# Simulation of an Aquifer Test on the Tesuque Pueblo Grant, New Mexico

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Prepared in cooperation with the U.S. Bureau of Indian Affairs

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By GLENN A. HEARNE

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# CONTENTS



## FIGURES

## TABLES

# Simulation of an Aquifer Test on the Tesuque Pueblo Grant, New Mexico

*By* Glenn A. Hearne

**Abstract**

An aquifer test was designed and conducted in the anisotropic dipping beds of the Tesuque Formation on the Tesuque Pueblo Grant, New Mexico. The three-dimensional digital model used to analyze the test approximated the response to the test. The analysis of the geohydrology of the test site in combination with the model calibration has provided estimates of average aquifer characteristics for the group of beds penetrated at the test site; the hydraulic conductivity parallel to the beds is about 2 feet per day, the hydraulic conductivity normal to the beds is about 0.0001 foot per day or lower, the specific yield is about 0.15, and the specific storage is about $2 \times 10^{-6}$ per foot.

## INTRODUCTION

The U.S. Bureau of Indian Affairs has prepared a plan for an irrigation development within the Pojoaque River basin (fig. 1). The U.S. Geological Survey was requested to evaluate the effect of proposed ground-water withdrawals and surface-water diversions on ground-water levels and streamflows.

An aquifer test was designed, executed, and analyzed as a preliminary step to evaluating the effect of the irrigation development plan. Analysis of the test demonstrates that a digital model can approximate the effect of ground-water withdrawals from the aquifer system underlying the Pojoaque River basin and provides estimates of the values of aquifer characteristics in the vicinity of the test site. The aquifer test was conducted using a production well on the Tesuque Pueblo Grant (fig. 1).

This report describes the design, execution, and analysis of the aquifer test. The aquifer system tested consists of interbedded permeable and less permeable layers which dip from the horizontal. Flow through the aquifer system is such that the hydraulic heads are higher in the deeper beds. These boundary and initial conditions dictate the method required for analysis. Due to the dip of the beds, water in the beds being tested is under confined conditions downdip and under water-table conditions updip. The distance updip from the test well to water-table conditions is greater for the deeper beds than for the shallower ones. Due to the change in hydraulic head with depth, the deeper beds penetrated by the production well have a higher hydraulic head than the shallower beds. When withdrawals cause the hydraulic head in the production well to decline, the hydraulic gradient toward the pumping well is higher in the beds with a higher hydraulic head. To approximate these boundary and initial conditions, a three-dimensional digital model is used for the analysis.

A three-dimensional digital model was constructed to simulate the aquifer test and was calibrated using data from the test. This report describes the geohydrology of the area and the test site, the design and results of the test itself, and the analysis of the test using a digital model.

## GEOHYDROLOGIC SETTING FOR THE AQUIFER TEST

The description of the geohydrology of the test site presented in this section consists of a definition of the aquifer system to be tested, a description of the pattern of flow through the aquifer system, and a discussion of the surface appearance of the test site. A more detailed description appears in the section "Geohydrology of the Test Site."

The Tesuque aquifer system is the proposed source for ground water in the irrigation development plan presented by the U.S. Bureau of Indian Affairs. The Tesuque Formation, of Miocene age, underlies most of the Pojoaque River basin and is composed of interbedded layers of gravel, sand, silt, and clay with some intercalated volcanic ash beds. The degree of both sorting and cementation is variable, but the beds are typically poorly sorted and poorly cemented. Because of the interbedding, the ability of the formation to transmit

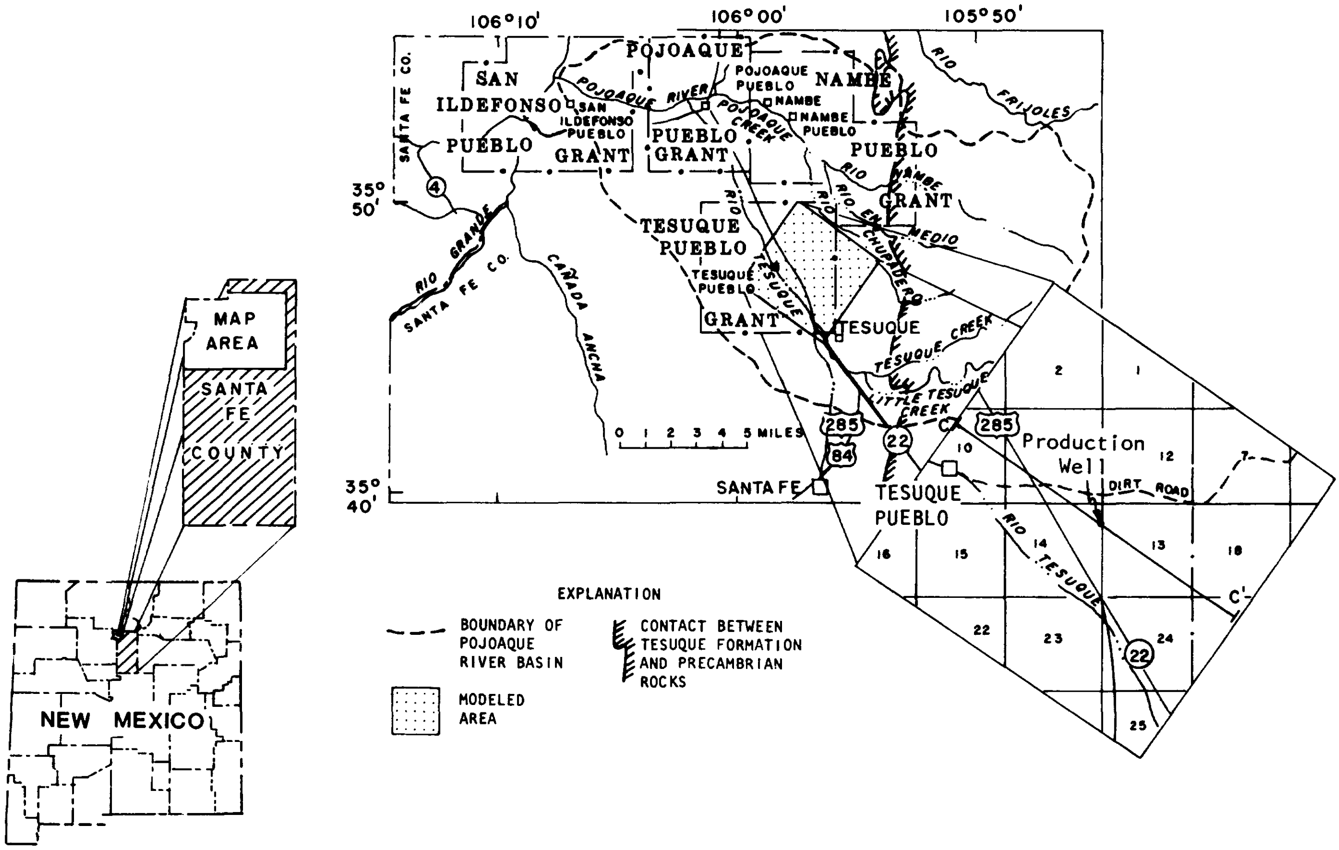


**Figure 1.** Location of the modeled area.

water parallel to the beds is many times greater than its ability to transmit water normal to the beds. Within the Pojoaque River basin the beds of the Tesuque Formation dip predominantly to the west or northwest (fig. 2). Except for the ash beds, the Tesuque was deposited as coalescing alluvial deposits. As a result, individual clastic beds are probably not continuous over the basin, and predominantly north-south trending faults further disrupt the continuity of the beds (fig. 2). This heterogeneous, anisotropic hydraulic unit of interbedded material is called the Tesuque aquifer system in this report.

The thickness of the Tesuque Formation is unknown but has been estimated (Galusha and Blick, 1971) to exceed 3,700 feet in some places. Kelley (1978) estimates that the thickness of the Tesuque Formation may exceed 8,000–9,000 feet near the Rio Grande. Manley (1978) estimates the dip of the Precambrian crystalline rocks as approximately 4°, which would imply a depth of about 4,000 feet for the Tesuque Formation beneath Espanola (on the Rio Grande about 4 miles north of the Pojoaque Pueblo Grant boundary, fig. 1).

The nature of the rocks underlying the Tesuque Formation is also not known. Throughout most of the basin the Tesuque probably overlies Precambrian crystalline rock (fig. 2). In the southwestern part of the basin Paleozoic, Mesozoic, and lower Tertiary rocks overlie the Precambrian crystalline rock and underlie the Tesuque Formation. These wedge out to the northeast, but their extent is unknown.

Most recharge to the Tesuque aquifer system in the Pojoaque River basin occurs as infiltration from streams along the front of the Sangre de Cristo Mountains as the streams flow onto the more permeable beds of the Tesuque aquifer system (fig. 2). Infiltration of precipitation may also recharge water to the system.

The Rio Grande is the major discharge area for the Tesuque aquifer system (fig. 2). In addition, some water discharges from springs and by evapotranspiration in areas where the water table is at or near the land surface.

The water flows from the recharge area through the Tesuque aquifer system to discharge along the Rio Grande. This pattern of flow forces the water to move across the beds of the Tesuque aquifer system (fig. 2).

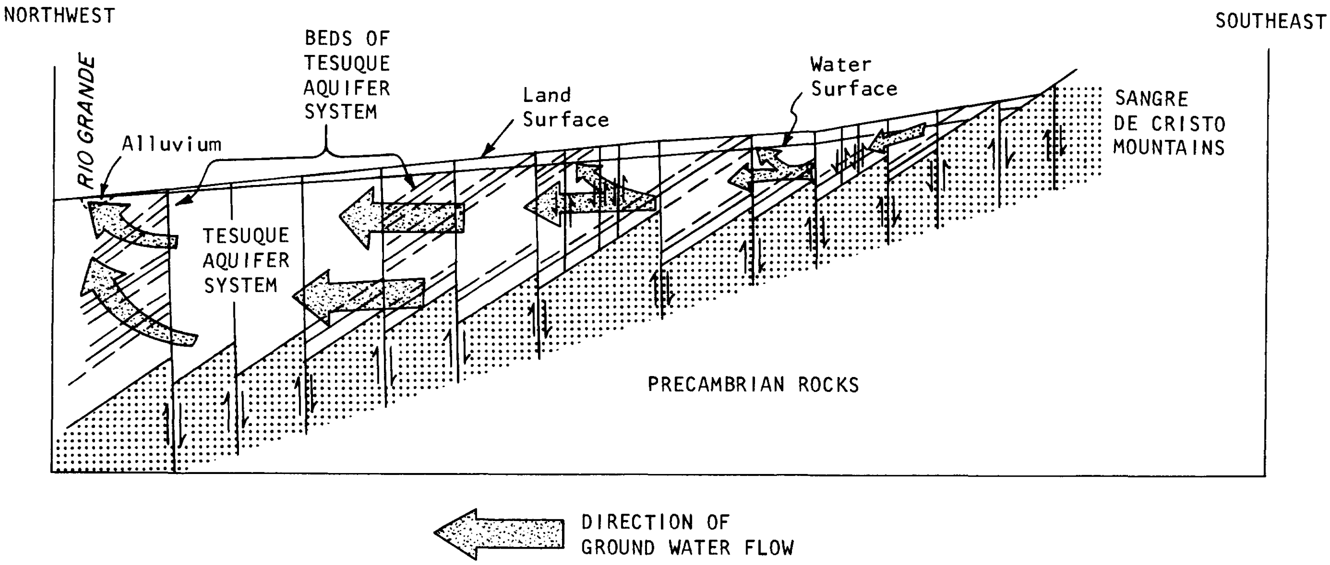


**Figure 2.** Generalized section near Tesuque Pueblo Grant, N. Mex.

The component of flow normal to these beds requires a hydraulic gradient normal to the beds. The water must move up through the beds (fig. 2), and the hydraulic head must be higher in the deeper beds.

The site selected for the aquifer test is on the Tesuque Pueblo Grant about 2 miles east-southeast of Tesuque Pueblo and about 1 mile northeast of the Rio Tesuque (fig. 1). The site was selected because it appeared to be typical of the Tesuque aquifer system, and there was an existing well capable of withdrawing enough water to test the characteristics of the system.

At the surface, the site appears to be typical of the Tesuque Formation as described above. The beds at the land surface dip about 7° to the northwest with a strike of about N. 35° E.

Data on the subsurface conditions at the site were obtained during the test and will be discussed in the section on geohydrology of the test site.

## AQUIFER-TEST DESIGN

The aquifer test was designed to determine the ability of the Tesuque aquifer system to store and transmit water. In an aquifer test the response of the aquifer system to a stress (typically the withdrawal of water) is monitored, and this response is used to estimate the aquifer characteristics. The response is usually observed as a change in the hydraulic head. The geophysical logs, analyses of water quality, and hydraulic heads under unstressed conditions provide supplemental data on the geohydrologic properties of the test site.

