HYDROLOGIC INVESTIGATIONS OF THE SATURATED ZONE IN SOUTH-CENTRAL HUDSPETH COUNTY, TEXAS

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ABSTRACT

Hydrologic investigations are in progress in Trans-Pecos Texas at the proposed site of a low-level radioactive waste repository. The site is approximately 40 mi (65 km) southeast of El Paso in the Hueco Bolson, a fault-bounded desert basin that developed in the late Tertiary. Ground water in the area of the proposed site is found at depths of 478 ft (146 m) and 592 ft (180 m) in bolson silt and sand and Cretaceous limestone, respectively. The unsaturated zone consists of approximately 50 ft (15 m) of alluvial silt, sand, and gravel underlain by 450 ft (137 m) of lacustrine and fluvial clay, silt, and fine sand. High-priority tasks for characterizing the ground-water regime include (1) evaluating ground-water resources in the area, (2) determining ground-water flow paths and velocities, (3) testing hydrologic hypotheses using ground-water flow models, and (4) determining ground-water hydrochemistry. The objective of this report is to evaluate the ground-water resources and to discuss our current understanding of ground-water flow paths and velocities.

Ground-water resources in the vicinity of the site are limited by two key factors: (1) costs of drilling and completing wells and of producing water at depths greater than 400 ft (122 m) and (2) very low productivity of aquifers. Typical transmissivities of aquifers producing from bolson and Cretaceous strata, based on four tests, range from approximately 4.3×10^{-2} ft^2/day (4.0×10^{-3} m^2/day) to 2.9×10^{2} ft^2/day (2.7×10^{1} m^2/day). A composite potentiometric surface has been mapped on the basis of static water levels measured in all available wells. Regional ground-water flow is interpreted from the potentiometric surface to be generally south-southwest toward the Rio Grande.

INTRODUCTION

The Texas Low-Level Radioactive Waste Disposal Authority (TLLRWDA) contracted the Bureau of Economic Geology (BEG) at The University of Texas at Austin in 1986 to conduct investigations of sites possibly suitable for a disposal facility. Six potential sites have been evaluated in West Texas by the

BEG; current efforts focus on one proposed site located approximately 40 mi (65 km) southeast of El Paso and 15.5 mi (25 km) north of the Rio Grande in southern Hudspeth County (fig. 1). The program and status of our hydrologic investigations of the saturated zone are presented in this report. Interpretations of the hydrogeologic setting, hydrologic properties, and ground-water resources are discussed. Evaluation of ground-water resources has involved locating any existing wells, operational or abandoned, at which water levels, discharge rates, and/or water samples could be measured or collected (fig. 1). Characterization of ground-water systems has included the delineation of water-bearing units, measurement of representative transmissivities (this report) and hydrochemistry of the ground water (Fisher and Mullican, 1989), and interpretation of local and regional flow patterns.

HYDROGEOLOGIC SETTING

The proposed site lies within the Hueco Bolson, a large desert basin in the eastern portion of the Basin and Range structural province. Fine-grained lacustrine and fluvial sediments were deposited in the Hueco Bolson over a basement of mostly Cretaceous shallow-marine strata. Hill (1900) was the first to apply the term "bolson," Spanish for "purse," to the intermontane basins of the Trans-Pecos region of Texas and New Mexico. The term bolson is used to describe closed basins with centripetal drainage (Sayre and Livingston, 1945). The Hueco Bolson has been filled with detrital materials washed in from adjacent mountains such as the Franklin, Huecos, Organ, Sacramento, Finlay, Quitman, Malone, and other mountain chains in Mexico. Individual strata within bolsons range in thickness up to 100 ft (30 m) and are typically composed of poorly sorted sediment (Davis and Leggat, 1965). Cretaceous and older rocks are exposed on the Diablo Plateau north of the site, and equivalent strata, strongly deformed by Laramide tectonism, are exposed in isolated outcrops south of the site. Basin and Range extension, which began regionally about 24 mya (Henry and Price, 1985), produced areas of normal faulting, including the northwest-oriented Campo Grande fault trend located about 3.7 mi (6.0 km) southwest of well no. 22, located along the southern boundary of the proposed site.

Regional hydrologic investigations conducted on the Diablo Plateau have indicated a range in transmissivities for Cretaceous units of 3.2 x 10^{-1} ft^2/day (3.0 x 10^{-2} m^2/day) to 6.7 x 10^3 ft^2/day (6.2 x 10^2 m^2/day) (Kreitler and others, 1987). In most of the pumping tests conducted on the Diablo Plateau, fracture flow was clearly a controlling factor on individual wellbore hydraulics.

Kreitler and others (1987) referred to hydrostratigraphic units on the Diablo Plateau as aquifers A and B because no formal unit has been defined outside of the Dell City irrigation district. In the Dell City area, the producing aquifer is named the Bone Spring and Victoria Peak limestone aquifer (Texas Department of Water Resources, 1984). The use of aquifers A and B served to discriminate areas where water was found in Cretaceous limestones and sandstones (aquifer A) from areas where ground water probably was being produced from Permian strata (aquifer B). Several lines of evidence (potentiometric surface, isotopic composition, hydrochemical facies) indicate that ground waters produced from Cretaceous and Permian strata on the Diablo Plateau are, to varying degrees, in hydrologic communication with Cretaceous strata producing ground water under the Hueco Bolson. We herein propose naming the hydrostratigraphic unit previously mapped as aquifers A and B on the Diablo Plateau (Kreitler and others, 1987) and the Cretaceous strata that yields ground water beneath the Hueco Bolson collectively as the Diablo Plateau aquifer.

The Hueco Bolson silt and sand aquifer is locally a highly transmissive unit. Bolson deposits consist of unconsolidated sand, silt, gravel, clay, and caliche. Current water resources for the city of El Paso are produced from thick bolson sand within and adjacent to the city limits. This deposit is a rather local feature, however, and is absent within the study area. Transmissivities in the El Paso area range from 1,335 ft^2/day (124.2 m^2/day) to 37,384 ft^2/day (3,477.6 m^2/day) (Alvarez and Buckner, 1980). Sayre and Livingston (1945) and Peckham (1963) reported that Hueco Bolson deposits range in thickness from a few feet to more than 4,900 ft (1,493 m).

The Rio Grande alluvial aquifer covers the bolson in a narrow band adjacent to the Rio Grande and typically consists of poorly sorted sand, gravel, clay, and silt. The aquifer is typically lower in water quantity and quality than the Hueco Bolson silt and sand aquifer in the El Paso area. Peckham (1963) reported the alluvial deposits as typically being around 200 ft (61 m) thick, thinning to the northwest. Davis and Leggat (1965) stated that the Rio Grande alluvium probably never exceeds 150 ft (45.7 m) in thickness.

