EVALUATION OF THE BIDAHOCHI AND SAN ANDRES-GLORIETA AQUIFERS ON PARTS OF THE ZUNI INDIAN RESERVATION, McKINLEY AND CIBOLA COUNTIES, NEW MEXICO

By Thomas M. Crouch

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
acre	0.4047	hectare
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 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
foot per mile	0.1894	meter per kilometer
foot per day	0.3048	meter per day
foot squared per day	0.09290	meter squared per day

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

$$°C = (°F - 32)/1.8$$

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

The need for additional water supplies for the Zuni Tribe has prompted evaluation of two aquifers on parts of the Zuni Indian Reservation in west-central New Mexico. A previous study indicated a potential source of good-quality water in the Bidahochi aquifer near the northwest corner of the reservation and a probability of large transmissivity and suitable water quality in the San Andres-Glorieta aquifer on the southwestern part of the reservation.

In the northwest corner of the reservation, seismic surveys indicated and test drilling confirmed a southwest-trending channel on the buried erosion surface of the Chinle Formation, filled by sediments of the Bidahochi Formation. A test well penetrated more than 800 feet of very fine to medium sandstone and silty sandstone having a water table 602 feet below land surface. An aquifer test resulted in discharge of 7.6 gallons per minute for 30 hours. Analyses of drawdown and recovery in the pumped well, for which the most reliable data were obtained, resulted in estimated values of transmissivity of 450 and 470 feet squared per day. Analysis of the more erratic data for the observation well resulted in an estimated transmissivity of 900 feet squared per day and a storage coefficient of 0.02. The water is of good quality; all constituents tested were within established limits, and the dissolved-solids concentration was 211 milligrams per liter.

The San Andres-Glorieta aquifer-test site, in the southwestern part of the reservation, was selected on the basis of indications of major lineaments and fracture traces by satellite imagery and aerial photographs. Test wells penetrated as much as 135 feet of San Andres Limestone and the upper 21 to 125 feet of the Glorieta Sandstone. The six test wells intercepted numerous fractures in both formations, and four of the six penetrated caves from a few inches to 17 feet high in the limestone. The fractures interconnect the formations to form the San Andres-Glorieta aquifer, which is under confined conditions at the test site. This aquifer has a water level about 485 feet below land surface in test wells. Pumping for 67 hours at 350 gallons per minute produced only 14 feet of drawdown in the pumped well, all in the first hour of the test. The single observation well completed for that test did not show any water-level response to the pumping. A later test made after the drilling of additional observation wells produced a response in only one of the observation wells. That observation well and the pumped well did not

intercept any caves and are aligned along a minor fracture-trace direction. Three injection tests in wells that did intercept caves produced small instantaneous responses in other wells that intercepted caves. These wells are aligned along the major lineament-fracture direction. Analyses of selected injection responses suggest that transmissivity is very large between wells intercepting caves, and as much as 33 to 83 times as great as the transmissivity between the two wells that intercept fractures only. The system of caverns and fractures results in conditions of extreme heterogeneity and anisotropy, which are departures from the assumptions for analysis of porous aquifers and nonturbulent flow. Therefore, values of transmissivity and storage coefficient are not considered adequate for predicting drawdown or yield. The water is of suitable quality for most anticipated uses, exceeding existing limits only for hardness and iron.

INTRODUCTION

The scarce water resources of the Zuni Reservation and the surrounding areas of west-central New Mexico and east-central Arizona increasingly are being used by power companies, municipalities, agriculture, and other interests. In recent years, two power-generation facilities have begun to withdraw large amounts of water from the San Andres-Glorieta aquifer (the Glorieta-San Andres aquifer of Orr, 1987; the formation names are reversed in keeping with the convention of naming the younger unit first) southwest of Zuni in the vicinity of St. Johns and Springerville, Arizona. In addition, the City of Gallup, New Mexico, has taken steps toward developing a water-supply source near the northeastern boundary of the Zuni Reservation that could eventually lead to withdrawals from the San Andres-Glorieta and other aquifers. The Zuni Tribe has experienced population growth and expansion of its economy during recent years; these trends are expected to continue. As a result of this growth, the water use and estimated future water requirements of the tribe have increased.

Purpose of Investigation

An assessment of water resources of the Zuni Reservation by Orr (1987) indicated areas where aquifers might be developed as major water-supply sources. The purpose of this study was to explore the geology and to determine aquifer properties and water quality in two such areas. The necessary information was obtained by drilling exploratory wells and conducting aquifer tests. The study was conducted by the U.S. Geological Survey in cooperation with the Pueblo of Zuni. This report presents the results of a drilling and aquifer-testing program that may be useful in planning for the development, use, and preservation of the Zunis' water resources.

Location and Geography

The Zuni Reservation encompasses approximately 640 square miles in New Mexico adjacent to the Arizona State line (fig. 1). The tribe also owns other small parcels in New Mexico and Arizona that are not included in this study. The two areas where drilling and aquifer testing were conducted during this study are shown in figure 1.

Most of the Zunis and other residents of the reservation live in Zuni Village and Black Rock (fig. 1). Several hundred new housing units have been constructed in these two villages since 1975 (Zuni Housing Authority, oral commun., 1987). The total population on the reservation increased from 6,450 in 1975 to about 8,750 in 1986 (Zuni Tribal officials, oral commun., 1987).

The topography of the Zuni Reservation is dominated by steep-walled mesas and buttes with intervening broad valleys or canyons along major drainageways. The Zuni River, formed by the confluence of the Rio Nutria and the Rio Pescado, is an intermittent stream that carries surface drainage southwestward from the Zuni Mountains, northeast of the reservation, toward the Little Colorado River in Arizona. Smaller intermittent streams that drain the reservation are tributary to these rivers. Altitudes on the reservation range from about 7,700 feet in the southeast and 7,500 feet in the northeast to about 6,000 feet where the Zuni River crosses the Arizona State line. Average annual precipitation ranges from about 12 to 17 inches, being generally greater at higher altitude.

Regional Geology

The Zuni Reservation lies almost entirely on the Gallup embayment, a synclinal trough that extends southward from the southwest margin of the San Juan Basin (fig. 2). This embayment is situated between the Zuni uplift to the east and the Defiance uplift to the west. The steeply dipping beds of the Nutria monocline and the Defiance monocline form the east and west sides of the embayment from Gallup to the northern part of the reservation. These monoclines gradually flatten to the south and merge with the Mogollon slope, whose gentle northward slope forms the southern margin of the Gallup embayment south of the reservation. The floor of the embayment is of moderate structural relief, consisting of synclinal and anticlinal folds that trend north (fig. 2). The Ojo Caliente "fault" described by Orr (1987, p. 7) is referred to as the Ojo Caliente monocline in this report on the basis of examination of additional surface exposures of affected pre-Tertiary rocks. The Ojo Caliente monocline may be a faulted monocline or may change from a monocline to a fault at depth. Orr (1987, pl. 2) presented geologic sections that show the structure of the Gallup embayment on the Zuni Reservation.

The tectonic forces that formed the Gallup embayment and adjacent uplifts occurred in Late Cretaceous and early Tertiary times, resulting in deformation of rocks of Precambrian through Late Cretaceous age. Subsequent periods of erosion formed tablelands, buttes, and canyons over much of the Gallup embayment. Streams and wind deposited the sands of the upper Tertiary Bidahochi Formation over much of the southwestern part of the embayment.

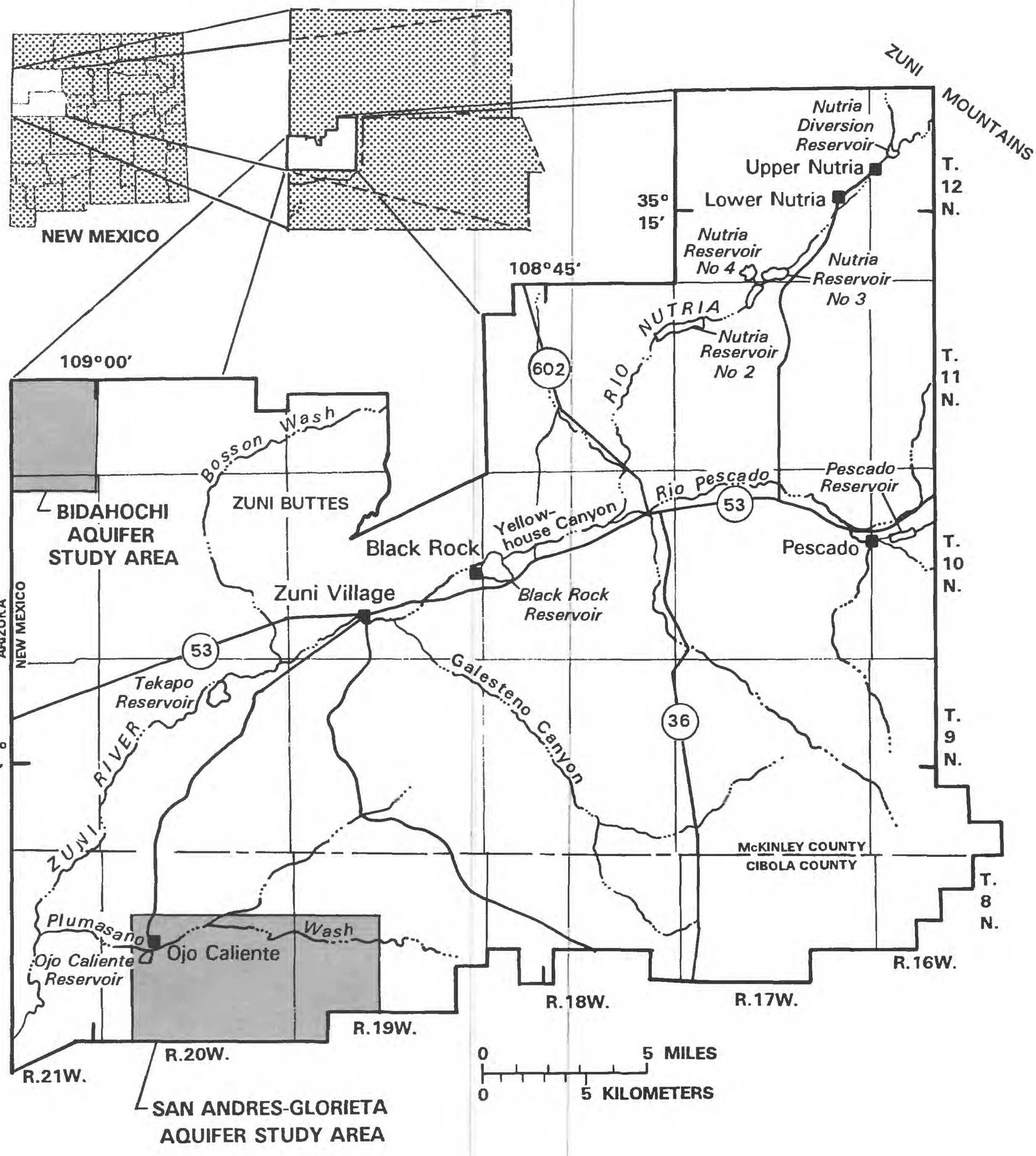


Figure 1.--Location of the study areas on the Zuni Indian Reservation (modified from Orr, 1987, fig. 1).

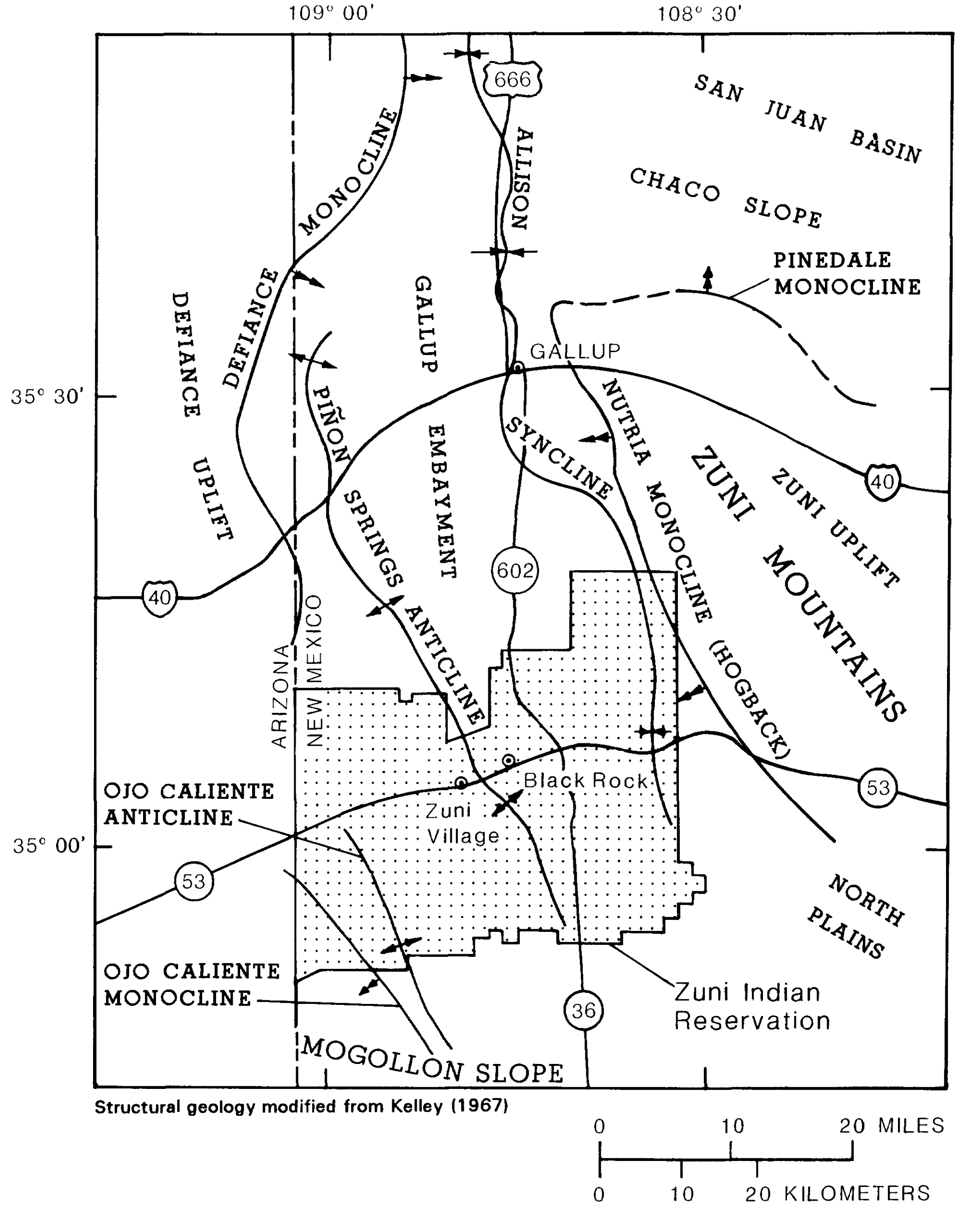


Figure 2.--Major structural features of the Zuni Indian Reservation and vicinity (modified from Orr, 1987, fig. 2).

Previous Investigations

Orr (1987) described the hydrogeology of aquifers, tabulated well characteristics and water quality, and described surface-water availability and quality characteristics. His report also includes a glossary of hydrologic and geologic terms (Orr, 1987, p. 48) that defines most such terms used in this report. Kelley (1967) provided a description of the tectonics and structural features of the area. Additional reports and articles are listed in Orr's reference list (1987, p. 45).

Well-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. To the degree a well or spring cannot be accurately map 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 wells in the same tract.

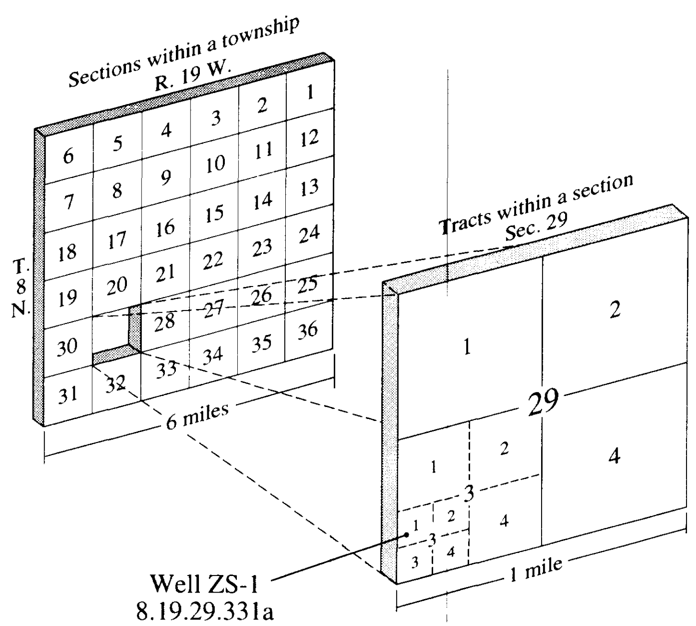


Figure 3.--System of numbering wells and springs in New Mexico.

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 is then numbered by its location on the superimposed square grid, extending grid lines to the north, west, and south where necessary to the boundaries of the irregular section.

HYDROGEOLOGY

Surface water is used for most irrigation on the Zuni Indian Reservation, but water from wells in several aquifers (Orr, 1987) is used for all other needs. The aquifers that underlie the reservation are the only dependable source of additional water for the Zuni Tribe. The Bidahochi aquifer on the northwestern part of the reservation is pumped by only three small-yield stock wells, but has potential for additional development in that area. Water quality probably is suitable for most uses on the reservation. The San Andres-Glorieta aquifer is being pumped by only one well on the reservation. This well, in the Black Rock area, is pumped at an average rate of less than 50 gallons per minute without producing any significant lasting drawdown in the area. This aquifer has considerable potential for development in this and other areas of the reservation, especially in the southwest. Water quality in the San Andres-Glorieta aquifer probably is suitable for most uses on the reservation.