### Production Well

The production well (fig. 3) was completed in 1972 with ⅝-inch-diameter casing to a depth of about 820 feet. The altitude of the land surface at the production well is about 6,612 feet. The production well was screened in the sand units between the altitudes of about 5,792 and 6,308 feet (300–820 feet below land surface, figs. 4 and 5). The well was gravel packed with about 200 cubic feet of pea gravel from 100–820 feet below land surface and cemented off in the upper 100 feet with 23 cubic feet of cement.

### Piezometers

A total of 13 piezometers were installed during 1975 in the vicinity of the production well. Each piezometer was a galvanized 2-inch-diameter pipe with a 5-foot-long screen which was placed in a 6-inch-diameter hole. Gravel was packed into the anulus around the screen in the bottom 15 feet of the hole. Each piezometer was sealed from the overlying beds of the aquifer system by backfilling above the gravel pack with drilling mud. Each piezometer provided a measurement of the hydraulic head in the aquifer system at the position of the 5-foot screen. Six groups, of one to three piezometers each, were located near the production well. Gamma, density, neutron, and caliper logs were obtained prior to casing emplacement for the deepest piezometer of each group; and gamma, density, neutron, and temperature logs were obtained for the production well.

One group of piezometers (1, 2, and 3) was installed along the strike about 150 feet to the southwest of the production well (fig. 3) at a land-surface altitude of about

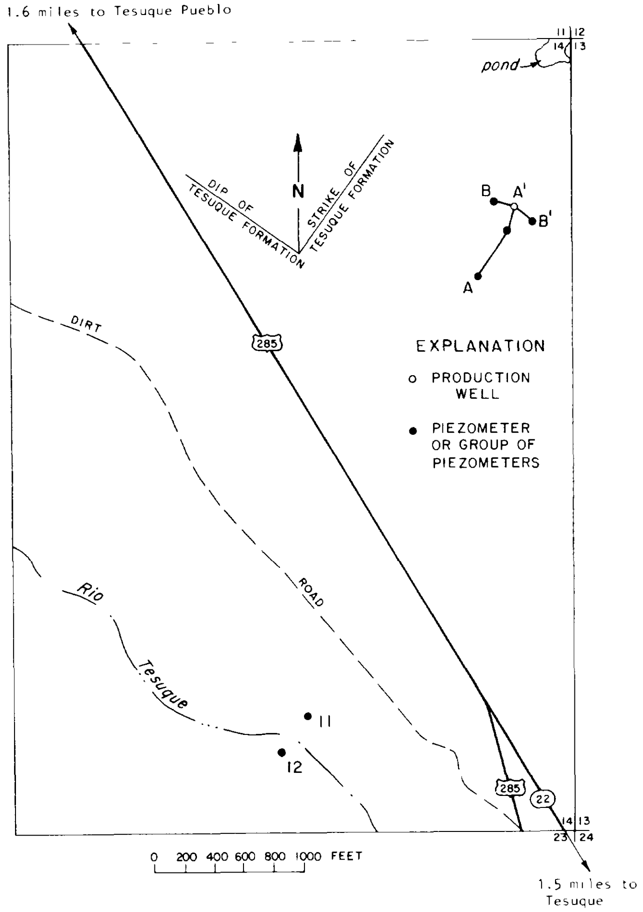


**Figure 3.** Site of the aquifer test.

6,607 feet. Piezometers 1, 2, and 3 were completed at altitudes of about 5,670, 6,010, and 6,210 feet, respectively (fig. 4). Piezometer altitudes are the altitude of the top of the 5-foot screen rounded to the nearest 10 feet.

A second group of piezometers (4, 5, and 6) was installed along the strike about 550 feet to the southwest of the production well (fig. 3) at a land-surface altitude of about 6,582 feet. Piezometers 4, 5, and 6 were completed at altitudes of about 5,630, 5,980, and 6,200 feet (fig. 4).

A third group of piezometers (7, 8, and 9) was installed downdip from the production well about 150 feet to the northwest (fig. 3) at a land-surface altitude of about 6,640 feet. Piezometers 7, 8, and 9 were completed at altitudes of about 6,450, 5,960, and 5,620 feet (fig. 5).

A fourth group of piezometers (10 and 14) was installed updip from the production well about 150 feet to the southeast (fig. 3) at a land-surface altitude of about 6,604 feet. Piezometers 10 and 14 were completed at altitudes of about 5,640 and 5,980 feet (fig. 5).

The screened intervals of the piezometers were installed to allow observation of changes in hydraulic head in four horizons during the test. The lowest horizon monitored was about 120–170 feet below the lowest bed screened in the production well. Piezometers 1, 4, 9, and 10 were completed in this horizon at altitudes of about 5,620–5,670 feet (figs. 4 and 5). This group of four is referred to as the piezometers at an altitude of about 5,650 feet.

The second lowest horizon monitored was about 170–220 feet above the lowest bed screened in the production well. Piezometers 2, 5, 8, and 14 were completed in this horizon at altitudes of about 5,960–6,010 feet (figs. 4 and 5). This group of four is referred to as the piezometers at an altitude of about 6,000 feet.

The next highest horizon monitored was about 100–110 feet below the highest bed screened in the production well. Piezometers 3 and 6 were completed in this horizon at altitudes of about 6,200–6,210 feet (fig. 4). This group of two is referred to as the piezometers at an altitude of about 6,200 feet.

The highest horizon monitored was about 140 feet above the highest bed screened in the production well. Piezometer 7 was completed at an altitude of about 6,450 feet (fig. 5).

Piezometers at altitudes of about 6,000 feet (piezometers 2, 5, 8, and 14) and 6,200 feet (piezometers 3 and 6) were completed in beds screened in the production well. It was thought that the response in these beds would be most sensitive to the hydraulic conductivity along the beds. These piezometers were arranged in a cross pattern to detect any anisotropy in the bedding plane.

Piezometers at an altitude of about 5,650 feet (piezometers 1, 4, 9, and 10) were completed below the beds screened in the production well. Piezometer 7 at an altitude of about 6,450 feet was completed above the beds screened in the production well. It was thought that the response in these beds would be most sensitive to the hydraulic conductivity normal to the bedding plane. These piezometers were installed to allow estimation of the crossbed hydraulic conductivity by the Neuman-Witherspoon method (Neuman and Witherspoon, 1972).

The distances from the production well to the piezometers were chosen because prior estimates of the aquifer characteristics indicated that the response to the aquifer test would be measurable in all of these piezometers.

Two additional piezometers were installed about a mile southwest of the production well along the alluvial channel of the Rio Tesuque (fig. 3), piezometer 11 on the northeast and piezometer 12 on the southwest side of the alluvial channel. The land-surface altitude is about 6,500 feet at both sites. Both piezometers 11 and 12 were completed at an altitude of about 6,430 feet. It was thought that the response in these piezometers would reflect changes in hydraulic head due to surface flows.

## Samples of Water Quality

As a part of the test, the chemical quality was determined for water samples believed to be representative of the water contained in beds of the Tesuque aquifer system at the site. A water sample was collected from the production well during the pumping phase of the aquifer test. The hydraulic head in piezometer 4 was above the altitude of the land surface. Almost a year after pumping was discontinued, piezometer 4 was allowed to flow for several days before a water sample was collected.

## Withdrawals From the Production Well

Prior to the aquifer test conducted in December 1975, the production well had not been pumped for almost 2 years. During a step-drawdown test conducted in February 1974, the production well had been pumped for about 33 hours at rates no greater than about 300 gallons per minute (Emery, 1974). In 1974, the depth to water had been about 35 feet below land surface prior to the test, as much as 150 feet below land surface during the test, and about 60 feet below land surface several days after pumping was stopped. No significant withdrawals of water from the production well had been made between the time of the step-drawdown test and the aquifer test described in this report.

In preparation for the December 16, 1975, aquifer test, a pump was installed in the production well on December 3, 1975, and about 300 gallons per minute were withdrawn for about 2 hours. After this pumping period, the pump was turned off and the aquifer system was allowed to recover for 13 days prior to the aquifer test.

For the aquifer test, the rate of withdrawal was maintained at about 320 gallons per minute for 13 days, beginning December 16, 1975. The water was discharged into a pond about 1,000 feet north of the production well (fig. 3). The changes in hydraulic head were monitored in all piezometers and in the production well during the test. After withdrawals were stopped, hydraulic heads in the piezometers and the production well were monitored as the aquifer system was allowed to recover from the stress of the 13-day pumping period.

# GEOHYDROLOGY OF THE TEST SITE

Additional geohydrologic data (geophysical logs, analyses of water samples, and hydraulic heads under unstressed conditions) were collected. This section discusses these data and what they imply about the geohydrology of the test site.

## Geophysical Logs

Gamma, density, neutron, and caliper logs were obtained in the 6-inch-diameter open hole prior to emplacement of the deepest piezometer of each group. All logs were produced by the logging equipment of the New Mexico District of the U.S. Geological Survey. Geophysical logs indicate that the test site is typical of the Tesuque aquifer system in that it consists of interbedded sand, silt, and clay. The strike and dip of the beds at depth were found to be about the same as for the beds on the surface. That is, the strike is about N. 35° E. and the dip is about 7° to the northwest. The sections shown in figures 4 and 5 indicate the nature of the material as inferred from geophysical logs. The geophysical logs were used (in the section on "Estimation of Aquifer Characteristics and Apportionment in Model") to assign values representing the ability to store and transmit water to the cells of the model.

## Chemical Quality of Water Samples

Water samples were collected from the production well and from piezometer 4. The chemical quality of the water samples is summarized in table 1. The sample from the production well contained nearly equal concentrations of calcium and sodium, and neither iron nor manganese was detected. In contrast, the sample from piezometer 4 contained about twice as much calcium as sodium with measurable concentrations of iron and manganese. These apparent differences in chemical quality may be an indication of the extent to which the units are hydraulically separated by the intervening silts and clays (fig. 4).

## Hydraulic Heads Under Unstressed Conditions

The hydraulic heads under unstressed conditions provide additional information on the geohydrology of the test site. Those in the piezometers provide an estimate of the extent to which the crossbed anisotropy confines the more transmissive beds of the Tesuque aquifer system; those in the production well and piezometers provide some insight into the communication between the well and these more transmissive beds.

It is not known whether piezometers 11 and 12 were completed in the alluvium or in the Tesuque Formation. Because the alluvium is so similar to the Tesuque Formation, there was no distinctive separation on the geophysical logs. Correlation of geophysical logs from piezometers 11 and 12 with those from the piezometers nearer the production well was inconclusive. The hydraulic heads in piezometers 11 and 12 were much lower than in piezometer 7 even though the piezometers were completed in about the same horizon. The hydraulic heads in piezomet-