In summary, within the study area, three hydrostratigraphic aquifer units have been identified: the Diablo Plateau aquifer, the Hueco Bolson silt and sand aquifer, and the Rio Grande alluvium aquifer. The proposed waste disposal site is underlain by a thick unsaturated section consisting of silty and sandy alluvial gravels from land surface to a depth of about 50 ft (15 m) and lacustrine clay, silt, and sand from depths of about 50 to 450 ft (15 to 137 m).

Climate at the proposed site is subtropical arid (classification of Thornthwaite, 1931, as modified by Larkin and Bomar, 1983) with a mean rainfall of 9.8 in/yr (24.9 cm/yr); minimum and maximum average annual temperatures are 7.2°C and 27.2°C, respectively. Subtropical arid climates are characterized by (1) marked fluctuations of temperature over broad diurnal and annual ranges and (2) low mean precipitation with widely seperated annual extremes (Orton, 1964). Approximately 60 percent of the annual precipitation occurs during afternoon thunderstorms from June to September. Summer storms in this desert region are intense, brief, and localized. Evaporation pan data at the Ysleta station near El Paso averaged 99 inches (2.51 m) per year for the period of 1953-1960; thus, the rate of evaporation was approximately 10 times greater than the rate of precipitation.

PREVIOUS REGIONAL HYDROLOGIC INVESTIGATIONS

No published data on pumping tests from the regional study area exist with which to determine hydrologic characteristics for any of the three aquifers encountered. Limited data exist for the Hueco Bolson silt and sand aquifer and Rio Grande alluvium aquifer in and around the city of El Paso and for Cretaceous strata to the north of the study area on the Diablo Plateau. The following is a sequential review and compilation of a portion of this data.

Slichter (1905), in one of the earliest reports on the regional hydrology of West Texas and El Paso, studied the various hydrologic and geologic implications of a proposed dam to be constructed a few miles upstream from El Paso on the Rio Grande. He compiled data on static water levels, basic water chemical composition, specific yield, and specific capacity for water wells in southern New Mexico and Trans-Pecos Texas. The ranges in specific yield and specific capacity from 18 pumping tests reported are 191 to 1,325 gpm and 5.83 to 88.0 gpm, respectively.

Sayre and Livingston (1945) provided a detailed description of the geology and hydrology of the El Paso area. They cited an average coefficient of permeability of about 200 gallons (gal) per day. They also estimated, based on Slichter's (1905) water level records, that the maximum drawdown from original static water levels (prior to well pumpage) was 45 ft (13.7 m) in the old Mesa well field for the period 1901-1936. They also calculated that in the area the volume of the 45-ft (13.7-m) deep cone of depression was equivalent to 22,000 acre-ft of water. For the period of record, however, 90,000 acre-ft of water had been produced, and, therefore, only about 25 percent of the water produced was from storage and the rest was from recharge.

Smith (1956) reported the results of a study to determine the ground-water resources in the El Paso area. He divided the study area into four subareas: the Hueco Bolson, the City artesian system, the Upper Valley, and the Lower Valley. The average daily pumpage in 1954 from the Hueco Bolson and City artesian system was 38,800,000 gal and from the Upper and Lower Valleys was 143 million gal. The maximum water-level decline was reported to be near Biggs Air Force Base and near El Paso's Mesa field. The maximum amount of decline was 10 ft (3 m), and the cone of influence extended 9 mi (14.5 km) to the north and 6 mi (9.6 km) to the east of the main area of withdrawal.

Leggat (1962), in a study expanding upon the Smith report (1956), stated that ground-water usage increased from 43 million gallons per day (mgd) in 1955 to 62.3 mgd in 1959. Water levels in one of the well fields in the Mesa area had declined 33.9 ft (10.3 m) from 1937 to 1962. Coefficients of transmissibility ranged from 22,000 to 150,000 g/d - ft in bolson deposits and from 34,000 to 155,000 g/d - ft in deposits of the Upper Valley (Leggat, 1962). Coefficients of transmissivity and storage for 22 pumping tests are also reported by Leggat (1962). Myers (1969) listed data from the Leggat (1962) report and assigned well ID numbers still in use by the Texas Water Commission (table 1).

Peckham (1963) reported that in the El Paso area of the Rio Grande drainage basin, bolson deposits are hydrologically connected with Rio Grande alluvial deposits and therefore considered to collectively compose one aquifer. His defined limits of the Rio Grande basin in Hudspeth County, however, are much narrower than the currently mapped Hueco Bolson silt and sand aquifer of this report. Peckham reported well yields in El Paso County from 1,000 to 3,000 gpm, whereas wells in Hudspeth County were typically less than 500 gpm. Reported specific capacities ranged from 3 to 61 gpm per ft of drawdown and averaged about 20 gpm per ft of drawdown.

Davis and Leggat (1965) reported a range of transmissivities from 200,000 gal/d-ft of drawdown for the Mesa subarea of the Hueco Bolson to 22,000 gal/d-ft in the city artesian subarea of El Paso. They calculated that the bolson deposits near El Paso contain at least 9 million acre-ft of theoretically recoverable water in storage.

Myers (1969) reported the results of several pumping tests conducted in El Paso County and one pumping test (48-15-201) in Hudspeth County. A summary of this data is presented in table 1.

The Dell City area, located along the Texas-New Mexico border in northeast Hudspeth County, has clearly the most productive ground-water system in Hudspeth County. Ground water in this area is produced from Permian carbonates, named the Victorio Peak and Bone Spring limestone aquifer. Well yield is almost entirely dependent on the density of intersected fractures and solution cavities. The depth to Victorio Peak and Bone Spring strata in the Dell City area ranges from 5 to 150 ft (1.5 to 45.7 m) (Davis and Leggat, 1965).

The Soil Conservation Service (SCS) used aerial photographs to successfully locate 10 of 11 wells to be used as artificial recharge wells in a flood control project (Logan, 1984). In this project, the SCS was able to project fracture systems visible on the surface into the subsurface so that a maximum number of fractures could be intersected by each recharge well. The minimum requirement for a successful recharge well was that the well have a minimum specific capacity of 2,000 gal/m-ft of drawdown (267.4 ft^2/m or 24.8 m^2/m).

Young (1976) conducted a water-resource survey in Hudspeth County and discussed ground-water quality and resources from the Rio Grande alluvial aquifer in the Fort Hancock area. Typical well yields ranged from 150 gpm in the Fort Hancock area to 530 gpm for a well southwest of Fabens (Young, 1976). After 15 years of production, maximum drawdown of water levels in the area was 31 ft (9.4 m).