Bidahochi Aquifer

Much of the northwestern part of the Zuni Reservation (fig. 4) is blanketed by a sequence of stream sediments known as the Bidahochi Formation (Orr, 1987, pl. 1). Cooley and others (1969, pls. 1 and 2) mapped the areas immediately to the west and nearby to the north as the upper member of the Bidahochi of Pliocene age; Akers (1964, pl. 1) showed the adjacent area in Arizona as a thin veneer of Quaternary sediments overlying the upper member of the Bidahochi. The extent of the upper member of the Bidahochi Formation in the Bidahochi aquifer study area is shown in figure 4. The formation consists of as much as 840 feet of weakly cemented fine sandstone that locally may be interbedded with conglomerate and volcanic ash. The Bidahochi Formation, where saturated and of sufficient hydraulic conductivity, constitutes the Bidahochi aquifer.

Geologic Framework

The Bidahochi aquifer study area (fig. 1) is in an area of low structural relief with no substantial folds or faults in the immediate vicinity (fig. 2). The Piñon Springs anticline lies several miles to the east. The south end of the Defiance monocline is a few miles to the north. The upper member of the Bidahochi Formation was deposited on an erosion surface of low relief that sloped gently to the southwest (McCann, 1938, p. 271-273). This surface, which McCann named the Zuni erosion surface, was developed on pre-Tertiary beds; in the study area, the Zuni erosion surface is on the upper part of the Chinle Formation. Akers (1964, pl. 2) showed the present slope of the erosion surface in New Mexico varying from about 70 to 200 feet per mile westward in the Bidahochi study area.

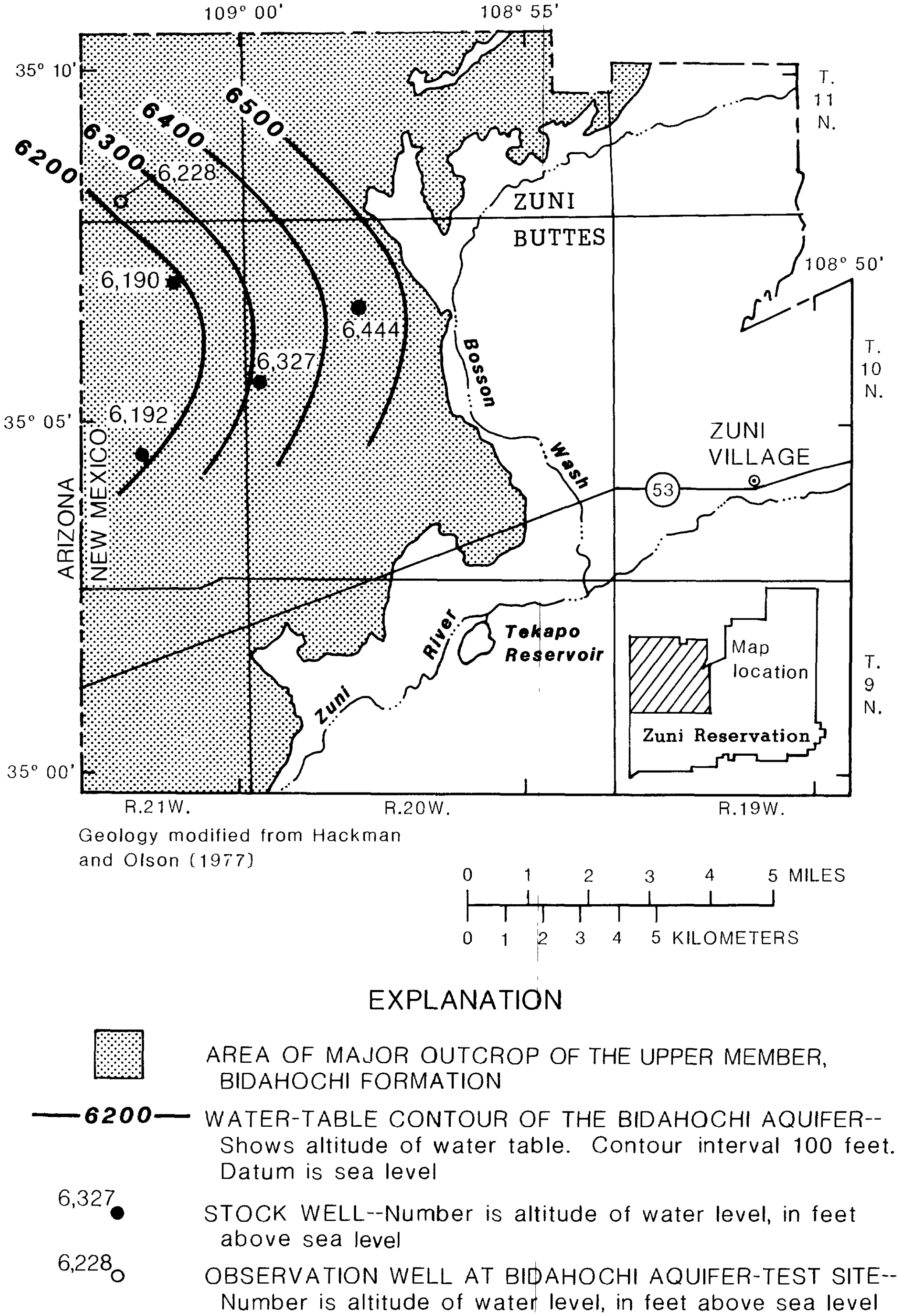


Figure 4.--Water-table contours, June 1987, and outcrop of the Bidahochi Formation.

Structural Controls on Hydrogeology

The primary hydrogeologic factors controlling the occurrence and movement of ground water in the Bidahochi aquifer are the topography of the Bidahochi Formation-Chinle Formation contact (Zuni erosion surface) and the small hydraulic conductivity of the underlying Chinle Formation. The direction and degree of slope at the time of deposition of the Bidahochi aquifer and the location of channels on the Zuni erosion surface controlled the general texture (grain size and sorting) of the aquifer and possibly the localization of coarse sediments. The presence of channels and ridges buried by the Bidahochi sediments causes variation in the saturated thickness of the Bidahochi; maximum saturated thicknesses and probably the coarsest sediments with largest hydraulic conductivity occur in the channels. Saturation levels may be too low to cover buried ridges in some areas. The Zuni erosion surface apparently has been tilted westward by moderate uplift to the east during or since deposition of the Bidahochi Formation. This has steepened the gradient of the erosion surface to the west or southwest, increasing the rate of movement of ground water through the aquifer.

Recharge, Flow, and Discharge

Recharge to the Bidahochi aquifer occurs by direct infiltration of precipitation or by infiltration of runoff from ephemeral streams that flow over or along the margins of the exposed Bidahochi Formation. No significant recharge by leakage from the underlying Chinle Formation is thought to occur because there is no significant change in water quality as water moves westward in the Bidahochi aquifer. The drainage system on the outcrop of the Bidahochi Formation is poorly developed; channels are small in proportion to channel-basin areas and there are many depressions of closed drainage. These conditions indicate that much of the precipitation, which annually averages about 14 inches, infiltrates into the porous sand and gravel of the Bidahochi Formation. Infiltration that is not consumed by evapotranspiration moves downward to the saturated zone of the Bidahochi above the Chinle Formation. No studies have been made in this area to determine how much recharge occurs. A water-balance study in northwestern Colorado (Wymore, 1974) indicates an average annual deep percolation (recharge) of 0.9 inch (about 5 percent of average annual precipitation) for piñon-juniper forested areas at an average altitude of 7,500 feet. The Bidahochi aquifer study area, at an average altitude of 6,800 feet, and at a lower latitude having greater solar radiation, probably has greater evapotranspiration losses, resulting in a smaller percentage of recharge. If runoff is assumed to be negligible and recharge assumed to be 0.5 inch per year (3.6 percent of average annual precipitation), the recharge on an area of 1,000 acres would be about 42 acre-feet per year, or about 26 gallons per minute.

Ground water in the Bidahochi aquifer, which occurs under water-table (unconfined) conditions in the study area, moves generally westward over the Zuni erosion surface. The rate of flow is proportional to the transmissivity, gradient, and width of the section through which flow occurs. Because the transmissivity and water-table gradient are unknown in most of the Bidahochi aquifer-study area, the rate of ground-water flow through the general area cannot be estimated. However, where such properties of the aquifer are known locally, ground-water flow rates can be estimated.

The following example is an estimate of flow through a buried channel interpreted from seismic lines and verified by test well ZB-2 (11.21.35.313b) (fig. 5). The gradient of the water table was estimated to be the same as the floor of the channel, 140 feet per mile. A width of 3,000 feet was used, including the channel and some adjacent saturated aquifer. Freeze and Cherry (1979, p. 29) showed a range of hydraulic conductivity for silty sand of about 0.01 to 400 feet per day. A hydraulic conductivity of 2 feet per day was used for this example, based on the average texture and sorting throughout the saturated section and the weak cementation of these sands. This value, together with an average saturated thickness of 200 feet across the 3,000-foot width, resulted in a transmissivity of 400 feet squared per day. The flow through a vertical section across the channel through well ZB-2 was calculated as follows:

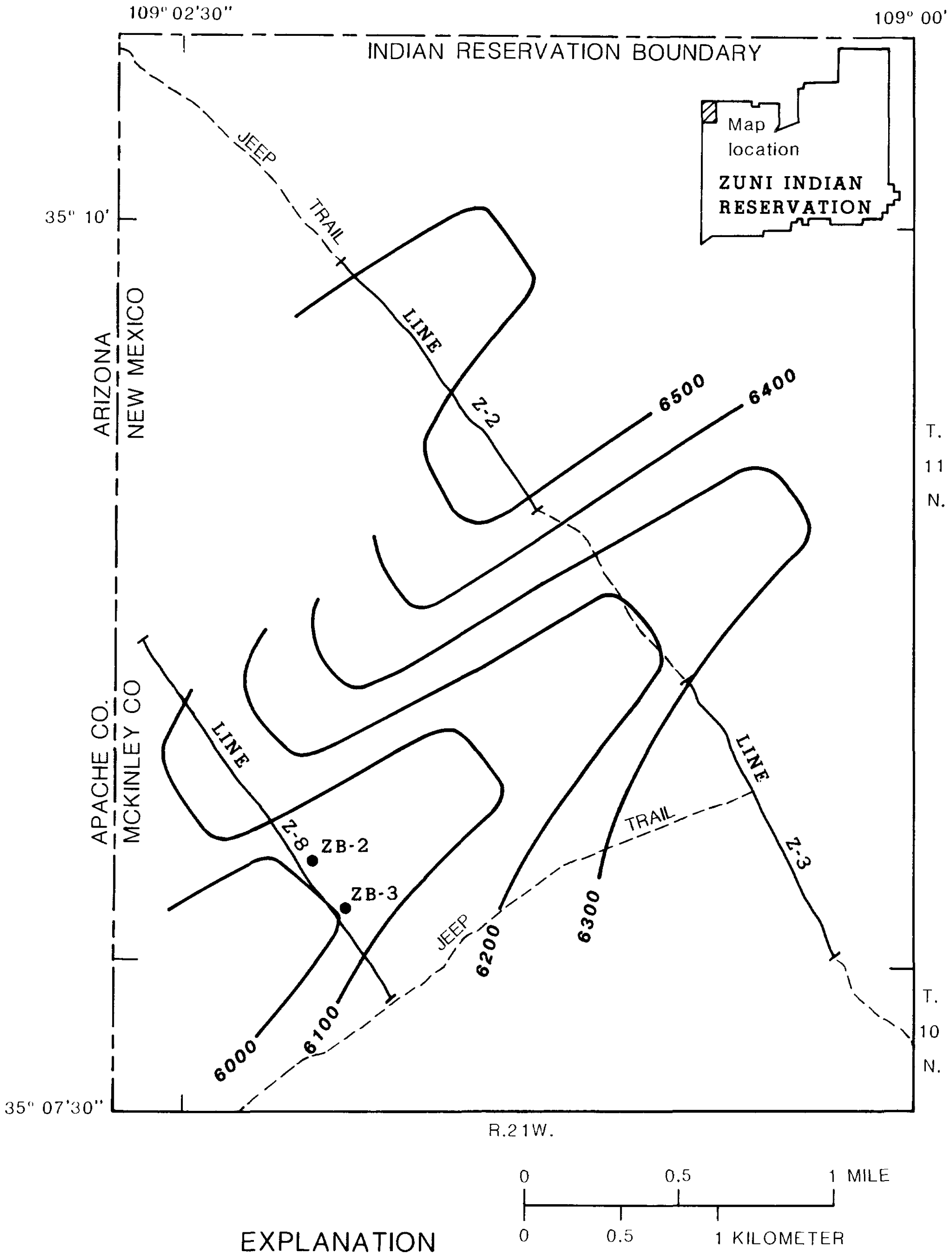
Flow = transmissivity x gradient x width

= 400 feet squared per day x 140 feet/5,280 feet

x 3,000 feet = 32,000 cubic feet per day

= 165 gallons per minute.

Regional discharge from the Bidahochi aquifer occurs from springs to the west at the downslope edge of the aquifer in eastern Arizona and from scattered stock wells. At present (1989) there are minor withdrawals from the Bidahochi aquifer in the study area at three stock wells: RWP-27 (10.20.8.243), Irrigation 1 (10.20.18.314), and RWP-24 (10.21.23.322) (Orr, 1987, p. 6, 30, and table 2). Another stock well, RWP-30 (10.21.11.221), is out of service and the windmill has been removed. The three active wells intermittently produce a few gallons per minute, depending on winds, and average pumpage probably is less than 1,000 gallons per day for each.



EXPLANATION

LINE Z-2 — SEISMIC-PROFILE LINE

6200 — STRUCTURE CONTOUR--Shows approximate altitude of bottom of Bidahochi aquifer from seismic data. Contour interval 100 feet. Datum is sea level

ZB-2 ● — TEST WELL AND NUMBER

Figure 5.--Structure contours on the base of the Bidahochi Formation.

Results of Seismic Exploration and Drilling

The Bidahochi Formation of the northwest Zuni Reservation was selected for exploration because the aquifer in this area is of relatively large hydraulic conductivity and saturated thickness and contains water of better quality than other areas of the reservation. Stock wells that penetrate a sufficient thickness of saturated Bidahochi sands are capable of yielding from 3 to 44 gallons per minute of water with dissolved-solids concentration of less than 300 milligrams per liter (Orr, 1987, p. 27-30). A 1-mile seismic-reflection survey line described by Orr (1987, p. 30) indicated that seismic techniques could be used to delineate the contact between the Bidahochi sandstone and the underlying, less permeable Triassic shale or siltstone. Subsequently, six additional seismic-survey lines were run on the Bidahochi Formation. Three of these lines, Z-2, Z-3, and Z-8, indicated an area of thick Bidahochi sandstone near the New Mexico State line about 3 miles south of the north boundary of the reservation (fig. 5).

The area of thick sandstone is a buried channel that has a southwestward gradient of about 140 feet per mile. This channel lies on the Zuni erosion surface at a depth of about 560 to 840 feet. The channel at seismic-profile line Z-8 (fig. 6) is about 2,000 feet wide and has a channel depth (relief) of about 100 to 120 feet and a channel floor about 800 to 840 feet below land surface. Test well ZB-2 (fig. 6) penetrated the Chinle Formation at the base of the Bidahochi at a depth of 820 feet, as predicted by the seismic survey. Test hole ZB-3 (fig. 5), about 1,000 feet southeast of ZB-2, penetrated the top of the Chinle at a depth of 740 feet, about 50 feet higher than predicted by seismic survey. Test hole ZB-3 was abandoned because it had less saturated thickness of Bidahochi than ZB-2 and geophysical logs indicated that yields from the aquifer would be substantially less than at ZB-2. Seismic lines Z-2 and Z-3 do not give any direct indication of how deeply incised the channel might be between the two lines but, on the basis of seismic trends, were useful in defining the channel as shown. Other interpretations are possible, which would indicate different gradients. This channel is roughly parallel to the larger, deeper channel shown by Akers (1964, pl. 2) southeast of Lupton, Arizona.

Rock samples from test well ZB-2 indicate that the Bidahochi Formation is a weakly cemented, silty, very fine to medium-grained sandstone; the formation generally is coarser and less silty near its base. Below the Bidahochi Formation, red clayey siltstone and medium to coarse silty sandstone of the Chinle Formation were penetrated to a depth of 842 feet below land surface (fig. 6). Borehole-geophysical logs of the well are shown in figure 7. Neutron and resistivity logs indicate that the coarsest, best sorted layers probably are at depths of 696 to 705 feet and 725 to 740 feet. The water level has remained at about 602 feet below land surface (altitude 6,228 feet) since the well was completed as a screened observation well. Geophysical logs of test hole ZB-3 indicate a water level at nearly the same altitude (6,230 feet) as at ZB-2.

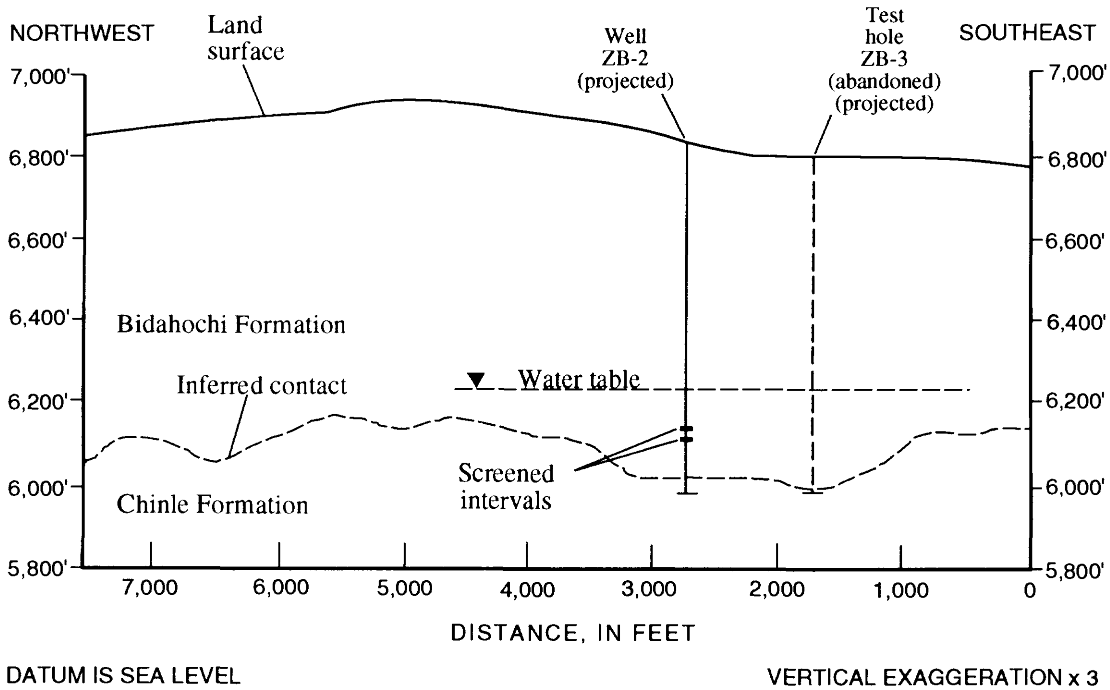


Figure 6.--Seismic profile of the Bidahochi Formation-Chinle Formation contact surface (Zuni erosion surface) along line Z-8 (location shown in fig. 5).