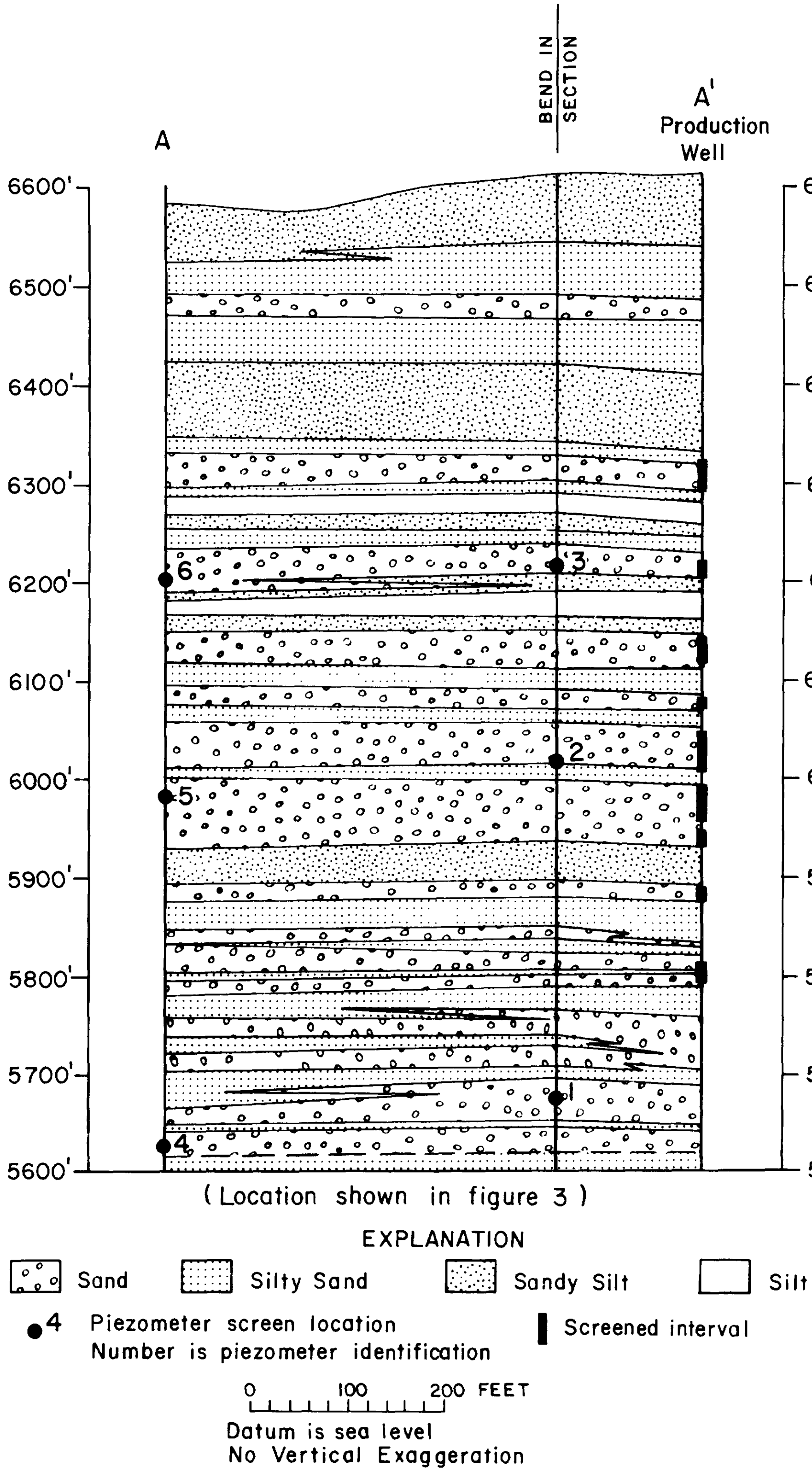


**Figure 4.** Section A–A' showing beds at test site.

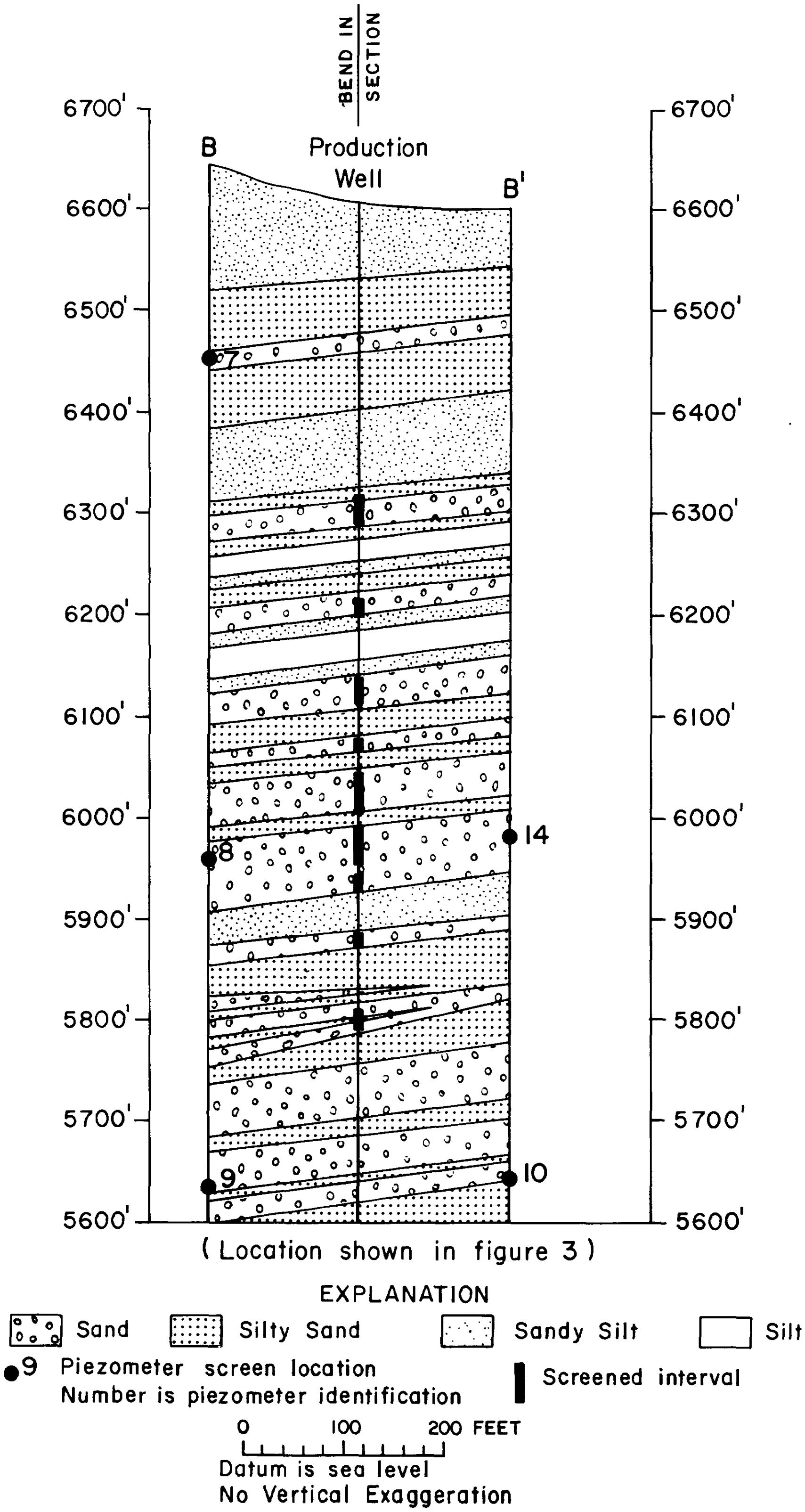


**Figure 5.** Section B–B′ showing beds at test site.

**Table 1.** Chemical quality of water samples from the production well and piezometer 4

| Constituent | Concentration reported in units of | Concentration in sample collected from | |
|---|---|---|---|
| | | Production well, Dec. 18, 1975 | Piezometer 4, Nov. 8, 1976 |
| Alkalinity, total (as $CaCO_3$) | mg/L | 129 | 175 |
| Arsenic, dissolved | µg/L | - | 2 |
| Barium, dissolved | µg/L | - | 0 |
| Bicarbonate | mg/L | 157 | 213 |
| Boron, dissolved | µg/L | - | 30 |
| Cadmium, dissolved | µg/L | - | 0 |
| Calcium, dissolved | mg/L | 26 | 47 |
| Carbon, total organic | mg/L | - | 0.0 |
| Carbonate | mg/L | 0 | 0 |
| Chloride, dissolved | mg/L | 6.9 | 4.9 |
| Chromium, dissolved | µg/L | - | 0 |
| Chromium, hexavalent | µg/L | - | 0 |
| Copper, dissolved | µg/L | - | 0 |
| Dissolved solids, calculated sum of constituents | mg/L | 182 | 226 |
| Dissolved solids, residue at 180'C | mg/L | - | 236 |
| Fluoride, dissolved | mg/L | 0.5 | 0.2 |
| Hardness, noncarbonate | mg/L | 0 | 0 |
| Hardness, total | mg/L | 81 | 140 |
| Iron, dissolved | µg/L | 0 | 30 |
| Lead, dissolved | µg/L | - | 3 |
| Magnesium, dissolved | mg/L | 3.9 | 4.3 |
| Manganese, dissolved | µg/L | 0 | 140 |
| Mercury, dissolved | µg/L | - | 0.0 |
| Nitrate, plus nitrite, dissolved (as N) | mg/L | 0.61 | 0.63 |
| Phosphorus, ortho, dissolved (as P) | mg/L | 0.03 | 0.03 |
| Phosphate, ortho, dissolved (as $PO_4$) | mg/L | 0.09 | 0.09 |
| pH, as field value | | 8.3 | 7.4 |
| Potassium, dissolved | mg/L | 1.6 | 1.6 |
| Selenium, dissolved | µg/L | - | 0 |
| Silica, dissolved | mg/L | 20 | 24 |
| Silver, dissolved | µg/L | - | 0 |
| Sodium-adsorption ratio (SAR) | | 1.5 | 0.9 |
| Sodium, dissolved | mg/L | 30 | 24 |
| Sodium, percent | | 44 | 28 |
| Specific conductance, field value | | - | 350 |
| Specific conductance, lab value | | 290 | 357 |
| Sulfate, dissolved | mg/L | 13 | 11 |
| Water temperature in degrees Celsius | | - | 15.0 |
| Zinc, dissolved | µg/L | - | 750 |

ers 11 and 12 were about 6,500 feet, and in piezometer 7 about 6,530 feet. Because the relationship of the beds tapped by piezometers 11 and 12 to the other beds of the aquifer system was uncertain, the hydraulic heads in these piezometers were not used in the evaluation of the geohydrology of the test site.

The transducer used to measure the pressure in piezometer 4 malfunctioned. Consequently, no hydraulic-head data for piezometer 4 are presented in this report.

### Anisotropy Ratio

The hydraulic head in the piezometers prior to the withdrawal of water for the aquifer test is shown in figure 6. The higher hydraulic head at depth produces a vertical hydraulic gradient consistent with flow through the dipping anisotropic beds of the Tesuque aquifer system (fig. 2). The vertical and the horizontal hydraulic gradients can provide an estimate of the anisotropy of the system.

For horizontal flow in the vertical plane containing the dip, it can be shown (C. V. Theis, U.S. Geological Survey, written commun., 1974) that

$$\frac{\partial h/\partial z}{\partial h/\partial x} = \frac{(K_n - K_p)\cos A \sin A}{K_p \sin^2 A + K_n \cos^2 A}, \qquad (1)$$

in which

- $K_p$ = the hydraulic conductivity parallel to the bedding (L/T);
- $K_n$ = the hydraulic conductivity normal to the bedding (L/T);
- $A$ = the angle of the dip of the bedding (negative for downdip flow, positive for updip flow) (dimensionless);
- $\partial h/\partial x$ = the horizontal hydraulic gradient in the direction of the dip (dimensionless); and
- $\partial h/\partial z$ = the vertical hydraulic gradient (dimensionless).

Solving for the ratio of hydraulic conductivities yields

$$\frac{K_n}{K_p} = \frac{\sin A\left(\cos A\,\frac{\partial h}{\partial x} + \sin A\,\frac{\partial h}{\partial z}\right)}{\cos A\left(\sin A\,\frac{\partial h}{\partial x} - \cos A\,\frac{\partial h}{\partial z}\right)}. \qquad (2)$$

When flow is downdip, the angle A is negative and the equation is constrained by

$$\frac{\partial h/\partial x}{\partial h/\partial z} > -\tan A. \qquad (3)$$

If data do not satisfy this condition, the calculated anisotropy ratio is less than or equal to zero. This implies that either the basic assumptions have been violated or the data are inconsistent because of measurement errors. The equation assumes horizontal flow in the plane containing the dip. This assumption is inadequate if there is a significant component of vertical flow or flow along the strike. The equation is sensitive to hydraulic gradient; that is, a small error in hydraulic gradient may produce a large error in the estimated anisotropy ratio. The criterion is satisfied at the Tesuque site; the difference between the left and right sides of the inequality is 0.03. Therefore, the equation can be used to estimate the anisotropy ratio, although the estimate may not be very precise

Flow through the Tesuque site was assumed to be toward the Rio Grande, downdip, and nearly horizontal. The horizontal hydraulic gradient was estimated as 100 feet per mile or about 0.02 from the contours of the water surface (Trauger, 1967; Borton, 1968). The vertical hydraulic gradient was estimated to range from 0.012 to 0.13 from the hydraulic heads in the piezometers (fig. 6). The beds of the Tesuque dip toward the Rio Grande about 7°.

Substituting these values into equation 2, the calculated ratio of crossbed to inbed hydraulic conductivities provides an estimate of the anisotropy of the aquifer system. For a vertical component of hydraulic gradient of 0.01, the estimated ratio of hydraulic conductivities is about 0.2. For a vertical component of hydraulic gradient of 0.13, the estimated ratio of hydraulic conductivities is about 0.004. The difference in the vertical component of hydraulic gradient above and below the piezometers at an altitude of about 6,200 feet (fig. 6) may be the result of significant flow along the strike in the beds above 6,200 feet. If so, the assumption of flow in the plane containing the dip is violated and the ratio of vertical to horizontal components of hydraulic gradient cannot be used to estimate the anistropy ratio. The average vertical component of gradient between the piezometers at an altitude of about 5,650 feet and those at an altitude of about 6,200 feet is about 0.12, from which the ratio of crossbed to inbed hydraulic conductivities is estimated to be about 0.004. If this ratio is representative of the Tesuque aquifer system and the average hydraulic conductivity parallel to the bedding is 1 foot per day, then the average hydraulic conductivity normal to the bedding is 0.004 foot per day.

