. Johns-Springerville area and minor uses of water from the San Andres-Glorieta aquifer on and near the Zuni Indian Reservation.

An assessment of water resources of the Zuni Indian Reservation by Orr (1987) during 1975 to 1980 indicated that the San Andres-Glorieta aquifer could be developed as a major water-supply source on the southwestern part of the reservation. Subsequent evaluation of that area by aquifer tests of the San Andres-Glorieta in 1984 and 1986 (Crouch, 1991) demonstrated that wells with moderately large yields could be constructed and indicated that wells with much larger yields probably could be completed in the San Andres Limestone cave-fracture system that was penetrated by observation wells drilled for those tests.

The population growth and economic expansion experienced by the Zuni Tribe in recent years are expected to continue along with development in adjacent areas. In addition, water use and estimates of future water requirements of the tribe have increased. The San Andres-Glorieta aquifer likely will be the only reliable source of water on parts of the reservation. To address these concerns, the U.S. Geological Survey in cooperation with the Pueblo of Zuni conducted a study to evaluate the aquifer properties, the potential effects of large-scale development on the aquifer, and the water quality of the San Andres-Glorieta aquifer.

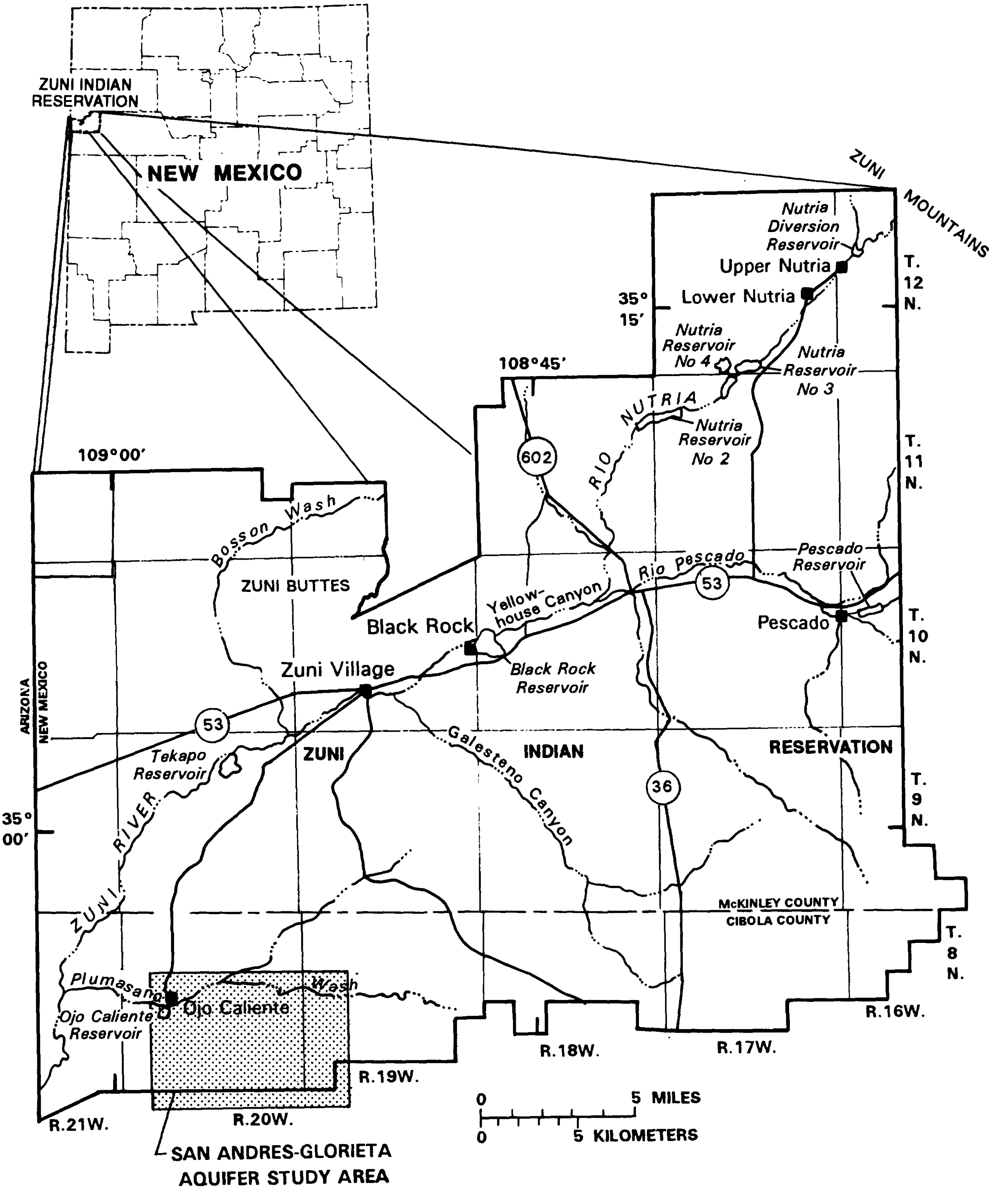


Figure 1.--Location of the study area on the Zuni Indian Reservation (modified from Orr, 1987, fig. 1).

Purpose and Scope

This report presents the results of a study to determine aquifer properties of the San Andres-Glorieta aquifer, the magnitude and extent of the effects of a large-yield aquifer test conducted in 1988 east of Ojo Caliente at the location of the 1984 and 1986 tests, and the chemical quality of water from selected wells and a spring in the southwestern part of the Zuni Indian Reservation. The results of the aquifer test, the observed drawdown, and the water-quality information are expected to be useful in evaluating the effects of large-scale development and use of the aquifer and in the preservation of the Zunis' ground-water resources. A production well and two additional observation wells were drilled in the study area to conduct the aquifer test. Time-drawdown data from the test were analyzed using a method by Jacob (1950). The effects of the large-yield aquifer test were monitored over a larger area than that monitored for previous aquifer tests.

Location and Geography

The Zuni Indian Reservation encompasses approximately 640 square miles in New Mexico adjacent to the Arizona State line (fig. 1). Most Zunis and other residents of the reservation live in Zuni Village and Black Rock, where almost all of the municipal and domestic water needed on the reservation is used. The San Andres-Glorieta aquifer study area (figs. 1 and 2) is within the Zuni Indian Reservation and is situated on the southwestern part of the Gallup Embayment (Crouch, 1991, fig. 2). The study area covers about 24 square miles, extending about 6 miles east to west and 4 miles north to south. This area includes the drilling and aquifer-test sites and all observation wells and springs monitored as part of the aquifer test of October 1988. The aquifer-test site (fig. 2) is located about 12 miles south of Zuni Village in the southeastern part of the study area.

The San Andres-Glorieta aquifer study area has gentle to moderate relief between altitudes of 6,200 and 6,900 feet. The broad valley of Plumasano Wash carries intermittent runoff from the northern part of the study area westward past Ojo Caliente. Yellowrock Canyon (fig. 2) and smaller valleys drain southwestward from the southern part of the study area. Orr (1987, p. 1) and Crouch (1991, p. 3) provided additional information on the geography of the reservation.

Previous Investigations

Ground- and surface-water resources of the Zuni Indian Reservation were discussed by Orr (1987). His report describes the hydrogeology of aquifers, tabulates well characteristics and water quality, and describes surface-water availability and quality. Orr (1987, p. 48) also included a glossary of hydrologic and geologic terms that defines most such terms used in this report. Crouch (1991) reported the results of 1984 and 1986 aquifer tests of the San Andres-Glorieta aquifer east of Ojo Caliente. Kelley (1967) provided a description of the tectonics and structural features of the area. Additional reports and articles are cited in Orr (1987) and Crouch (1991). Recharge, flow, and discharge of water in the San Andres-Glorieta aquifer in the Zuni Indian Reservation area were described by Crouch (1991, p. 27-29).

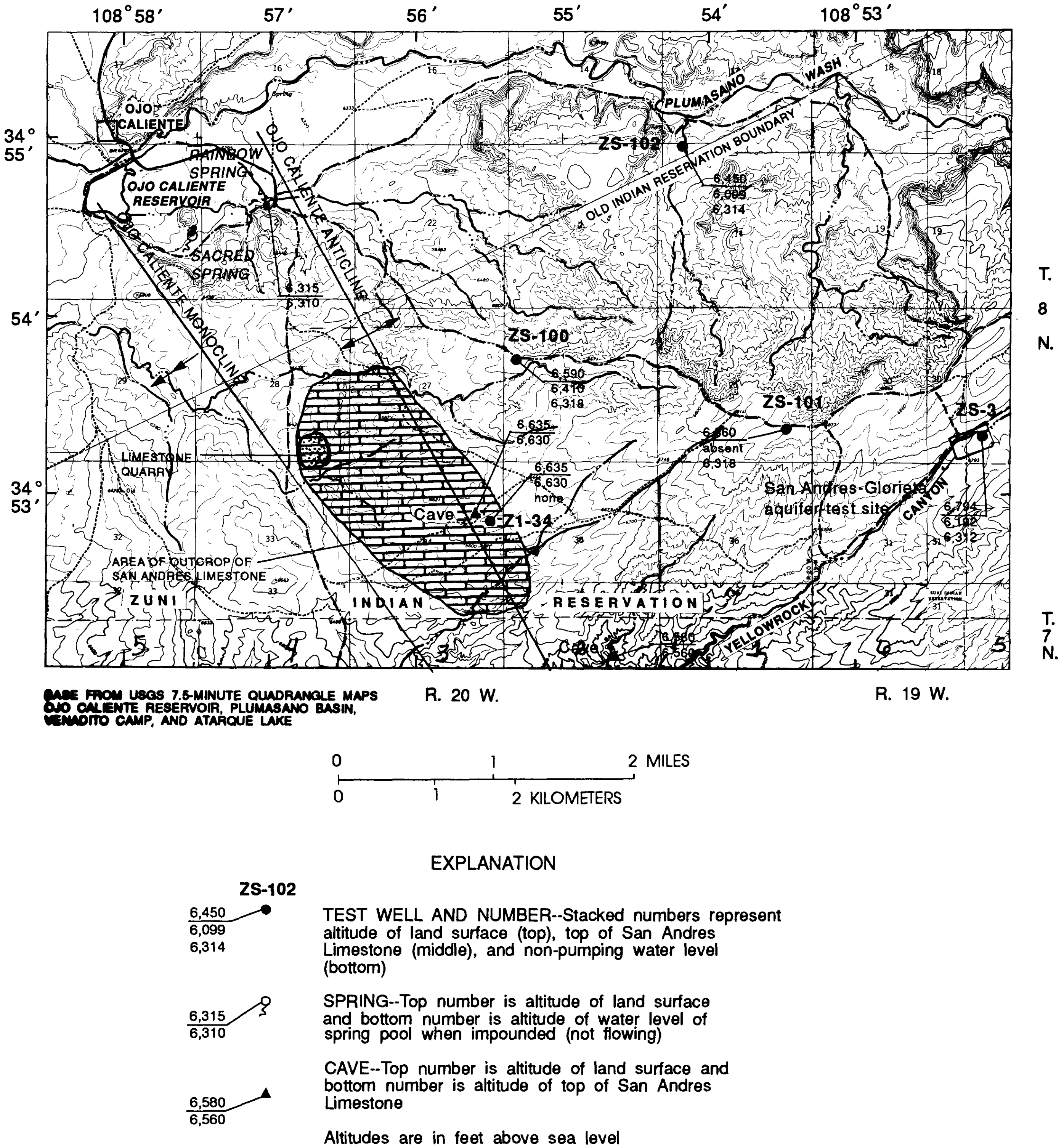


Figure 2.--San Andres-Glorieta aquifer study area.

Well- and Spring-Numbering System

The system of numbering wells and springs in New Mexico (fig. 3) is based on the common subdivision of land into townships, ranges, and sections. The location number, based on the township-range system, is divided by periods into four segments. The first segment indicates the township north of the New Mexico Base Line, and the second denotes the range west of the New Mexico Principal Meridian. The third segment is the number of the section within the township, and the fourth indicates the tract within which the well or spring is situated. To determine the fourth segment, the section is divided into quarters numbered 1, 2, 3, and 4 for the NW1/4, NE1/4, SW1/4, and SE1/4, respectively. This quarter-section number provides the first digit of the fourth segment. The second and third digits correspond to similar subdivision and numbering of quarter and sixteenth sections. If a well or spring cannot be accurately located, the last one or more digits of the fourth segment become zeros. The letters a, b, c, etc. are added to the fourth segment to designate multiple wells in the same tract.

Where sections are irregularly shaped, the well is located on the basis of a square section grid that is superimposed on the irregular section with the southeast corner and eastern section lines matching. The well then is numbered by its location on the superimposed square grid, and grid lines are extended north, west, and south, where necessary, to the boundaries of the irregular section.