Kreitler and others (1987) reported results of a series of seven pumping tests conducted on the Diablo Plateau. Regional ground-water flow on the Diablo Plateau is predominantly from the southwest to the northeast. The hydrologic divide separating ground-water flow in the Hueco Bolson from that in the Diablo Plateau occurs within the study area and is located along the southwest edge of the plateau (fig. 2). A cross-sectional view of this hydrologic divide is also illustrated in figure 3. Flow velocities in the Diablo Plateau aquifer reported by Kreitler and others (1987) are greater than those in the Diablo Plateau aquifer where it is overlain by the Hueco Bolson (this report). Controlling factors for these greater flow velocities include very shallow depth to bedrock (often exposed at the surface) and extensive fracture systems that trend southeast-northwest over large areas of the plateau (for example, the Babb Flexure; see Kreitler and others, 1987). Modern tritium was found to be occurring throughout the entire Diablo Plateau study area. Chloride profiles indicate that recharge to the water table occurs during flash floods in fracture-controlled arroyos where bedrock is either very shallow (less than 30 to 40 ft [9.1 to 12.2 m]) or commonly exposed at the surface.

Kreitler and others (1987) found transmissivities on the Diablo Plateau to range from 3.2×10^{-1} ft^2/d (3.0×10^{-2} m^2/d) to 6.9×10^{1} ft^2/d (6.4×10^{0} m^2/d). The mean transmissivity calculated from 22 separate interpretations for the seven wells tested was 2.1×10^{1} ft^2/d (1.9×10^{0} m^2/d), with a rather large standard deviation of 2.2×10^{1} ft^2/d (2.1×10^{0} m^2/d). In all seven tests, fractures were determined to be either directly or indirectly controlling production of the wells. In three of the wells, the discharge rate over extended periods (48 hr and longer) was insufficient to stress the aquifer, and no drawdown was recorded.

METHODS

Because of limited data and the nonuniform distribution of hydraulic head measurements, a composite potentiometric surface was constructed for the entire area (fig. 2). Figure 3 depicts the hydrogeologic cross-section delineated in figure 2. In the southern part of the study area, water-level data are mostly from the Rio Grande alluvium aquifer. In the western and central areas, wells from the Hueco Bolson silt and sand aquifer were used, and in the northeastern area, only water levels from the Diablo Plateau aquifer, both on the Diablo Plateau and near the site, were available. The degree of hydrologic communication between the Rio Grande alluvium, Hueco Bolson silt and sand, and the underlying and adjacent Cretaceous and older strata is poorly known, and the hydraulic-head gradient between the different units may not accurately represent the actual flow patterns.

For monitoring water level fluctuations, water levels in wells 22, 98, 99, and 126 were recorded at hourly intervals using a pressure transducer that was connected to a computerized datalogger (fig. 4). Pumping tests were performed at wells 98 and 99 in the Bolson silt and sand aquifer and at wells 22 and 91 in the Diablo Plateau aquifer (22 and 91). Production rates varied from 22.9 ft^3/day (0.027 m^3/day) to 33.9 ft^3/day (0.040 m^3/day)for wells 22 and 99 and from 1,155 ft^3/day (32.7 m^3/day) to 6,353 ft^3/day (179.9 m^3/day) for wells 98 and 91, respectively. Water levels were recorded in the pumped well using a pressure transducer and computerized datalogger. Pumping test results were analyzed using standard techniques including type curve matching using the Theis curve (Theis, 1935), Jacob's semilogarithmic approximation method for drawdown data (Cooper and Jacob, 1946), and Theis' semilogarithmic approximation method for recovery data (Kruseman and De Ridder, 1983).

The duration of pumping tests of the different wells generally was brief (less than 30 min to 1 day), and drawdown and recovery curves were influenced by wellbore storage and skin effects. Recovery data from the different well tests were further analyzed using type curves by Agarwal and others (1970) with specific values of dimensionless wellbore storage (C_D) and skin effect (S), which are not taken into account in the standard pumping test analyses mentioned above. Hydraulic conductivity was calculated using the following equation by matching type curves (Agarwal and others, 1970) to data plots of water-level rise during drawdown or recovery, which is expressed as the logarithm of pressure change versus the logarithm of time during the drawdown or recovery period:

$$K = \frac{0.0689\ Q\ B\ \mu}{h} \left(\frac{P_D}{\Delta P} \right),$$

where K is hydraulic conductivity (ft/d), Q is pumping rate(ft^3/d), h is test zone interval (ft), B is a dimensionless formation volume factor (assumed to be 1.0), μ is the viscosity (cp), and P_D and ΔP are dimensionless pressure and observed pressure change (psi) of the match point, respectively; 0.0689 is a unit conversion factor.

Results of pumping test analyses using the different methods are summarized in table 2. Note that hydraulic conductivity values calculated from Agarwal's method are consistently higher by about one order of magnitude than those obtained using the standard methods. The latter techniques yielded reasonably consistant values of hydraulic conductivity. Typically, only the late part of the brief data record was fitted with the type curves, resulting in uncertainty of the match point location. Selection of the type curve by Agarwal and others (1970) for a specific dimensionless wellbore storage (C_D) was assisted by estimating C_D from well and formation specification. Dimensionless wellbore storage (Van Everdingen and Hurst, 1949) is given by

$$C_D = \frac{C\ E_w}{2\ \pi\ n\ h\ r^2},$$

where E_w is bulk modulus of elasticity of water (psi), n is porosity, r is well radius (ft), and C is the unit storage factor, given by

$$C = \frac{Q\ B\ \Delta t}{\Delta P},$$

where Δt and ΔP are time and pressure during the early part of the curve dominated by wellbore storage (Ramey, 1970). Although accurate estimates of C_D are limited mostly by uncertainty in formation porosity (assumed to be 0.25 for all wells), they were used to select the appropriate type curve for data fitting.

Analysis of pumping test data is ongoing; it is not clear if the discrepancy in calculated hydraulic conductivities using type curves by Agarwal and others (1970) and those of standard methods can be attributed simply to wellbore storage and skin effects that are not taken into account by the other method.

RESULTS

Well no. 22 pumping test

An aquifer test was conducted on October 5, 1988, at well no. 22, located on the northern boundary of the candidate site (fig. 1) and completed in the saturated zone in Lower Cretaceous limestones of the Diablo Plateau aquifer. The construction of this well (fig. 5) includes 8-in (20.3-cm) steel casing cemented from a depth of 480 ft (146 m) to the surface with 6-in (15.2-cm) stainless steel production screen (slot size 0.020-inch) installed from 555 ft (169 m) to 615 ft (187 m). The production screen is attached to a 6-in (15.2 cm) I.D. steel, 80 ft (24 m) riser pipe serving as a screen hanger. Original total depth of the well was 875 ft (267 m). A plug is currently installed at a depth of 615 ft (187 m).