### Hydraulic Communication With Production Well

The hydraulic communication between the production well and the more permeable beds of the Tesuque aquifer system is indicated by the hydraulic heads in the production well and in the piezometers. When water is not being withdrawn from the production well, the hydraulic head there responds to the hydraulic head in each of the beds with which

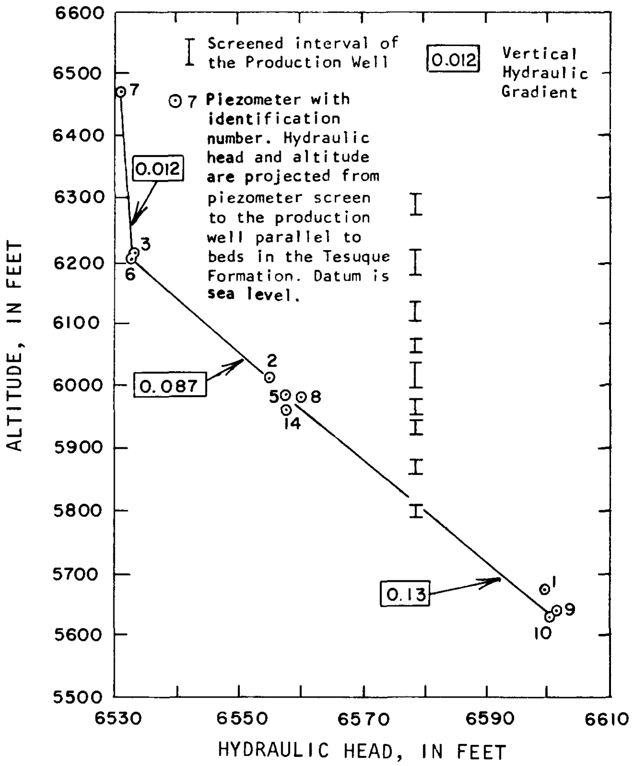


**Figure 6.** Relationship between altitude and hydraulic head observed at test site on December 3, 1975.

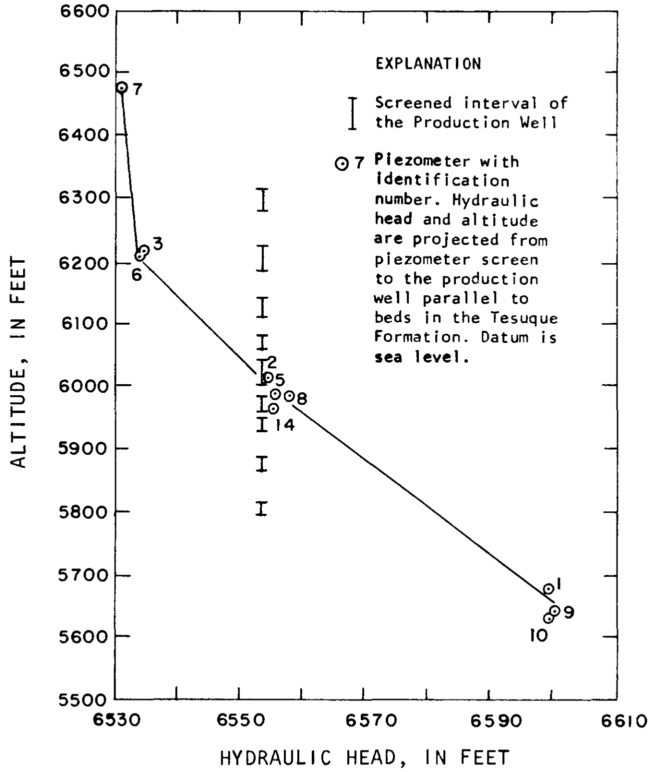


**Figure 7.** Relationship between altitude and hydraulic head observed at test site on December 16, 1975.

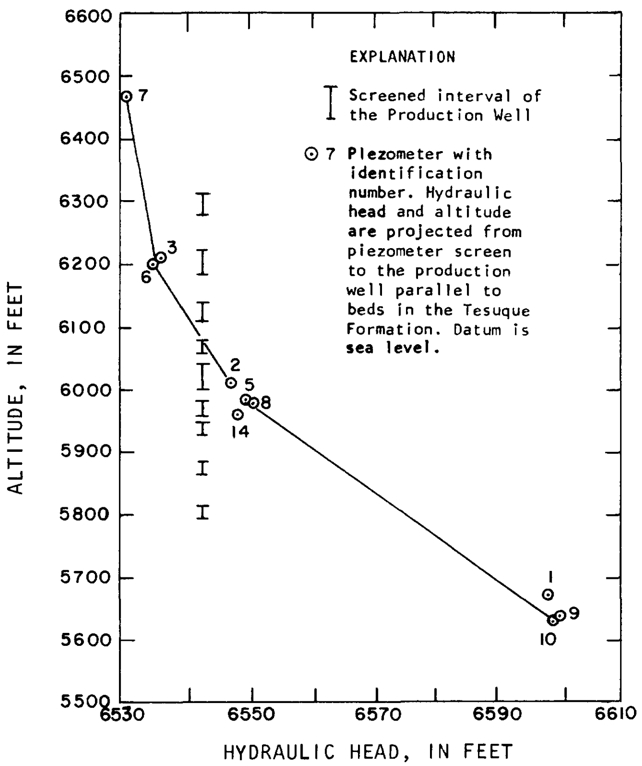


**Figure 8.** Relationship between altitude and hydraulic head observed at test site on February 11, 1976.

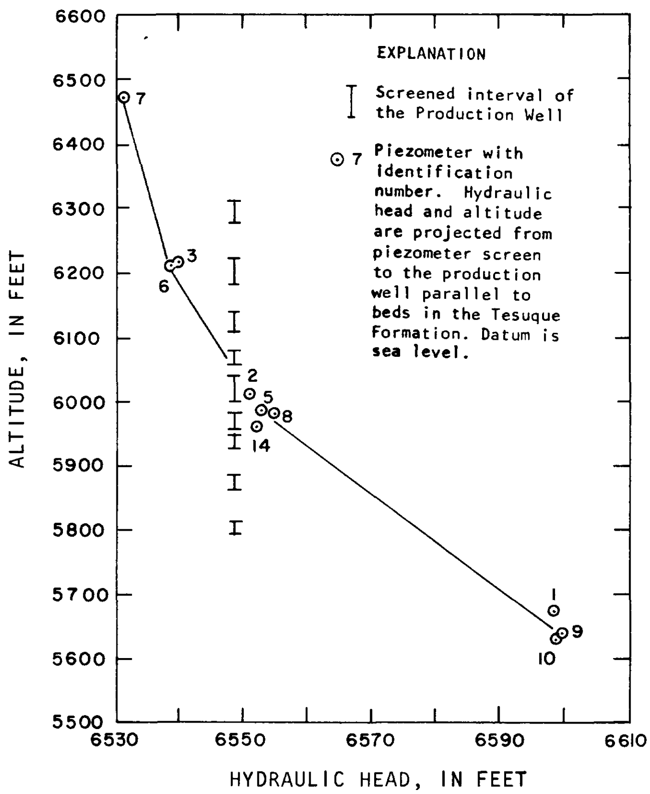


**Figure 9.** Relationship between altitude and hydraulic head observed at test site on March 19, 1977.

the well is in hydraulic connection. When water has not been withdrawn for several days, the flows to and from the production well approach steady-state conditions. The Thiem equation for confined aquifers (Lohman, 1972, eq. 32) can be used to estimate the steady-state flow to the production well from each bed of the aquifer system. The sum of these flows over all the beds in which the well is completed must be zero; the resulting equation can be solved for hydraulic head in the production well to yield

$$h_w = \frac{\sum_{i=1}^{i=n} b_i K_i h_i}{\sum_{i=1}^{i=n} b_i K_i}, \qquad (4)$$

in which

$h_w$ = the hydraulic head in the production well (L);
$h_i$ = the hydraulic head in the $i$-th bed at a constant distance from the well (L), within which steady-state flow is assumed;
$b_i$ = the thickness of the $i$-th bed (L);
$K_i$ = the hydraulic conductivity of the $i$-th bed (L/T); and
$n$ = the number of beds with which the well is in hydraulic connection (dimensionless).

That is, the hydraulic head in the production well is the weighted average of the hydraulic heads in each of the beds with which the well is in hydraulic connection. The weighting factor is the product of the thickness and hydraulic conductivity of the bed.

Four sets of measurements for which the flow through the production well is probably close to steady state are shown in figures 6, 7, 8, and 9. Hydraulic heads on December 3, 1975 (fig. 6), reflect the condition more than a year after any significant withdrawals. Hydraulic heads on December 16, 1975 (fig. 7), reflect the condition 13 days after a 2-hour pumping stress. Hydraulic heads on February 11, 1976 (fig. 8), reflect the condition 44 days after the pumping stress of the 13-day aquifer test. Hydraulic heads on March 19, 1977 (fig. 9), reflect the condition more than a year after the aquifer test. If each of these conditions approximates steady state, then hydraulic head in the production well changes in response to changes in the hydraulic communication between the production well and the penetrated beds. Individual beds appear to be progressively sealed off during periods of disuse and unsealed during periods of withdrawals.

The term "production zone" will be used to describe the group of beds between the uppermost and lowermost screens of the production well. Since the withdrawals in 1974, flow from the lower to the upper beds of the production zone through the production well has occurred because of the vertical hydraulic gradients. The upper beds appear to have become progressively sealed off from the production well. The hydraulic head in the production zone on December 3,1975 (fig. 6), appears to have reflected the hydraulic head in the lowermost bed (at an altitude of about 5,800 feet). The withdrawals made on that date appear to have at least partially unsealed some of the upper beds. Consequently, the hydraulic head in the production well on December 16, 1975 (fig. 7), 23 feet lower than on December 3, 1975 (fig. 6), appears to have reflected an average of several beds. The withdrawals made from December 16 through 29, 1975, appear to have unsealed even more of the upper beds. Consequently, on February 11, 1976, the hydraulic head in the production well (fig. 8) was 30 feet lower than on December 3, 1975 (fig. 6). Although withdrawals had stopped, flow from the lower beds to the upper beds through the production well continued. There again appears to have been progressive sealing off of the upper beds. Consequently, on March 19, 1977, the hydraulic head in the production well (fig. 9) had increased about 5 feet over its level on February 11, 1976 (fig. 8).

The difference in hydraulic heads between the piezometers and the production well appears to be consistent with this scenario. The beds at an altitude of about 6,000 feet are in the lower half of the production zone. Hydraulic heads in the piezometers (2, 5, 8, and 14) at this level declined (figs. 6–8) as the production well was developed during the aquifer test. Water in the beds at an altitude of about 6,000 feet appears to have been flowing from these beds through the production well to overlying beds in the production zone. The hydraulic-head difference between the piezometers at an altitude of about 6,000 feet and the production well was about −20 feet on December 3, 1975 (fig. 6), 2 feet on December 16, 1975 (fig. 7), and 6 feet on February 11, 1976 (fig. 8). The flow from the lower beds appears to have decreased as the upper beds were progressively sealed off. The hydraulic-head difference between the piezometers at an altitude of about 6,000 feet and the production well decreased about 2 feet from February 11, 1976 (fig. 8), to March 19, 1977 (fig. 9).

The beds at an altitude of about 6,200 feet are in the upper half of the production zone. Hydraulic heads in the piezometers (3 and 6) at this level rose (figs. 6–8) as the production well was developed during the aquifer test. Water appears to have been flowing from underlying beds in the production zone through the production well to these beds. The hydraulic-head difference between the production well and the piezometers at an altitude of about 6,200 feet decreased from more than 40 feet on December 3, 1975 (fig. 6), to about 20 feet on December 16, 1975 (fig. 7), to about 8 feet on February 11, 1976 (fig. 8). The flow to the upper beds appears to have decreased as the upper beds were progressively sealed off. The hydraulic-head difference between the production well and the piezometers at an altitude of about 6,200 feet increased about 2 feet from February 11, 1976 (fig. 8), to March 19, 1977 (fig. 9).

## AQUIFER-TEST RESULTS

The primary data collected during the aquifer test were the declines in hydraulic head observed in the piezometers as a response to the withdrawal of water at the production well from December 16 through 29, 1975. At piezometers 11 and 12 the changes in hydraulic head showed no apparent correlation with the aquifer test. Because the relationship of the material tapped by these piezometers with the other beds of the aquifer system is uncertain, the hydraulic heads in these piezometers were not included in the analysis. As noted above, the hydraulic head in piezometer 4 was not measured because of a transducer malfunction. The changes in hydraulic head at the remaining piezometers are believed to represent the response of the aquifer system to the withdrawal of water at the production well during the aquifer test.