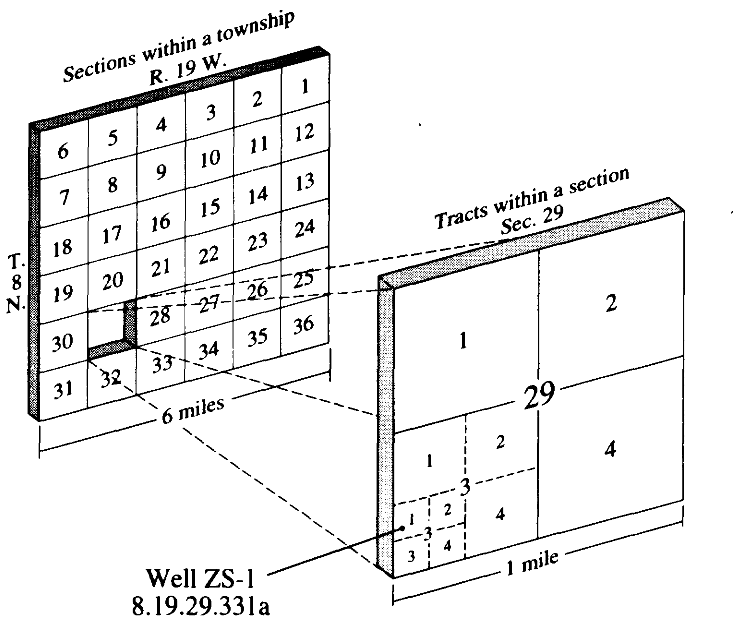


Figure 3.--System of numbering wells and springs in New Mexico.

HYDROGEOLOGY

The hydrogeologic setting of the Zuni Indian Reservation is described briefly below. More detailed descriptions can be found in Orr (1987, pls. 1 and 2), who provided a geologic map and sections of the reservation, and Crouch (1991, p. 3, 23, and fig. 2).

Hydrogeologic Framework

Rocks in the study area include granitic crystalline rocks, which form the Precambrian basement underlying the Zuni Indian Reservation, and about 2,500 feet or more of overlying sedimentary rock consisting of limestone, sandstone, siltstone, and anhydrite. The sedimentary rocks found in the vicinity of the test site primarily include the Abo Formation and Yeso Formation, Glorieta Sandstone and San Andres Limestone, Petrified Forest Member of the Chinle Formation, and Bidahochi Formation.

The Abo and Yeso Formations underlie the Glorieta Sandstone and act primarily as a lower confining bed to the San Andres-Glorieta aquifer. The Abo and Yeso consist of more than 900 feet of interbedded sandstone, siltstone, limestone, and anhydrite. No water wells have been completed in either unit in the study area.

The San Andres Limestone and the underlying Glorieta Sandstone, of Permian age, together constitute the San Andres-Glorieta aquifer (see figs. 8 and 9). The Glorieta Sandstone conformably overlies the Yeso Formation and consists of buff to white, medium-grained, well-sorted, crossbedded, and well-cemented sandstone. The Glorieta Sandstone is about 200 feet thick. The San Andres Limestone conformably overlies the Glorieta Sandstone and consists of about 150 feet of gray to pink, thick-bedded limestone.

The Petrified Forest Member of the Chinle Formation unconformably overlies the San Andres Limestone and may be subdivided, on the basis of available well data, into the lower and upper parts separated by the Sonsela Sandstone Bed. The lower part of the Petrified Forest Member consists of approximately 600 feet of channel deposits of grayish-red, white, and purple mudstone and siltstone. The Sonsela Sandstone Bed consists of approximately 100 feet of grayish-red to brown channel sandstone, conglomerate, and interbedded siltstone and mudstone shale. The upper part of the Petrified Forest Member consists of approximately 600 feet of fluvial grayish-red to reddish-brown mudstone and siltstone with some interbedded, lenticular sandstone. Deposition of the mostly fine grained sediments of the Petrified Forest Member of the Chinle Formation filled sinks and caves in the San Andres Limestone in some areas. The Petrified Forest Member acts as a confining bed in part of the area.

The Bidahochi Formation overlies the Petrified Forest Member of the Chinle Formation in the study area and consists of white to very pale brown, loosely consolidated fluvial sandstone interbedded with gravelly conglomerate and volcanic ash. The Bidahochi is present in only part of the study area where its maximum thickness is believed to be about 200 feet.

Structural Framework

The uplifts and folds in the Zuni Indian Reservation control the recharge, movement, and discharge of water in the San Andres-Glorieta aquifer. An additional effect of structural deformation on hydrogeology is the formation of fractures that may increase the hydraulic conductivity of the aquifer. The fractures may form in extended linear trends expressed topographically as lineaments. Water moving in the system of interconnected fractures may dissolve rock materials, further increasing the hydraulic conductivity. This process eventually can form a system of interconnected caves and fractures that can increase greatly the storage and transmissive properties of the rocks. Within the study area, a productive cave-fracture system occurs along a northeast-southwest lineament that is parallel to major lineaments in New Mexico and Colorado. The effects of structures and fracture systems on the Zuni Indian Reservation were discussed by Orr (1987, p. 7-8).

The western part of the study area includes segments of the northwest-trending Ojo Caliente Monocline and Ojo Caliente Anticline (fig. 2). The limestone outcrop southeast of Ojo Caliente is the structural high along the axis of the Ojo Caliente Anticline, which plunges gently to the northwest and southeast. At the Ojo Caliente Monocline, strata are offset downward in excess of 1,000 feet southwest of the monocline (Anderson, 1987, sheet 2, col. 2; his "Atarque Monocline" is the Ojo Caliente Monocline of this report). The top of the San Andres Limestone generally rises from less than 6,100 feet in altitude in the northeast part of the study area to about 6,630 feet at the highest part of the limestone outcrop. The top of the San Andres Limestone lies at depths of 0 to about 650 feet northeast of the monocline (fig. 2) and 1,000 feet or deeper southwest of the monocline.

Lineaments and fracture traces were identified from aerial photographs and satellite imagery of the southwest part of the Zuni Indian Reservation (Crouch, 1991, p. 26). The lineaments and some fracture traces trend N. 55° E., parallel to several major lineaments in New Mexico and Colorado. These lineaments are described by Chapin and others (1978, p. 115) as "major crustal lineaments" and "northeast-trending shear zones" that are "deeply penetrating flaws in the lithosphere that tend to * * * influence deformation in the brittle near-surface rocks." Lineaments that trend N. 55° E. at Ojo Caliente and southeast of the study area and their possible relation to the Ojo Caliente Monocline and other parallel structures of the Gallup Embayment were discussed by Anderson (1987, sheet 2) in the following excerpts:

> The Zuni Basin [Gallup Embayment in this report] is a northwest-trending, asymmetric structural sag bounded abruptly on the northeast by the Nutria Monocline [Crouch, 1991, fig. 2] with steep southwesterly dips [nearly vertical locally; fig. 2]. * * * Structures similar to, and parallel to, the Nutria Monocline, but of lesser magnitude, extend nearly the length of the Zuni Basin and account for the northwest-trending outcrop pattern. The Atarque Monocline [Ojo Caliente Monocline] is the most prominent of these subordinate parallel structures.

*   *   *   *   *   *   *

The monoclines [the Nutria, Galestina, and Atarque Monoclines; Anderson, 1987, sheets 1 and 2; fig. 2] are considered to be the result of northeastward-directed compression during the Laramide orogeny.

* * * * * * *

A significant feature of the Atarque and the Galestina Monoclines is that they terminate southeastward along a line that trends N. 55° E. and is coincident with the course of Pinitos Draw [Anderson, 1987, sheet 1]. This is 90 degrees to the monoclinal axes, which trend approximately N. 35° W. Given this geometry plus the fact that no compressional features have been found southeast of the Pinitos Draw trend, there is a real possibility that Pinitos Draw follows the trace of a minor strike-slip fault.

The Atarque Monocline apparently terminates abruptly to the northwest as well, in the vicinity of Ojo Caliente, and it is possible that a northeast-trending zone of strike-slip movement exists there also. This results in the segmentation of monoclinal-fold trends on the Zuni Basin. Fold segmentation was recognized by Brown (1984) as a characteristic of Rocky Mountain foreland deformation; he referred to it as compartmental deformation and related it to a movement of discrete basement blocks.

Fold structures do not match up across the controlling strike-slip faults, but more importantly one large structure may be balanced by several smaller structures on the opposite side of the fault. This concept applies in all likelihood to the Zuni Basin, inasmuch as the Nutria Monocline on one 'compartment' may be balanced by the Atarque and Galestina Monoclines on another.

* * * * * * *

Both northeast-trending strike-slip fault zones that Anderson (1987) described appear on satellite imagery as lineaments trending about N. 55° E.; these probably are smaller scale shear features parallel to the major lineaments described by Chapin and others (1978). The lineament that passes through or near the springs at Ojo Caliente could be a manifestation of a crustal weakness that promoted the formation of presumed caves in the San Andres Limestone that may channel water to the springs. Crouch (1991, p. 26 and 29) discussed a northeast-trending lineament through the San Andres-Glorieta aquifer-test site (fig. 2) and caves that were penetrated by four of five test wells (see fig. 7) drilled along the lineament.

San Andres-Glorieta Aquifer

The Glorieta Sandstone and the overlying San Andres Limestone together constitute the San Andres-Glorieta aquifer. They are considered as one aquifer in the study area because they are hydraulically connected. These formations underlie the entire Zuni Indian Reservation and extend through much of west-central New Mexico and northern Arizona. Both formations are exposed at the northeast corner of the reservation; the San Andres Limestone also is exposed near Ojo Caliente (fig. 2). The San Andres-Glorieta aquifer contains water under confined (artesian) conditions under nearly all of the reservation except in or near the two areas of its exposure.

Hydraulic Head

The hydraulic head of the San Andres-Glorieta aquifer, measured at nonpumped wells (fig. 2), is nearly flat in the study area. The altitudes of the wells and springs were determined from topographic maps and are accurate only to within about 10 feet. Thus, a flow pattern for the San Andres-Glorieta aquifer cannot be determined from the water levels shown, which are based on measured depth to water from land surface. The probable flow direction is generally northwest through the study area on the basis of the regional flow pattern from the recharge area in and south of the Zuni Mountains (Crouch, 1991, p. 27-29 and fig. 13) toward the springs at Ojo Caliente. The rise of the San Andres Limestone and adjacent strata from the northeast toward the Ojo Caliente Anticline places the top of the limestone above the hydraulic head along the northeast flank of the anticline (see data for well ZS-100, fig. 2). Continued rise of the units southwest of well ZS-100 places most or all of the San Andres Limestone and Glorieta Sandstone along the crest of the anticline in the area of the limestone exposure and southeastward above a plane extrapolated from the hydraulic heads. Oil-test well Z1-34 (fig. 2) penetrates the entire 300-foot thickness of the San Andres Limestone and Glorieta Sandstone, which were dry. The bottom of the Glorieta Sandstone is at an altitude of 6,331 feet, about 20 feet higher than the potentiometric surface at Rainbow Spring and well ZS-3.

The water level in well ZS-1 (8.19.29.331a) (fig. 4) has been recorded since 1984. The hydrograph for well ZS-1 shows that the water level has been very steady except for a gradual rise from late 1985 to early 1987 and a response to the pumping of well ZS-3 in October 1988. The hydrograph for well ZS-100, which begins in 1986, closely parallels that for well ZS-1. The day-to-day fluctuations are a result of changes in barometric pressure and earth tides; these vary from more than 0.2 foot during the winter and spring when frontal storms are frequent to less than 0.05 foot during the summer and fall. Water levels recorded in other test wells after 1986 show similar fluctuations and trends.