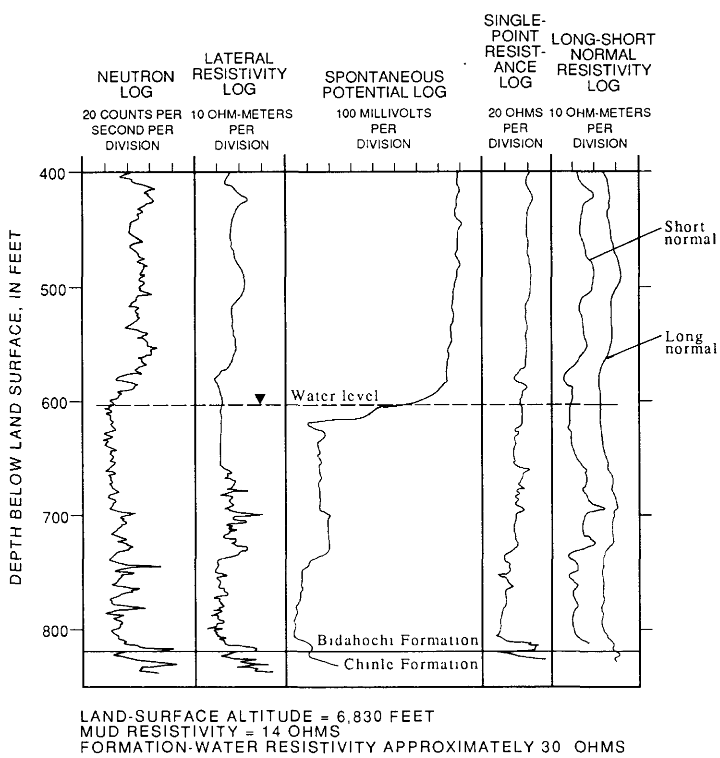


Figure 7.--Borehole-geophysical logs from well ZB-2.

A test-production well, ZB-1 (11.21.35.313a), was drilled 43 feet northeast of ZB-2 to a depth of 782 feet below land surface. The depths and materials penetrated were nearly the same as at ZB-2. Depths of screened intervals and other construction details of the wells are shown in figure 8.

Results of Aquifer Test

An aquifer test was run in April 1986, using well ZB-1 as the production well and well ZB-2 as an observation well. Hydrologic properties of the Bidahochi aquifer in the buried channel shown in figure 5 were estimated from this test. Both wells partially penetrate the aquifer, having screens in the zones of largest hydraulic conductivity. The lower screen in well ZB-1 extends 10 feet deeper than the lower screen in well ZB-2. Partial penetration results in greater drawdown at the pumped well for a given pumping rate than would occur in a fully penetrating well, and therefore results in a transmissivity that is smaller than the true formation transmissivity. However, because the pumped and observation wells are screened at the same levels and in the zones of largest hydraulic conductivity, this effect is diminished. The maximum pumping rate for this test was limited by increasing concentration of sand in the water as the pumping rate was increased. It is likely that the well could be pumped at a greater rate if the pump intake were placed a few feet above the upper well screen in well ZB-1. The pump intake, however, was set in the upper screen for this test.

Well ZB-1 was pumped for 30 hours at an average rate of 7.6 gallons per minute (fig. 9) and measured rates that varied from 6.5 to 8.2 gallons per minute. Water-level response was monitored in the pumped well by an electronic sounding device. Observation-well response was monitored by a downhole pressure transducer and the data were stored in a digital recorder. Adjustments to transducer readings were made by subtracting atmospheric-pressure-change effects from the transducer values. Periodic steel-tape measurements in the observation well revealed that transducer values varied in an erratic manner that could not be corrected. Transducer-measured drawdowns exceeded tape-measured drawdowns by as much as 22 percent during the first 6 hours of the test and were as much as 24 percent less than taped drawdowns during the remainder of the test.

The drawdown in the pumped well for this test is shown in figure 10. Drawdown data were corrected to compensate for the decreasing saturated thickness of the aquifer at the pumped well by a method described by Jacob (1963). No correction was needed for the prepumping water-level trend, which was flat. Transmissivity of the aquifer is estimated as 450 feet squared per day, using the modified nonequilibrium formula (Ferris and others, 1962, p. 98). The drawdowns during the first 50 minutes of the test were probably nonlinear due to borehole storage effects and therefore were not considered in estimating transmissivity. The erratic drawdowns likely result from fluctuations in pumping rate. This is indicated by the correspondence between times of small pumping rates and decreased drawdown, as at 120, 240, and 1,220 to 1,800 minutes, and between large pumping rates and increased drawdown, as at 420 and 960 minutes.

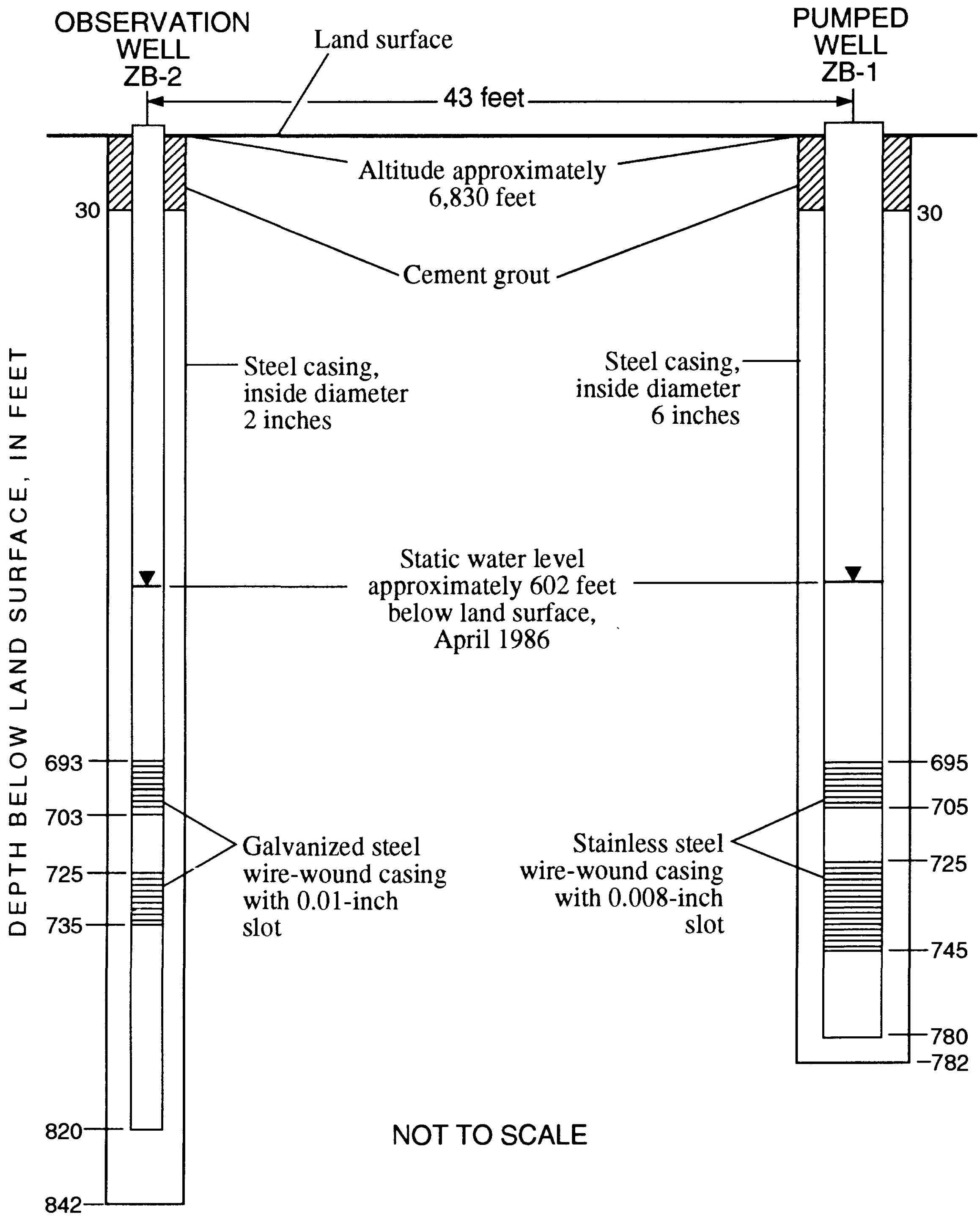


Figure 8.--Construction details of Bidahochi test wells ZB-1 and ZB-2.

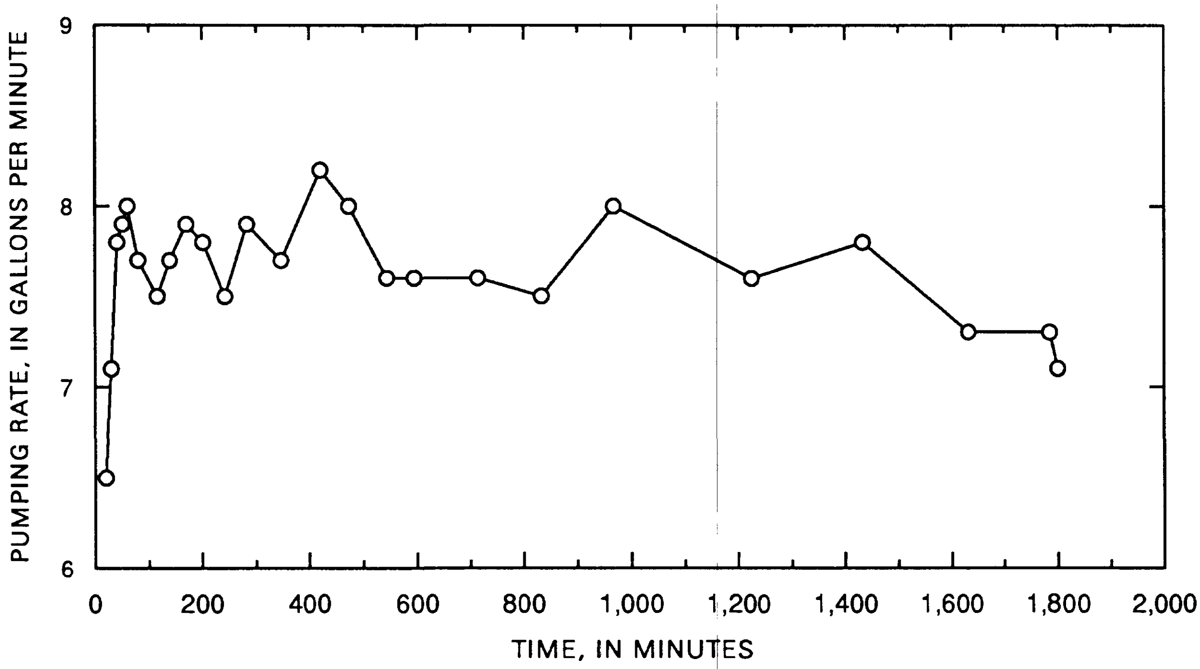


Figure 9.--Pumping rate during aquifer test at well ZB-1.

Recovery data from the pumped well also were used to estimate transmissivity (fig. 10). Recovery was calculated by subtracting the residual drawdown from the projected drawdown, projected at the rate indicated by the straight line on the drawdown plot. This method, a modified form of the Theis recovery method (Ferris and others, 1962, p. 100) results in an estimated transmissivity of 470 feet squared per day. The nonlinearity of the curve for recovery time ratios of t/t′ greater than 11, corresponding to recovery times of less than 180 minutes, probably was caused by the effect of borehole storage.

A third estimate of transmissivity (fig. 11) was made from drawdown data in the observation well (ZB-2) using the Theis nonequilibrium method (Ferris and others, 1962, p. 92). This method also provided an estimate of an early storage coefficient of the aquifer. The curve match is considered more accurate for times after the first hour, which form the more horizontal part of the curve and fix the vertical position of the match point (fig. 11). This determines the match-point drawdown and the estimate of transmissivity of 900 feet squared per day. This estimate is considered to be less accurate than those from pumped-well data, due to the erratic nature of the transducer data. The less definite horizontal position of the curve determines the match-point time and the estimate of storage coefficient of 0.02. This value probably is smaller than the true specific yield of this aquifer, which is expected to be between about 0.10 and 0.20, a typical range for moderately sorted, fine-grained sandstone. The smaller value estimated from the test may be a result of delayed drainage effects of the fine silty sand.

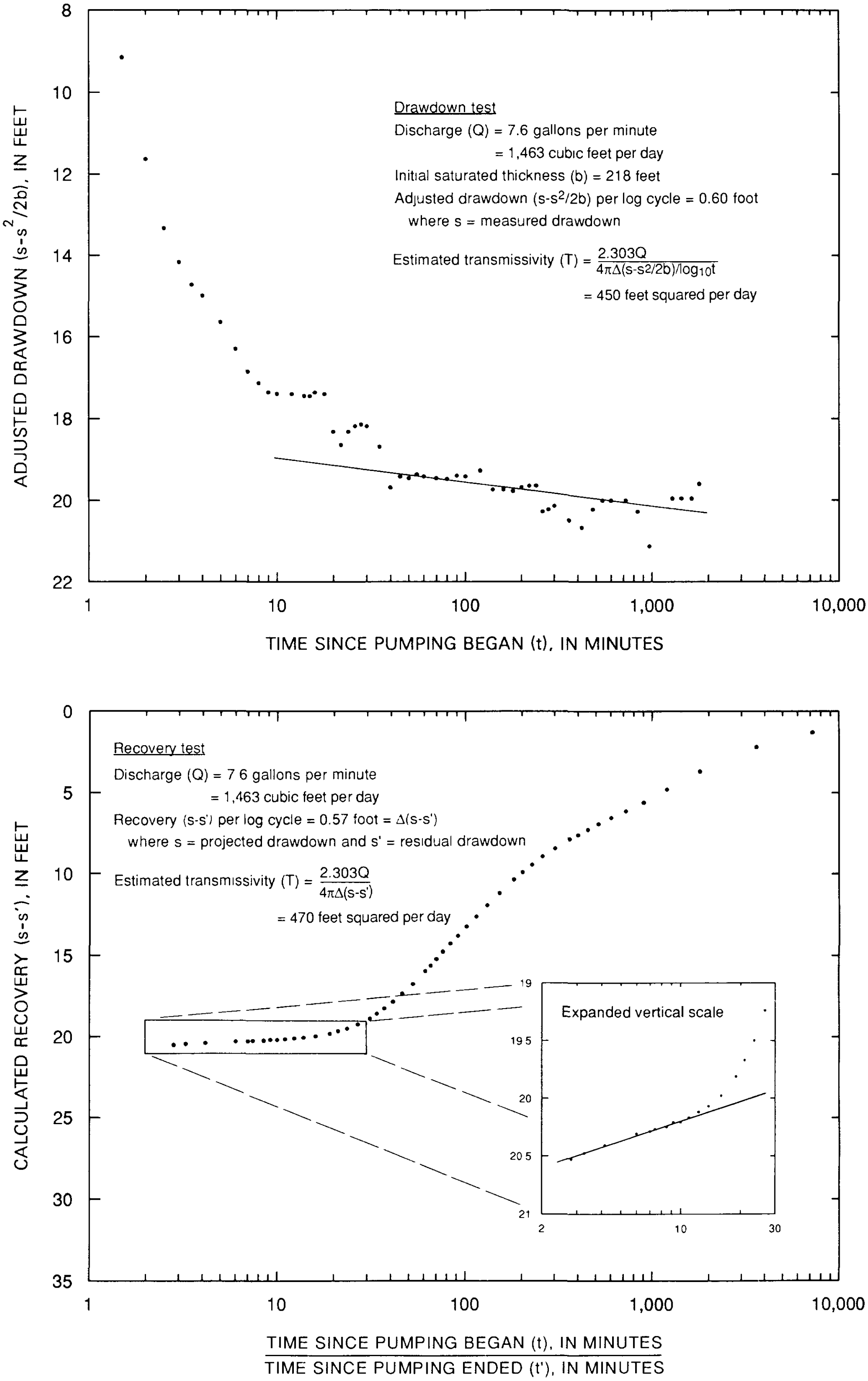


Figure 10.--Drawdown and recovery in pumped well ZB-1, April 22-24, 1986.