Changes in hydraulic head in the piezometers at altitudes of about 5,650 and 6,450 feet (piezometers 1, 7, 9, and 10) were only a few tenths of a foot and showed no apparent correlation with the time of the pumping stress of the aquifer test. Any response to the pumping stress was apparently less than a few tenths of a foot and was masked by noise in the system. Because of the lack of response in these piezometers, the crossbed hydraulic conductivity was not estimated by the Neuman-Witherspoon method (Neuman and Witherspoon, 1972) as planned.

The observed declines in hydraulic head are shown in figure 10 for piezometers at an altitude of about 6,200 feet (piezometers 3 and 6) and in figure 11 for piezometers at an altitude of about 6,000 feet (piezometers 2, 5, 8, and 14). A smooth curve was drawn which follows the general trend of all the data obtained from piezometers at an altitude of about 6,200 feet (fig. 10). The responses at 150 feet (piezometer 3) and 550 feet (piezometer 6) from the production well follow the same general trend. A smooth curve was also drawn which follows the general trend of the early data obtained from piezometers at an altitude of about 6,000 feet (fig. 11). The responses at 150 feet (piezometers 2, 8, and 14) and 550 feet (piezometer 5) from the production well diverge from this general trend at different points (fig. 11). This could indicate that the piezometers at an altitude of about 6,000 feet responded to one or more boundaries at which the hydraulic conductivity is low. There was no significant difference between the responses at piezometers completed 150 feet updip (piezometer 14), downdip (piezometer 8), and along the strike (piezometer 2) from the production well (fig. 11). The response in piezometers at an altitude of about 6,000 feet (fig. 11) was greater than in piezometers at an altitude of about 6,200 feet (fig. 10) at all times during the test.

## DIGITAL MODEL

A model is a description that can be useful in visualizing something not directly observable. Its purpose is to assist in the analysis of a system. A mathematical ground-water model is a mathematical description of a geohydrologic system. The validity of the analysis made with such a model depends on the extent to which the mathematical description reflects the properties of the geohydrologic system and accurately quantifies the aquifer characteristics, boundaries, and hydrologic stresses.

For the aquifer test, the geohydrologic system to be described is the Tesuque aquifer system in the vicinity of the test site. The properties represented in the model include flow across the dipping anisotropic beds, water-table conditions (high storage) encountered updip from the production well, and flow to a single production well from several beds with different initial hydraulic heads and aquifer characteristics. To approximate these boundary and initial conditions, a three-dimensional digital model was used for the analysis.

The model cannot incorporate the full complexity of the aquifer system, and the values of aquifer characteristics are not well known. Consequently, the model was calibrated by adjusting the initial estimated values of aquifer characteristics so that the response simulated by the model approximated the observed response of the aquifer system.

### Flow Equations

Flow of water in the Tesuque aquifer system is three dimensional. That is, flow vectors can be resolved into three components, one parallel to each of three orthogonal axes. Conventionally, these axes are oriented such that the x- and y-axes are horizontal and the z-axis is vertical. For the Tesuque aquifer system, it is convenient to orient the x- and y-axes along the plane of the beds and the z-axis orthogonal to the beds of the Tesuque Formation. With this orientation of axes, the equation for three-dimensional flow of ground water in a porous medium can be written (Trescott, 1975) as

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} + W, \quad (5)$$

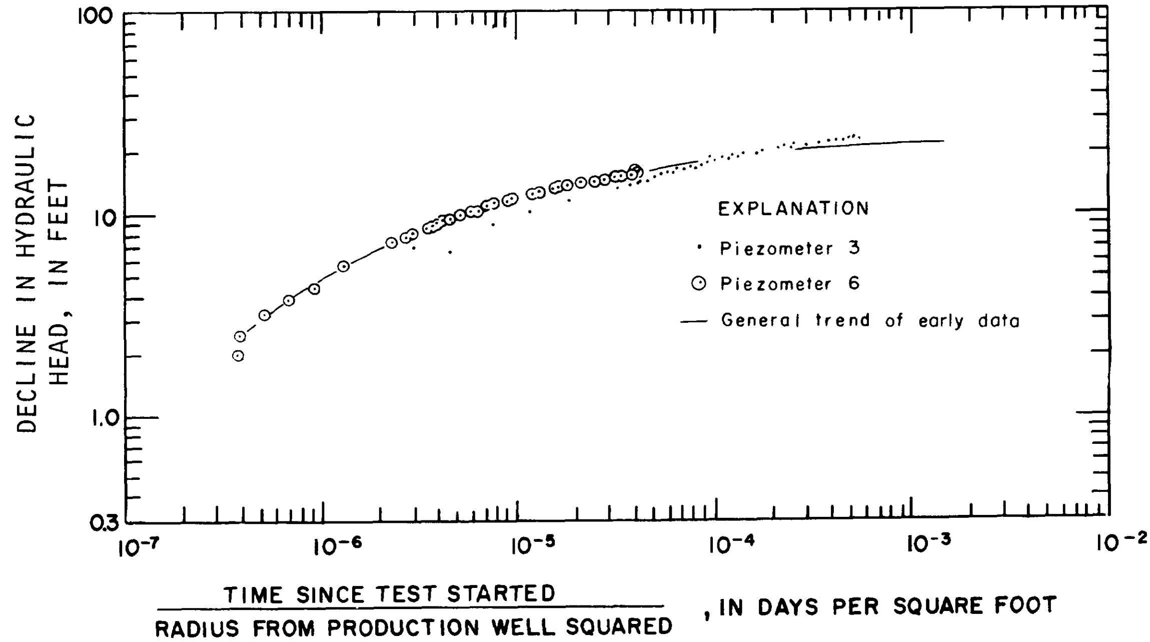


**Figure 10.** Observed decline in hydraulic head during the aquifer test in piezometers at an altitude of about 6,200 feet.

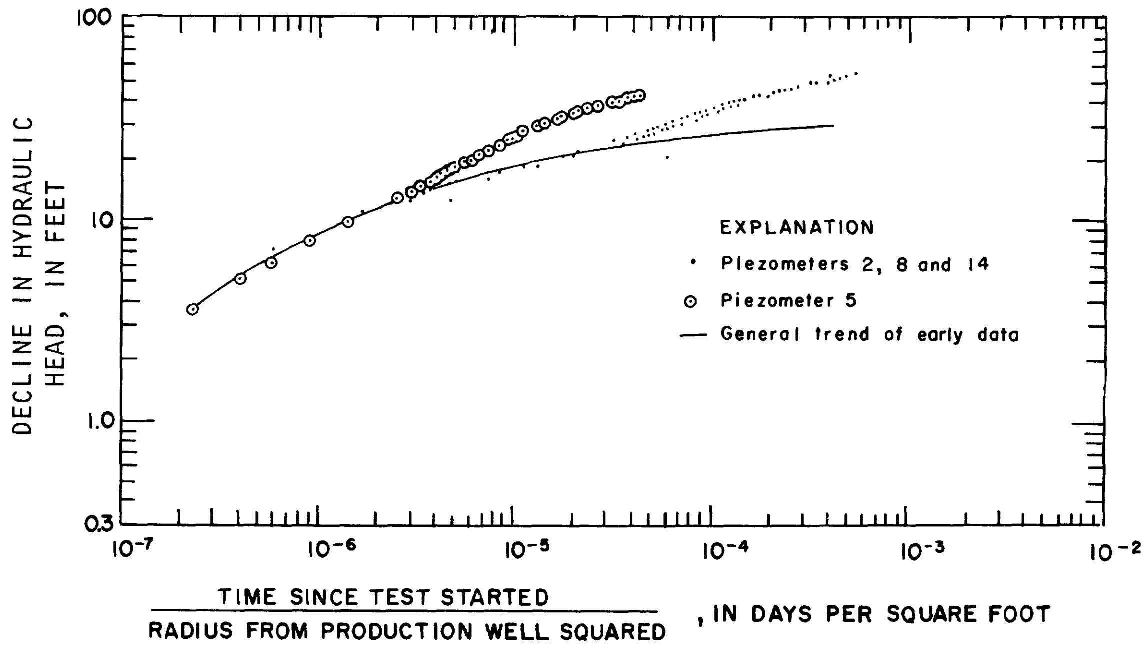


**Figure 11.** Observed decline in hydraulic head during the aquifer test in piezometers at an altitude of about 6,000 feet.

in which

| | | |
|---|---|---|
| $K_x$, $K_y$, $K_z$ | = | the hydraulic conductivities in the $x$, $y$, and $z$ directions respectively (L/T); |
| $h$ | = | the hydraulic head (L); |
| $S_s$ | = | the specific storage ($L^{-1}$); |
| $W$ | = | the volume of water released from or taken into storage per unit volume of the porous medium per unit time and represents a source-sink term ($T^{-1}$); and |
| $t$ | = | time (T). |

To simulate a three-dimensional flow system, the description of the aquifer system provided by the conceptual model is divided into a large number of brick-shaped cells. The continuous characteristics of the porous medium (that is, its ability to store and transmit water) are made discrete functions of space by assuming them to be uniform within each cell. Heterogeneity is possible in that characteristics may be varied from cell to cell. The hydraulic head associated with each cell is that at the center of the cell. At each cell, a finite-difference approximation for the derivatives in the equation yields an algebraic equation in seven unknowns (hydraulic head in the cell and hydraulic head in each of six adjacent cells). For a model with N cells, a set of N simultaneous equations in N unknowns is generated. The simulation program solves this set of simultaneous equations subject to prescribed initial and boundary conditions. Trescott (1975) and Trescott and Larsen (1976) provide details of the solution algorithm. The computer program used for this study (Posson and others, 1980) evolved from that of Trescott.

## Geohydrologic System Assumed for the Model

The model of the aquifer test on the Tesuque Pueblo Grant cannot incorporate the full complexity of the Tesuque aquifer system and the stress applied to that system. However, the validity of the model depends in part on the extent to which its description reflects these complexities. The model represents the Tesuque aquifer system as a network of contiguous but discrete cells aligned with the bedding planes in the Tesuque Formation and assumed to dip 7° to the northwest with a strike of N. 35° E. The orientation of the cells along a row of the model is shown in figure 12. Boundary conditions were imposed on the model so that the simulated steady-state condition approximated the hydraulic-head distribution observed at the test site prior to the aquifer test. The stress of the aquifer test is superimposed on this stable initial condition.

### Extent of Modeled Volume

Southeast from the production well each layer in the model extends to a boundary that approximates the location where the corresponding beds of the Tesuque aquifer system are estimated to become unsaturated (fig. 12).

In all other directions, the modeled volume is extended far enough that the response to the aquifer test is negligible at the boundary. Using preliminary estimates of hydraulic conductivity normal to the beds, the model was initially defined to represent a greater thickness of the Tesuque aquifer system than is shown in figure 12. However, the first phase of the calibration indicated a greater anisotropy than had been anticipated. The costs of computer time and storage capacity were made less by reducing the thickness represented in the model to that shown in figure 12. With the anisotropy as strong as indicated by calibration, the lower boundary of the model (fig. 12) is sufficiently distant from the lowest beds open to the production well that the boundary effects are negligible during the simulated 13-day aquifer test.

The modeled volume extends northwest along the dip about 2 miles from the production well (figs. 1 and 12) and southwest along the strike about 2 miles from the production well (fig. 1). These boundaries do not represent geologic boundaries in the Tesuque aquifer system but are located far enough from the test site that boundary effects will be negligible during the simulated 13-day test. These boundaries are represented as no-flow boundaries in the model.

The modeled volume contains a plane of symmetry normal to the strike passing through the production well. Any row normal to the strike resembles figure 12 except for the production well. The response of the model to the simulated withdrawal of water at the production well will be identical on both sides of the plane of symmetry, which, therefore, forms a no-flow boundary. The digital model takes advantage of this symmetry by simulating the response on only one side of the plane of symmetry.

### Estimation of Aquifer Characteristics and Apportionment in Model

Within the boundaries defined above, each cell in the model must be described in terms of the estimated ability of the corresponding beds of the Tesuque aquifer system to store and transmit water. This is accomplished by assuming a degree of homogeneity which almost certainly does not exist in the aquifer system itself. The assumption is necessary because the specific nature of the heterogeneity of the complex system is largely unknown. The success of the model rests on the dual assumptions that the effect on the response of the aquifer system of a single nonuniformity is negligible and that many nonuniformities randomly located throughout the system produce a homogeneous system.