Before and after the pumping test, a pressure transducer attached to a computerized data logger was installed in the well to determine the static water level and water level fluctuation patterns (fig. 4a). Water-level fluctuations in this well are semidiurnal and have a maximum range of approximately 1.0 ft. Static water level at the start of the pumping test was 592 ft (180.4 m) below land surface (3,644 ft [1,111 m] above sea level). The test began at 10:29:30 hr on October 5 by pumping the well at an initial rate of 28 to 30 gal/hr using a Model 1800-3 Bennett Pump. At 226 min into the drawdown phase, a surge of mud temporarily clogged up the pump, decreasing flow rate and allowing partial recovery of the water level. Figure 6 illustrates water-level response during this pumping test.

Drawdown data from this pumping test was analyzed using the Jacob semilogarithmic approximation method, which assumes a constant discharge (fig. 7). Recovery data were analyzed using the Theis recovery semilogarithmic approximation method (fig. 8). Type curve matching using Agarwal and Theis type curves are illustrated in figures 9 and 10, respectively. Estimated dimensionless wellbore storage coefficient for well no. 22 is $C_D = 10^{5.5}$; skin effect was not apparent (s=0) and the data were fitted with the type curve for $C_D=10^5$ and S=0 (fig. 9). For the Theis method, only drawdown data after 40 min into the test were matched to the Theis curve (fig. 10). Calculated transmissivities and permeabilities for this well producing from the Diablo Plateau aquifer ranges from 4.5×10^{-1} ft^2/d (4.2×10^{-2} m^2/d) to 6.0×10^0 ft^2/d (5.6×10^{-1} m^2/d) and from 6.9×10^{-2} ft/d (6.4×10^{-3} m/d), respectively (table 2). Transmissivity and permeability data for well no. 22 for the various methods of analysis is given in table 2.

Well no. 99 pumping test

The second aquifer test conducted as part of these investigations was performed on well no. 99, located just below the breached Cavette Lake Dam on the Alamo Arroyo, west of the primary study area (fig. 1). The test was conducted during November 9-12, 1988, in the Hueco Bolson silt and sand aquifer. The original well construction for this well is unknown. The well currently has 6 inch (15.2 cm) I. D. surface casing to an unknown depth (believed to be less than 40 ft (12.2 m) based on conversation with current owner) and a measured total depth of 230.54 ft (70.3 m) and a static water level prior to pumping of 140 ft (42.7 m).

Prior to and following the pumping test a pressure transducer, set at 202.76 ft (61.8 m), and connected to a computerized data logger, was used to monitor water levels. Static water level fluctuations monitored in this well following the pumping test (fig. 4c) are semidiurnal and have a maximum range of almost 2.5 ft (0.76 m) from 61 to 63.5 ft (18.59 to 19.35 m) of water column above the pressure transducer, 140 ft (42.7 m) below land surface and 3,705 ft (1,129 m) above sea level. The test was started at 10:55:15 hr on November 9 by pumping the well at basically a constant discharge rate of

45 gph (144.4 ft^3/d; 4.1 m^3/d) using a Model 1800-3 Bennett Pump. The drawdown phase of this pumping test was terminated at 12:50:30 hr, 115.25 minutes after the start of the test. The subsequent recovery phase of the test was monitored until 6:51:03 hr on November 12, at which time the static water level had recovered to 62.18 ft (18.9 m) above the pressure transducer, or 99.1 percent of original static water level. Figure 11 illustrates the water-level response throughout the performance of the pumping test.

The results of analysis of transmissivity and permeability for this pumping test are given in table 2. Match points from plots of field data and the Agarwal and Theis type curves are shown in figures 12 and 13. Jacob drawdown and Theis recovery semilogarithmic approximation methods are illustrated in figures 14 and 15, respectively. In this pumping test, basically all of the drawdown was from well bore storage. Thus, no match was possible using the Theis type curves. Recovery data were fitted with Agarwal's type curve for dimensionless storage $C_D=10^{-5}$ and skin effect S=10 (fig 12). Estimated C_D value was $10^{-5.4}$. The positive skin effect of S=10 indicates either damaged wellbore conditions that restricted inflow of formation water into the well, or partial penetration of the well in only part of the aquifer. Calculated transmissivities and permeabilities for this well producing from the Hueco Bolson silt and sand aquifer range from 4.3×10^{-2} ft^2/d (4.0×10^{-3} m^2/d) to 7.1×10^{0} ft^2/d (6.6×10^{-1} m^2/d) and from 2.3×10^{-3} ft/d (2.1×10^{-4} m/d) to 3.6×10^{-1} ft/d (3.4×10^{-2} m/d), respectively.

Well no. 91 pumping test

Three aquifer tests were conducted on April 26 and April 28, 1989, at well no. 91, located immediately west of Campo Grande Mountain (fig. 1) and completed in Lower Cretaceous strata of the Diablo Plateau aquifer. This well is located south of the proposed site in an area where Lower Cretaceous strata crop out within the Campo Grande fault trend. The original construction of this well is unknown. Currently the well has 8-inch (20.3-cm) I. D. surface casing to an unknown depth. This well was originally drilled as on oil test by Haymon Krupp Oil and Land Co. and named the #1 Thaxton well. The original well depth was 6,402 ft (1,951.3 m), but it now is plugged back to approximately 420 ft

(128 m). Static water level is 317.25 ft (96.7 m) below land surface (3,727.8 ft (1,136 m) above sea level). According to Albritton and Smith (1965), this well was drilled originally to test rocks of Paleozoic age but crossed thrust faults and never reached strata older than the Permian. According to lithology logs from the well, the producing interval in this well is is brown to dark gray, fine-grained Cretaceous limestone.

During the pumping test, water-level fluctuations were monitored using a pressure transducer connected to a computerized data logger. Water-level fluctuations for the test conducted on April 28 at a discharge rate of 33 gpm (6,353 ft^3/d; 179.9 m^3/d) are illustrated in figure 16. Water was pumped by a 10 horsepower (HP) submersible pump powered by a portable 460V, three-phase generator. Due to electrical problems, the tests were conducted in several segments, the first on April 26 and the rest on April 28. Static water level at the start of the test on April 26 was 317.25 ft (96.7 m) below land surface with a water column of 94.73 ft (28.87 m) above the pressure transducer. This test began at 16:20:20 hr with an unstable discharge rate that stabilized at 16:44:20 hr at 10 gpm (1925 ft^3/d; 54.5 m^3/d). At 17:08:20 hr, 40 min after the start of the test, the discharge rate was increased to 12 gpm (2310 ft^3/d; 65.4 m^3/d). At 17:17:20, 17:20:20, and 17:28:20 hr, the pump automatically shut off due to electrical problems after a drawdown of 41.07 ft (12.52 m) was reached. The recovery phase was started immediately after the third pump shutdown. The recovery phase was terminated at 17:55:50 hr when the water column above the pressure transducer equaled 95.36 ft (29.1 m), equivalent to 100.6 percent of the original water column.