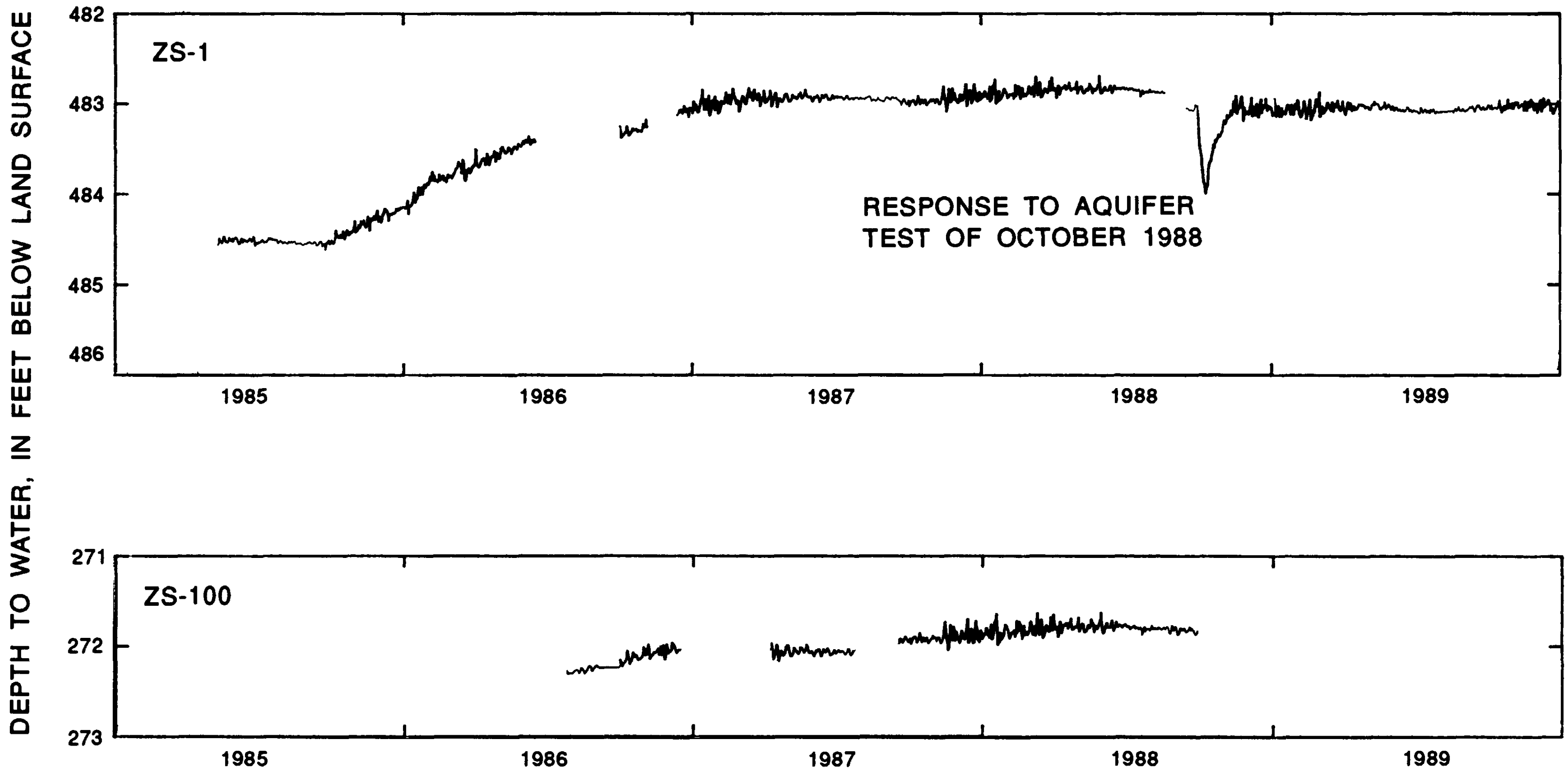


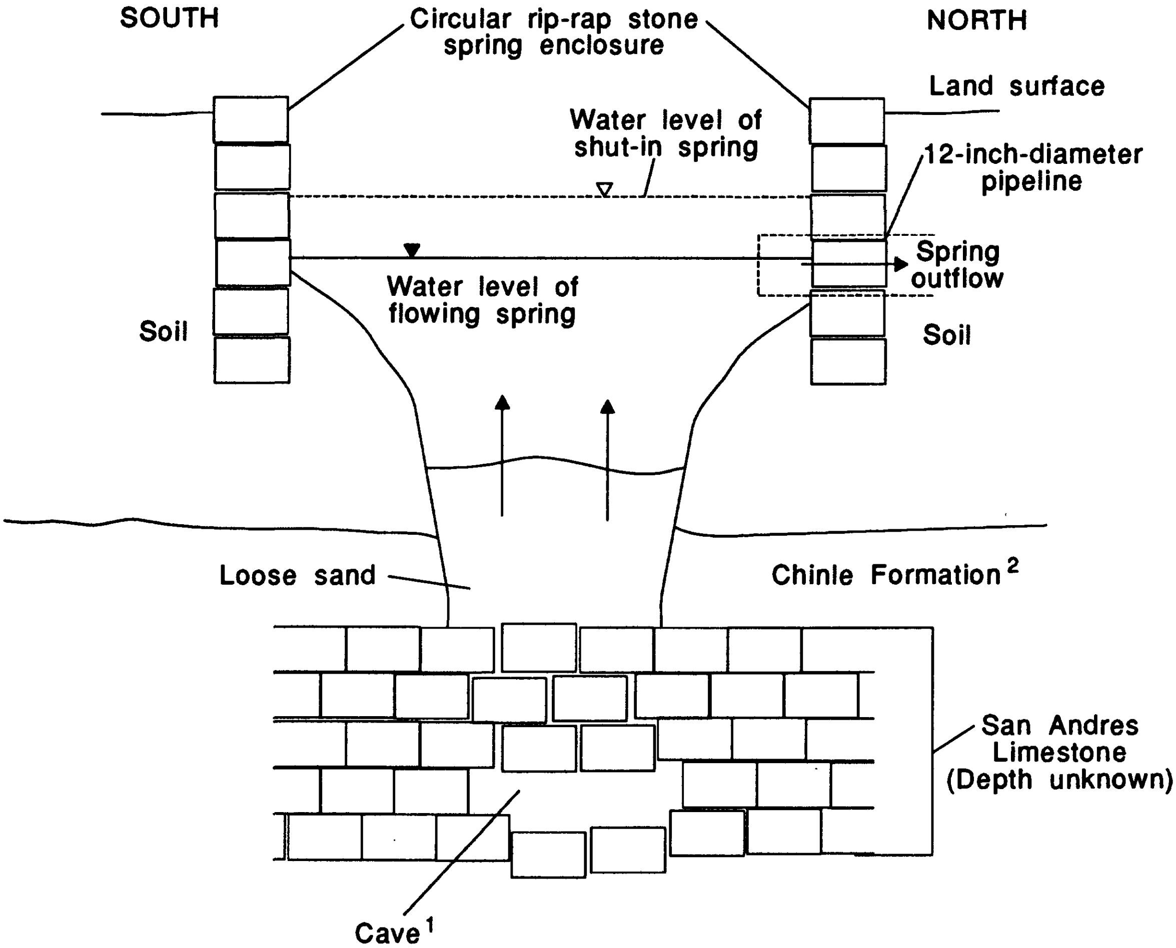
Figure 4.--Water levels in wells ZS-1 and ZS-100, 1985 to 1989.

Spring Discharge

The only known natural discharges from the San Andres-Glorieta aquifer in or near the study area are the springs and seeps at Ojo Caliente (Orr, 1987, p. 9-12). B.R. Orr (U.S. Geological Survey, oral commun., 1990) provided discharge data for Rainbow Spring from his discharge measurements of the springs near Ojo Caliente (Orr, 1987, fig. 4). In 1979-80, Rainbow Spring discharge averaged 330 gallons per minute (0.73 cubic foot per second), about 75 percent of the average combined spring discharge from the San Andres-Glorieta aquifer of 440 gallons per minute (0.98 cubic foot per second).

The discharge of Rainbow Spring was measured in October 1988 by plugging the outflow pipe of the spring pool enclosure (fig. 5) and measuring the rate of water-level rise in the pool. The amount of leakage from the spring into the Chinle Formation and the soil zone is unknown but is assumed to be minor. The hydrograph and calculations for this measurement are shown in figure 6. The initial rate of the water-level rise of the pond plus minor leakage past the outflow plug resulted in a calculated discharge of about 600 gallons per minute (about 1.34 cubic feet per second). The rate of water-level rise decreased to zero after about 2.8 feet of rise, and springflow decreased to about 60 gallons per minute (the visually estimated leakage past the outflow plug) within 4 hours of plugging. This rise is the added head required to diminish the springflow by about 540 gallons per minute, from 600 to 60 gallons per minute. The approximate specific capacity of the spring is, therefore, about 193 gallons per minute per foot of change in hydraulic head.

If Rainbow Spring still provides about 75 percent of the average combined discharge in or near the study area from the San Andres-Glorieta aquifer, then the total discharge of Rainbow Spring, Sacred Spring, and the seepage area between them is about 800 gallons per minute (about 1.78 cubic feet per second), an increase of more than 80 percent from the 1979-80 average. From September 1985 to early 1987, the San Andres-Glorieta hydraulic head increased about 1.6 feet at well ZS-1 (fig. 4). With a 1.6-foot increase in head and a specific capacity of 193 gallons per minute per foot of change in hydraulic head obtained from the 1988 shut-in test, this increase in head could account for all of the increase in flow of Rainbow Spring from 1980 to 1988.



Notes:

1. Cave openings are likely but not known to exist.
2. Chinle Formation may not be present above San Andres Limestone.

Figure 5.--Schematic section of Rainbow Spring and flow connection to the San Andres Limestone.

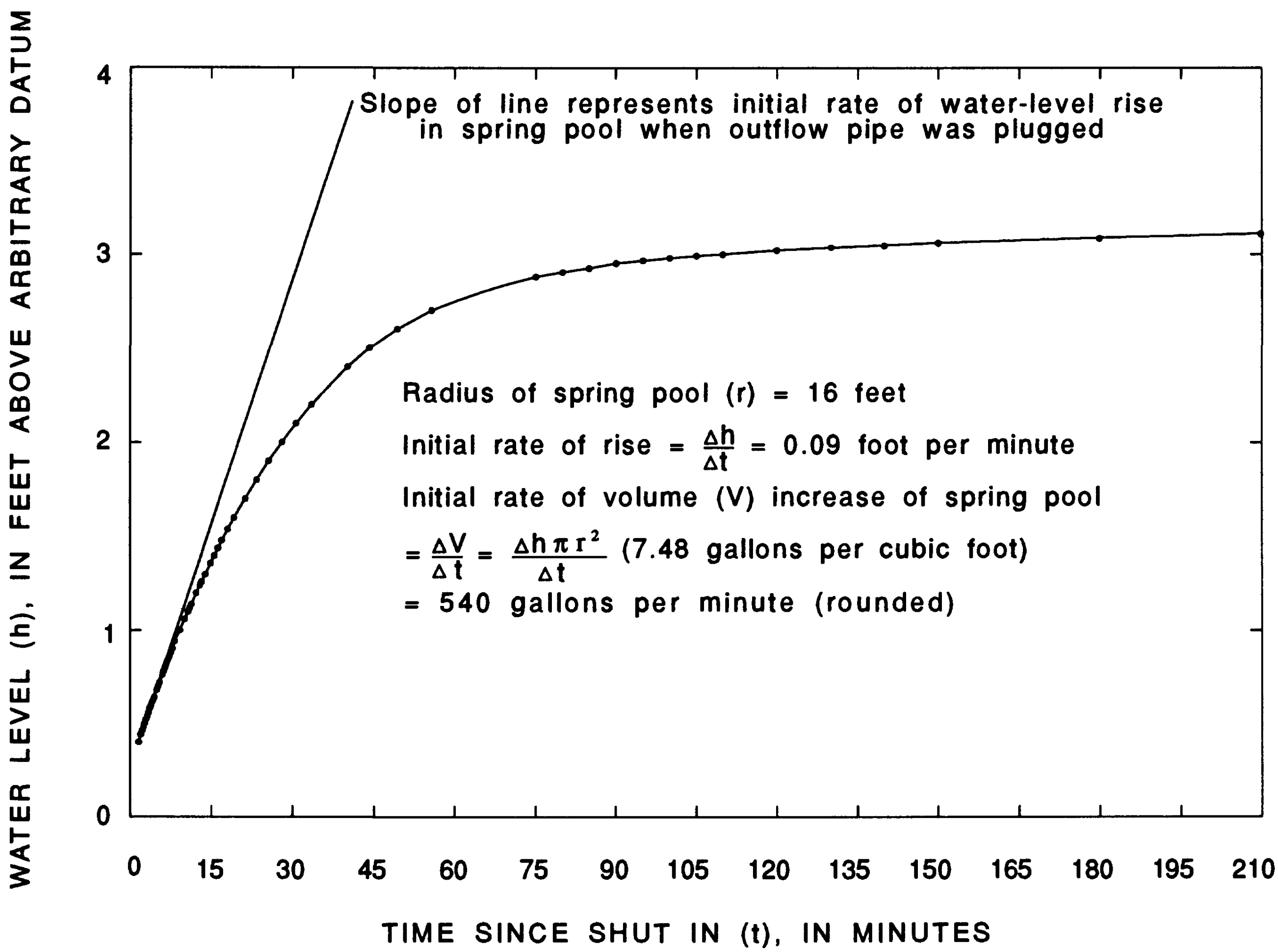


Figure 6.--Water level in Rainbow Spring during a shut-in test in October 1988.