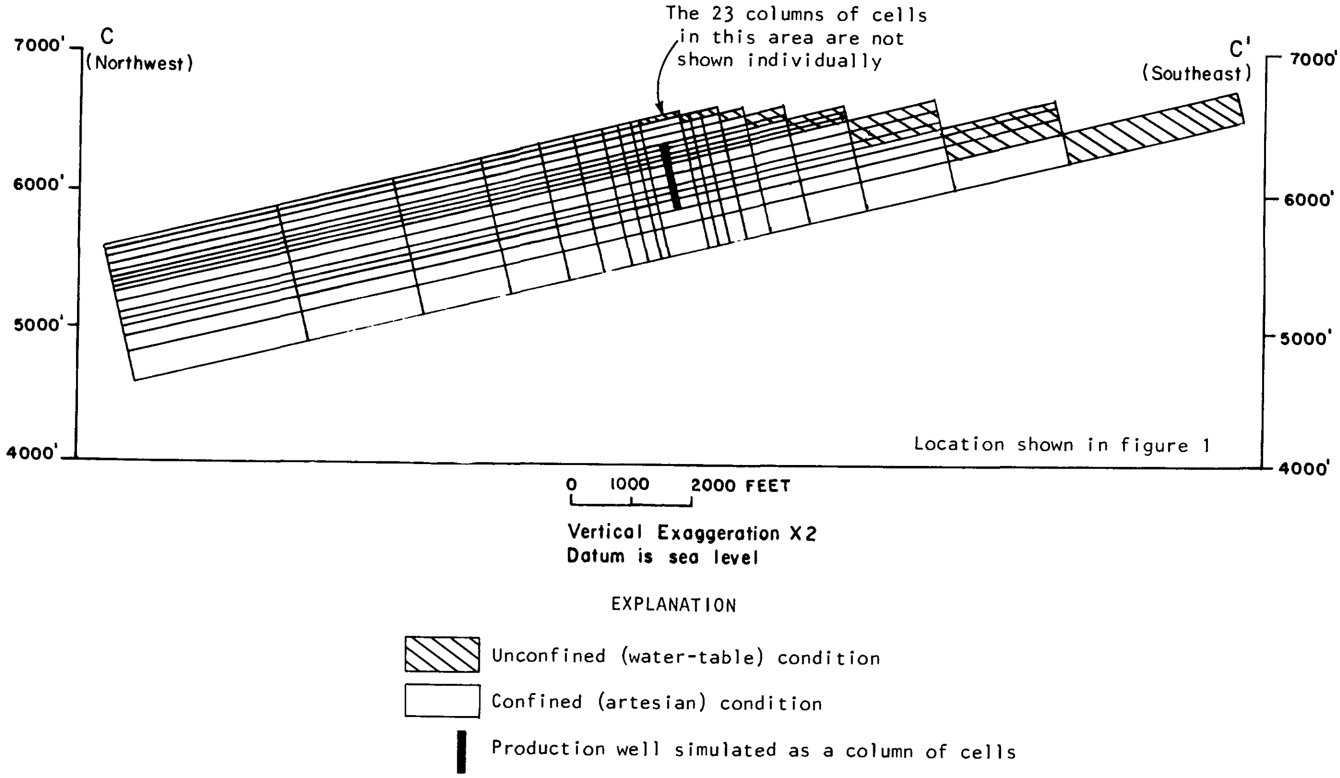


**Figure 12.** Orientation of the layers along a row of the model.

The aquifer characteristics are assumed to be homogeneous in the plane of the aquifer. Thus, parameters estimated for each of the 30 or so beds encountered at the test site are assumed to be uniform throughout the modeled area.

Data on the geohydrology of the test site are used to apportion values representing the ability to store and transmit water among the layers of the model. Model calibration is made feasible by reducing to three the number of values to be estimated: specific storage and two constants of proportionality—one for the relative hydraulic conductivity parallel to the beds and one for that conductivity normal to the beds.

J. D. Hudson (written commun., 1977) developed empirical relationships between aquifer characteristics and the geophysical logs produced by the logging equipment of the New Mexico District of the U.S. Geological Survey. The percentage of sand in the bed was related to the gamma log, the porosity of the bed to the neutron log, and the degree of cementation to the density log. The empirical relationships and the initial hydraulic-head distribution were used to apportion the ability to store and transmit water among the layers of the model. The correlation between the beds penetrated at the test site and the layers in the model is shown in figure 13. The empirical relationships were applied to each bed, and the values for each bed were averaged to obtain a value for the group of beds represented by the cells in that layer of the model.

Empirical techniques represent only the general trends of a group of data. Therefore, the calculated value for an individual bed may be unreliable. However, the average over several beds should be more reliable. The constant of proportionality between the aquifer characteristics and the value estimated from geophysical logs was adjusted during calibration of the model. Therefore, the estimates from geophysical logs were assumed to be reliable only in reflecting the relative properties of the beds penetrated at the test site. For example, the estimates are used to determine whether the hydraulic conductivity in layer 5 is more or less than that in layer 6, but not to determine the value of hydraulic conductivity in layer 5.

### Specific Storage

Most of the modeled aquifer system is under confined conditions (fig. 12). When the hydraulic head in a confined aquifer is reduced, water is released from storage due to compression of the porous medium in which the water is stored and expansion of the water within the medium. Specific storage is the volume of water released from storage per unit volume of the porous medium per unit decline in hydraulic head. If the porous medium is incompressible, the compressibility of water

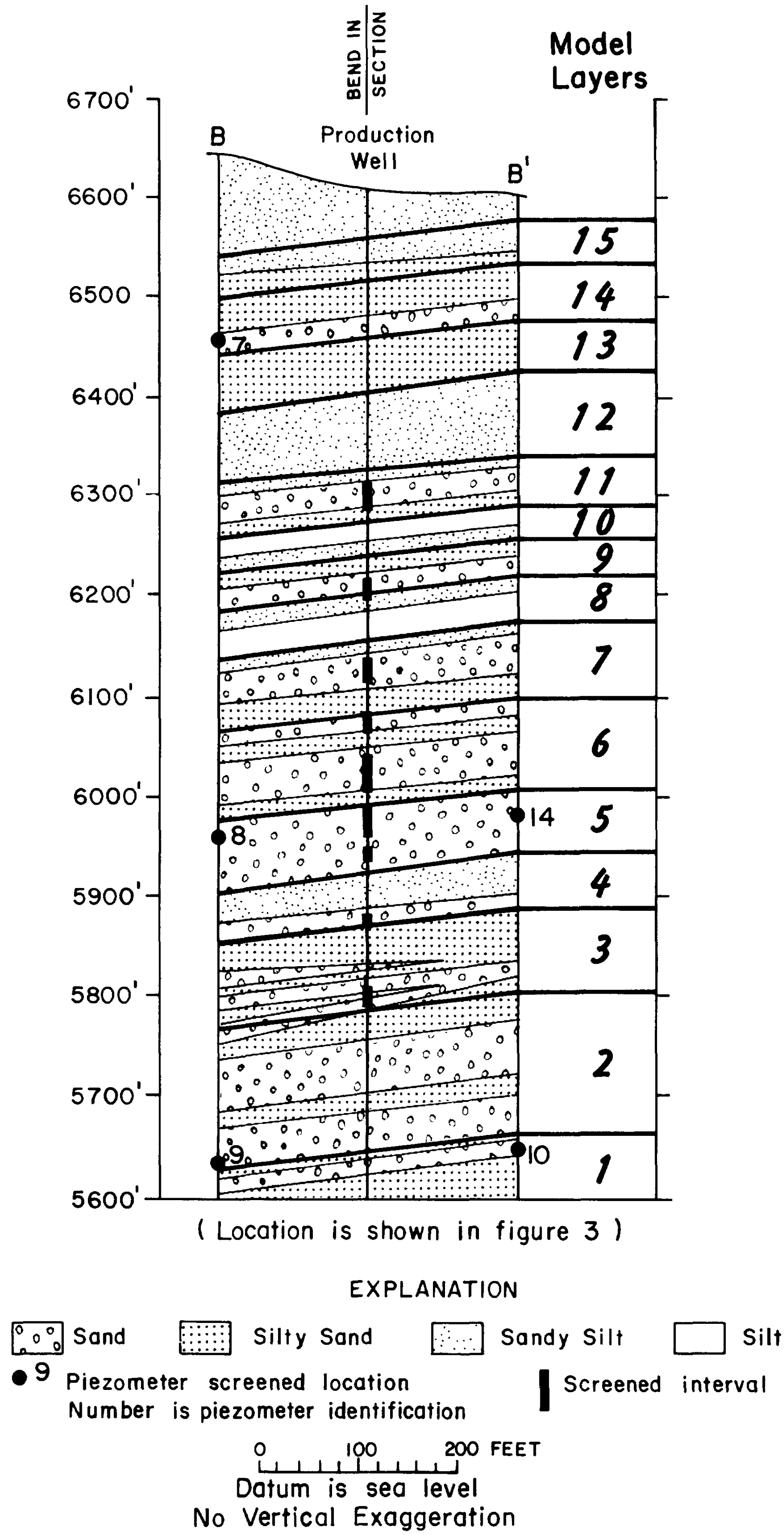


**Figure 13.** Correlation between layers in the model and beds at the test site.

would produce a specific storage of about $10^{-6}$ per foot times the porosity of the medium. For the Tesuque aquifer system, the porous medium was assumed to be at least as compressible as water. Assuming a porosity of 0.30, the specific storage is about $2 \times 10^{-6}$ per foot. This value was assumed as a lower limit for the calibration procedure. For lack of more definitive information, the specific storage was assumed to be uniform throughout the model.

### Specific Yield

For unconfined conditions the change of the volume of water in storage per unit area as the result of a unit change in hydraulic head is produced by the draining or filling of pore space. This change is dependent upon pore size, rate of change of the water surface, and time. Only an approximate measure of the relationship between change in hydraulic head and storage is obtainable for unconfined conditions. This measure is the specific yield. No aquifer tests of the Tesuque aquifer system have been conducted long enough to determine the specific yield. Specific yield may be estimated, however, if the materials composing the formation are known. The materials in the Tesuque aquifer system are poorly sorted and generally contain considerable clay and silt. Johnson (1967, p. D–1) has compiled storage coefficient values determined by various investigators and lists 12 values of storage coefficients for sandy clay and 16 for silt, ranging from 0.03 to 0.19. Johnson lists 17 values ranging from 0.10 to 0.28 for the specific yields of fine sands, and 17 values ranging from 0.15 to 0.32 for medium sand. Because the Tesuque aquifer system is an interbedded group of sands, silts, and clays, the specific yield was assumed to be in the range of about 0.10 to 0.20.

The average weighted specific yield for the beds penetrated at the test site was assumed to be about 15 percent. The specific yield for each bed of the Tesuque aquifer system was assumed to be proportional to the product of the porosity and the percentage of sand. Estimated specific yield is shown in table 2 for all layers. Because the character of the beds may change from the test site to the outcrop area and the estimates for individual beds may contain considerable error, the values in table 2 may or may not reflect the range of specific yields likely to be encountered in the Tesuque aquifer system. Because the model is insensitive to this parameter for a stress of short duration such as the aquifer test, even large errors in the estimated value will have little effect on the simulated results.

After completion of the study, the value used for layer 5 was found to be wrong. A value of 0.24 was used in the digital model rather than the 0.18 shown in table 2. Because the model is not sensitive to this parameter, the effect on the simulation was negligible.

### Hydraulic Conductivity Parallel to the Beds

The relative hydraulic conductivity parallel to the beds was estimated from the sand percentage, the porosity, and the degree of cementation. The product of the sand percentage and the porosity was adjusted to account for the degree of cementation. For the beds at the test site, the adjustment was less than about 20 percent. The estimates for each layer of the model shown in table 2 are relative to the value for layer 10. For example, it was estimated that the hydraulic conductivity of layer 9 is about 8 times that of layer 10. The constant of proportionality was adjusted during the calibration procedure.

### Hydraulic Conductivity Normal to the Beds

The following discussion is phrased in terms of hydraulic resistivity, the inverse of hydraulic conductivity. Thus, the average expressed as the weighted average of the hydraulic resistivity is the reciprocal of the more cumbersome weighted harmonic mean of the hydraulic conductivity. Unless otherwise specified, resistivity will refer to the resistivity normal to the beds of the Tesuque aquifer system. The relative resistivity was assumed to be proportional to the product of the percentage of silt and clay and the vertical component of hydraulic gradient.

The relative resistivity of sand is much lower than that of silt and clay. Therefore, the resistivity of each layer is assumed to be proportional to the percentage of silt and clay (1 minus the sand percentage) (table 2).