After repairs had been completed on surface equipment, the well was again tested at two discharge rates, 33 gpm (6,353 ft^3/d; 179.9 m^3/d) and 12 gpm (2,310 ft^3; 65.4 m^3/d). The test using a discharge rate of 33 gpm (6,353 ft^3/d;179.9 m^3/d) was started at 12:27:19 hr with an original water column of 94.31 ft (28.7 m). By 12:38:06 hr, 10.76 min after the test was initiated, the water column was drawn down to the transducer. The recovery phase was started at 12:39:06 hr and monitored until 13:10:26 hr when the water column above the pressure transducer registered 94.9 ft (28.9 m), 100.6 percent of the original water column. The test was then repeated at a discharge rate of 12 gpm (2,310 ft^3; 65.4 m^3)

starting at 13:17:08 hr. Once the maximum drawdown for this discharge rate had been achieved, production of the well was continued from 13:24:08 until 16:16:01 hr so that a complete set of water samples could be collected for chemical and isotopic analysis. The recovery phase of this last test was started at 16:16:01 hr and terminated at 16:25:01 when the water column above the transducer had recovered to a height of 92.11 ft (28.1 m), 97.3 percent of the original height.

The results of pumping test analyses presented in table 2 are for the test conducted at a discharge rate of 33 gpm (6,353 ft^3/d; 179.9 m^3/d). Agarwal and Theis type curve matches and Jacob drawdown and Theis recovery semilogarithmic approximation methods are illustrated in figures 17 to 20. Recovery data were fitted with Agarwal's type curve for $C_D=10^{-4}$ and S=20 (fig. 17). Estimated C_D value was $10^{-4.4}$. The large positive skin effect suggests partial penetration of the aquifer or damaged wellbore conditions. Distinct breaks in both the drawdown and recovery curve (fig. 16) suggest changes in wellbore storage about 390 ft below land surface. Calculated transmissivities and permeabilities at this well were the highest of any of the four wells tested. The estimates range from 5.9×10^0 ft^2/d (5.5×10^{-1} m^2/d) to 2.9×10^2 ft^2/d (2.7×10^1 m^2/d) and from 1.2×10^{-2} ft/d (1.1×10^{-3} m/d) to 1.9×10^0 ft/d (1.8×10^{-1} m/d), respectively.

Well no. 98 pumping test

Field reconnaissance of well no. 98, located immediately north of the Camp Rice Reservoir no. 1, producing from the Hueco Bolson silt and sand aquifer, indicated that significant workover of the well would be required before an aquifer test could be performed. The initial inspection indicated that the well had 8-inch (20.3-cm) steel surface casing down to a depth of approximately 200 ft (70 m), a static water level of 200 ft (70 m), and an abandoned submersible pump at an unknown depth. Once the submersible pump was removed, the well was reentered with a 7-7/8 inch diameter (20.0-cm) drill bit so that the well could be cleaned out and deepened. At a depth of approximately 245 ft (74.7 m) a 20-ft (6.1-m), 5-inch (12.7-cm) diameter brass production screen was encountered and removed from the well. The well then was deepened to 300 ft (91.4 m) and a 6-inch (15.2-cm) I. D., slotted (0.020 slot size) PVC screen was installed from 200 to 300 ft (70.0 to 91.4 m). The screen was lowered into place with a 200 ft (70 m) string of 6-inch (15.2-cm) riser pipe (now at the surface). A 2 HP submersible pump was then installed to a depth of 295 ft (89.9 m) and was powered by a portable 460V, three-phase generator. A complete well completion schematic for well no. 98 is illustrated in figure 21.

A series of six aquifer tests were conducted; five during May 10 to May 12, 1989, and one during May 30 to May 31, 1989. While deepening this well, a high-viscosity drilling mud was required to keep the wellbore from caving due to the very loose, unconsolidated nature of the bolson materials in this area. This required extensive well development to remove the gel-based drilling muds from the formation so that reasonably representative aquifer characteristics could be determined. Only the results from the pumping test conducted on May 30-31 are presented here. Additional well development and pumping tests are scheduled for the fall of 1989 to determine whether all residual drilling mud (which inhibits ground-water inflow) has been removed.

Since the well no. 98 recompletion, the static water level fluctuations have been monitored continuously using a pressure transducer connected to a computerized data logger. Water-level fluctuations during May 18 to May 30, 1989, are illustrated in figure 4b. Water-level fluctuations in this well are semidiurnal, as has been found wherever wells in the region are equipped with continuous water-level recorders. The maximum recorded range of fluctuation has been approximately 3.5 ft (1.1 m), from 85 to 88.5 ft (25.9 -o 26.9 m) of water column above the pressure transducer. Static water level in the well prior to the start of the pumping test was measured at 204.18 ft (62.23 m) below land surface; the water column above the transducer was 86.46 ft (26.3 m). This starting water level is 4.18 ft (1.27 m) below the mean static water level for this well due to pretest pumping to calibrate discharge rates. Static water level prior to any pumping was 200 ft (61 m) below land surface, 3,544 ft (1,080 m) above sea level.

The drawdown phase was started at 22:24:10 hr and stopped at 23:26:16 hr after the water level reached 0.93 ft (0.28 m), the drawdown phase being 62.1 min total duration. The discharge rate throughout the drawdown phase was maintained at 6 gpm (1,155 ft^3/d; 32.7 m^3/d). The recovery phase started immediately after pumping was terminated. The recovery phase of the pumping test was terminated at 03:04:16 hr when the water column above the transducer stabilized at 90.67 ft (27.6 m).