AQUIFER TEST

The following evaluation of the San Andres-Glorieta aquifer involves estimation of aquifer properties and drawdown projections using techniques based on the Jacob method (Jacob, 1950), which is developed from the Theis equation (Theis, 1935). The assumptions for the Theis equation are (1) the aquifer is homogeneous and isotropic, (2) the aquifer is infinite in areal extent, (3) the discharging well penetrates the entire thickness of the aquifer, (4) the well has an infinitesimal diameter, and (5) the water removed from storage is discharged instantaneously with a decline in head (Lohman, 1972, p. 15). The San Andres-Glorieta aquifer in parts of the study area has hydraulic properties and boundary conditions that, individually or collectively, may cause it to respond much differently than an aquifer meeting the conditions for the Theis equation. Boundary conditions may include:

(1) Caves and fractures of varying size and orientation that result in pronounced anisotropy and inhomogeneity.

(2) Fractures that contact various size blocks of porous sandstone, resulting in a dual- or multiple-porosity system.

(3) Areal differences in the effective storage coefficient, especially where the aquifer is unconfined in the vicinity of well ZS-100 (fig. 2) and the outcrop of the San Andres Limestone. The storage coefficient is probably 10 to 100 times greater in the unconfined area.

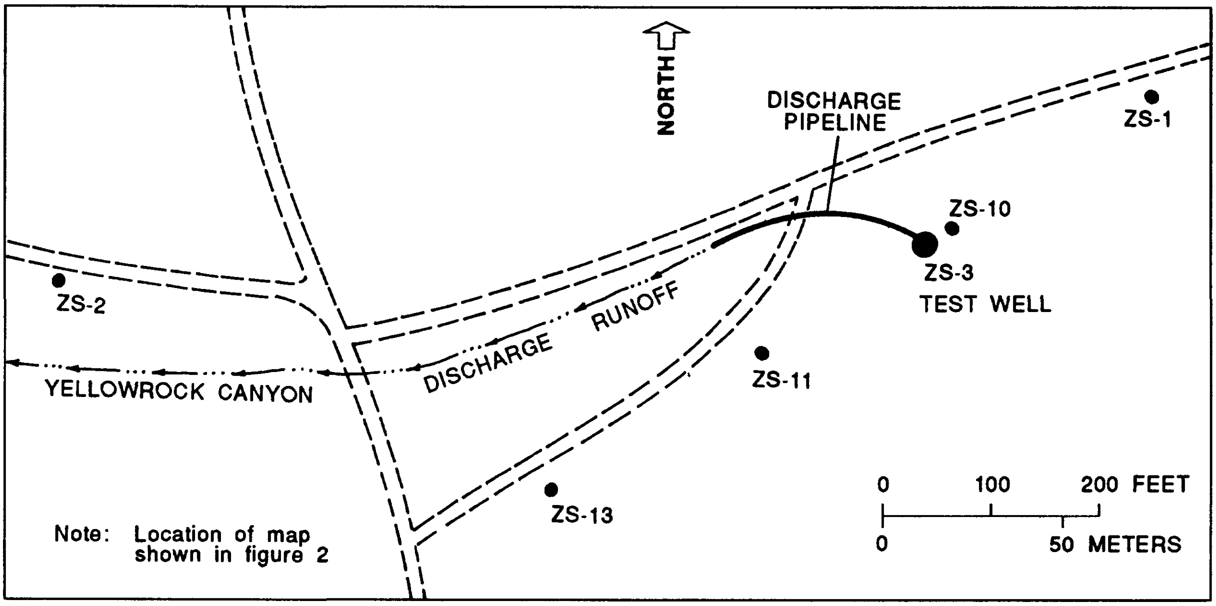
(4) Leakage from the overlying Chinle Formation, especially where interconnecting fractures cross the formational contact or where coarse sandstone or conglomerate lies at the base of the Chinle, as observed south of the San Andres Limestone outcrop.

(5) Areas where the San Andres Limestone is absent, such as the vicinity of well ZS-101.

(6) Other low-permeability boundaries, such as the Ojo Caliente Monocline.

The Theis method commonly is applied to more homogeneous and isotropic material, such as alluvial or sandstone aquifers. The San Andres-Glorieta aquifer, however, is mainly a fractured system and does not conform to most of the assumptions used for the Theis analytical method. Therefore, use of aquifer property estimates from the test needs to include consideration of this limitation.

Previous tests of the San Andres-Glorieta aquifer were conducted in the southwest part of the Zuni Indian Reservation in 1984 and 1986 (Crouch, 1991, p. 29-41 and 45-46). Well ZS-1 (fig. 7) was pumped at 260 to 372 gallons per minute (the largest rate practical for that 9-inch-diameter well) and two to five observation wells were monitored. However, none of the observation wells that penetrate caves in the aquifer responded to the pumping. Drawdowns in the pumped well and an observation well (Crouch, 1991, p. 33 and fig. 18), both of which penetrate fractures but no caves, resulted in transmissivity estimates of 6,000 to 24,000 feet squared per day. On the other hand, injection tests, at rates of 180 to 240 gallons per minute, in observation wells (Crouch, 1991, p. 38-41) that penetrate caves produced small, instantaneous responses in other wells penetrating caves; these tests resulted in much larger transmissivity estimates of 200,000 and 500,000 feet squared per day. The injection tests suggest that a well with much larger yield than well ZS-1 could be completed in the aquifer in this area.



Well	ZS-3	ZS-1	ZS-2	ZS-10	ZS-11	ZS-13
Distance from ZS-3 (feet)		247	793	28	179	409
Diameter of casing/slotted liner (inches)	18/8	9/6	6/2	2/2	2/2	2/2
Depth, top of San Andres Limestone (feet)	602	605	612	601	650	610
Depth, top of Glorieta Sandstone (feet)	737	740	745	736	729	729
Total depth (feet)	782	865	860	780	750	781
Depth interval open to San Andres-Glorieta aquifer (feet)	602-782	609-865	616-860	608-780	652-750	613-781
Depths of probable major water-producing intervals (feet); c=cave, f=fracture	c,f 603-685 f 721-759	f 695-698 f 737-745 f 800-805	c,f 695-745 f 745-835	c,f 614-674 c 712-726 f 732-736 f 774-778	c,f 652-680	f 620-663 c 663-691 f 705-739

Figure 7.--Test-well layout, depths, and water-producing features at the San Andres-Glorieta aquifer-test site.

Test Wells

During the summer of 1988, test-production well ZS-3 (fig. 7) was drilled next to well ZS-10 (8.19.29.331b) to penetrate the many large caves penetrated by well ZS-10 (Crouch, 1991, p. 8, 40, and fig. 18). Construction details of well ZS-3 and a geologic column of the strata penetrated are shown in figure 8. A 23-inch-diameter borehole was drilled to 600 feet and 18-inch outside-diameter casing was set and grouted. The pilot hole was reamed to a 15-inch diameter to a depth of 691 feet, and an intake casing consisting of 8-inch steel casing and well screen was set to a depth of 674 feet; a cave-in at that depth prevented deeper placement. Nearly all of the caves and fractures penetrated are adjacent to the intake casing. After completion of the well, the nonpumping water level in well ZS-3 was about 482 feet below land surface, the same as in well ZS-10.

Two wells, ZS-101 (8.20.25.441) and ZS-102 (8.20.13.333) (fig. 2), were drilled during the summer of 1988 to permit observations of water levels at longer distances from well ZS-3 than the observation wells at the aquifer-test site. Well ZS-101 was drilled 1.2 miles west of ZS-3 and well ZS-102 was drilled 2.7 miles northwest of ZS-3 (fig. 2 and table 1).

Depths of boreholes, packers, and casing openings for and strata penetrated by wells ZS-101 and ZS-102 are shown in figure 9. Well ZS-101 penetrated approximately 225 feet of fine- to medium-grained sandstone of the Bidahochi Formation and the Sonsela Sandstone Bed of the Petrified Forest Member of the Chinle Formation, 454 feet of mudstone and siltstone of the Petrified Forest Member of the Chinle Formation, and 124 feet of Glorieta Sandstone; the San Andres Limestone was absent at this site. Well ZS-102 penetrated 351 feet of mudstone and siltstone of the Petrified Forest Member of the Chinle Formation, 149 feet of limestone and dolomite of the San Andres Limestone, and 102 feet of Glorieta Sandstone.

The thickness of the San Andres Limestone in other wells drilled in the aquifer-study area (fig. 7) ranges from 79 to 153 feet. At test well ZS-11 (fig. 7), the San Andres Limestone is 79 feet thick. At observation well ZS-100 (8.20.26.131) (fig. 2), about 3 miles to the west, the limestone is 133 feet thick. The upper part of the limestone was probably eroded prior to deposition of the overlying Chinle Formation at locations where the limestone is significantly thinner than 133 feet (Crouch, 1991, p. 23). An oil-test well, Z1-34 (8.20.34.241) (fig. 2), drilled in 1990 about 1 mile south-southwest of well ZS-100, penetrates 153 feet of San Andres Limestone and 147 feet of Glorieta Sandstone. Well Z1-34 is the only well in the study area that penetrates the full thickness of Glorieta Sandstone.

Table 1.--Information pertaining to Rainbow Spring and observation wells more than 1 mile from test-production well ZS-3

[See figure 2 for location. Altitude of land surface was obtained from U.S. Geological Survey 7 1/2-minute topographic maps. m, geologic unit missing; u, unknown; --, does not apply]

	Well ZS-100	Well ZS-101	Well ZS-102	Rainbow Spring
Location	8.20.26.131	8.20.25.441	8.20.13.333	8.20.21.144
Distance from ZS-3 (feet)	15,950	6,470	14,300	25,500
Direction from ZS-3	West-northwest	West	Northwest	West-northwest
Casing diameter (inches)	5	2	2	--
Depth interval open to San Andres-Glorieta aquifer (feet below land surface)	188-420	690-803	371-602	--
Approximate land-surface altitude (feet above sea level)	6,590	6,860	6,450	6,315
Depth to nonpumping water level (feet below land surface)	272	542	136	5
Altitude/depth, top of San Andres Limestone (feet)	6,410/180	m	6,099/351	u
Altitude/depth, top of Glorieta Sandstone (feet)	6,277/313	6,181/679	5,950/500	u

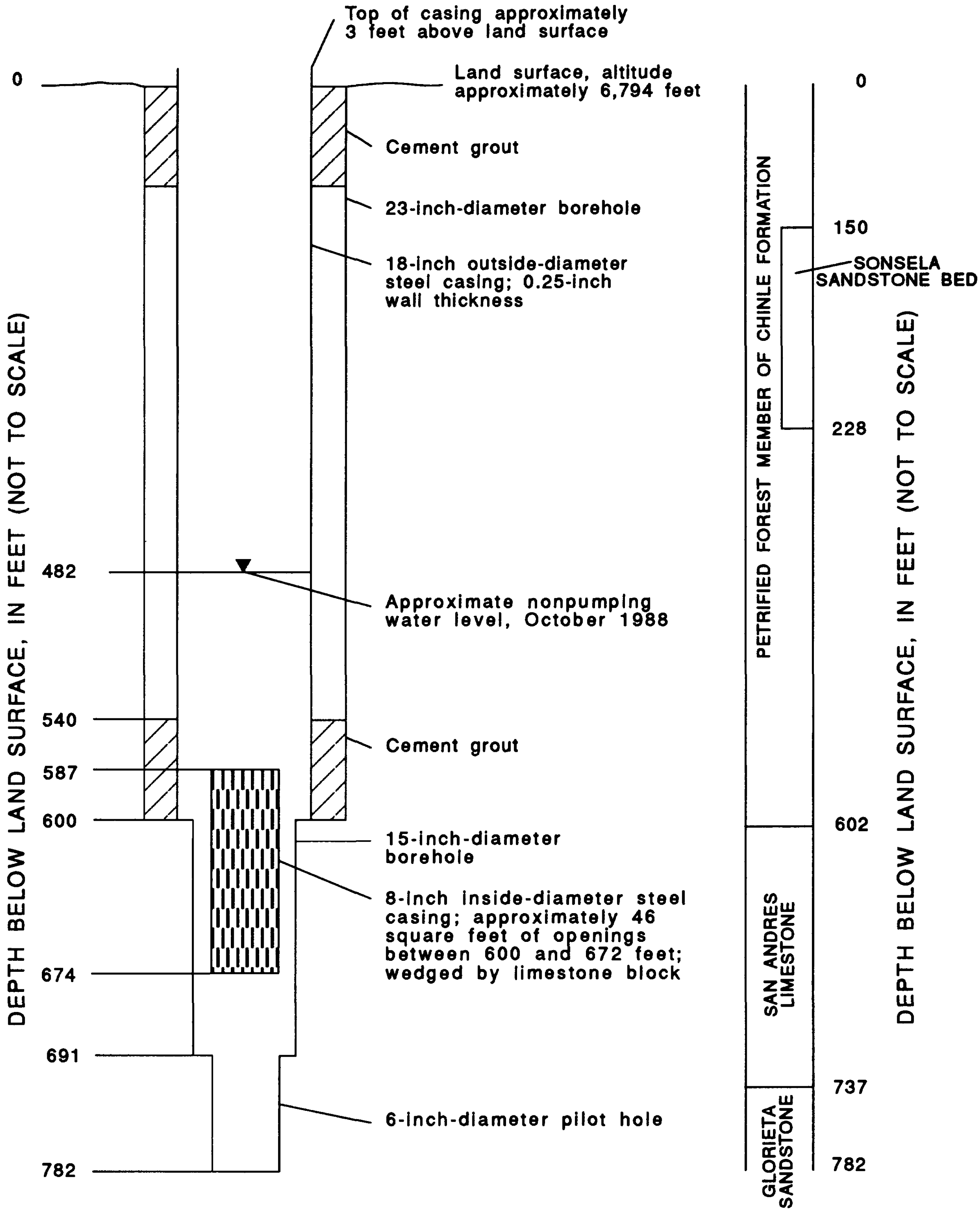


Figure 8.--Construction details and generalized geologic column of test-production well ZS-3.