Estimates of the vertical hydraulic gradient from piezometers (fig. 6) were used to divide the model into three intervals in which the vertical gradient was assumed constant (table 2). The estimated relative resistivity for each layer was obtained by multiplying the percentage of silt and clay by a constant selected so that the average (weighted by thickness) estimated relative resistivity for all layers in the interval is equal to the vertical gradient. To illustrate the method, consider layer 7 of the model (fig. 13). Layer 7 is 24 percent silt and clay. Layers 6 through 8 represent the interval between the piezometers at an altitude of about 6,000 feet and those at an altitude of about 6,200 feet (fig. 13). The vertical component of hydraulic gradient in this interval is about 0.087 (fig. 6). Multiplying the percentage of silt and clay by 0.00241, the relative resistivity for layer 7 is 0.058, and the weighted (by thickness) average resistivity for layers 6 through 8 is 0.087 (the vertical component of hydraulic gradient for the interval).

The estimates for each layer of the model shown in table 2 are relative. For example, it was estimated that the average resistivity for layer 8 is about 4 times that of layer 7. Or, equivalently, the vertical hydraulic conductivity of layer 8 is about one-fourth that of layer 7.

Table 2. Relative values of aquifer characteristics estimated from geophysical logs and vertical gradients

| Layer | Thickness (feet) | Estimated specific yield | Estimated relative hydraulic conductivity (parallel to beds) | Estimated percent of silt and clay | Average estimated vertical gradient over interval | Estimated relative hydraulic resistivity (normal to beds) |
|---|---|---|---|---|---|---|
| 15 | 45 | 0.09 | 4.7 | 49 | | 0.015 |
| 14 | 56 | .16 | 7.7 | 28 | | .008 |
| 13 | 60 | .13 | 6.7 | 43 | | .013 |
| 12 | 75 | .10 | 5.4 | 59 | 0.012 | .018 |
| 11 | 47 | .18 | 8.9 | 17 | | .005 |
| 10 | 37 | .02 | 1.0 | 73 | | .022 |
| 9 | 42 | .16 | 8.1 | 21 | | .006 |
| 8 | 40 | .04 | 2.0 | 88 | | .212 |
| 7 | 78 | .14 | 7.3 | 24 | .087 | .058 |
| 6 | 92 | .17 | 7.1 | 24 | | .058 |
| 5 | 66 | .18 | 8.2 | 8 | | .036 |
| 4 | 54 | .11 | 5.3 | 50 | | .226 |
| 3 | 82 | .17 | 8.4 | 37 | .13 | .168 |
| 2 | 142 | .18 | 8.9 | 17 | | .077 |
| 1 | 250 | .16 | 8.8 | 34 | | .154 |

### Simulation of Stable Initial Condition

Before simulating the stress of the aquifer test, a stable initial condition was simulated. The initial hydraulic-head distribution was assumed to be the result of flow through the test site, approximated in the model by specified-head boundaries. In the lowermost level, the row of nodes parallel to the strike at the production well and the row of nodes at the far southeast boundary were defined as specified- head boundaries. In the uppermost level of the model, the row of nodes parallel to the strike at the production well and the row of nodes at the far northwest boundary were defined as specified-head boundaries. This distribution of specified-head boundaries in conjunction with the crossbed hydraulic conductivity distribution succeeded in producing steady-state vertical head differences in the model similar to those observed at the Tesuque test site (fig. 14). Flow through the model under steady-state conditions is from southeast to northwest in the plane containing the dip. Water enters the model in the lowermost layer, moves downdip along the layers and up across the layers, and exits the model in the uppermost layer.

To simulate the stable initial condition, the hydrologic properties associated with the cells representing the production well were made the same as those for the rest of the model, and thus did not affect the hydraulic communication between layers. This was done because the initial hydraulic-head data (fig. 6) indicate that the upper zones in the production well were sealed, as described earlier in this report in the section entitled "Hydraulic Communication with Production Well."

### Representation of the Stress of the Aquifer Test

The boundary condition and aquifer characteristics specified for the cells representing the production well were changed to represent the stress of the aquifer test. Because of the plane of symmetry, described earlier in this report in the section entitled "Extent of Modeled Volume," only one-half of the production well was represented in the model, by a column of 1-foot by 2-foot cells totaling 538 feet vertically. The stress to be represented included both the withdrawal of water from the production well and the improved communication between the production well and the beds that were sealed prior to the test.

To simulate this improved communication within the production zone, the crossbed hydraulic conductivity of the column of cells representing the production zone of the production well was increased (to about a million times that used in the simulation of initial conditions). Although such communication probably improved gradually, rather than instantaneously, too few data were available to show the development during the aquifer test.

The model simulated the withdrawal of 320 gallons per minute for 13 days. Due to the increased crossbed hydraulic conductivity, the problem of apportioning these withdrawals among the cells corresponding to the produc-

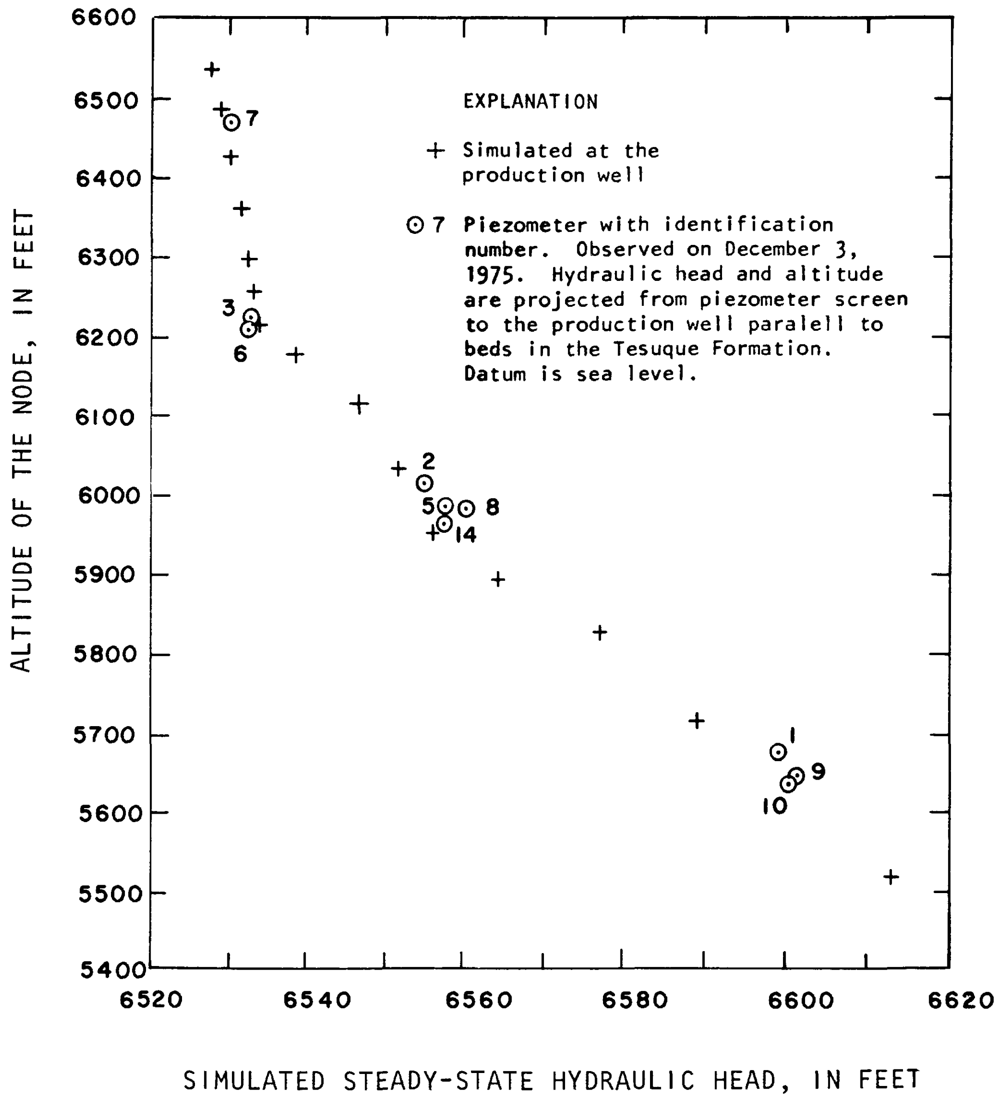


**Figure 14.** Relationship between altitude of nodes and simulated steady-state hydraulic head.

tion well was solved implicitly by the three-dimensional flow equation. During the simulation, the difference in hydraulic head between any two of the cells representing the production well was less than a few tenths of a foot.

The other boundaries of the model were the same for the representation of the aquifer test as for the establishment of initial conditions.

## Calibration

The data used to calibrate the model were those measuring response (change in hydraulic head) to a known hydrologic stress (withdrawal of water). The aquifer characteristics were adjusted so that the response simulated by the model approximated the response observed in the aquifer system.

The calibration of the model is described in three phases according to the aspect of the response being compared. In the first phase, the lack of response in piezometers above and below the production zone produced an estimate of the constant of proportionality for the crossbed hydraulic conductivity. In the second phase, the general trend of the observed declines in hydraulic head produced estimates of the constant of proportionality for the inbed hydraulic conductivity and the specific storage. In the third phase, the departure from the general trend of the observed hydraulic-head declines was attributed to the limited areal extent of the individual beds of the Tesuque aquifer system. The initial estimate of specific yield for unconfined conditions was not varied because for a stress of short duration, like that imposed during the aquifer test, the model response was relatively insensitive to this characteristic.

The first phase of the calibration concentrated on the response in the piezometers above and below the production zone, at altitudes of about 6,450 and 5,650 feet. The only changes in hydraulic heads observed in these piezometers during the test were apparently not associated with the stress of the test. The variation in hydraulic head was about 2 to 3 tenths of a foot. For this phase of the calibration, a model was constructed to include deeper sections of the aquifer system. The lower boundary was more than 400 feet below the level corresponding to the deep piezometers (1, 4, 9, and 10). Any effect of the lower boundary on the simulated response was negligible even in the deep piezometers. Simulations with this model indicated that to limit the simulated decline in hydraulic head at the altitudes of these piezometers (about 6,450 and 5,650 feet) to less than 0.2 foot required the average crossbed resistivity of the model to be 10,000 days per foot or higher. Or equivalently, the harmonic mean of the hydraulic conductivity normal to the beds would be 0.0001 foot per day or lower.

The crossbed hydraulic conductivity estimated from calibration (0.0001 foot per day) was much lower than was estimated in the section "Hydraulic Heads Under Unstressed Conditions" (0.004 foot per day). The difference between these two estimates may result from discontinuity of low - permeability zones. The crossbed hydraulic conductivity estimated from calibration may be representative of the beds at the test site. On a larger scale, the discontinuity of low-permeability zones may improve the crossbed communication. If so, the value estimated from the steady-state gradients is probably more representative of the regional condition.

Because the crossbed hydraulic conductivity obtained by calibration was lower than anticipated, it was possible to reduce the saturated thickness represented in the model to that shown in figure 12. The values of crossbed hydraulic conductivity for each layer are shown in table 3. The harmonic mean (weighted by thickness) of these values is 0.0001 foot per day.

In the second phase of the calibration, the general trends of the decline in hydraulic head in the piezometers at altitudes of about 6,000 and 6,200 feet were approximated. The response in piezometers at an altitude of about 6,000 feet was compared with the response simulated in layer 5. The response in piezometers at an altitude of about 6,200 feet was compared with the response simulated in layer 9. The extent to which the general trends of the declines in hydraulic head were approximated is shown in figures 15 and 16. The simulated response in each layer was sensitive not only to the aquifer characteristics and boundary and initial conditions for the layer, but also to those of the other layers in the model, particularly the layers representing the production zone. Considering the probable errors in apportioning the relative values of aquifer characteristics among the layers in the model, the likelihood that the properties of the beds are not homogeneous over the area of the model, and the representation of each layer as being instantaneously developed with the start of withdrawals, a more precise calibration is not justified.

**Table 3.** Values of hydraulic conductivity determined by calibration of the model

| Level | Hydraulic conductivity in feet per day | |
|---|---|---|
| | Parallel to beds | Normal to beds |
| 15 | 1.41 | 0.00059 |
| 14 | 2.3 | .00103 |
| 13 | 2.0 | .00067 |
| 12 | 1.6 | .00049 |
| 11 | 2.6 | .00169 |
| 10 | .30 | .00040 |
| 9 | 2.4 | .00137 |
| 8 | .59 | .00004 |
| 7 | 2.2 | .00015 |
| 6 | 2.1 | .00015 |
| 5 | 2.4 | .00023 |
| 4 | 1.6 | .00004 |
| 3 | 2.5 | .00005 |
| 2 | 2.7 | .00011 |
| 1 | 2.6 | .00006 |

The specific storage and the constant of proportionality between the hydraulic conductivity parallel to the bedding plane and the relative hydraulic conductivities (table 2) were varied to obtain a close approximation of the observed response. A specific storage of $2 \times 10^{-6}$ per foot was used to simulate the response shown in figures 15 and 16. A lower value might have produced a closer approximation of the observed response. But, as discussed earlier in the report, in the section entitled "Specific Storage," the specific storage for the Tesuque aquifer system was estimated to be no lower than about $2 \times 10^{-6}$ per foot. The response shown in figures 15 and 16 was simulated using an average hydraulic conductivity of 2 feet per day parallel to the beds. The hydraulic conductivity for each layer is shown in table 3.