Water-level fluctuations for the complete aquifer test are shown in figure 22. Agarwal and Theis type curve matches and Jacob drawdown and Theis recovery semilogarithmic approximation methods are illustrated in figures 23 to 26. Recovery data are fitted with the Agarwal type curve for $C_D=10^{-4}$ and S=20 (fig. 23). Estimated C_D value was $10^{-4.2}$. The large positive skin effect suggests partial penetration of the aquifer, damaged wellbore, or retardation to inflow by drilling mud. The drawdown data were fitted with the Theis curve for an elapsed time greater than 20 min (fig. 24). Calculated transmissivities and permeabilities for this well producing from the Hueco Bolson silt and sand aquifer range from 1.5×10^{0} ft^2/d (1.4×10^{-1} m^2/d) to 5.3×10^{1} ft^2/d (4.9×10^{0} m^2/d) and from 1.2×10^{-2} ft/d (1.1×10^{-3} m/d) to 1.9×10^{0} ft/d (1.8×10^{-1} m/d), respectively (table 2).

HYDROLOGIC CHARACTERIZATION

Ground-water Flow Patterns

Regional ground-water flow in the area is inferred from a potentiometric surface map constructed from static water-level measurements from the Diablo Plateau, Hueco Bolson silts and sands, and Rio Grande alluvium aquifers in the study area (fig. 2). Figure 3 depicts the general geometry of the different hydrostratigraphic units from the Diablo Plateau to the Rio Grande. Cretaceous strata crop out locally near the northwest-oriented Campo Grande fault trend. Along this fault trend Cretaceous strata are displaced against bolson deposits southwest of the fault. The southwestern edge of the Diablo Plateau shows a flexure of Cretaceous strata that dip beneath bolson deposits in the central part of the area.

We initially assumed that the three hydrostratigraphic units are hydrologically well connected. The composite potentiometric surface (fig. 2) shows a regional hydraulic gradient from the Diablo Plateau toward the Rio Grande, representing regional recharge and discharge areas, respectively. However, water-level elevations in two wells, located at the Cretaceous outcrop near the Campo Grande fault trend (wells 116 and 91), are 3,714 ft (1,132 m) and 3,727.8 ft (1,136 m), respectively, which are higher than those measured in Cretaceous well no. 22 (3,644 ft; 1,110 m), and bolson well no. 126 (3,702 ft; 1,128 m), located near the site. This suggests that, in addition to the regional recharge zone on the Diablo Plateau, the Cretaceous outcrops near the Campo Grande fault trend may act as local recharge areas if they are continuous with the regional aquifers. Differences in hydraulic head may also be the result of a deep-seated source of water greater than of local meteoric recharge.

The apparently low hydraulic head near the proposed site creates a relatively steep southwest gradient between the Diablo Plateau and the proposed site in the central part, and a relatively low, northeast gradient from the local Cretaceous outcrop along the Campo Grande fault trend toward the site (figs. 2 and 3). The water level in the bolson well no. 99 (3,705 ft; 1,129 m), located farther to the west, is slightly higher than that in bolson well no. 126 (3,702 ft; 1,127 m), located near the site (fig. 2), suggesting that there is locally a similar northeast gradient in the overlying bolson deposits. However, uncertainty in exact topographic elevation of well no. 99 allows a range of water-level elevations in this well, and the inferred northeastward gradient should be confirmed with more accurate survey data in the future.

Hydrologic Properties

Both the bolson and Cretaceous aquifers show semidiurnal variations, indicating water-level responses associated with barometric pressure variations. Semidiurnal water-level variations are typical indications of confined and semiconfined aquifers.

Recovery tests in two wells yielded relatively low mean transmissivities of 2.5×10^{0} ft^2/d (2.3×10^{-1} m^2/d) in the Hueco Bolson silt and sand aquifer well no. 99 and 1.9×10^{0} ft^2/d (1.8×10^{-1} m^2/day) in Diablo Plateau aquifer well no. 22. Somewhat higher transmissivities were recorded in the Hueco Bolson silt and sand well no. 98 (1.5×10^1 ft^2/d; m^2/d), and even higher values came from Diablo Plateau aquifer well no. 91 (7.8×10^1 ft^2/d; 7.3×10^0 m^2/d). Another pumping test was performed in bolson well no. 126, which was pumped at the same maximum rate of 144.4 ft^3/d (4.08 m^3/day) as that in well no. 99. Water levels in no. 126, however, showed no noticeable response, suggesting that the transmissivity of bolson deposits in this well is significantly higher than that obtained from wells 99 and 22. In wells 22 and 99, the water level declined approximately linearly with time, indicating that most of the produced discharge was derived from well-bore storage. Recovery was relatively slow and in well 99 took more than 3 days to reach the pre-pumping water level, indicating low formation permeability. Additional pumping tests are planned for this well at a higher discharge rate to attempt to stress the well enough to result in significant drawdown.

WATER RESOURCES - HUDSPETH COUNTY

The Texas Water Commission (TWC) and the Texas Department of Water Resources (TDWR) have divided Hudspeth County into three major aquifer subregions and two minor aquifer subregions with regard to ground-water resources (figs. 27 and 28) (TDWR, 1984). The major aquifers include Rio Grande alluvial deposits, Red Light Bolson deposits, and Salt Basin alluvial deposits. The two minor aquifer subregions include the Bone Springs and Victoria Peak limestone aquifers of the Dell City Irrigation District and a local area of Capitan Limestone along the Hudspeth-Culberson county border (TDWR, 1984). Due to the economic importance of the Rio Grande surface water and adjacent alluvial ground water for agricultural purposes, previous studies by the TDWR and TWC have either been selectively or exclusively focused on this hydrologic system (Leggat, 1962; Peckham, 1963; Davis and Leggat, 1965; Alvarez and Buckner, 1980).

Within a 10-mi radius of the proposed site, however, TDWR (1984) did not map a major or minor aquifer system. With rare exceptions, previous hydrologic investigations focused on westernmost Texas have failed to identify the existence of any ground-water resources within the Hueco Bolson of Hudspeth

County. Smith (1956) did not locate any water wells in the Hueco Bolson of Hudspeth County (this area includes the 10-mi radius from the proposed site previously described).

Leggat (1962) identified four water wells within the area examined by Smith (1956) and described them as having small to moderate quantities of water that is generally too highly mineralized for municipal use. Well U-8 (Leggat, 1962) is the most promising water supply well with a reported discharge rate of 50 gpm and total dissolved solids of 2,160 mg/L (Leggat, 1962). This well was probably used by the Soil Conservation Service during the construction of the Alamo Arroyo Reservoir no. 3 flood control dam and abandoned after completion of the structure. Davis and Leggat (1965, their Plate U1) indicated six water wells in the Hueco Bolson of Hudspeth County, four of which are within 10 mi of the proposed site. Only one sentence of text, however, was dedicated to any discussion of the area; it simply stated that the wells probably produce from Cretaceous Cox sandstone.