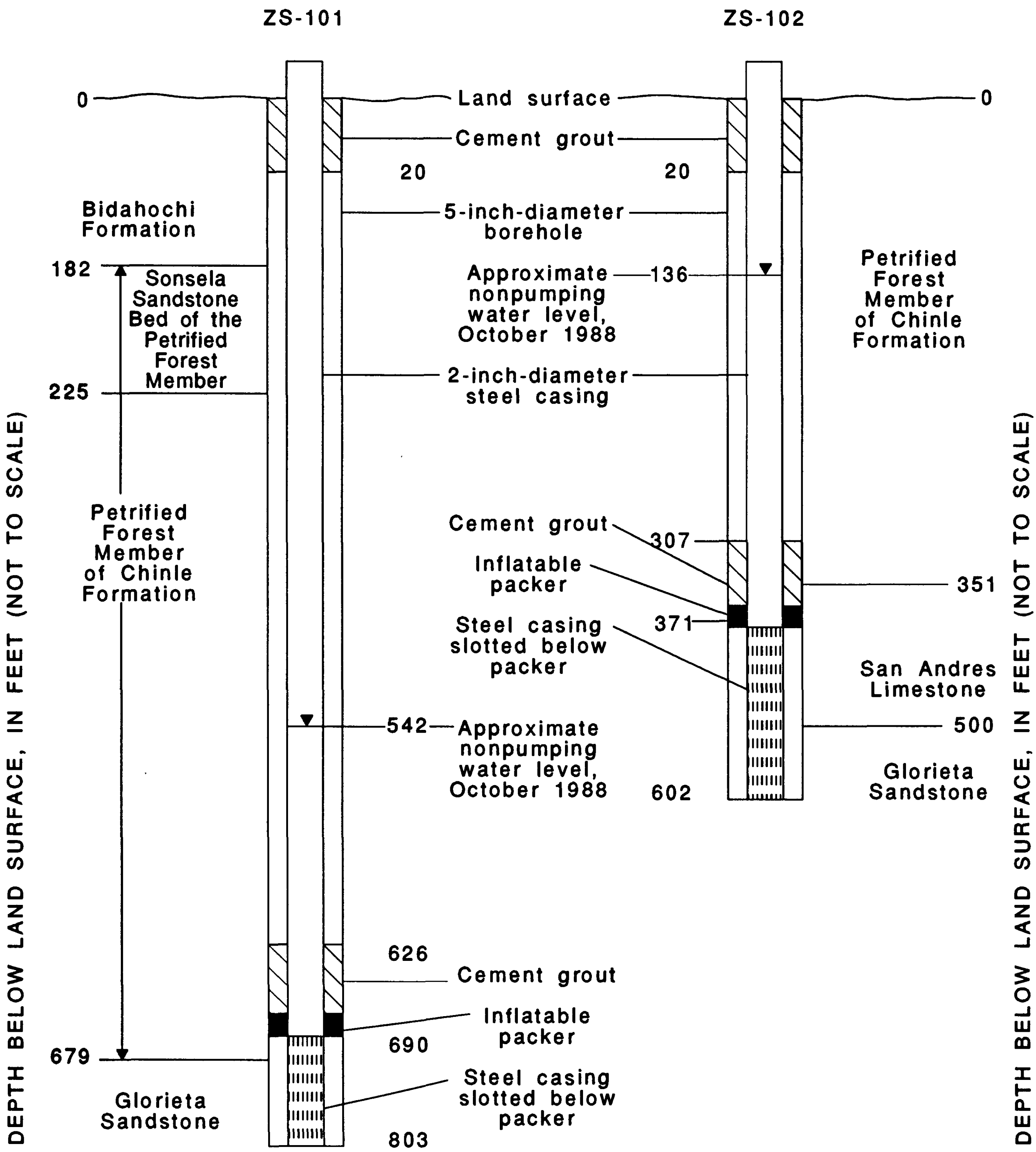


Figure 9.--Construction details and generalized geologic column of observation wells ZS-101 and ZS-102.

Aquifer-Test Results

A test of the San Andres-Glorieta aquifer was conducted by pumping well ZS-3 in early October 1988. The pumping rates during the test (fig. 10) are periodic averages between successive orifice weir meter readings. The average pumping rate during the entire test was about 2,580 gallons per minute. The average pumping rate before the 14.5-hour nonpumping period of October 10-11 was 2,540 gallons per minute, including periods when pumping was stopped for service (3 hours on October 4 and 32 minutes on October 7). The pump was stopped for 14.5 hours on October 10-11 to test for any response in the distant observation wells. However, due to the small drawdowns in those wells and the relatively large fluctuations due to atmospheric-pressure changes and earth tides, any response was indiscernible. This pump stoppage and the subsequent 23.5 hours of pumping prevented the use of water-level-recovery analysis.

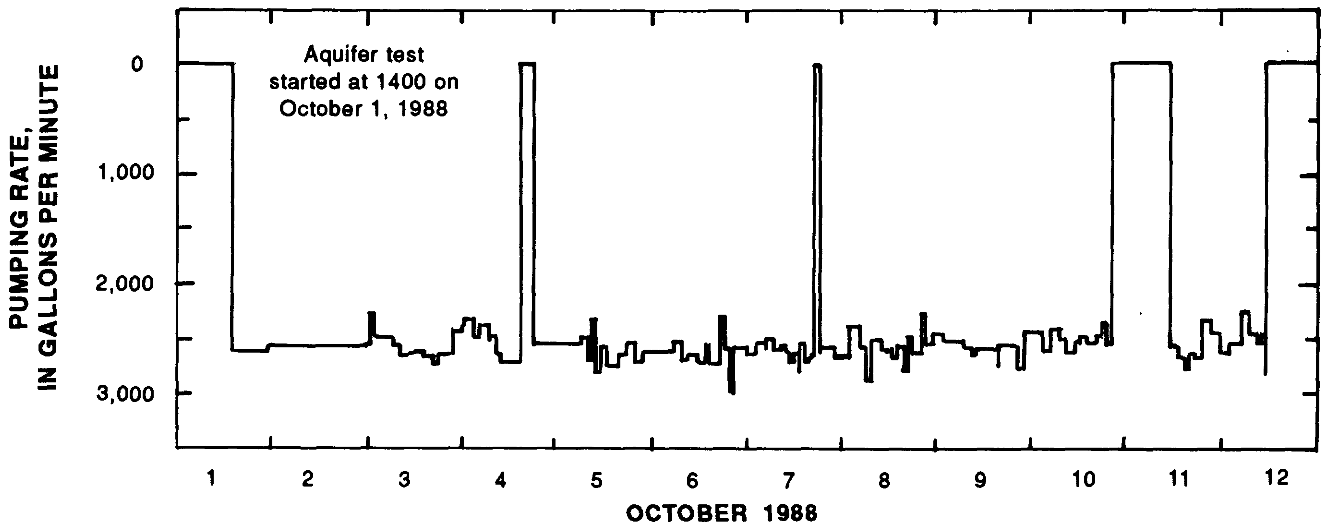


Figure 10.--Pumping rate during aquifer test at well ZS-3.

The pumped water was discharged through a 16-inch line to a point about 200 feet downslope of well ZS-3 (fig. 7), and flowed away to the southwest in Yellowrock Canyon, a small, shallow drainage in the aquifer-test area. The mudstone strata of the Chinle Formation that underlie the drainage probably prevented any pumped water from returning to the San Andres-Glorieta aquifer.

Water levels were monitored in eight wells and one spring during the 1988 aquifer test (figs. 2 and 7). The test-production well, ZS-3, and observation wells ZS-13 (8.19.30.442b), ZS-100, ZS-101, and ZS-102 were monitored with pressure transducers and continuous data loggers. Well ZS-1 and Rainbow Spring were monitored with continuous mechanical recorders. Two other wells, ZS-10 and ZS-11 (8.19.29.331c), were measured periodically with a sounding tape. Tape measurements also were made periodically in all recorded wells to verify or adjust recorder settings. Well ZS-2 (8.19.30.442a) was monitored with a transducer that malfunctioned and rendered the data useless.

Water-level changes in well ZS-3 occurred almost instantaneously with changes in the pumping rate. During the test of October 1-12 at an average pumping rate of 2,580 gallons per minute, drawdown in well ZS-3 averaged about 4.3 feet, but varied as much as 1.5 feet within a few minutes on several occasions. More than 95 percent of drawdown and recovery occurred within a few minutes of pump starts and stops. Water-level data from this well were not used in the aquifer analysis because of the rapid decline.

Distance-Drawdown Relation

The relation between distance from the pumped well, ZS-3, and drawdown in five observation wells and Rainbow Spring is shown in figure 11. The distances and directions of wells ZS-11 and ZS-13 from well ZS-3 are shown in figure 7, and the distances and directions of the distant wells and Rainbow Spring are shown in figure 2 and table 1. Hydraulic properties of the San Andres-Glorieta aquifer were not estimated from this relation because of the boundary conditions indicated by water-level data collected during the test. The plotted drawdowns are based on the assumption that the flat, prepumping trends would have continued throughout the test. Drawdowns are corrected for barometric-pressure change between the observation time and the beginning of pumping at 1400 hours on October 1, 1988. The plotted values for well ZS-11 at 3 and 9 days and for well ZS-100 at 9 days are based on time extrapolations using data from continuous-record wells, which have a constant difference from measured depths to water in these two wells.

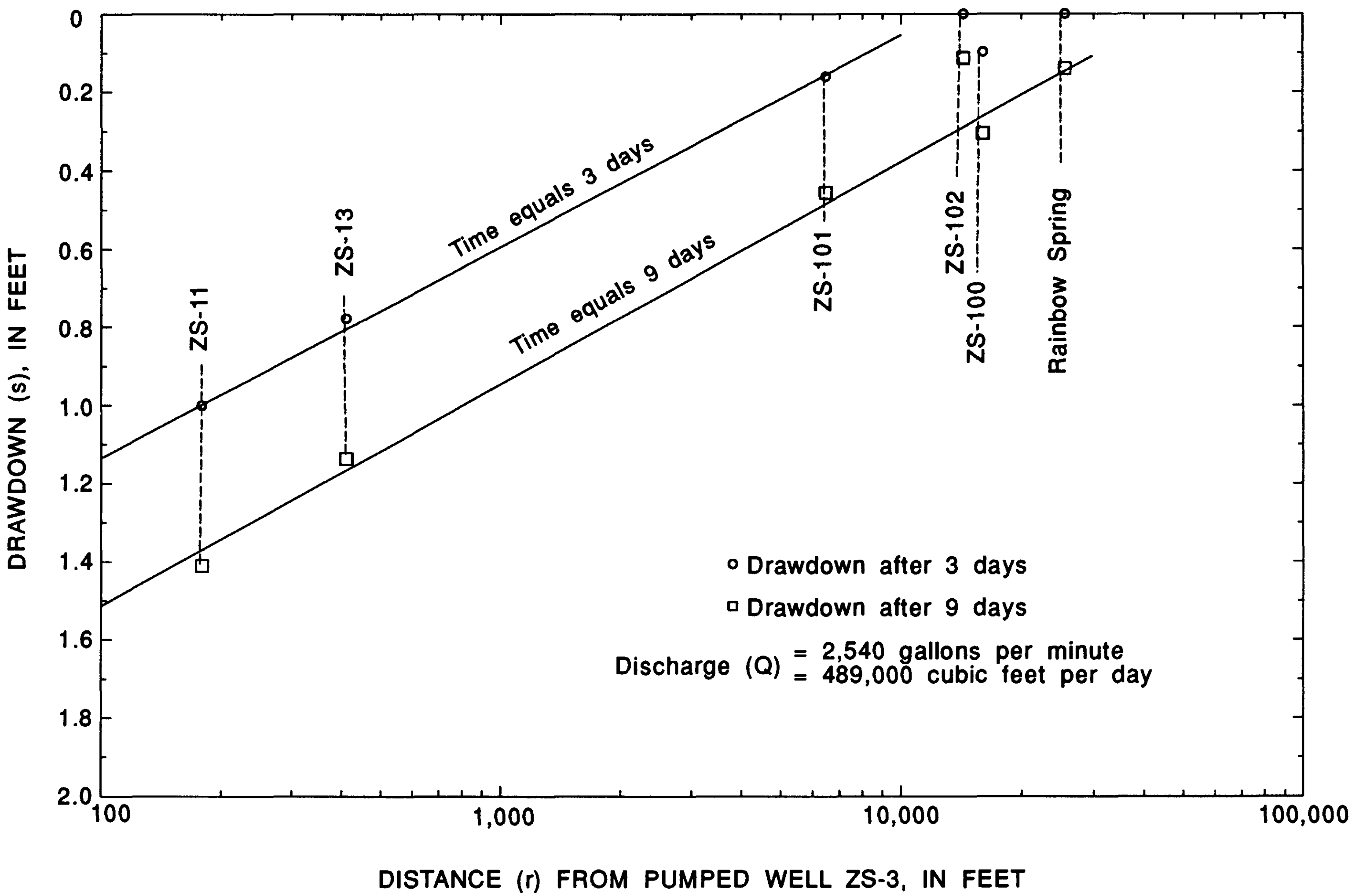


Figure 11.--Drawdown after 3 and 9 days at various distances from well ZS-3 during pumping.