In the third phase of the calibration, a qualitative explanation is suggested for the divergence from the general trend of the decline in hydraulic head that was observed in the lower piezometers but was not shown by the model with the assumed homogeneity. By representing impermeable boundaries in the lower seven layers, the model simulated a divergence from the general trend similar to that observed (fig. 17). For each of the lower seven layers, the row of cells parallel to the strike about 1,000 feet downdip from the production well and the row of cells parallel to the strike about 2,000 feet updip from the production well were represented as impermeable boundaries. These locations in the model were arbitrary and not intended to imply the existence of geohydrologic barriers at corresponding locations on the test site. However, the

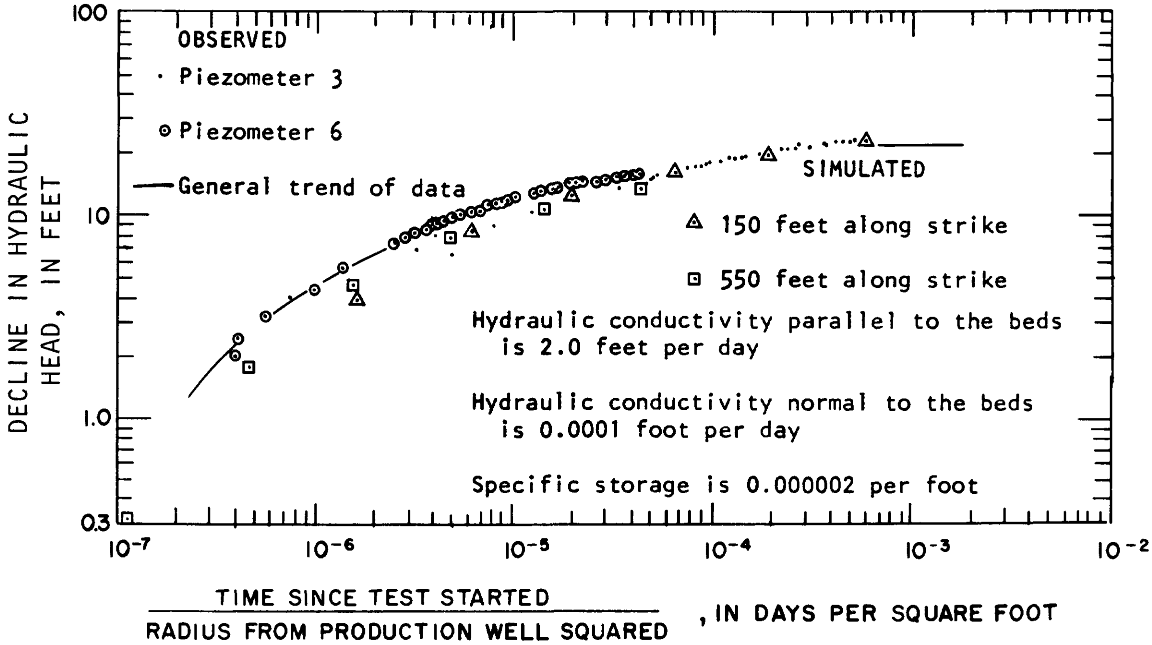


**Figure 15.** Comparison between the simulated decline in hydraulic head in layer 9 of the model and the observed decline in hydraulic head in the piezometers at an altitude of about 6,200 feet.

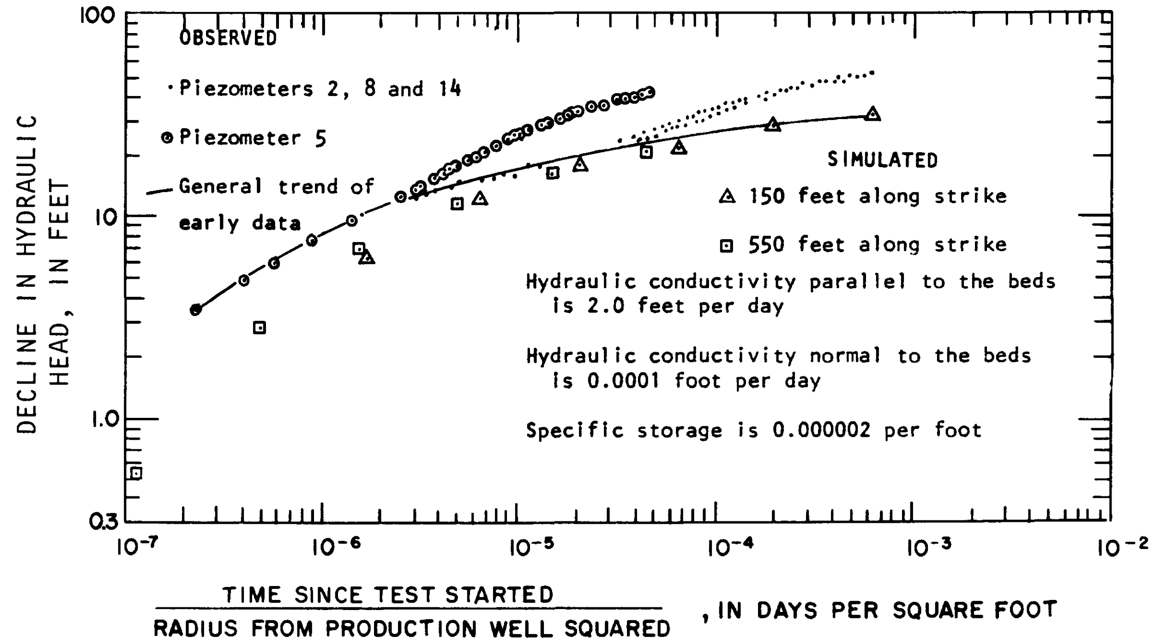


**Figure 16.** Comparison between the simulated decline in hydraulic head in layer 5 of the model and the observed decline in hydraulic head in the piezometers at an altitude of about 6,000 feet.

simulated results imply that by allowing the hydraulic character of the layers to change at reasonably short distances from the production well, the divergence from the general trend can be approximated in the model. Such a lack in continuity of the beds is consistent with the description of the Tesuque aquifer system.

The comparison of observed data with simulated results indicated that a three-dimensional model can simulate the short-term local response of the Tesuque aquifer system. The calibration also provided estimates of the local aquifer characteristics. A close approximation of the observed response was obtained with a specific storage of

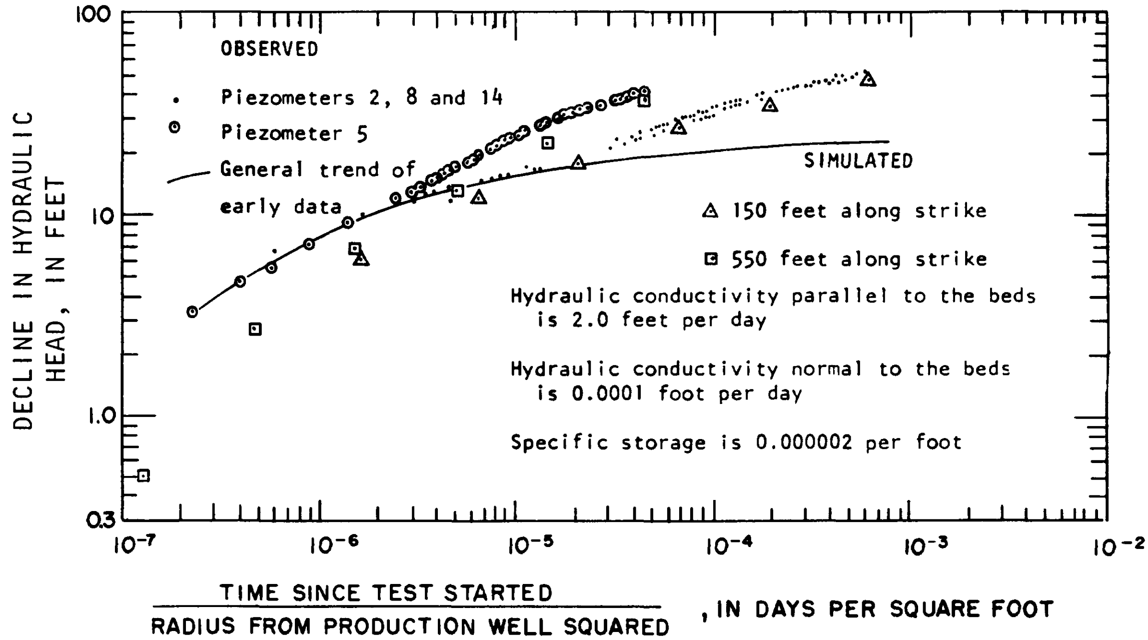


**Figure 17.** Comparison between the simulated decline in hydraulic head in layer 5 of the model (having impermeable boundaries in the lower 7 layers) and the observed decline in hydraulic head in the piezometers at an altitude of about 6,000 feet.

$2 \times 10^{-6}$ per foot and the hydraulic conductivities shown in table 3; the average hydraulic conductivity parallel to the bedding plane was 2 feet per day; the average hydraulic conductivity normal to the bedding plane was 0.0001 foot per day. Specific yield was not varied during the calibration, but values of specific yield averaging about 0.15 (table 2) were used in the model.

## SUMMARY AND CONCLUSIONS

An aquifer test was designed and conducted in the vicinity of an existing production well on Tesuque Pueblo Grant. A three-dimensional digital model of the Tesuque aquifer system near the site was constructed. This model was calibrated using data obtained from the aquifer test.

The results of the study demonstrate that a three-dimensional digital model can approximate the effect of ground-water withdrawals on the Tesuque aquifer system, which consists of strongly anisotropic dipping beds. Analysis of the geohydrology of the test site in combination with model calibration has provided estimates of aquifer characteristics for the group of beds encountered at the test site. The hydraulic conductivity parallel to the beds is about 2 feet per day, the hydraulic conductivity normal to the beds is about 0.0001 foot per day or lower, the specific yield is about 0.15, and the specific storage is about $2 \times 10^{-6}$ per foot.

Extrapolation of aquifer characteristics from a particular site to the whole basin should be done with care. The aquifer test indicates that a boundary is located close to the site in at least one of the producing zones. The deposition of the Tesuque Formation as coalescing alluvial deposits and the multiple faults of the area support the hypothesis that most of the beds terminate or change character within a few miles or less. The discontinuity of the more permeable beds may force water to travel a more tortuous path or to pass through beds of low hydraulic conductivity. Therefore, on the larger scale of a basin model, the effective hydraulic conductivity parallel to the beds is probably less than the average of 2 feet per day determined at the Tesuque site.

The discontinuity of less permeable beds may improve the crossbed communication by providing a tortuous path around rather than through these beds. If so, then on the larger scale of a basin model, the effective hydraulic conductivity normal to the beds may be higher than the average value of 0.0001 foot per day determined from model calibration. The ratio of hydraulic conductivities (normal and parallel to the beds) from model calibration is 0.00005 (0.0001 foot per day divided by 2 feet per day). This value may be representative of the beds at the test site. However, the value of 0.004 estimated from the steady-state ratio of vertical to horizontal components of hydraulic gradients observed at the Tesuque site is probably more representative of the regional condition.

The average specific storage of about $2 \times 10^{-6}$ per foot does not imply that the aquifer is rigid and will not undergo compaction. It may be that the apparent low specific storage is due to the low magnitude of the stress and the short time it was applied. Withdrawals of large volumes of water over extended periods of time may produce nonelastic deformation of the porous medium and resultant subsidence of the land surface. Any program for development of ground-water resources would be enhanced by a monitoring program to measure subsidence.

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**Inch-Pound Unit to Metric Unit Conversion Factors**

In this report values for measurements are given in inch-pound units only. The following table contains factors for converting these units to metric units.

| Multiply inch-pound units | By | To obtain metric units |
|---|---|---|
| foot (ft) | 0.3048 | meter (m) |
| cubic foot ($ft^3$) | 0.02831 | cubic meter ($m^3$) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| inch (in.) | 2.54 | centimeter (cm) |
| mile (mi) | 1.609 | kilometer (km) |