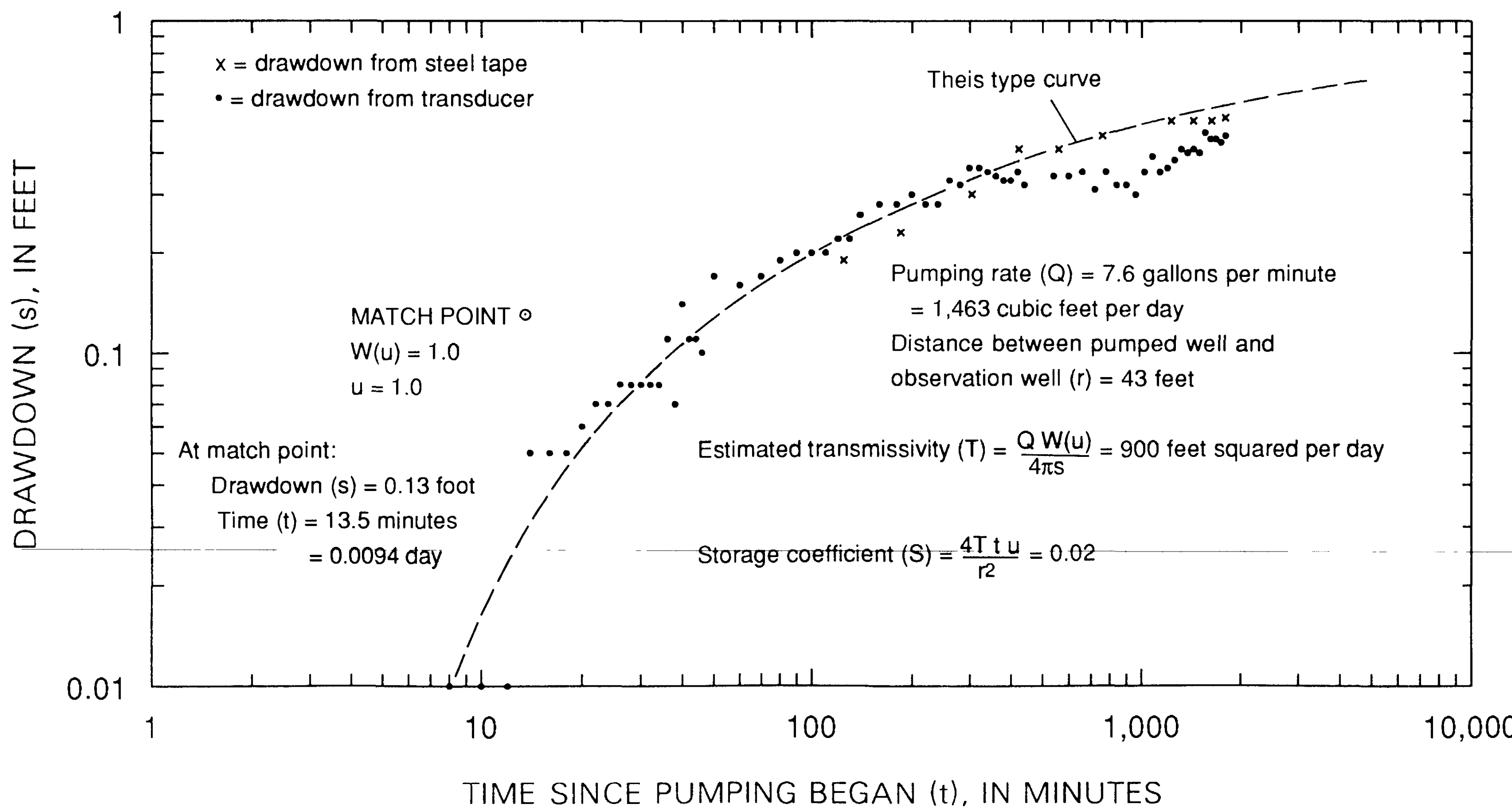


Figure 11.--Drawdown in observation well ZB-2, April 22-23, 1986.

Water Quality

A water sample was collected from the discharge of well ZB-1 after 25 hours of pumping. Specific conductance during well development by bailing had decreased from 360 to 345 microsiemens per centimeter at 25 degrees Celsius. During pumping, conductance continued to decrease and stabilized at 315 microsiemens. Results of the water analysis are shown in table 1. The water from ZB-1 is similar to that from stock wells in the vicinity, RWP-27 and Irrigation 1 (Orr, 1987, table 3). A trilinear plot (fig. 12) of water analyses from these three wells shows the similarity in major dissolved constituents. The water from ZB-1 is within Federal primary and secondary maximum contaminant levels for the constituents tested (U.S. Environmental Protection Agency, 1986a, b). However, no sampling or testing was done for trace elements or radionuclides. The analyses from the three Bidahochi wells indicate that this aquifer contains the best quality water of all aquifers on the Zuni Reservation.

San Andres-Glorieta Aquifer

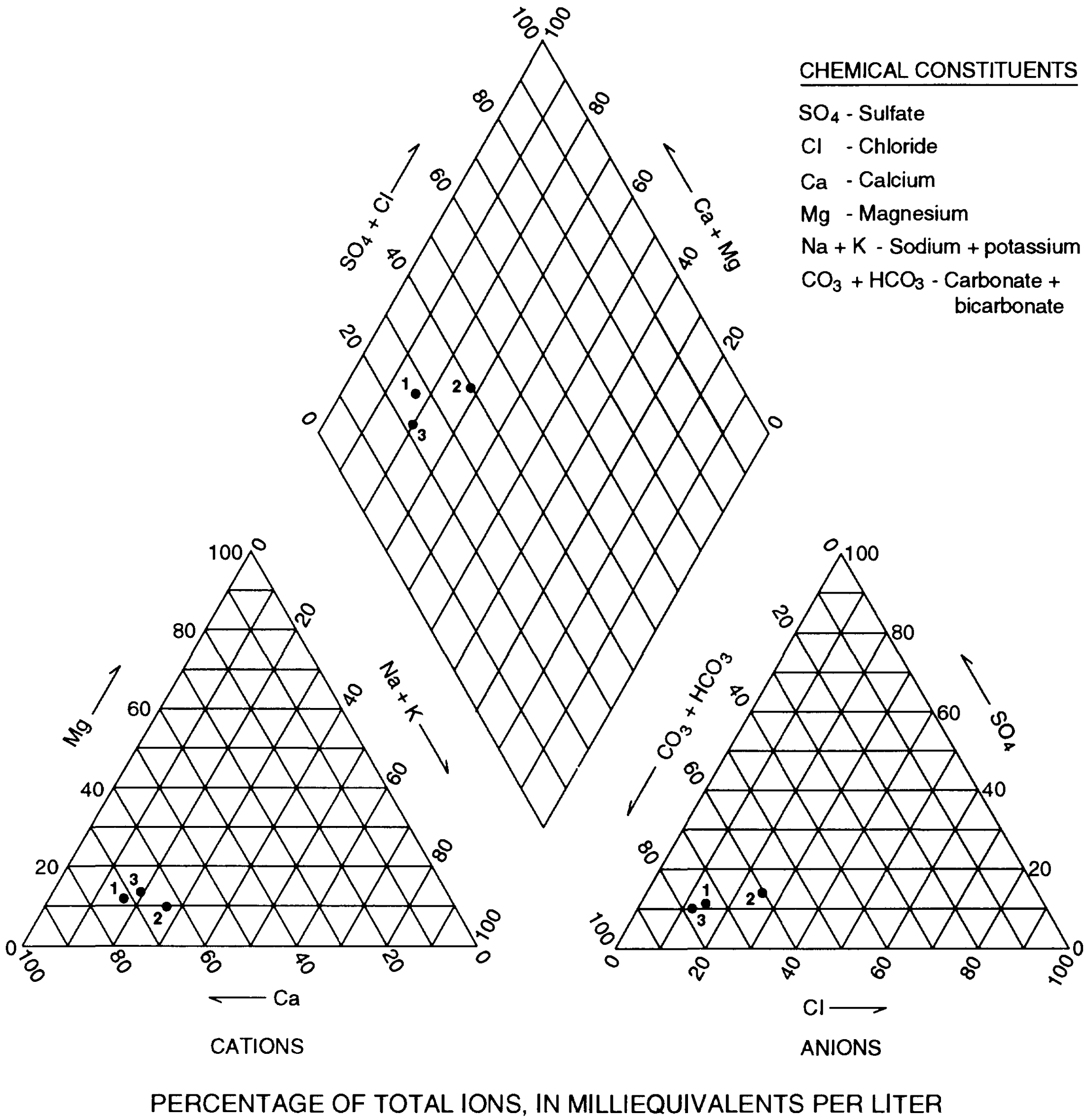
The Glorieta Sandstone and the overlying San Andres Limestone, of Permian age, together constitute the San Andres-Glorieta aquifer. These formations underlie the entire Zuni Reservation and extend through much of west-central New Mexico and northern Arizona. Both formations are exposed at the northeast corner of the reservation; the San Andres Limestone also is exposed near Ojo Caliente (fig. 13) (Orr, 1987, pl. 1). The Glorieta Sandstone is the equivalent of the Coconino Sandstone in Arizona (Baars, 1962, p. 195), and the San Andres Limestone is the equivalent of the Kaibab Limestone in Arizona (Akers, 1964, p. 23). These two formations are considered as a single aquifer on the Zuni Reservation, as in surrounding areas (Gordon, 1961, p. 26; Mann and Nemecek, 1983, p. 11), due to interconnection by fractures. 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.

Table 1.--Water-quality analyses from selected wells: major and minor constituents

EXPLANATION

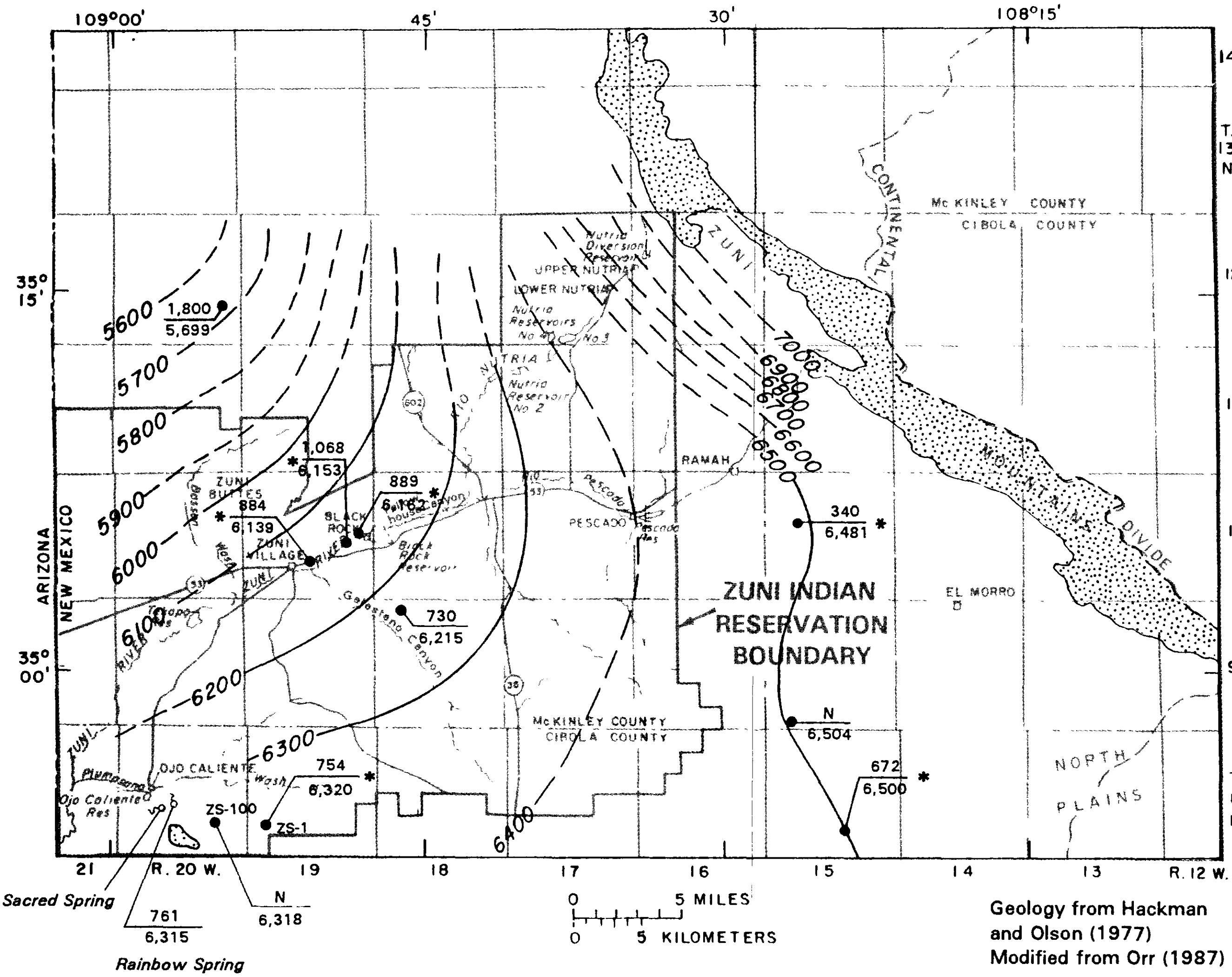
Location: See text
Specific conductance: Microsiemens per centimeter at 25 degrees Celsius
Laboratory: USGS, U.S. Geological Survey; BIA, Bureau of Indian Affairs
Abbreviations: °C, degrees Celsius
--, not analyzed
<, less than
Tb, Bidahochi aquifer
Psg, San Andres-Glorieta aquifer
Note: All constituents are dissolved and reported in milligrams per liter, except as labeled

	Well ZB-1	Well ZS-1	Well Zuni F-5
Location	11.21.35.313a	8.19.29.331a	10.19.27.112
Date sampled	04-23-86	12-07-84	- -87
Specific conductance	315	1,080	1,140
pH, field (units)	7.8	6.5	--
pH, laboratory (units)	8.0	7.4	6.0
Temperature (°C)	23.5	28.0	--
Hardness (Ca + Mg)	136	506	494
Noncarbonate hardness	21	226	324
Total alkalinity ($CaCO_3$)	115	280	170
Dissolved solids (calculated sum)	211	754	869
Calcium	46	140	155
Magnesium	5.1	38	26
Sodium	14	52	74
Sodium adsorption ratio	.52	1.01	1.45
Potassium	1.9	3.3	7
Bicarbonate as HCO_3	140	340	207
Carbonate as CO_3	0	0	0
Sulfate as SO_4	14	300	464
Chloride	14	37	9
Fluoride	.1	.5	.98
Silica	23	16	--
Nitrate as N	5.3	.09	--
Boron	--	.1	< .05
Iron	.09	.37	1.75
Laboratory	USGS	USGS	BIA
Geologic unit	Tb	Psg	Psg



Number on plot	Well name	Location number	Dissolved-solids concentration, in milligrams per liter
1	RWP-27	10.20.8.243	256
2	Irrigation 1	10.20.18.314	263
3	ZB-1	11.21.35.313a	211

Figure 12.--Chemical composition of ground water from the Bidahochi aquifer.



EXPLANATION

AREA OF OUTCROP OF THE SAN ANDRES-GLORIETA AQUIFER

6400 — POTENTIOMETRIC CONTOUR OF THE SAN ANDRES-GLORIETA AQUIFER--Dashed where approximate. Contour interval 100 feet. Datum is sea level. Contours based on static water levels in wells measured during 1975-86, and in the Cheechilgeetho well (12.20.25.123), abandoned in 1953, and the Roy Eidal test well (9.15.32.330), abandoned in 1971

754 / 6,320 ● WELL
761 / 6,315 SPRING

--Top number is dissolved-solids concentration of water, in milligrams per liter. N = no dissolved-solids concentration reported. Bottom number is altitude of water level, in feet above sea level. * = aquifer tests available

Figure 13.--Potentiometric surface and outcrop area of the San Andres-Glorieta aquifer on the Zuni Indian Reservation and vicinity.

Geologic Framework

The San Andres-Glorieta aquifer study area, near Ojo Caliente (fig. 1), is situated on the floor of the Gallup embayment (fig. 2). The Ojo Caliente anticline and the Ojo Caliente monocline are in the western part of this study area (figs. 14 and 15). The Ojo Caliente monocline is the only major structural feature in the vicinity, having dips of as much as 50 degrees to the southwest. The Piñon Springs anticline, a broad, gentle arch, lies several miles to the east. Other folds trending north-northwest through the study area cause only minor relief in the San Andres-Glorieta strata.

In middle Permian time, the Zuni area was the site of mostly marine sedimentation (Baars, 1962). The Yeso Formation, an interbedded sequence of redbeds, carbonates, and evaporites underlying the Glorieta Sandstone, was deposited in a near-shore environment, and evaporites such as gypsum and halite were deposited during times when the shallow seas had restricted circulation. Sedimentation continued with deposition of the Glorieta Sandstone and the San Andres Limestone, but with less restricted circulation. This was followed by uplift and erosion in Late Permian or Early Triassic time. This period of erosion removed the San Andres Limestone in some areas, and in other areas developed karst conditions in the limestone, characterized by sinkholes and caves (Gordon, 1961, p. 29; Baars, 1962, p. 209; Akers, 1964, p. 23). Deposition of the mostly fine grained sediments of the Petrified Forest Member of the Upper Triassic Chinle Formation followed, filling the sinks and caves of the San Andres in some areas. Deposition of shale, siltstone, and sandstone continued through Jurassic and Cretaceous time. This entire sequence of sedimentary rocks, together with the Precambrian basement rocks, was deformed in Late Cretaceous and early Tertiary time, when the Zuni and Defiance uplifts and the Gallup embayment were formed. Subsequent erosion removed part or all of the post-Permian strata across the western part of the Zuni Reservation. During this period, ground water moving generally westward from the Zuni uplift dissolved part of the San Andres Limestone, developing a cavernous network and forming springs and travertine deposits at Ojo Caliente (Orr, 1987, pl. 1).