Time-Drawdown Evaluation

The responses of four wells and Rainbow Spring to the pumping of well ZS-3 are shown in figure 12. The graphs end after the first 13,380 minutes of the test, except for well ZS-100, which ends after only 6,720 minutes because of malfunction of the instrumentation. The water-level data for the wells were corrected for barometric and earth-tide effects. The graphs show drawdown of water levels below a horizontal extension of the flat prepumping trend of each well. Well ZS-13 responded instantaneously to pumping. Drawdown was 0.03 foot (not shown) 6 seconds after pumping started. This response indicates that the caves penetrated by this well and ZS-3 are in direct connection. The curvature (inflections) on the ZS-13 graph (fig. 12) reverses as the area influenced by the pumping of well ZS-3 encompasses various boundary conditions. The last inflection, which is downward, occurred about 6,000 minutes into the test, which also was about the time that Rainbow Spring began to respond. This coincidence may be a result of the expansion of the influence of pumping to the cave system from which the spring flows. Wells near ZS-3 (ZS-10, ZS-11, and ZS-2) that penetrate caves also responded instantaneously to pumping, but with different drawdowns.

Well ZS-1, a production well that does not penetrate caves (Crouch, 1991, p. 30-37), showed no response until 4.5 minutes into the 1988 test (fig. 12). This well, when pumped at 375 gallons per minute in 1986, produced no measurable drawdown in nearby wells that penetrated caves. However, the 1986 test caused more than 2 feet of drawdown in an observation well not penetrating caves (Crouch, 1991, p. 33 and fig. 20); drawdown in the observation well, located 315 feet southeast, started within 20 seconds of pumping in the 1986 test.

The more distant wells and Rainbow Spring responded to pumping with smaller drawdowns and at later times than the wells at the aquifer-test site. Well ZS-101, 6,470 feet from well ZS-3, responded much sooner than the other distant wells and Rainbow Spring; drawdown started about 15 minutes after pumping started. The onset of drawdown at the other distant wells was about 960 minutes at well ZS-100; 3,600 minutes at well ZS-102 (not shown in fig. 12); and 6,000 minutes at Rainbow Spring.

The response of well ZS-13 to the pumping of well ZS-3 is shown in figure 13. The time-drawdown data for this well are plotted on semilogarithmic paper, so that a constant transmissivity is represented by a straight line. Heath (1983, p. 38) described a method by Jacob (1950) of analyzing aquifer properties from such a time-drawdown plot. By using this method, the straight line that fits the well ZS-13 data from about 10 to 1,000 minutes results in an estimated transmissivity of 640,000 feet squared per day and a storage coefficient of 0.00048 for the San Andres-Glorieta aquifer. The response of well ZS-1 was analyzed similarly using a straight line fitted to the data from 200 to 700 minutes (fig. 14). This analysis resulted in a transmissivity estimate of 750,000 feet squared per day and a storage coefficient of 0.07. The response of well ZS-101 to the pumping of well ZS-3 is shown in figure 15 for comparison purposes.

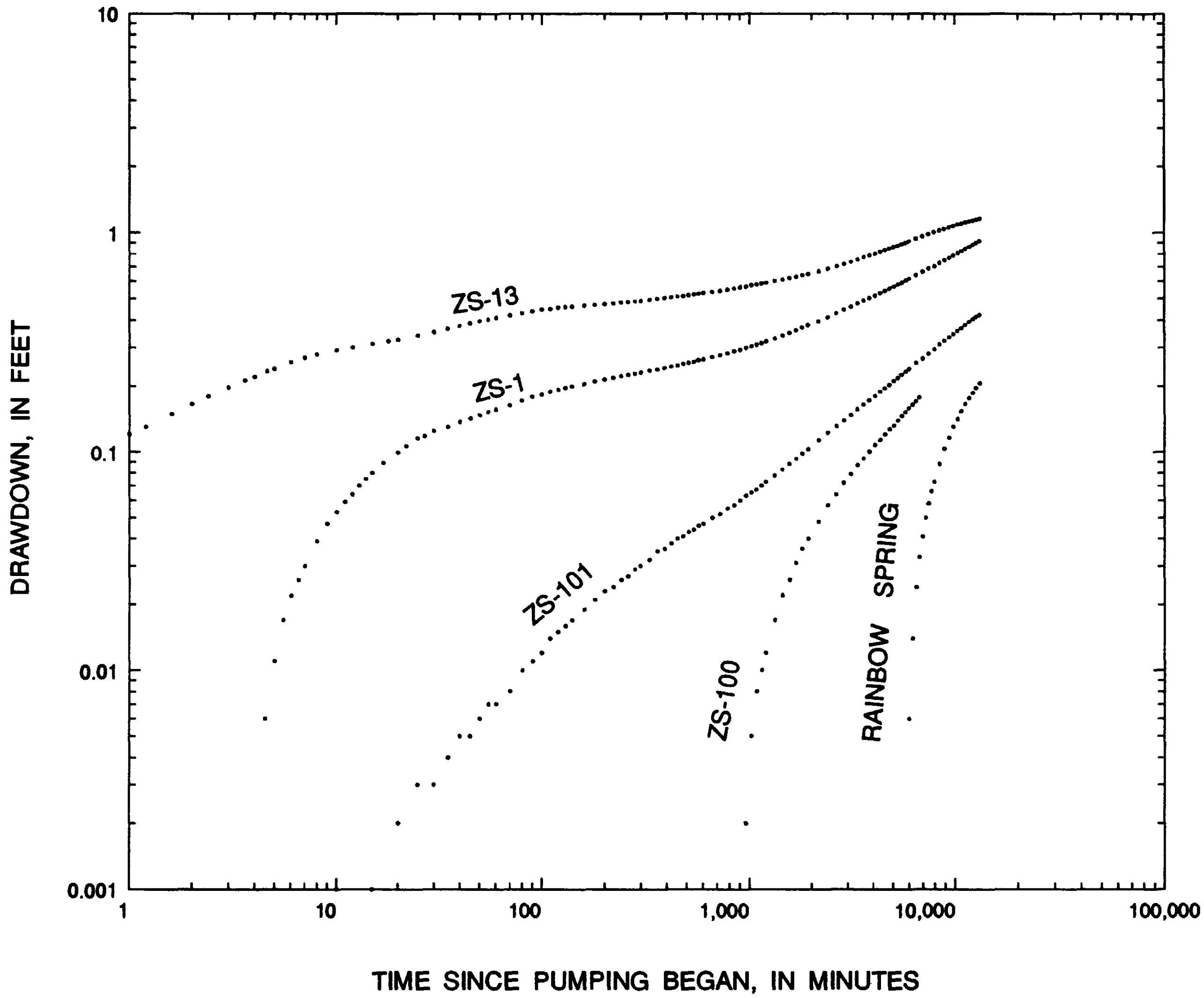


Figure 12.--Drawdown in observation wells during pumping of well ZS-3, October 1-10, 1988.

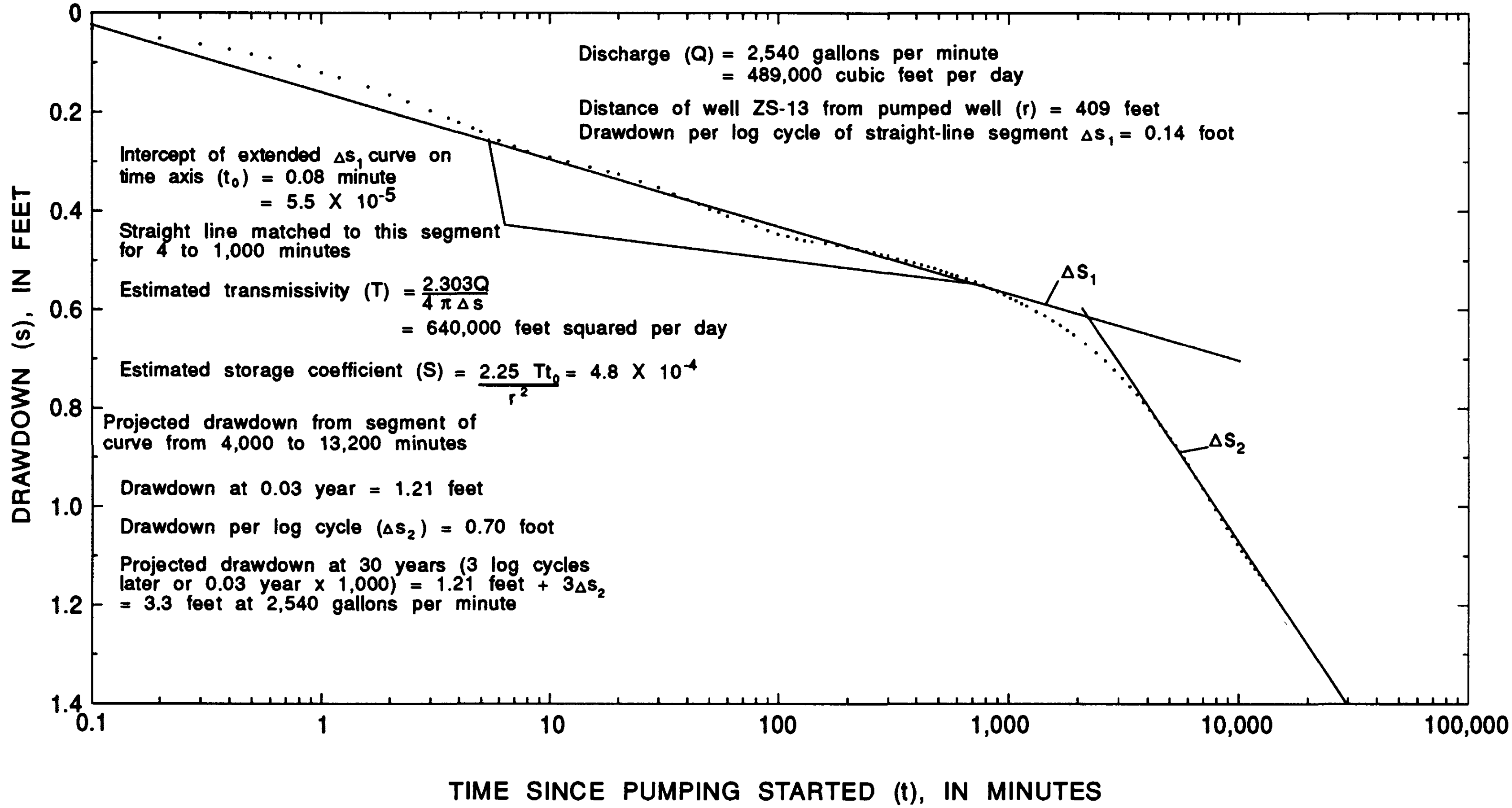


Figure 13.--Drawdown in observation well ZS-13, October 1-10, 1988.