Gates and Stanley (1976) reported that the discovery of significant ground-water resources from Cretaceous strata was unlikely. Their reasons include poor water quality due to slow water circulation due to low permeabilities and the presence of soluble materials within the strata.

Within a 10-mi radius of the proposed site, 16 water wells and 1 spring producing from saturated sections within Hueco Bolson silts and sands and Cretaceous limestones and sandstones have been located, tested, and sampled as part of this investigation. Table 3 gives a complete listing of these active and inactive water wells.

The majority of water usage within the regional hydrologic study area (including areas outside the 10-mi radius, fig. 1) involves extensive irrigation for agricultural purposes along the edge of the Rio Grande. Both diverted river water and ground water have been used for this purpose. Surface water from the Rio Grande was first appropriated for irrigation in 1918 (Young, 1981). Since then, various treaties and contracts have served to distribute waters from the Rio Grande for irrigation. The current agreement, the Rio Grande Federal Irrigation Project, failed to appropriate any primary water rights from the Rio Grande to the Fort Hancock District. Fort Hancock does, however, have secondary rights to return flow and surplus waters (Young, 1976).

Due to severe drought conditions in the Rio Grande drainage basin from 1951 to 1957, the amount of water available for irrigation within what has been referred to as the Hudspeth Valley (the Rio Grande Valley from the El Paso-Hudspeth County line to where the Guayuca Arroyo enters the Rio Grande near the site of Old Fort Quitman) dropped from an average 354,000 acre-ft per annum (1941-1950) to 44,000 acre-ft per annum (1951-1957) (Young, 1981). This reduction in available water for irrigation resulted in the drilling of 148 irrigation wells in 1954 to supplement the reduction of available river water due to the drought. During 1954, 27,000 acre-ft of ground water was produced for the irrigation of approximately 12,000 acres. High salinity content and low capacity resulted in the abandonment of 50 of these wells by 1955 (Lyerly, 1957).

Using data from Alvarez and Buckner (1980), Young (1981) calculated that for the five Hudspeth Valley quadrangles (PD 48-33, PD 48-41, PD 48-42, PD 48-50, and PD 48-51) adjacent to the Rio Grande, salt content of waters used to irrigate in 1955 ranged from 4.14 to 7.55 tons per acre-ft. These values indicate very high sodium hazard and fall below the requirements for extremely low quality irrigation waters. Davis and Leggat (1965) reported that in 56 wells tested in Hudspeth County the salt content averaged 5.34 tons per acre-ft.

SUMMARY AND DISCUSSION

The hydrologic controls on the inferred potentiometric low near the proposed site are incompletely known. A potentiometric low is typically an area of ground-water discharge or cross-formational flow. Here the water table is greater than 500 ft (152 m) below land surface (fig. 2), and seeps and springs do not exist. While no. 22 was being drilled, observations suggested separation between the hydraulic heads in Cretaceous strata and the overlying bolson. While the bolson section from 500 ft (152 m) to 590 ft (180 m) was being cored, the annular water level appeared to remain constant at approximately 500 ft (152 m) below land surface, similar to the water level measured in well no. 126. Once Cretaceous strata were penetrated, however, water levels fell for several days, finally reaching a constant level of

592 ft (180.4 m) below land surface. The apparent decline in water level suggests that water levels in Cretaceous rocks are as much as 100 ft (30 m) below those in the bolson within well no. 22. This suggests that relatively low water levels in the bolson may be due to cross-formational flow into the underlying Cretaceous rocks where they are hydrologically connected. However, the potentiometric low within the Cretaceous is difficult to interpret on the basis of available information and indicates a much more complex hydrologic regime.

Ground-water flow velocity is computed on the basis of regional head gradients determined from the potentiometric surface, transmissivities of the pumping tests, and porosities determined from compensated neutron and lithodensity geophysical logs of the pumping-test interval. Using a relatively high hydraulic-head gradient of 0.0026 measured between the site and the Diablo Plateau and permeability and porosity values of 0.029 ft/d (0.009 m/d) and 4.6 percent, respectively, we estimate ground-water flow velocity to be 0.0016 ft/d (0.0005 m/d). Variable hydraulic-head gradients in the area and uncertainty in hydraulic conductivity will strongly influence the accuracy of this flow velocity estimate. Furthermore, it is not known if fractures in the Cretaceous strata underlying the bolson strata control regional permeability as they do on the Diablo Plateau where Cretaceous strata crop out.

Within the hydrologic study area, ground water is used to meet ranching, irrigation, and municipal needs. Ground-water requirements for ranching are met by wells in the typically low-transmissivity formations that yield fresh to slightly saline waters. Windmills, pump jacks, and submersible pumps are used to produce water in isolated areas of the Hueco Bolson and Diablo Plateau. Wells are usually separated by several miles, and pipelines are often used to distribute the water to various tanks to water livestock. Dirt tanks have also been constructed by some of the ranchers across minor drainages to catch and hold precipitation runoff (fig. 29). The seasonal evaporation rate (relatively high in summer, low in winter) and lithology of the lining material (sand, silt, or clay) dictate the duration that surface water is available for livestock.

Irrigation requirements that are not satisfied by the Rio Grande are met exclusively from moderate-to-high-discharge water wells that yield high-salinity water producing from Rio Grande alluvial deposits. Through time, due to the circulation of irrigation waters back to the aquifer, the quality of Rio Grande alluvial ground waters has declined almost to the point of being unsuitable for even the most salt resistant crops (such as cotton).

Young (1976) reported that the Fort Hancock Water Control and Improvement District, established in 1952, served 154 customers in the community in 1975. Recorded average annual water usage by the Fort Hancock municipality ranged from 6.5 million gal in 1965 to 10,530,460 gal in 1970 (Young, 1976). Records indicate that as of 1986, 195 customers were served and the water usage for the year was 16,100,000 gal. Fort Hancock is currently using well #108 (TWC # 48-42-404) as the municipal supply well (table 1, fig. 1). This well probably is producing from a transition zone between the Rio Grande alluvial deposits and the Hueco Bolson deposits. Although water from this well has better water quality than water from wells previously used (48-42-702 and 48-42-708), it still fails to meet drinking water standards set by the Texas Department of Health for maximum acceptable levels of sulfate (300 mg/L recommended; 469 mg/L measured May 1, 1989) and total dissolved solids (1,000 mg/L recommended; 1,511 mg/L measured May 1, 1989). Young (1976) concluded that with rare exception, the quality of ground water in the Fort Hancock area is poor and would require treatment to remove dissolved inorganic solids. He also states that ground water from Rio Grande alluvial deposits is probably contaminated by recharging irrigation waters containing organic chemicals such as pesticides, herbicides, and fertilizers and also would require treatment for drinking water.