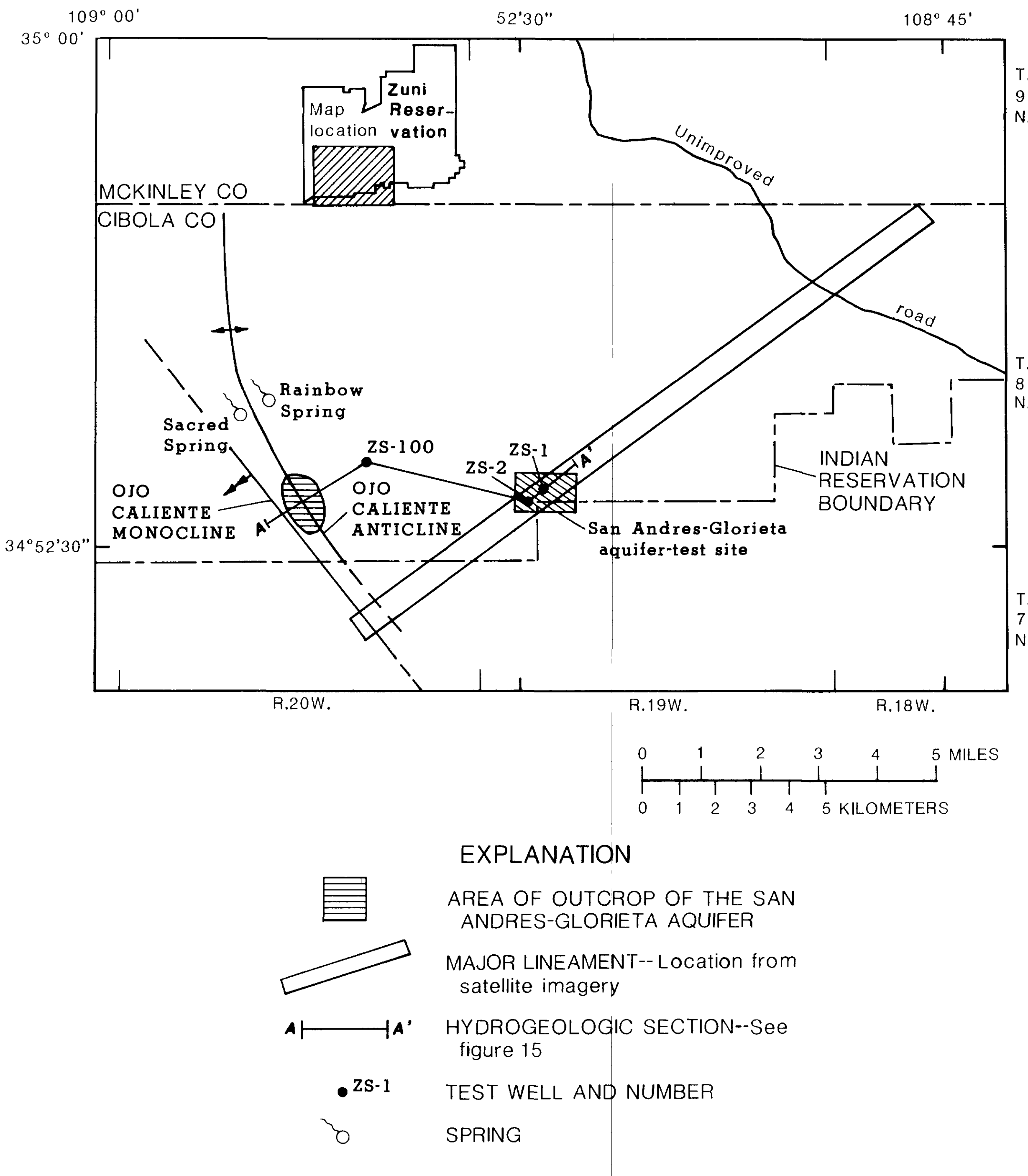


Figure 14.--San Andres-Glorieta aquifer study area and vicinity.

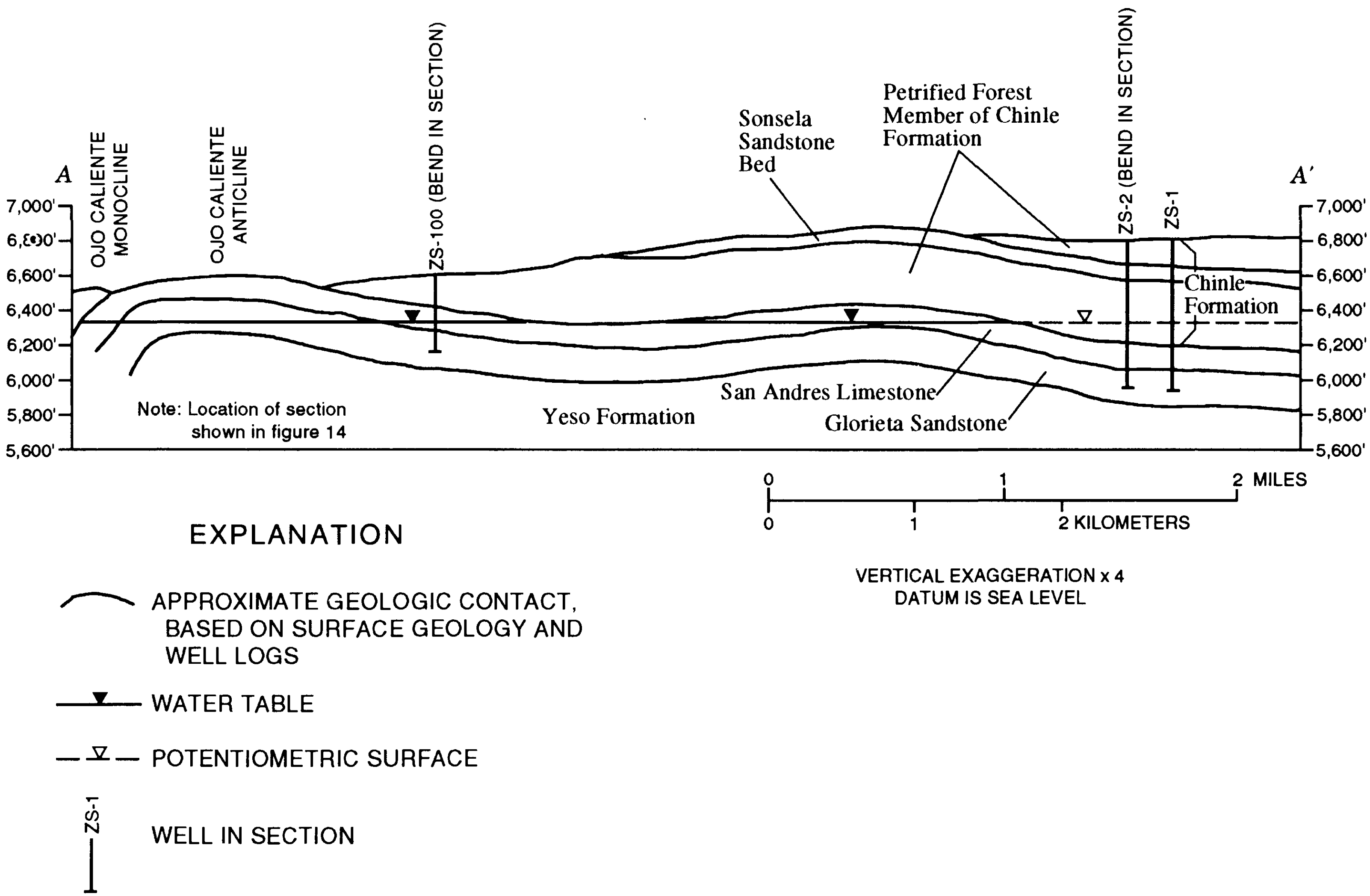


Figure 15.--Hydrogeologic section of the San Andres-Glorieta aquifer.

Structural Controls on Hydrogeology

The uplifts and folds of the Zuni area control the recharge, movement, and discharge of water in the San Andres-Glorieta aquifer. The Zuni uplift (fig. 2) exposes the San Andres Limestone and Glorieta Sandstone to precipitation and streamflow that provide recharge. Where downwarped in the Gallup embayment, the San Andres-Glorieta aquifer is covered by the small-hydraulic-conductivity mudstone and siltstone of the Chinle Formation, and in some areas, younger strata. Orr (1987, pl. 2) showed the San Andres Limestone at depths as great as 3,600 feet in the northeastern part of the Zuni Reservation. Over most of the central and western parts of the reservation, the San Andres is at depths of 1,000 to 2,000 feet, but locally is shallower or uncovered in the southwestern part of the reservation. Water moving through the aquifer from the higher recharge areas of the Zuni uplift is in most areas confined by the Chinle Formation. Unconfined (water-table) conditions occur locally where uplifts on the floor of the Gallup embayment, such as the Ojo Caliente anticline, raised part or all of the aquifer above the potentiometric surface (fig. 15). The abrupt downward bend of the aquifer and adjacent formations at the Ojo Caliente monocline, which may be faulted, seems to form an effective barrier to flow to the southwest and to divert most San Andres-Glorieta water to the northwest. This barrier also may prevent pumpage in nearby areas of Arizona from affecting water levels in or spring discharge from the San Andres-Glorieta aquifer northeast of the monocline.

Another effect of structural deformation on hydrogeology is the formation of fractures that may increase the hydraulic conductivity of the aquifer. Water moving in a system of interconnected fractures may dissolve rock materials, further increasing the hydraulic conductivity. This process can eventually form a system of interconnected caves and fractures that can greatly increase the storage and transmissive properties of the rocks. The effects of structures and fracture systems and their occurrence on the Zuni Reservation were discussed by Orr (1987, p. 7-8).

Aerial photographs and satellite imagery of the southwest Zuni area show several lineaments (topographic expressions of fractures or fracture systems) oriented approximately N. 55° E. (fig. 14). Chapin and others (1978, p. 114) showed the "Jemez lineament," some 25 miles to the southeast of the San Andres-Glorieta aquifer-test site, with virtually the same orientation. This major lineament runs from east-central Arizona diagonally across New Mexico to southeastern Colorado. Other major parallel lineaments exist to the north in Colorado and to the south in New Mexico. Numerous smaller scale manifestations of fracturing (fracture traces) in this approximate orientation are also apparent in streambed orientations and other topographic features. A few small fracture traces approximately perpendicular to these features are apparently expressed in stream patterns in the vicinity of test well ZS-1 (8.19.29.331a) (fig. 14).

Recharge, Flow, and Discharge

Recharge to the San Andres-Glorieta aquifer in the Zuni area occurs where the two formations are exposed on the southwest side of the Zuni Mountains (fig. 13) and also where they are directly overlain by basalt flows along the southwest side of the southern Zuni Mountains. Of the 16 to 20 inches of average annual precipitation that falls on the areas of San Andres-Glorieta exposure, probably only a small fraction infiltrates to the water table. Most precipitation either runs off in streams, evaporates, or is consumed by plants (transpires). Streams flowing across the San Andres-Glorieta exposures also supply some recharge to the aquifer. Some 90 square miles of Glorieta Sandstone and San Andres Limestone are exposed along the southwest flank of the Zuni Mountains. If average annual recharge over this area were 1/2 inch, about 2,400 acre-feet of water, equivalent to a continuous flow of about 1,500 gallons per minute, would be supplied to the aquifer.

Areas where the San Andres Limestone or Glorieta Sandstone directly underlies surface basalt flows hold a much greater potential for recharge. Akers (1964, p. 78) described a similar recharge situation for the Kaibab Limestone near Springerville, Arizona, and stated that lava and cinders absorb most of the precipitation and transmit it downward to the Kaibab Limestone and Coconino Sandstone. Geologic mapping by Maxwell (1986) suggests that in much of Townships 8 and 9 North, Range 12 West (fig. 13), and in parts of adjacent townships, the San Andres Limestone lies directly beneath basalt lava and cinders. The San Andres-Glorieta aquifer in this area, though east of the Continental Divide, dips to the southwest (Maxwell, 1986) and probably transmits water under the divide. The basalt flows are very porous and fractured in most of the area and water can quickly infiltrate below depths where evapotranspiration can occur. Much of this infiltration may continue downward into the San Andres and Glorieta formations. There may be more than 30 square miles of San Andres and Glorieta formations directly underlying the basalt that contribute ground-water flow to the west or southwest toward the Zuni Reservation. As an estimate of this potential recharge, considering an average annual recharge of 5 inches over an area of 30 square miles would amount to about 8,000 acre-feet per year, equivalent to a continuous flow of about 5,000 gallons per minute. No substantiated estimates of recharge have been made for this area. Somewhat smaller or larger amounts of recharge may actually occur in the exposed or the basalt-covered areas of the San Andres and Glorieta formations.

Recharge from strata adjacent to the San Andres Limestone or the Glorieta Sandstone may take place where hydraulic heads in the adjacent strata are higher than that in the San Andres-Glorieta aquifer. The underlying Yeso Formation has a small hydraulic conductivity in most surrounding areas, but little is known of its properties or water quality on the Zuni Reservation. The hydraulic head in the overlying Chinle Formation is known to be higher than that in the San Andres-Glorieta aquifer over much of the reservation. The Chinle likely has very small vertical hydraulic conductivity in most areas, except where fractures may cause an increase. Both the Yeso and Chinle Formations are known to contain gypsum, a mineral containing readily soluble sulfate, in areas adjacent to the reservation, and leakage from either could be responsible for the large sulfate concentration of water in the San Andres-

Glorieta aquifer. The amount of recharge from these formations cannot be calculated due to lack of necessary head and vertical-hydraulic-conductivity information. Either of these adjacent strata could also be receiving discharge from the San Andres-Glorieta aquifer where hydraulic heads may be lower than that of the aquifer.

Water recharging the San Andres-Glorieta aquifer along the southwest flank of the Zuni Mountains and adjacent basalt-covered areas moves generally to the southwest onto the Zuni Reservation. The potentiometric contours of the San Andres-Glorieta aquifer, shown in figure 13, illustrate the general flow pattern in the aquifer. The direction of flow is approximately at right angles to the contours, from higher potentiometric head to lower. Along the east side of the Zuni Reservation, the flow curves to the west and then northwest into Arizona. The flow pattern is actually much more complex than shown in figure 13, due to the directional influence of fracture and cavern systems and to the discharge at springs at Ojo Caliente.

The major point of discharge from the San Andres-Glorieta aquifer on the Zuni Reservation occurs at Rainbow and Sacred Springs (8.20.21.144 and 8.20.20.422) at Ojo Caliente (fig. 14). Orr (1987, p. 9-12) described these springs and related seeps and stated that their combined average discharge during 1979-80 was about 450 gallons per minute. Discharge from wells on the reservation and vicinity is minor compared to that of these springs. During 1982-85, the Black Rock PHS well (10.19.13.444) discharged at an average annual rate of 11 gallons per minute by pumping intermittently at about 110 gallons per minute. Since August 1985, water use from the Black Rock PHS well has increased markedly to an average rate of 40 gallons per minute or more. A stock well, Cities Service Zuni-1 (9.18.5.324), 4 miles southeast of Black Rock, is the only other San Andres-Glorieta well on the reservation that has been used since 1980. Its average discharge rate is probably less than 1 gallon per minute. Wells in the Ramah Navajo Reservation area east of the Zuni Reservation are the only other San Andres-Glorieta wells in the vicinity that pump significant amounts of water. Ramah 1 well (8.15.27.342) discharged at an average rate of about 13 gallons per minute in 1987. Ramah 2 well (8.15.27.311) has not been operated for 3 years or more due to large radionuclide content.

Since 1984, pumping discharge from the Coconino aquifer in the vicinity of St. Johns, Arizona (about 50 miles southwest of Zuni Village), has increased considerably, and further increases are expected as a new powerplant in the area increases to full power output. The Coconino aquifer consists of the combined strata of the Kaibab Limestone, the Coconino Sandstone, and in some areas, the underlying Supai Formation, and is continuous with the San Andres-Glorieta aquifer of the Zuni area. Mann and Nemecek (1983, p. 24) estimated that in 1975, about 7,700 acre-feet (about 4,800 gallons per minute) was pumped from the Coconino aquifer in the St. Johns-Springerville area (Springerville, Arizona, is about 25 miles south of St. Johns) and was used primarily for irrigation. They further estimated that an additional 23,000 acre-feet per year (about 14,000 gallons per minute) would be needed for two powerplants near St. Johns and Springerville, Arizona. Both of these powerplants are now in operation, at partial production, using several thousand acre-feet of water annually from the Coconino aquifer. Further increases are planned. The primary source of water for the pumpage in the St. Johns-Springerville area at present is probably the higher altitude areas immediately to the south (Akers, 1964, p. 76-78; Mann and Nemecek, 1983, p. 11 and pl. 3), rather than the Zuni Mountains to the east.

Results of Aquifer Tests

The following discussion of aquifer-test results for the San Andres-Glorieta aquifer involves estimation of aquifer properties using methods developed for the analysis of porous aquifers, such as sand, sandstone, or siltstone, that are homogeneous and isotropic. Such aquifers ideally have values of transmissivity and storage coefficient that are constant from point to point and equal in all directions. Such analytical methods also are commonly applied to fractured-rock aquifers where the fracture spacing is small relative to test-well spacing and where fractures occur in multiple orientations that result in general isotropy. At the southwest Zuni aquifer-test site such conditions apparently do not exist. Drilling and aquifer testing revealed that there are caverns of various size at different levels in the San Andres Limestone and fractures of various size that may be intercepted at any depth in the San Andres-Glorieta aquifer. Most of the large caverns and a set of relatively large, open fractures probably are oriented along the major lineament direction (N. 55° E.) previously discussed. A set of relatively small, tight fractures probably is oriented approximately perpendicular to the lineament direction. Other fracture sets and fractures undoubtedly exist. This network of interconnected caves and fractures constitutes an aquifer that is quite heterogeneous and anisotropic. The apparent transmissivity of the aquifer depends on the direction of an observation well from a pumped or injected well and on the number and size of caves and fractures intercepted by each, which can vary greatly within a few feet.

Other factors may add to the complexity of the San Andres-Glorieta aquifer hydraulics. The aquifer probably becomes unconfined within 1 mile or less of the aquifer-test site, resulting in an increase in storage coefficient by as much as 100 times. The overlying siltstone and sandstone of the lower part of the Chinle Formation may act as a leaky confining bed over the aquifer and may be locally interconnected to the aquifer by fractures. The termination of the cave system or the decrease in transmissivity of the interconnected cave-fracture system in any direction would constitute a ground-water boundary that could cause additional drawdown in the system with prolonged pumping.

Because the assumptions of the analytical method are not met by the aquifer at the test site, and because the aquifer-test results may include the effects of several unknown complexities, the estimates of transmissivity and storage coefficient presented have questionable value in predicting drawdowns or sustained yield of the aquifer. These estimates are considered useful only for estimating the relative transmissivity in the two directions tested and for demonstrating the relatively large transmissivity of the aquifer at the test site and vicinity.