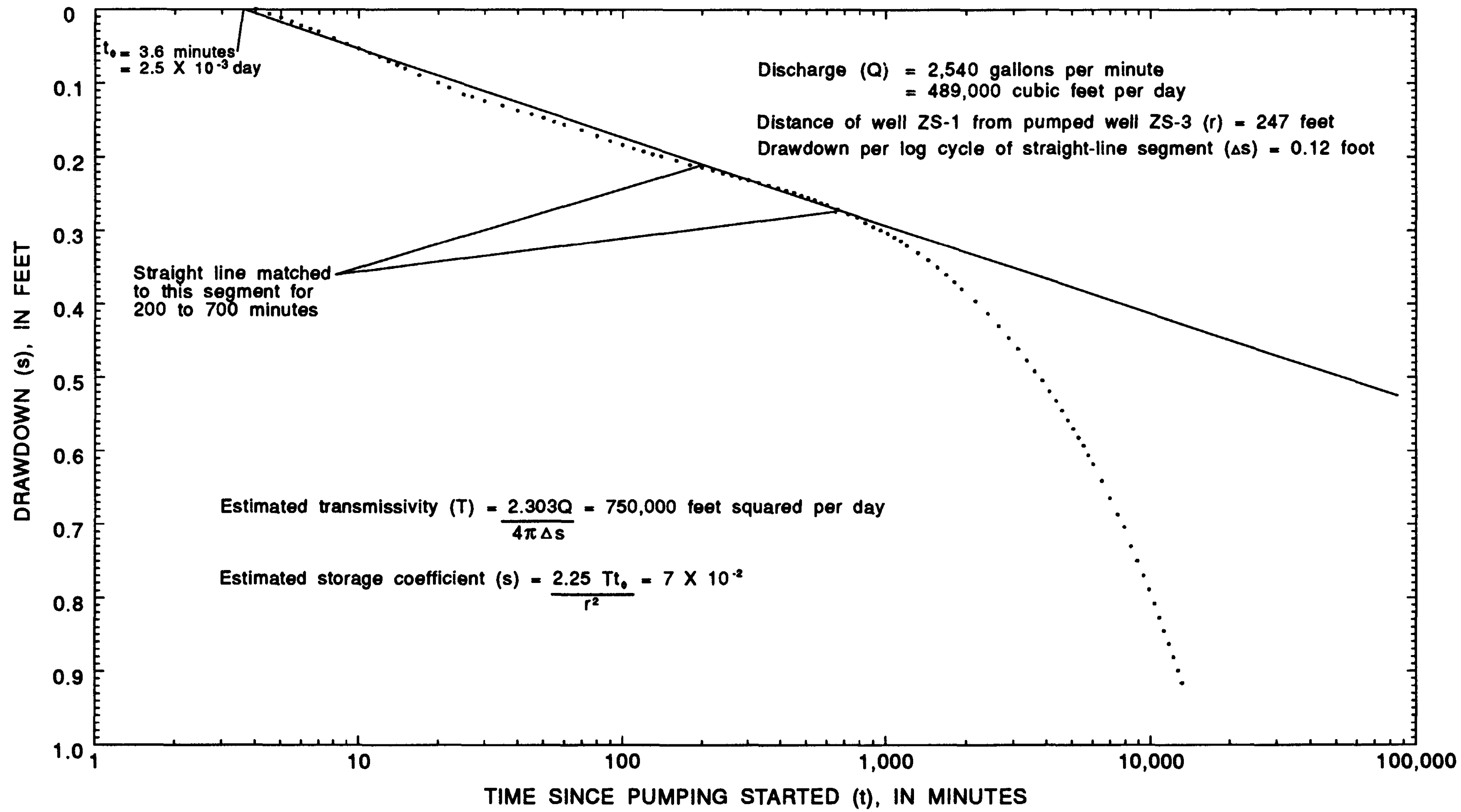


Figure 14.--Drawdown in observation well ZS-1, October 1-10, 1988.

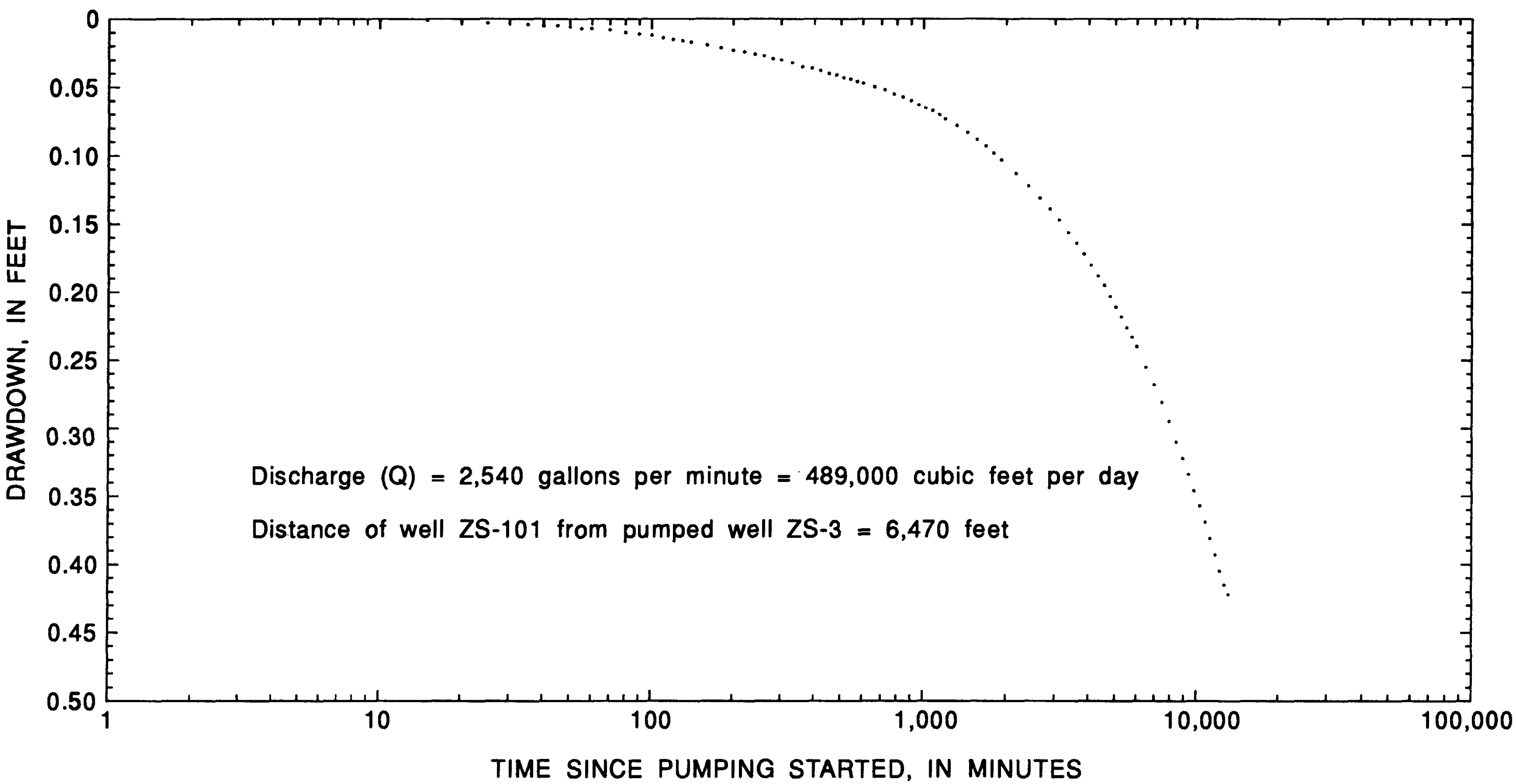


Figure 15.--Drawdown in observation well ZS-101, October 1-10, 1988.

If hydrogeologic conditions were such that aquifer response would remain constant with continued pumping at 2,540 gallons per minute, then future drawdown at well ZS-13 could be estimated by extending the straight line that fits the data from 4,000 to 13,200 minutes (fig. 13). The estimated drawdown after 30 years of pumping would be 3.3 feet.

Future drawdown at Rainbow Spring could also be estimated in a manner similar to well ZS-13. The response of Rainbow Spring to the pumping of well ZS-3 is shown in figure 16. If pumping were to continue at the same rate at the test well and aquifer properties and the effects of boundary conditions remained constant, Rainbow Spring would have about 2 feet of drawdown after 30 years. Rainbow Spring has a specific capacity of about 193 gallons per minute per foot of head change, and was discharging about 600 gallons per minute in 1988. Therefore, 2 feet of drawdown at the spring would be accompanied by a reduction in the flow of about 65 percent, to about 210 gallons per minute.

The estimates of transmissivity and storage coefficient presented have limited value in predicting drawdowns or the sustained yield of the aquifer because most of the assumptions of the analytical methods used in the analysis are not true for the San Andres-Glorieta aquifer in the study area. It is not known that the effects of the aquifer boundaries would remain constant with continued pumping at 2,540 gallons per minute or at other rates. Therefore, these projected drawdowns need to be considered as very approximate. Furthermore, regional water-level changes, such as the rise of 1.6 feet in 1985-87 (fig. 4), would be superposed on the effects of pumping. A regional water-level rise during a period of pumping would decrease the rate of water-level decline and a water-level drop would increase the rate of water-level decline. Nevertheless, the possible yields and drawdowns that may result from pumping are estimated to indicate the possibilities for use of this water resource and the possible effects of pumping on the aquifer and on Rainbow and Sacred Springs, which flow from it. The response of the aquifer to the large-yield test and the resulting estimates give an idea of the potential large yield of the aquifer in the test area and the possible effects of large-scale development. A numerical simulation of the system that incorporates the effects of the layered aquifer and known boundaries might produce improved estimates of aquifer properties and the effects of pumping.

Water Quality

Water-quality properties and constituents were monitored at the test site throughout the aquifer test. Figure 17 is a graph of water temperature. The temperature was measured intermittently in the outflow at the end of the discharge pipeline from well ZS-3 during the first 4 days of the test. For the remainder of the test, a temperature sensor was placed in the outflow at the end of the discharge pipeline and the temperature was recorded continuously while pumping. The temperature remained nearly constant at about 27.2 degrees Celsius. The specific conductance of the discharged water was measured periodically and remained about constant at 1,020 to 1,100 microsiemens per centimeter at 25 degrees Celsius.

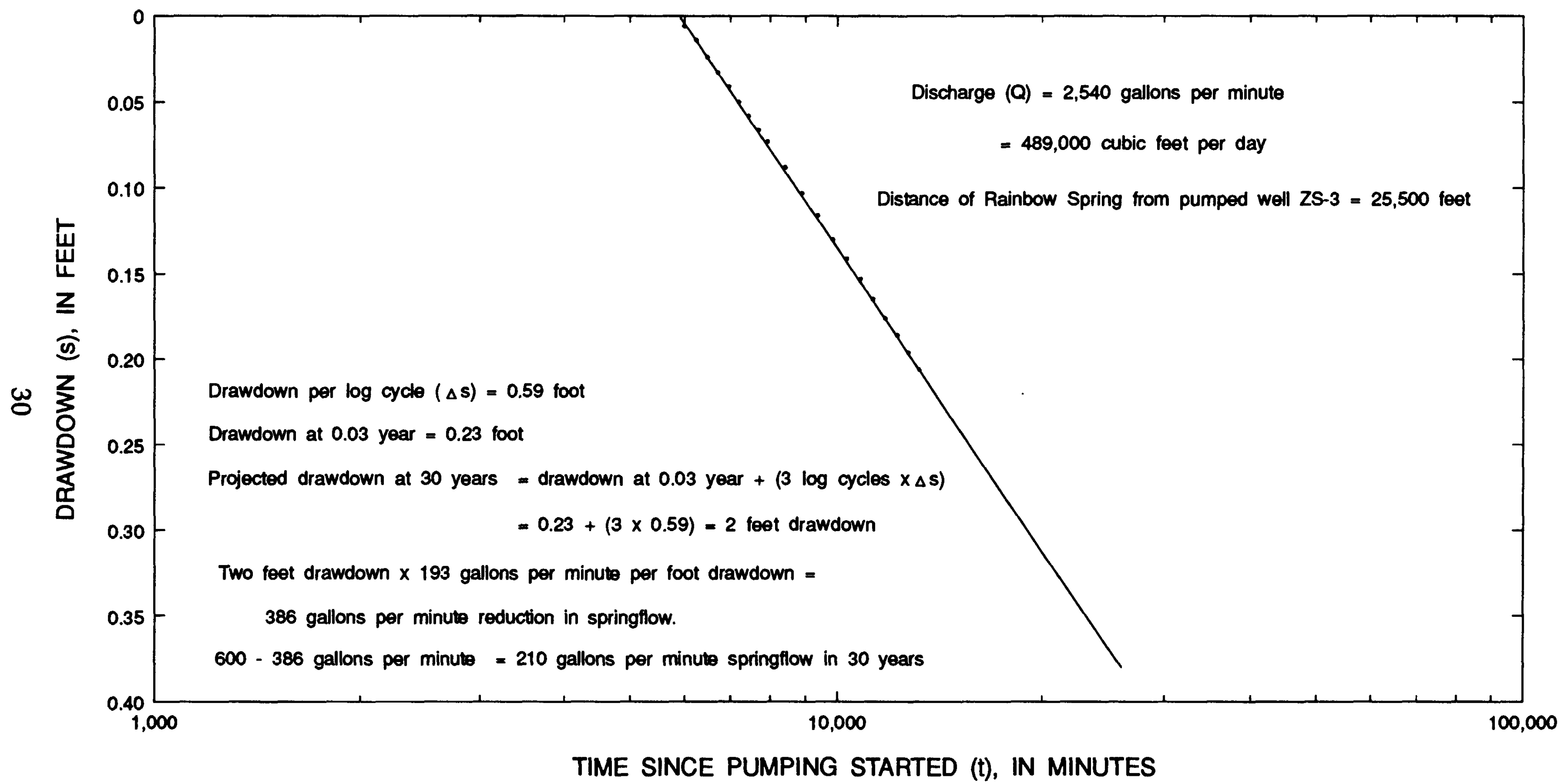


Figure 16.--Drawdown in Rainbow Spring, October 1-10, 1988.