Site selection

The selection of a test site for the San Andres-Glorieta aquifer test (fig. 14) was based on several considerations. The relatively flat potentiometric surface of the aquifer on the southern part of the Zuni Indian Reservation indicated that the transmissivity might be large in this area (fig. 13) (Orr, 1987, p. 12 and 14). The presence of travertine deposits near the springs at Ojo Caliente and of caves in the exposed San Andres Limestone nearby to the south further indicated a well-developed flow system in the aquifer (Orr, 1987, p. 9). Orr (1987, p. 14) suggested that the water quality of the springs at Ojo Caliente and their distance from recharge areas in the Zuni Mountains indicate a better developed solution-channel system across the southern Zuni Reservation than that to the north. The lineaments and fracture traces previously discussed under "San Andres-Glorieta Aquifer - Structural Controls on Hydrogeology" may represent extensive fracture systems that could increase the transmissivity in the aquifer and provide good connection between the recharge areas to the northeast and the Ojo Caliente area.

Other criteria involved in test-site selection were depth to the San Andres-Glorieta aquifer, distance from Ojo Caliente, and terrain. The depth to the top of the aquifer at the test site is about 600 to 650 feet, considerably shallower than in areas to the east on the Zuni Reservation. Areas closer to the springs at Ojo Caliente were avoided to minimize the effects of any possible future large-scale ground-water use at the test site on spring discharge. The particular area chosen has a suitable unimproved road for equipment access, and topography and soils are suitable for some types of irrigated agriculture.

Tests of December 1984

In October 1984, test well ZS-1 was drilled to a depth of 865 feet. Construction details of the well and the strata penetrated are shown in figure 16. The test well was drilled to 609 feet, and a 9-inch casing was set and grouted. The remainder of the drilling was by the air-rotary method with foam injection. This drilling method reveals the depths at which the aquifer yields water by the changes in the rate at which water is being blown from the hole. After drilling through all but the bottom 3 feet of the San Andres Limestone, about 15 gallons per minute was being produced. As the remaining 3 feet of the San Andres Limestone and the upper 3 to 5 feet of the Glorieta Sandstone were drilled, drilling action became very rough, indicating fractures, and the discharge increased about tenfold. Additional increases occurred while drilling in the Glorieta Sandstone, notably at 800 to 805 feet. No caves were penetrated by ZS-1 in the San Andres Limestone. A test well previously drilled about 90 feet to the northeast (and later abandoned) penetrated caves about 1 to 5 feet deep between 635 and 680 feet. These caves collectively produced about 200 gallons per minute during drilling. The nonpumping water level in ZS-1 was about 485 feet below land surface when well construction was completed and has since remained within 2 feet above that level.

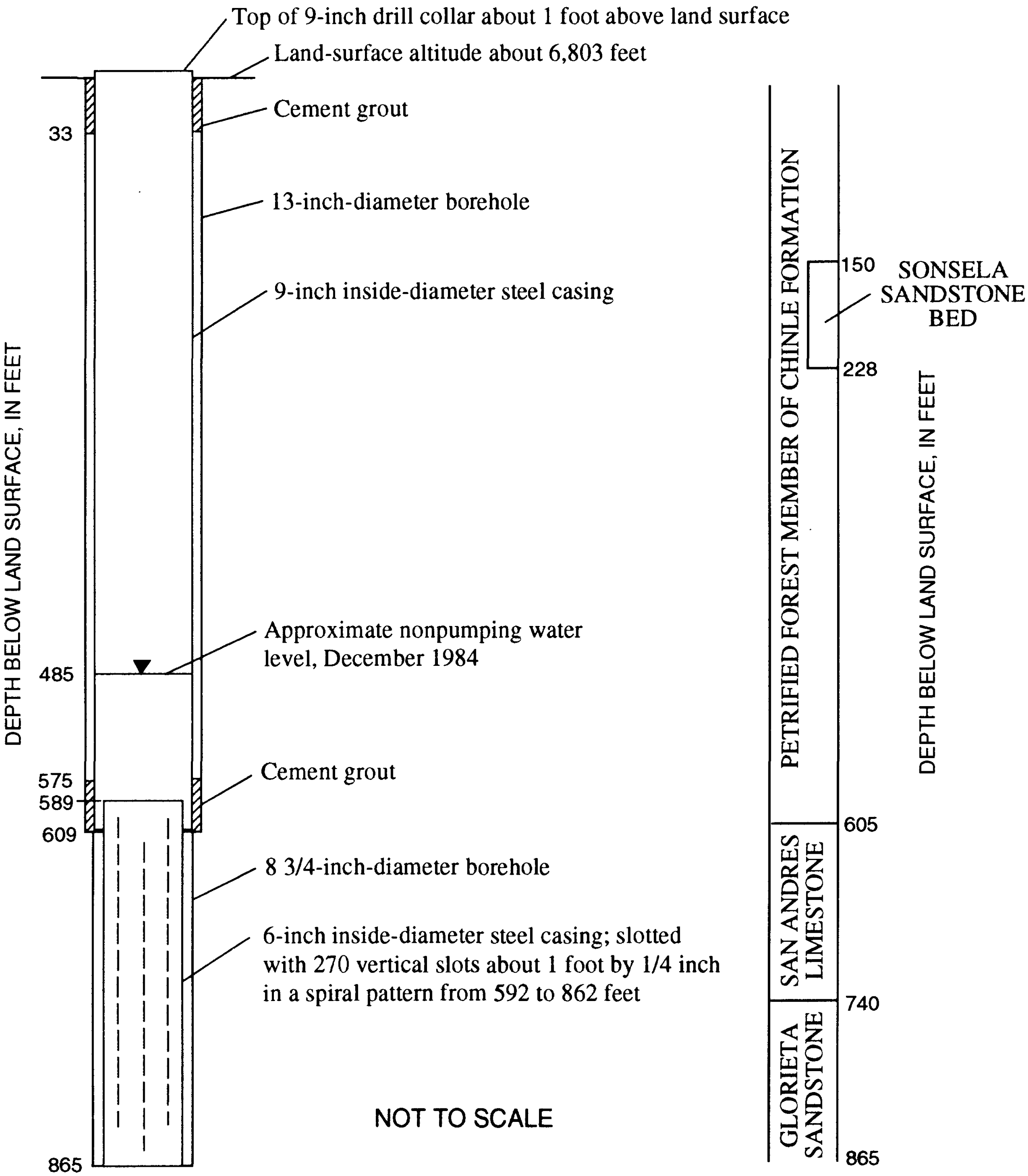


Figure 16.--Construction details of San Andres-Glorieta test well ZS-1 and general geologic column.

After completion of ZS-1, an observation well, ZS-2 (8.19.30.442a), was drilled about 1,000 feet to the west-southwest. Depths of boreholes and casings are shown in figures 16 and 17, and formation depths are shown in figure 18. The well penetrated numerous small caves or solutioned fractures in the lower third of the San Andres Limestone and occasional fractures in the Glorieta Sandstone, all water producing. After completion of ZS-2, it was discovered that a bentonitic clay layer at about the 625-foot depth had squeezed the borehole shut. A 2-inch-diameter, slotted, galvanized steel pipe liner was installed to provide a permanent opening through the clay to the underlying water-producing intervals of the San Andres-Glorieta aquifer. The well was then tested for connection with the aquifer by water injection at about 60 gallons per minute, during which the total head increased by less than 1 foot. The nonpumping water level was about 478 feet below land surface when well construction was completed.

In December 1984, a series of aquifer tests was run by pumping from well ZS-1. Downhole pressure transducers were used to monitor water levels in wells ZS-1 and ZS-2, and backup water-level measurements were made with an electronic sounding device and steel tape. The transducer data from ZS-2 included significant spurious water-level fluctuations that could not be detected with backup measuring devices. The nature of these data precluded any analysis of observation-well data. Backup measurements did not detect any response in ZS-2 to pumping at ZS-1. Transducer data for water levels in the pumped well included similar but smaller water-level fluctuations. Early drawdown and recovery responses in the pumped well were analyzed using the modified nonequilibrium formula (Ferris and others, 1962, p. 98) and the Theis recovery method (Ferris and others, 1962, p. 100). Virtually complete drawdown and recovery occurred within about the first hour of the tests. This may be due to interception of caves or sandstone porosity by the fractures intercepted and pumped by well ZS-1, resulting in a response similar to that for a leaky confined aquifer. A sustained aquifer test of 350 gallons per minute for 67 hours resulted in 14 feet of drawdown in ZS-1. Estimated transmissivity from early drawdown of the sustained test and a short-term test at 350 gallons per minute was 18,000 to 23,000 feet squared per day. Estimated transmissivity from early recovery of the same two tests was 13,000 to 17,000 feet squared per day. Estimated transmissivity from early drawdown of a test at 260 gallons per minute was 24,000 feet squared per day. Estimated transmissivity was 16,000 feet squared per day for early recovery of this test.

Well ZS-1 was pumped at several rates in order to determine the specific capacity of the well at these rates and to estimate the ultimate yield of the well. The variation of specific capacity versus pumping rate is shown in figure 19. Specific capacity decreases less with each added increment of pumping, as indicated by the curved line. The nonpumping water level in ZS-1 is about 485 feet below land surface. The deepest practical pump intake setting is about 580 feet below land surface due to the presence of the 6-inch slotted liner below about 589 feet (fig. 16). Assuming a lowest pumping level of 550 feet to prevent cavitation (required head above pump inlet varies with type and design of pump), available drawdown is about 65 feet. The curved line of figure 19 indicates a specific capacity of about 16 gallons per minute per foot of drawdown at a pumping rate of 700 gallons per minute. This specific capacity would result in drawdown of about 44 feet at 700 gallons per minute. In order to allow for decreasing specific capacity during long-term pumping, the estimated ultimate well yield is considered to be about 600 gallons per minute.

Tests of July-August 1986

Four additional observation wells were drilled in June and July 1986 to further test the San Andres-Glorieta aquifer. A diagram of typical construction of these wells is shown in figure 17. Borehole and casing depths, openings, and formation depths are shown in figure 18. Three of these wells, ZS-10 (8.19.29.331b), ZS-11 (8.19.29.331c), and ZS-13 (8.19.30.442b), are along the lineament direction (N. 55° E.), approximately southwest of the test-production well, ZS-1. The fourth well, ZS-12 (8.19.29.331d), is southeast of ZS-1, parallel to the minor fracture direction that is approximately perpendicular to the lineament direction. The locations of the observation wells in relation to ZS-1 are shown in figure 18. These four observation wells and well ZS-2 were instrumented with transducers connected to a digital recorder. Backup measurements were made as in the previous test (1984) for all the observation wells. Due to access problems, no transducer or backup measurements were made in the pumped well.

In July 1986, a sustained aquifer test of 50 hours duration was made by pumping well ZS-1 at an average rate of 372 gallons per minute. Well ZS-12, the only observation well to the southeast of ZS-1, was the only well in which a measurable response to this pumping occurred. Wells ZS-1 and ZS-12 are the only wells at this test site that intercept fractures but no caves. A time-drawdown curve (fig. 20) was plotted for ZS-12 after making corrections for water-level fluctuations resulting from barometric fluctuations and earth tides. The early segment of the curve, from 0.2 to 9 minutes, matched the 'v = 0.3' type curve of a family of leaky confined-aquifer type curves shown by Lohman (1972, p. 30 and pl. 3). The segment of the curve from 10 to 200 minutes shows increased drawdown, following which the curve became horizontal. This match resulted in an estimated transmissivity of 6,000 feet squared per day and a storage coefficient of 0.0001. Mann and Nemecek (1983, p. 13-14) listed values of transmissivity for wells in the fractured sandstone and limestone of the Coconino aquifer in the St. Johns area of southern Apache County, Arizona. Eight wells in fractured sandstone had values of transmissivity of 940 to 4,800 feet squared per day, and a well in fractured limestone had a transmissivity of 9,100 feet squared per day. They reported storage coefficients ranging from 0.00009 to 0.0038. These aquifer characteristics, similar to those estimated from ZS-1 single-well tests and from the ZS-12 observation-well response, show that the estimated values for the ZS-1 test site are reasonable for wells in the fractured aquifer.

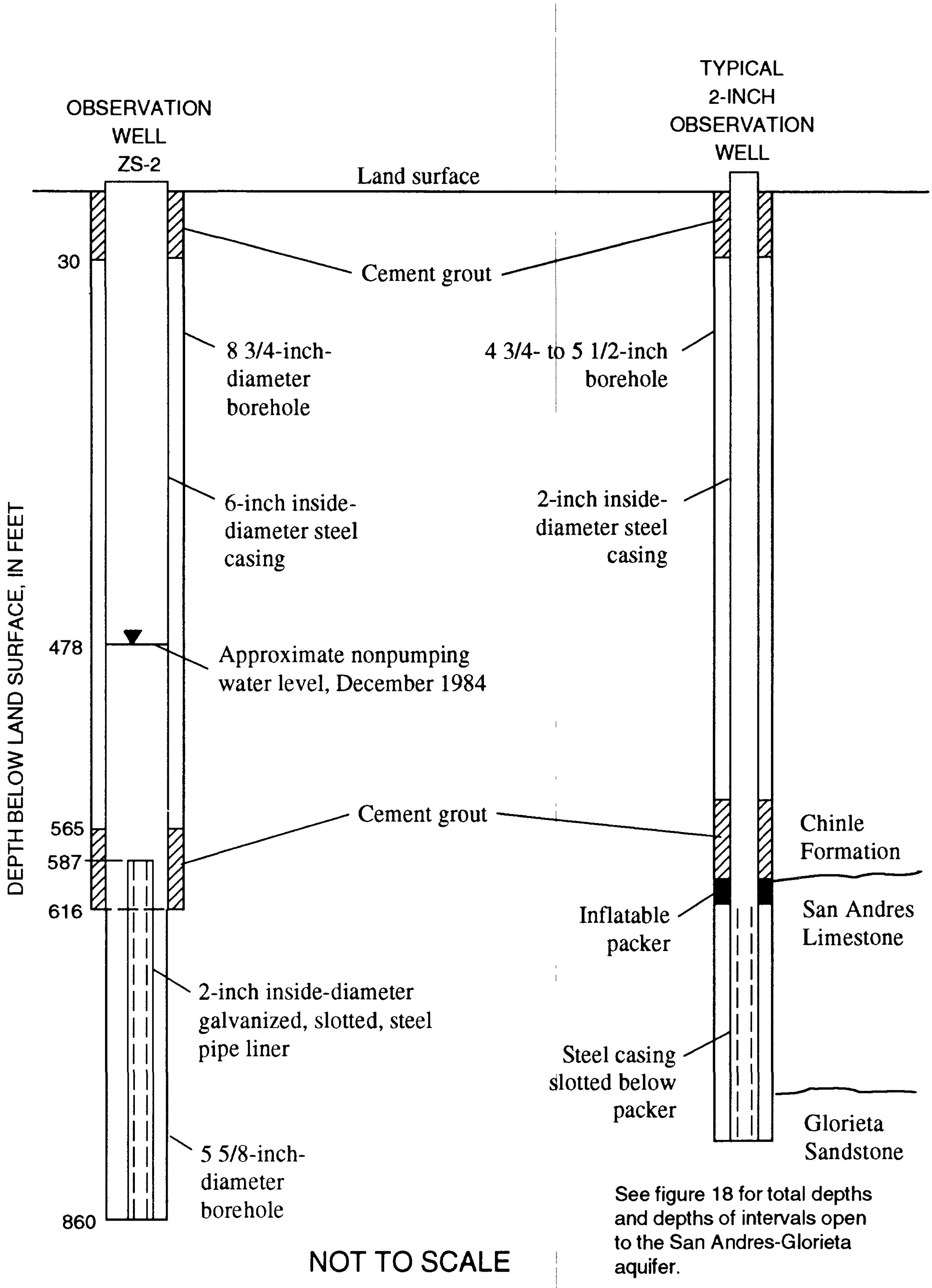
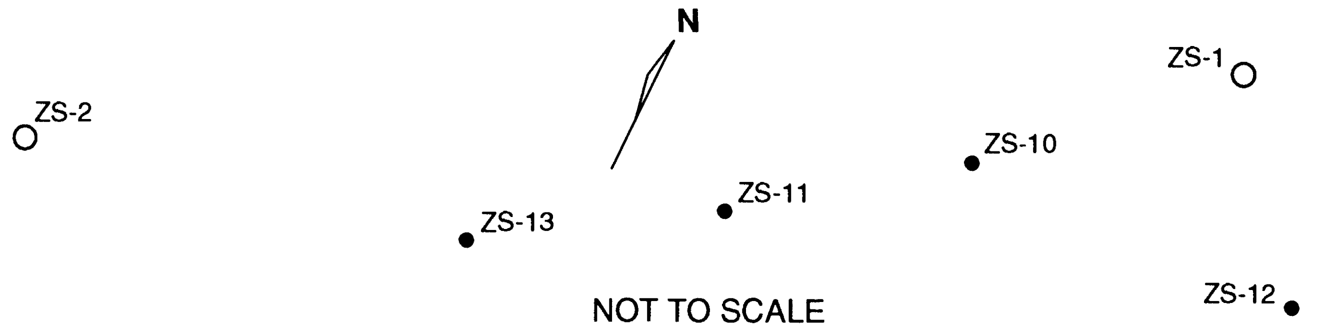


Figure 17.--Construction details of San Andres-Glorieta observation wells.



Well	ZS-1	ZS-2	ZS-10	ZS-11	ZS-12	ZS-13
Distance from ZS-1 (feet)	-	1,014	219	426	315	656
Diameter of slotted liner in aquifer (inches)	6	2	2	2	2	2
Depth, top of San Andres Limestone (feet)	605	612	601	650	620	610
Depth, top of Glorieta Sandstone (feet)	740	745	736	729	742	729
Total depth (feet)	865	860	780	750	858	781
Depth interval open to San Andres-Glorieta aquifer (feet)	609-865	616-860	608-780	652-750	624-858	613-781
Depths of probable major water-producing intervals (feet) c = cave, f = fracture	f 695-698 f 737-745 f 800-805	f,c 695-745 f 745-835	c 614-614.5 c 624-625 f 625-633 c 636-636.4 c 647-651 c 651.5-664.5 c 668-674 c 712-714 c 724-726 f 732-736 f 774-778	f 652-653 f,c 656-662 f,c 665-668 f,c 678-680	f 739-741 f 748-750 f 763-? f 820 f 831 f 852-854	f 620-? f 651 f 655-656 f 661-663 c 663-666.5 c 668-670 f 682-684 c 684-685 c 686-691 f 705-706 f 708-709 f 712 f 739-?

Figure 18.--Test-well layout, depths, and water-producing features at the San Andres-Glorieta aquifer-test site.

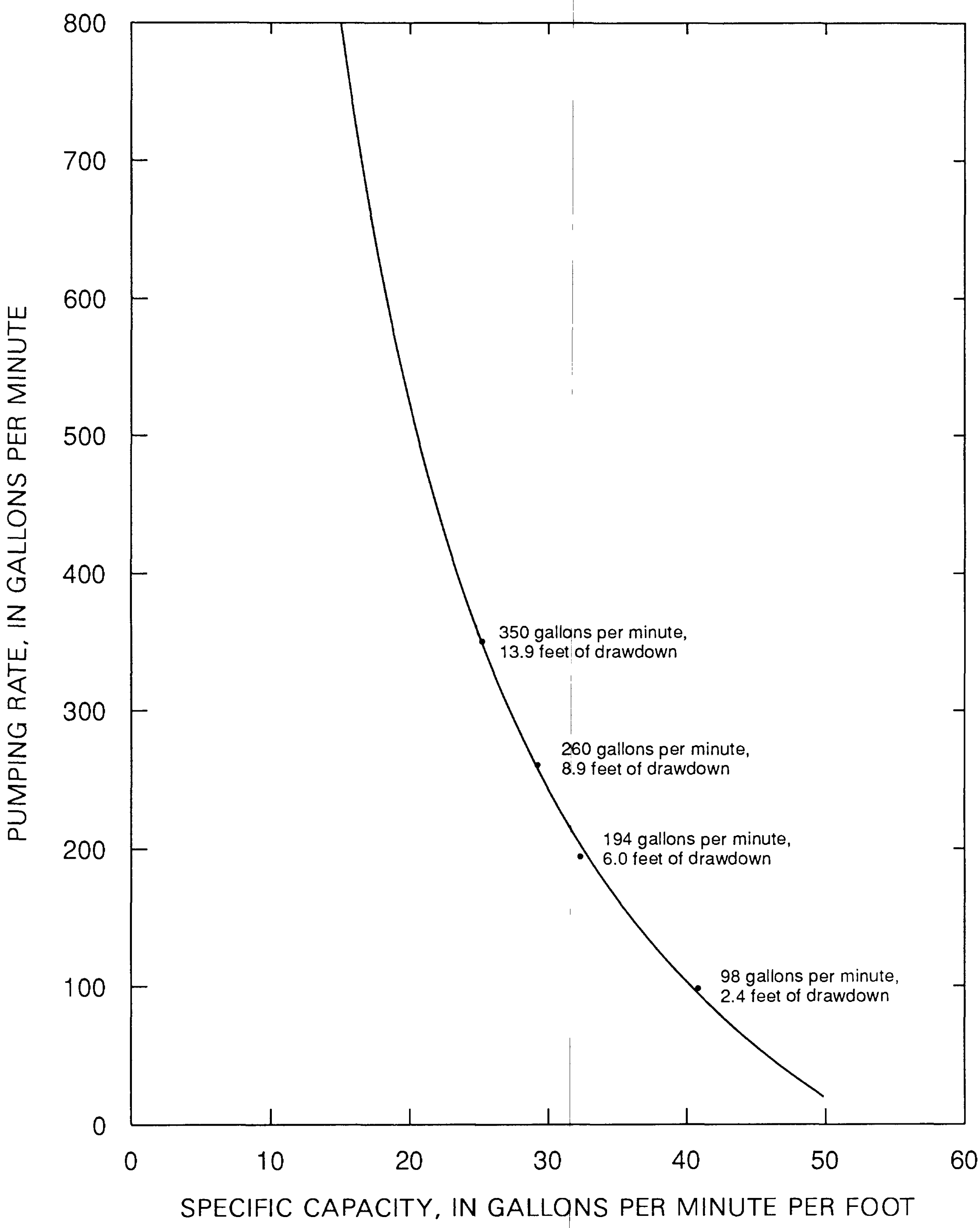


Figure 19.--Relation of specific capacity and pumping rate for well ZS-1.

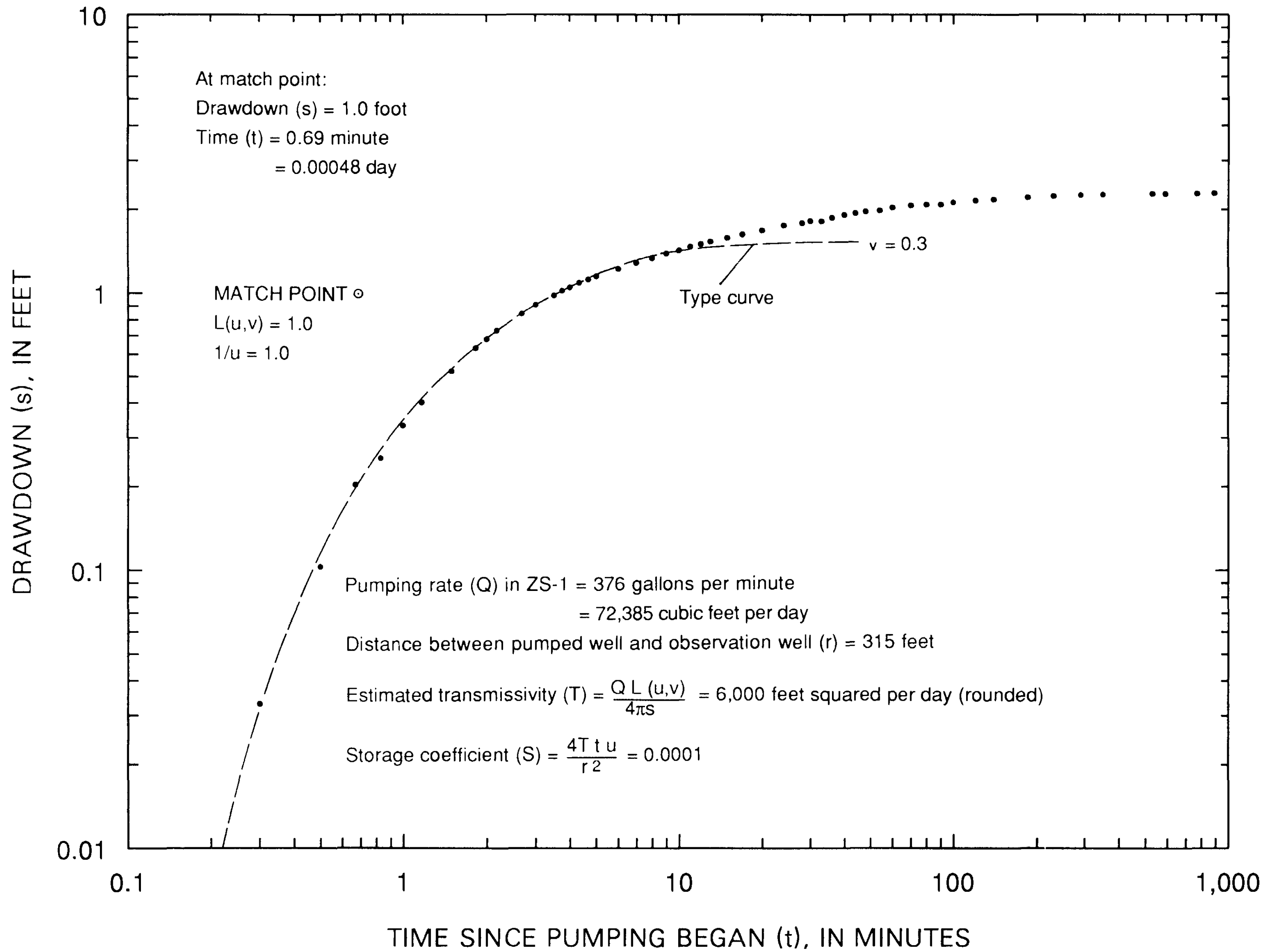


Figure 20.--Drawdown in observation well ZS-12, July 28-29, 1986.

On August 5, 1986, injection tests were made in observation wells ZS-11, ZS-10, and ZS-13 at rates of 180 to 240 gallons per minute for periods of 12 to 14 minutes. As each well was injected, all other wells at the test site were monitored with transducers. The injection times, rates, and observation-well responses are summarized in table 2. Hydrographs of selected wells through the injection periods are shown in figure 21. The periods of apparent rapid water-level fluctuation, during and after each injection period, are probably caused by inertial effects of the injections into thé caves. Wells ZS-10 and ZS-13 each show distinct, immediate water-level responses to injections. Well ZS-1 shows a slight, indistinct response only to the ZS-11 injection. Well ZS-2 shows a distinct response to the ZS-11 injection, but subsequent responses are less distinct due to apparent interference by erratic oscillations in water level that may have resulted from the injections. Well ZS-11 response was the largest and most erratic of all the wells. Numerous oscillations of 0.01 to 0.12 foot occurred before, during, and after the injections of ZS-10 and ZS-13, with no apparent time or amplitude pattern.

Table 2.--Summary of injection tests and responses, August 5, 1986

Injected well	Time of injection (24-hour time:seconds)	Injection rate (gallons per minute)	Response (rise) in observation well (feet)					
			ZS-1	ZS-2	ZS-10	ZS-11	ZS-12	ZS-13
ZS-11	0815:30 to 0829:30	180	Less than 0.01	0.05 during the first 8 minutes	0.01 during the first 9 minutes	--	Less than 0.01	0.03 during the first 9 minutes
ZS-10	1005:00 to 1019:00	210	None	*	--	*	None	0.02 during the first 3 minutes
ZS-13	1155:10 to 1207:10	240	None	*	0.026 during the first 5 minutes	*	None	--

* Apparent response of about 0.05 to 0.10 foot; indistinct because of irregular superposed oscillations.

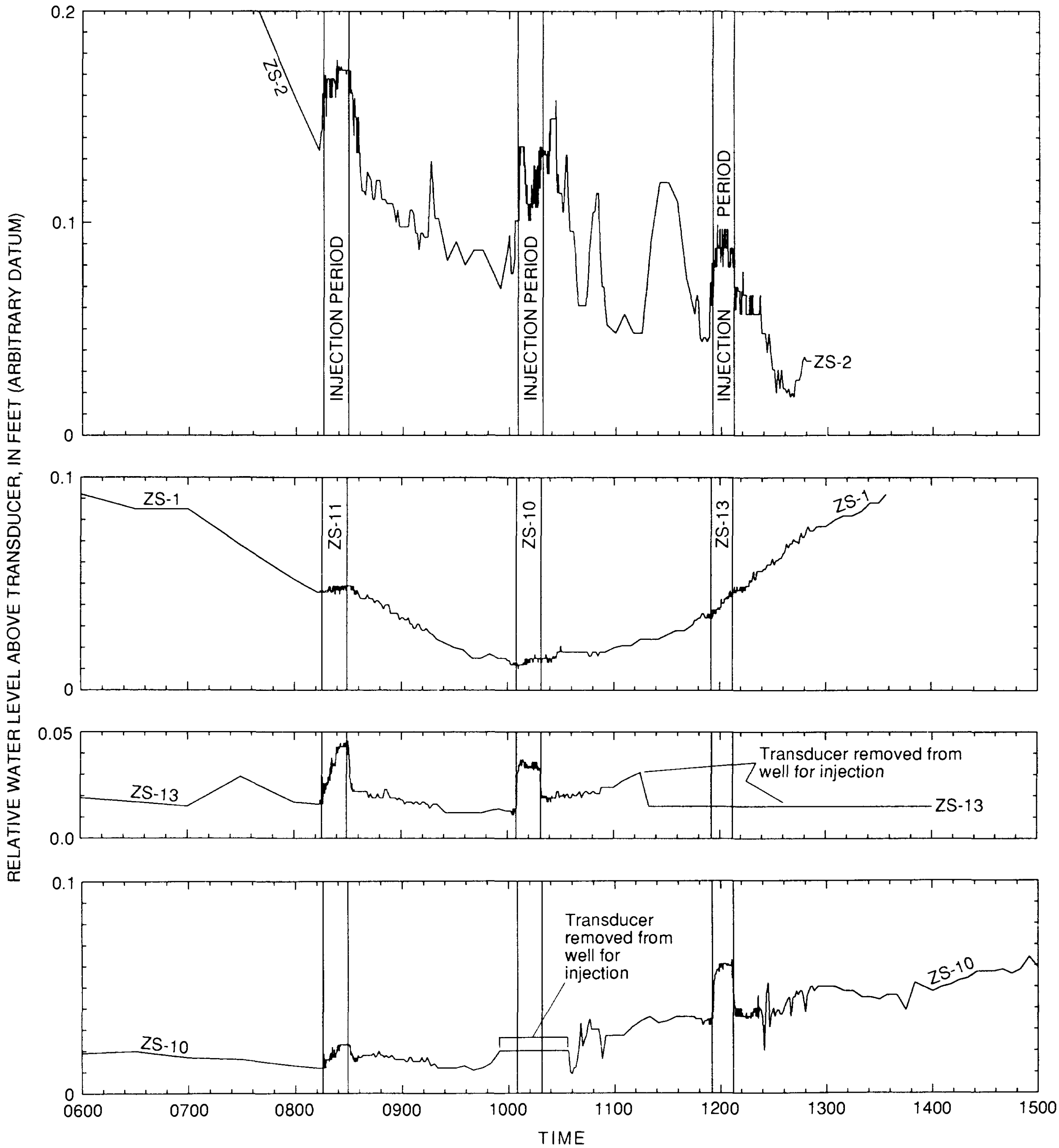
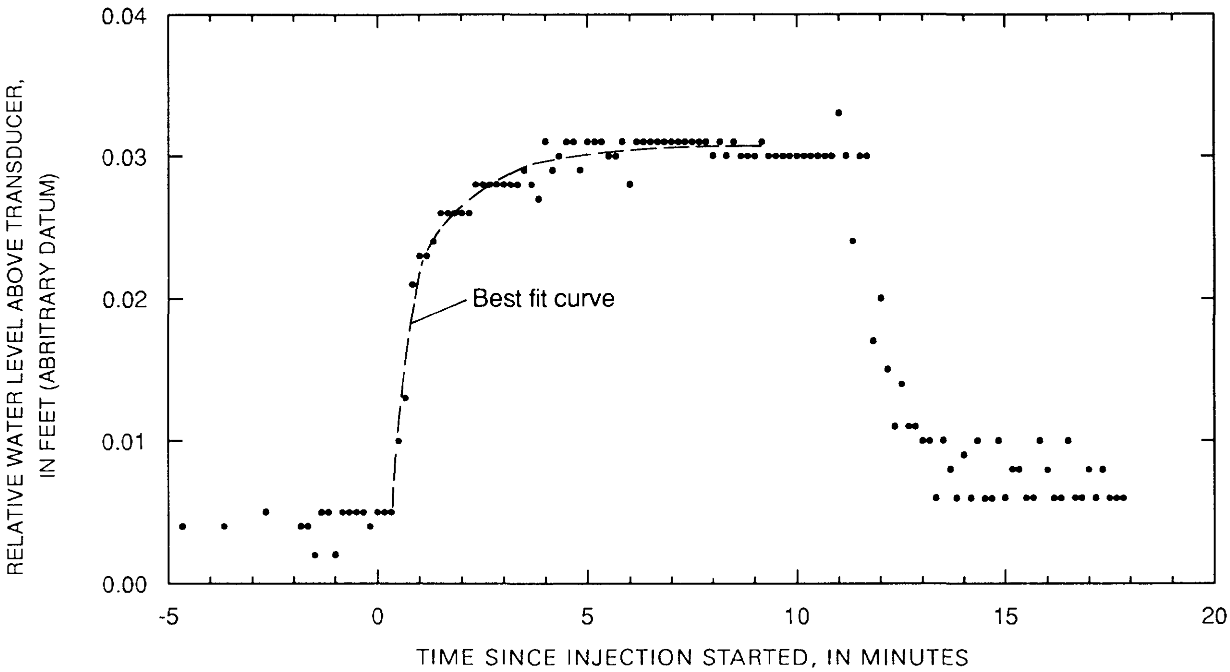


Figure 21.--Hydrographs of selected wells through the periods of injection testing, August 5, 1986.

The data for two of the observation-well injection responses were plotted on normal graph paper and best-fit curves made by hand, as in the top graph of figure 22. Data points from these curves were then plotted as double logarithmic graphs, as in the bottom graph of figure 22. Each of these curves was matched to one of the family of leaky confined-aquifer curves shown by Lohman (1972, p. 30 and pl. 3). This method resulted in an estimated transmissivity of 500,000 feet squared per day and a storage coefficient of 0.0003 for the response of observation well ZS-10 to injection of 240 gallons per minute of water into ZS-13. Similar analysis of the response of well ZS-2 to injection of 180 gallons per minute into ZS-11 resulted in an estimated transmissivity of 200,000 feet squared per day and a storage coefficient of 0.0003. The data for ZS-2 were coarser than for ZS-10 due to the lesser sensitivity of that transducer, resulting in a less definite curve fit. The application of this method to constant-rate injection tests is based on an analogy to pumping tests, namely that injection is negative discharge and the rise of water level is negative drawdown. This combination of negatives leaves the Hantush-Jacob equation (Lohman, 1972, p. 30, eq. 85) unchanged. Gordon (1961, p. 60-62) gave results of three aquifer tests in the San Andres Limestone or included sandstone near Bluewater, New Mexico, about 50 miles east-northeast of Zuni. Values of transmissivity ranged from 55,000 to 450,000 feet squared per day, and storage coefficient ranged from 0.0004 to 0.0014. Gordon (1961) described solution features in the San Andres Limestone in the vicinity of these tests. Such features probably account for the large transmissivity in the area. The caves intercepted by the injected and injection-response wells near ZS-1 probably account for the large estimates of transmissivity there.