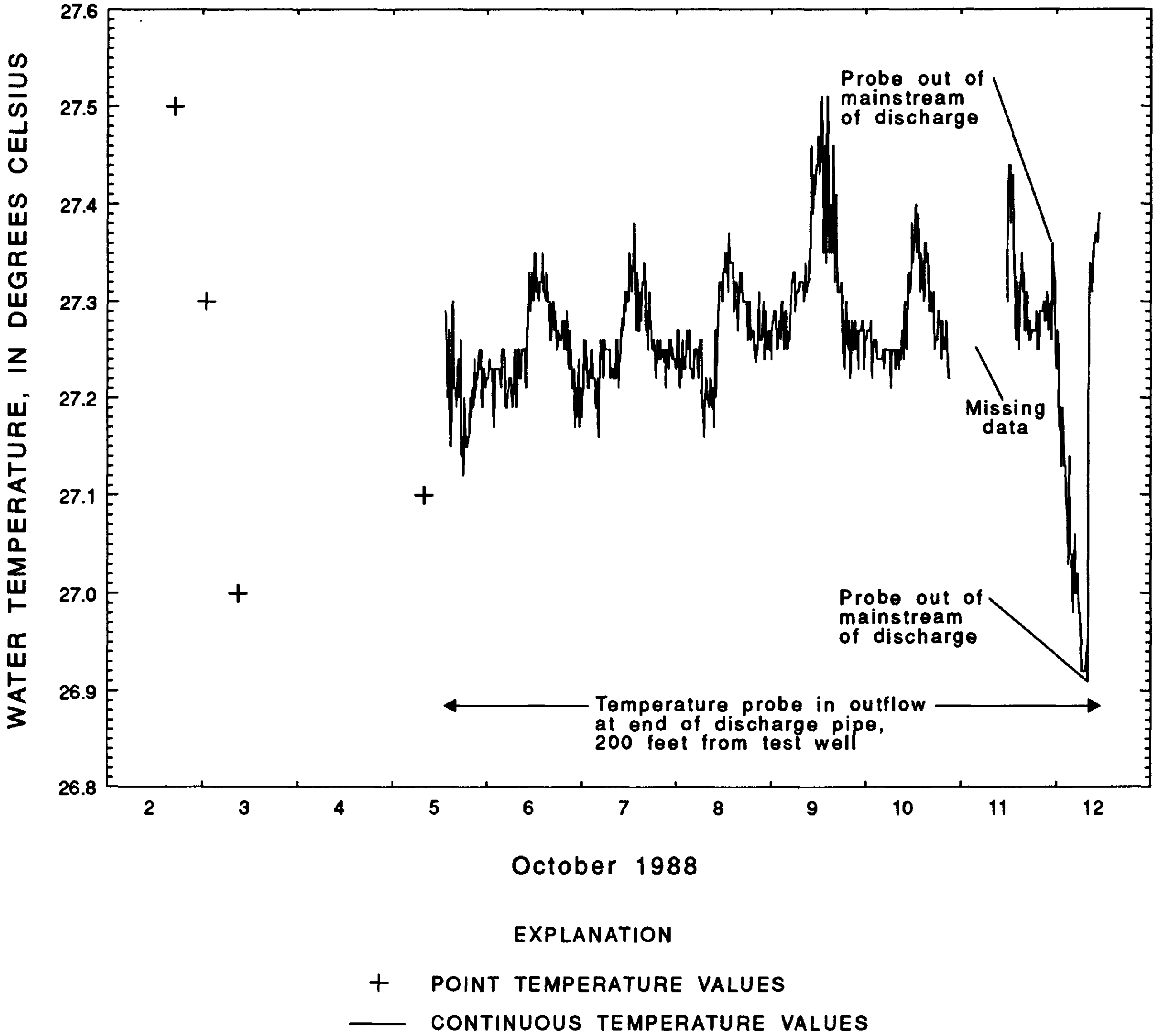


Figure 17.--Temperature of water during pumping of well ZS-3.

Water samples were collected four times during the test. These were analyzed for selected properties, major and minor constituents, selected trace elements, and radioactivity. Results of the water analyses are shown in table 2. Results of analyses of water pumped from well ZS-1 in 1984 and from Rainbow Spring in 1979 also are shown for comparison. The dissolved-solids concentration of water from well ZS-3 is practically the same as that of water from well ZS-1 and Rainbow Spring. The concentrations of all constituents except barium and iron remained nearly constant for the four samples from well ZS-3. Barium and iron concentrations were higher in the sample analyzed at the U.S. Bureau of Indian Affairs laboratory than in the three samples analyzed at the U.S. Geological Survey laboratory. The differences might be due to collection or analysis methods, contamination at the time of collection, or to variations in actual concentrations. A high concentration of barium could result from an influx of water containing drilling fluid, which was lost into the aquifer during drilling of test wells.

The water from well ZS-3 meets the U.S. Environmental Protection Agency (USEPA) primary drinking-water regulations for maximum contaminant levels for all tested constituents (U.S. Environmental Protection Agency, 1988a) except for the high barium concentration in one sample. The water exceeds the USEPA secondary regulations for secondary maximum contaminant levels (SMCL's) of 500 milligrams per liter for dissolved solids and 250 milligrams per liter for sulfate (U.S. Environmental Protection Agency, 1988b); the water meets all other SMCL's.

Table 2.--Water-quality analyses from selected San Andres-Glorieta wells and a spring

[Location: see figures 2 and 7. μS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; μg/L, micrograms per liter; pCi/L, picocuries per liter; NA, not available; --, no data; <, less than; USGS, U.S. Geological Survey; BIA, U.S. Bureau of Indian Affairs. All constituents are dissolved and reported in milligrams per liter unless otherwise indicated]

	Well					
	ZS-1	ZS-3				Rainbow Spring
Location	8.19.29.331a	8.19.29.331e				8.20.21.144
Date sampled	12-07-84	10-03-88	10-06-88	10-07-88	10-12-88	06-19-79
Time sampled	NA	0900	0845	1450	1020	NA
Specific conductance (μS/cm)	1,080	1,100	1,080	1,070	1,080	1,050
pH, field (standard units)	6.5	7.5	--	7.0	7.2	7.0
pH, laboratory (standard units)	7.4	7.8	7.2	7.5	7.9	NA
Temperature (°C)	28.0	27.0	27.5	27.0	27.0	22.0
Hardness (Ca + Mg)	506	490	527	520	520	520
Total alkalinity ($CaCO_3$)	280	272	267	272	275	270
Dissolved solids (calculated sum)	754	743	769	762	734	761
Calcium	140	130	144	140	140	140
Magnesium	38	41	41	42	41	41
Sodium	52	52	53	53	51	54
Sodium adsorption ratio	1	1	1	1	1	1
Potassium	3.3	5.5	4.7	5.4	3.3	5.8
Bicarbonate as HCO_3	340	332	325	332	336	329
Carbonate as CO_3	0	0	0	0	0	0
Sulfate as SO_4	300	310	313	310	310	310
Chloride	37	30	31	29	29	32
Fluoride	.5	.4	.5	.4	.5	.5
Silica	16	17	21	18	17	15
Nitrate as N	<.10	<.10	--	<.10	<.10	.01
Arsenic (μg/L)	13	8	13.6	10	8	--
Barium (μg/L)	28	24	1,500	23	22	--

Table 2.--Water-quality analyses from selected San Andres-Glorieta wells and a spring--Concluded

	Well					
	ZS-1	ZS-3				Rainbow Spring
Location	8.19.29.331a	8.19.29.331e				8.20.21.144
Date sampled	12-07-84	10-03-88	10-06-88	10-07-88	10-12-88	06-19-79
Boron	0.1	--	0.28	--	--	--
Cadmium (µg/L)	< 1	4	< .1	4	4	--
Chromium (µg/L)	< 10	2	< 1.0	2	1	--
Copper (µg/L)	1	1	--	1	1	--
Iron	.37	.082	.225	.036	.038	0.01
Lead (µg/L)	1	< 5	< 1.0	< 5	< 5	--
Manganese (µg/L)	7	6	8.0	5	3	--
Mercury (µg/L)	.4	< .1	< .2	< .1	< .1	--
Selenium (µg/L)	< 1	< 1	< 2.0	< 1	< 1	--
Silver (µg/L)	< 1	2.0	< .2	< 1.0	1.0	--
Zinc (µg/L)	47	11	--	7	12	--
Gross alpha as natural uranium (µg/L)	--	5.1	--	--	5.3	--
Gross beta as cesium-137 (pCi/L)	--	9.0	--	--	8.9	--
Gross beta as strontium/yttrium 90 (pCi/L)	--	6.0	--	--	6.0	--
Radium-226 (pCi/L)	--	.09	--	--	.16	--
Uranium (µg/L)	--	2.4	--	--	2.2	--
Laboratory	USGS	USGS	BIA	USGS	USGS	USGS

SUMMARY AND CONCLUSIONS

The San Andres-Glorieta aquifer underlies the Zuni Indian Reservation and in much of the area is the only aquifer capable of yielding large volumes of water to wells. A large-yield aquifer test was conducted in 1988 by pumping from a cave-fracture system on the southwest part of the Zuni Indian Reservation to evaluate the aquifer properties of the San Andres-Glorieta aquifer, the effects of a large-yield aquifer test on the aquifer, and the chemical quality of water from selected wells and a spring. The productive cave-fracture system occurs along a northeast-southwest lineament that is parallel to major lineaments in New Mexico and Colorado. The Glorieta Sandstone consists of about 200 feet of buff to white, medium-grained, well-sorted, crossbedded, and well-cemented sandstone. The San Andres Limestone conformably overlies the Glorieta Sandstone and consists of about 150 feet of gray to pink, thick-bedded limestone.

Test-production well ZS-3 was constructed in 1988, along with additional observation wells ZS-101 and ZS-102, to perform a large-yield aquifer test and to monitor aquifer response over a larger area than that monitored for previous aquifer tests. Well ZS-3 was pumped at about 2,580 gallons per minute for more than 10 days. Pumping produced almost instantaneous drawdown in all observation wells at the aquifer-test site except well ZS-1, which does not penetrate caves, and produced drawdowns after delays of about 15 minutes to 4 days at more distant wells and Rainbow Spring. Drawdown after 9 days varied from about 4 feet at the pumped well to about 0.2 foot at the most distant observation well and Rainbow Spring.

The aquifer-test analyses are based on assumptions that are commonly true for porous aquifers such as alluvium or sandstone, but that may not be true for the San Andres-Glorieta aquifer. Furthermore, the effects of pumping, which extended almost 5 miles to Rainbow Spring, may reach different boundary conditions with continued pumping. Nevertheless, the response of the aquifer to the large-yield aquifer test and the estimated transmissivity and storage coefficient indicate the potential large yield of the aquifer in the test area and the possible effects of large-scale development.

Analysis of the time-drawdown responses of wells ZS-13 and ZS-1 resulted in estimated transmissivities of 640,000 and 750,000 feet squared per day for each well and storage coefficients of 0.00048 and 0.07. If pumping were to continue at the same rate as for the first 9 days of the test and aquifer response remained constant, Rainbow Spring would have about 2 feet of drawdown after 30 years. Two feet of drawdown at Rainbow Spring probably would be accompanied by a reduction in springflow of about 65 percent, to about 210 gallons per minute. A numerical simulation of the system that incorporates the effects of the layered aquifer and known boundaries might produce improved estimates of aquifer properties and the effects of pumping.

Water quality remained generally unchanged throughout the aquifer test. The temperature of pumped water remained constant at about 27 degrees Celsius and the specific conductance was 1,020 to 1,100 microsiemens. Dissolved-solids concentration averaged about 750 milligrams per liter and calcium-magnesium hardness was about 520 milligrams per liter. The concentrations of all constituents except barium and iron remained about constant for four samples taken during the test. The water quality is practically the same as that of samples taken at well ZS-1 in 1984 and at Rainbow Spring in 1979. This consistency of water quality may indicate that water moving through the San Andres-Glorieta aquifer might be expected to continue unchanged in future years, regardless of whether pumping takes place.

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