The varying responses among injected and observation wells during the injections present a confusing picture in some respects. However, some tentative conclusions can be made. The very small responses or lack of responses of wells ZS-1 and ZS-12 to the three injections probably indicate that the fractures they intercept provide a relatively limited hydraulic connection to the cave system intercepted by the three wells. The nearly instantaneous responses of ZS-2, ZS-10, ZS-11, and ZS-13 to the injections indicate that the cave system that they each intercept provides rapid, easy hydraulic connection among these wells. Response among these wells, however, is not related to distance from the injection well as would be expected in a homogeneous, isotropic aquifer. The water level in well ZS-2, for example, rises some 0.05 foot in response to injection 595 feet away in ZS-11, whereas in well ZS-10, 207 feet from ZS-11, the rise is only about 0.01 foot. Apparently there is better interconnection between the more distant pair of wells than between the closer pair, due to a more direct or larger cave or fracture. Wells ZS-2 and ZS-11 exhibit water-level oscillations that are smaller in or absent from the other wells. This may indicate a more direct connection to a more extensive cave system. The oscillations may also be related to free-water-surface waves in a nearby area where the cave system is probably unconfined. Differences in background trends, especially in well ZS-2, are probably due to electronic drift of the water-level instrumentation.



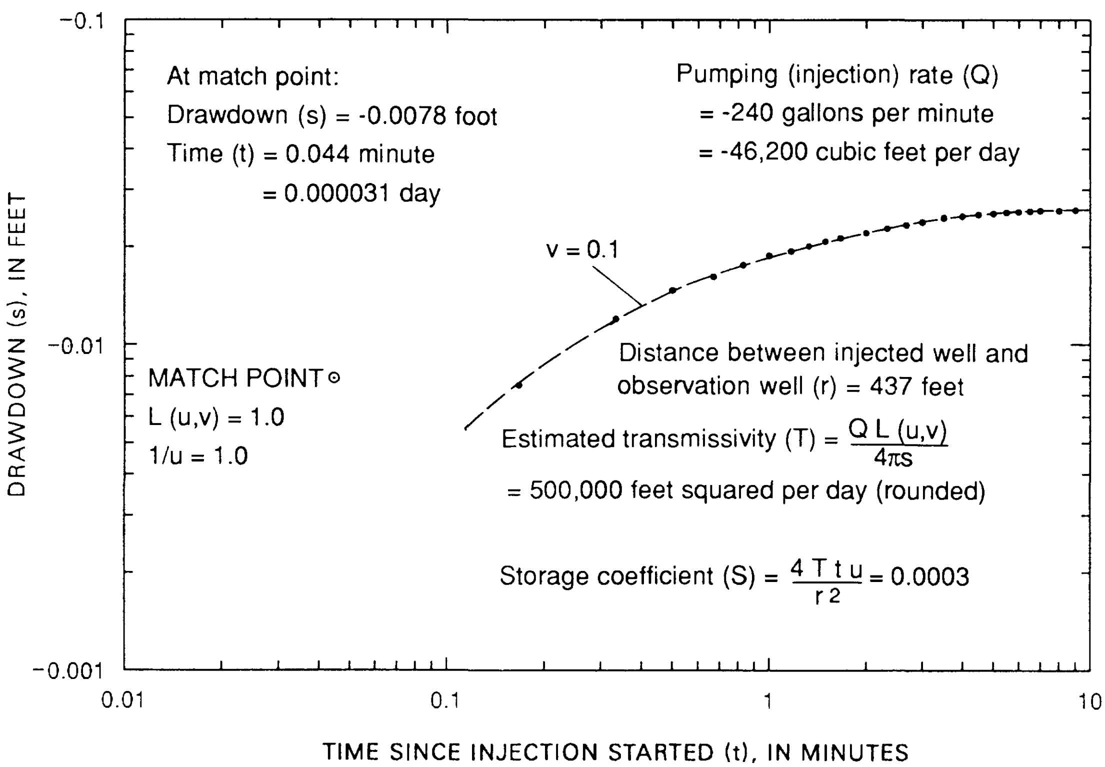


Figure 22.--Response of observation well ZS-10 to injection in well ZS-13.

Water Quality

During the first sustained aquifer test (December 1984) the specific conductance of water discharged from well ZS-1 remained nearly constant throughout the 67 hours of pumping, ranging from 1,080 to 1,100 microsiemens. Water temperature also remained constant at 28 degrees Celsius. A water sample collected from well ZS-1 after 19 hours of pumping was analyzed for major and minor constituents and selected trace elements. Results of the water analysis are shown in tables 1 and 3. The dissolved-solids concentration of water from ZS-1 is similar to that of water from Rainbow and Sacred Springs, some 5 miles to the west-northwest (Orr, 1987, table 3). Another San Andres-Glorieta well, Zuni F-5, located in Zuni Village, was pumped at about 100 gallons per minute in 1987. The analysis of a sample collected at that time is shown in tables 1 and 3; results of a previous analysis of water from well Zuni F-5 are given by Orr (1987, table 3). A trilinear plot of water analyses from ZS-1 and these two springs (fig. 23) shows the similarity in major dissolved constituents. The water from ZS-1 is within Federal secondary maximum contaminant levels (U.S. Environmental Protection Agency, 1986b) for all major and minor constituents except dissolved solids, sulfate, and iron. All of the trace elements tested were less than the Federal primary maximum contaminant levels (U.S. Environmental Protection Agency, 1986a).

No water-quality analysis was made for well ZS-100 (discussed below under "Zuni south observation well"). However, temperature and specific conductance of the water blown from the well during drilling were measured after air-pumping the well for 1 hour from total depth. The water temperature stabilized at 21.5 degrees Celsius and conductance stabilized at 1,100 microsiemens. The water is about 6.5 degrees Celsius cooler than that pumped from ZS-1. The cooling may be due to the shallower depth of the aquifer at ZS-100 than at ZS-1 or because of a smaller thermal gradient in the area of ZS-100. The specific conductance is about the same as that of water from ZS-1 to the east and Rainbow and Sacred Springs to the west. The chemical composition of the water at ZS-100 probably is quite similar to that at ZS-1 and these springs.

Zuni South Observation Well

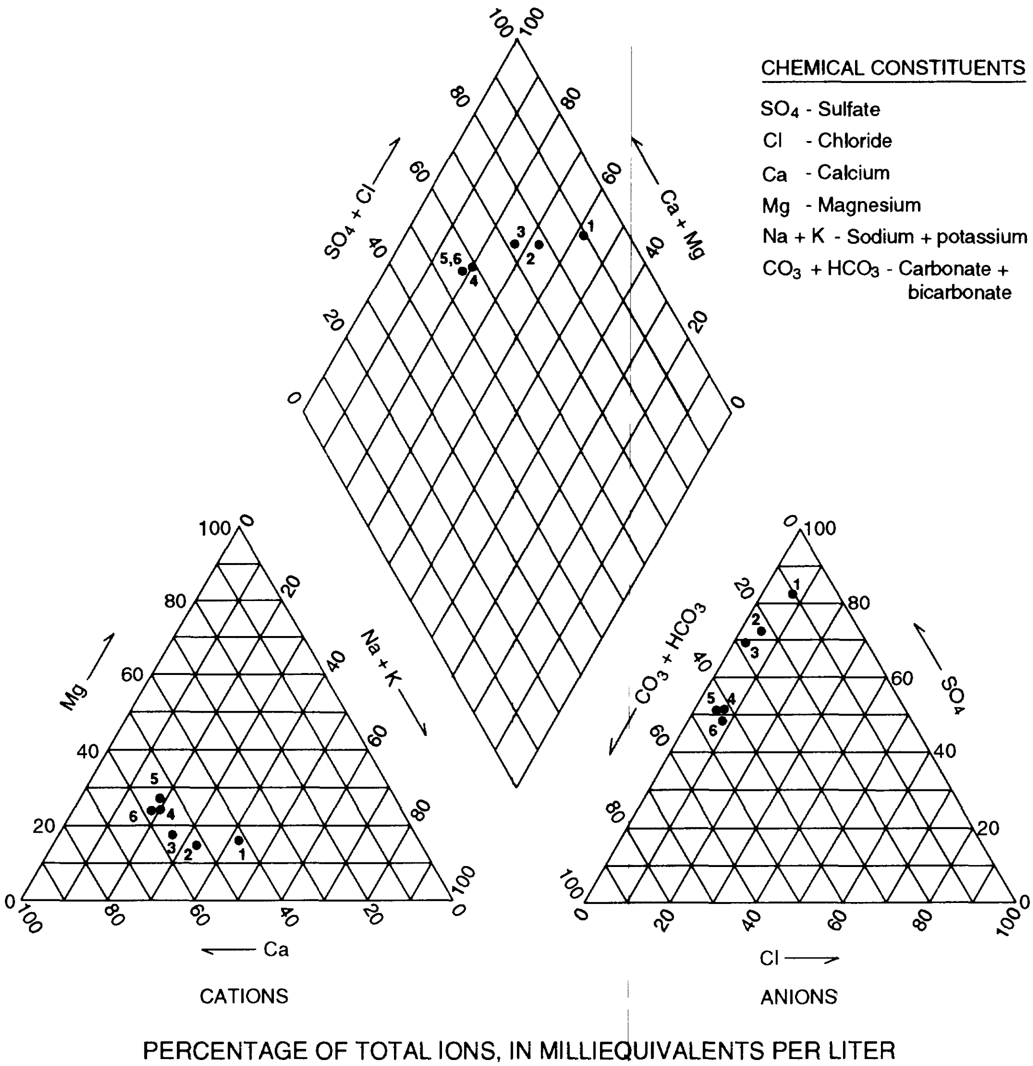
In May 1986, observation well ZS-100 (8.20.26.131) was drilled at a site about 2 miles southeast of Rainbow Spring (fig. 14). This well was constructed to monitor the water level in the San Andres-Glorieta aquifer in the vicinity of the springs at Ojo Caliente. The well was constructed by drilling through 180 feet of mudstone, siltstone, and sandstone of the Chinle Formation and the top 9 feet of the San Andres Limestone. A 5-inch inside-diameter steel casing was set from the surface to 188 feet and grouted in place. The well was completed by drilling a 4 3/4-inch borehole through the San Andres Limestone from 188 to 313 feet and in the Glorieta Sandstone to 420 feet. All drilling was done with compressed air and foam, which showed that the Chinle strata and the upper 92 feet of the San Andres (180 to 272 feet) were dry. Water was encountered in numerous fractures and possibly small caves in the San Andres from 280 to 313 feet and from fractures in the Glorieta from 313 to 420 feet. Notable water-producing zones are at 280, 293 to 297, 309 to 313, and 326 to 327 feet. The water level in well ZS-100 was 272.4 feet below land surface at the completion of drilling and has since remained within 0.1 foot below to 0.5 foot above that level.

Table 3.--Water-quality analyses from selected wells: trace elements

EXPLANATION

Location: See text
Laboratory: USGS, U.S. Geological Survey;
BIA, Bureau of Indian Affairs
Abbreviations: <, less than
--, not analyzed
Psg, San Andres-Glorieta aquifer
Note: All constituents are dissolved and reported in micrograms per liter

	Well ZS-1	Well Zuni F-5
Location	8.19.29.331a	10.19.27.112
Date sampled	12-07-84	- -87
Arsenic	13	9.7
Barium	28	475
Cadmium	< 1	2
Chromium	< 10	< 1
Copper	1	--
Lead	1	2.7
Manganese	7	.6
Selenium	< 1	< 2
Silver	< 1	< .2
Zinc	47	--
Laboratory	USGS	BIA
Geologic unit	Psg	Psg



Number on plot	Well name	Location number	Dissolved-solids concentration, in milligrams per liter
1	Black Rock PHS	10.19.13.444	889
2	Black Rock 3	10.19.24.122b	994
3	Zuni F-5	10.19.27.112	884
4	Sacred Spring	8.20.20.422	740
5	Rainbow Spring	8.20.21.144	761
6	ZS-1	8.19.29.331a	754

Figure 23.--Chemical composition of ground water from the San Andres-Glorieta aquifer.

WELL SITING AND DESIGN CRITERIA

The following criteria are set forth as general guidelines for additional wells in the vicinity of Bidahochi well ZB-1 and San Andres-Glorieta well ZS-1. They are not intended to imply that any particular additional well will encounter hydrologic conditions similar to wells already drilled at these sites.

Bidahochi Wells

The location of the Bidahochi aquifer-test site was based on seismic-reflection surveys that indicated a buried channel (fig. 5) on the Zuni erosion surface of the Chinle Formation. Additional seismic-reflection surveys could be made that might locate other similar channels. There is potential for developing the buried channel as a source of good-quality water by drilling several wells along the channel. An additional aquifer test at wells ZB-1 and ZB-2 needs to be made prior to further test drilling. A test at a rate of 10 to 20 gallons per minute for about 7 days would provide better estimates of transmissivity and storage coefficient. These estimates could be used to determine the spacing for test sites up or down the channel. Aquifer tests at those test sites would determine the spacing for additional test sites.

Differences in saturated thickness, lithology, and transmissivity along the channel would require different well designs at each location. Well design would be based on formation sampling and geophysical logging. For optimum production wells in fine, poorly sorted, poorly cemented sandstone, as at ZB-1, double well screens with enclosed filter sands would probably be the best type of construction. More of the aquifer could be screened and well yield increased in this way.

Well ZB-1 is suitable for use as a stock well. Pumping equipment with the intake set between 660 and 685 feet could produce as much as 15 gallons per minute with little or no sanding.

San Andres-Glorieta Wells

Wells ZS-1 and ZS-12 intercepted numerous fractures in the San Andres and Glorieta Formations, especially near the contact of the two formations (fig. 18). However, neither well penetrated caves in the San Andres Limestone. The other four wells drilled in the vicinity each penetrated one or more caves in the San Andres Limestone as well as numerous fractures at various depths. In order to obtain maximum production, wells drilled in the vicinity need to be sited for the best chance of intercepting caves. A site at or near well ZS-10 is considered the best location due to the number and size of caves intercepted. A well at this location of sufficient diameter to accommodate a large-capacity pump probably would yield more than 2,000 gallons per minute with only a few feet of drawdown during short-term pumping. However, its long-term yield and effects on Rainbow and Sacred Springs will be unknown until appropriate tests are run.

If large-capacity wells are desired at other locations on the southwestern part of the Zuni Reservation, exploration wells will be necessary to determine the depth and local aquifer characteristics of the San Andres-Glorieta aquifer. Knowledge of the structural geology of the area and of lineament and fracture-trace orientations can be used to select exploration sites where caves and fractures may be encountered.

Test well ZS-1 can be used as constructed for pumping as much as 600 gallons per minute if a pump capable of that discharge at 550 feet total head for a 9-inch well is extant. The effects of prolonged pumping of 600 gallons per minute on pumping water level, and ultimately on Rainbow and Sacred Springs, cannot be determined from the aquifer tests made to date. Prior to permanent construction of any facilities that would depend on long-term pumping at this test site, a long-term aquifer test needs to be made and water levels recorded in wells ZS-1, ZS-2, ZS-10, ZS-11, ZS-13, and ZS-100. Flow or water levels at Rainbow and Sacred Springs need to be monitored during the test.

SUMMARY

The Bidahochi aquifer on the northwestern part of the Zuni Indian Reservation has been developed only for a few stock wells of small yield. The water produced, however, has the smallest dissolved-solids concentration of all aquifers on the reservation. Seismic investigations indicated an area near the northwest corner of the reservation where the Bidahochi sandstone is more than 800 feet thick over a buried channel on the Zuni erosion surface. Test drilling confirmed the thickness within 10 feet at one location and within 50 feet at another.

A test-production well and an observation well were constructed in the buried channel with screened intervals in the coarsest sands of the Bidahochi aquifer. A sustained aquifer test was conducted for 30 hours at a pumping rate of 7.6 gallons per minute. Analysis of the drawdown and recovery in the pumped well resulted in estimates of transmissivity of 450 and 470 feet squared per day. Analysis of the more erratic drawdown data for the observation well resulted in an estimated transmissivity of 900 feet squared per day and a storage coefficient of 0.018. This storage coefficient is probably small due to the effects of delayed drainage from the fine sands of the Bidahochi. The true storage coefficient probably would be between 0.10 and 0.20 for this aquifer.

The San Andres-Glorieta aquifer on the southwestern part of the Zuni Indian Reservation lies at relatively shallow depth. It is exposed south of Ojo Caliente and lies under about 600 feet of Chinle sediments at the aquifer-test site approximately 5 miles to the east. In October 1984, two test wells were constructed. Test well ZS-1 intercepted fractures but no caves, and observation well ZS-2 intercepted fractures and caves.

During aquifer tests in December 1984, drawdown occurred in the pumped well, ZS-1, but not in the observation well, ZS-2, 1,014 feet away. Tests at 260 and 350 gallons per minute were analyzed for the pumped well, resulting in transmissivity estimates of 13,000 to 24,000 feet squared per day, based on drawdown and recovery responses. The storage coefficient could not be estimated from these tests.

Four additional observation wells were constructed in June and July 1986. The sustained aquifer test in July 1986, at 372 gallons per minute for 50 hours, produced a response in observation well ZS-12, 315 feet from pumped well ZS-1. Analysis of the drawdown in ZS-12 resulted in an estimated transmissivity of 6,000 feet squared per day and a storage coefficient of 0.0001. Both wells intercepted fractures throughout the San Andres-Glorieta aquifer, but no caves. The other observation wells, ZS-2, ZS-10, ZS-11, and ZS-13, all of which intercept numerous fractures and caves, did not respond to this pumping.

Injection tests in August 1986 resulted in estimates of transmissivity of 200,000 and 500,000 feet squared per day among wells that intercept caves in the San Andres Limestone and fractures throughout the San Andres-Glorieta aquifer. The estimated storage coefficient from these tests was 0.0003.

The transmissivity between wells that intercept caves along the major lineament-fracture direction is about 33 to 83 times greater than the transmissivity between ZS-1 and ZS-12, which intercept only fractures and are aligned along a minor fracture-trace direction. The estimates of transmissivity from pumped-well data for the 1984 test are probably larger than those between ZS-1 and ZS-12 because of fractures that connect ZS-1 to nearby caves.

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