Current and potential water resources in the area of the proposed site are minimal. The highest sustainable discharge rate for any well tested during this study was equal to 12 gpm (well no. 91). All well waters sampled during this study exceed maximum acceptable concentration levels for one or more of the following: total dissolved solids, sulfates, chlorides, or nitrates. Due to the heterogeneity of the Hueco Bolson strata and the limited number of wells, it is unlikely that a new significant water resource of acceptable water quality will be identified from bolson strata within the regional study area of the proposed site.

The potential for new water resources from Cretaceous limestones is more problematic. There is always the potential for a well-connected open fracture system that could significantly enhance the hydraulic conductivity at least locally. To date, only one probable fracture has been identified from pumping tests in the area in Diablo Plateau. As has been documented in the Dell City Irrigation District, however, only the drilling of tens or even hundreds of water wells can confirm the presence of such a fractured hydrologic system (Logan, 1984). The great depth to Cretaceous strata in wells drilled at the proposed site and locally (300-700 ft), the high cost to lift water from these depths, and the previous failure to locate a high-transmissivity fracture system suggests that future efforts to explore for such resources will be limited.

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Table 1. Summary of pumping test results in Bolson deposits. From Myers (1969).

TWC ID*	Lat/Long	Trans. gpd/ft	Stor.	Perm. gpd/ft²	Aquifer**
48-15-201	31°51'42"/105°10'27"	15,300	-	60	L
NA	31°57'03"/106°36'41"	28,800	-	-	B
49-04-104	31°57'57"/106°36'58"	73,500	-	147	B
49-04-105	31°58'07"/106°36'30"	49,500	-	122	B
49-04-106	31°57'34"/106°36'42"	61,000	-	112	B
49-04-107	31°57'34"/106°36'42"	61,000	0.0007	230	B
49-04-108	31°58'54"/106°35'20"	47'600	-	2,380	B
49-04-112	31°59'32"/106°36'37"	20,000	-	118	SF
49-04-113	31°58'19"/106°37'05"	62,500	-	110	SF
49-04-114	31°58'54"/106°35'20"	23,200	-	263	B
49-04-115	31°58'19"/106°37'05"	62,500	-	110	SF
49-04-401	31°57'16"/106°36'22"	61,000	-	124	B
49-04-402	31°51'03"/106°36'42"	60,000	0.0007	127	B
49-04-403	31°56'17"/106°36'56"	140,000	-	1,770	B
49-04-404	31°56'18"/106°37'04"	46,400	-	252	B
49-04-405	31°56'17"/106°36'42"	121,000	-	1,020	RG
49-04-410	31°55'57"/106°36'43"	34,800	-	184	SF
49-04-411	31°55'56"/106°36'43"	104,000	-	758	B
49-04-412	31°55'57"/106°36'18"	150,000	-	1,780	B
49-04-415	31°55'37"/106°36'15"	110,000	-	-	B
49-04-417	31°55'56"/106°36'31"	155,000	0.001	-	B
49-04-418	31°55'55"/106°36'57"	87,000	0.0009	-	B
49-04-419	31°57'17"/106°36'40"	60,000	0.0006	129	B
49-04-420	31°55'57"/106°36'58"	150,000	-	1,830	B
49-04-421	31°55'50"/106°37'23"	29,700	-	75	SF
49-04-422	31°57'20"/106°36'22"	41,500	-	216	B
49-05-202	31°59'09"/106°25'34"	156,000	-	590	B
49-05-204	31°58'16"/106°25'27"	86,000	-	550	B
49-05-301	31°58'16"/106°24'31"	123,000	-	353	B
49-05-306	31°59'00"/106°53'27"	106,000	-	500	B
49-05-501	31°55'40"/106°25'29"	32,700	-	80	B
49-05-503	31°56'33"/106°25'24"	47,000	-	224	B
49-05-504	31°55'48"/106°26'33"	31,600	-	47	B
49-05-601	31°57'24"/106°24'23"	137,000	-	406	B
49-05-602	31°57'24"/106°23'28"	171,000	-	495	B
49-05-603	31°56'33"/106°24'22"	152,000	-	440	B
49-05-604	31°56'32"/106°23'27"	205,000	-	436	B
49-05-605	31°56'32"/106°22'32"	143,000	-	234	B
49-05-606	31°55'40"/106°24'26"	105,000	-	233	B
49-05-607	31°55'40"/106°23'26"	110,000	-	213	B
49-05-609	31°57'25"/106°22'25"	114,000	-	356	B
49-05-801	31°54'48"/106°26'23"	27,000	-	38	B
49-05-803	31°53'56"/106°25'22"	153,000	0.0006	298	B

Table 1 (continued):

TWC ID*	Lat/Long	Trans. gpd/ft	Stor.	Perm. gpd/ft^2	Aquifer**
49-05-901	31°54'48"/106°24'26"	114,000	-	303	B
49-05-902	31°53'58"/106°24'32"	105,000	-	223	B
49-05-903	31°54'51"/106°23'43"	175,000	-	231	B
49-05-906	31°54'44"/106°22'48"	176,000	-	284	B
49-06-401	31°57'25"/106°21'40"	135,000	-	-	B
49-13-202	31°52'13"/106°25'24"	70,000	-	137	B
49-13-204	31°50'25"/106°25'39"	37,500	-	-	B
49-13-301	31°52'12"/106°24'52"	200,000	0.0002	834	B
49-13-502	31°49'35"/106°25'18"	64,500	0.0005	134	B
49-13-512	31°49'38"/106°25'28"	82,600	0.026	173	B
49-13-605	31°49'34"/106°24'17"	73,000	-	982	B
49-13-608	31°48'11"/106°24'11"	97,000	-	151	B
49-13-609	31°47'40"/106°24'04"	145,000	-	228	B
49-13-610	31°47'52"/106°23'46"	60,400	-	130	B
49-13-702	31°45'42"/106°28'27"	83,600	0.0006	-	B
49-13-703	31°45'42"/106°28'10"	95,200	0.0006	-	B
49-13-705	31°45'42"/106°28'02"	95,200	0.0009	388	B
49-13-803	31°46'29"/106°26'54"	5,600	0.00005	183	B
49-13-807	31°47'13"/106°26'01"	107,000	0.001	-	B
49-13-810	31°46'53"/106°25'31"	39,400	0.0034	215	B
49-14-101	31°52'14"/106°22'21"	55,000	-	183	B
49-14-401	31°47'45"/106°22'21"	59,200	-	121	B
49-14-402	31°47'46"/106°21'21"	73,500	-	165	B
49-14-701	31°46'52"/106°21'35"	60,200	-	158	B
49-14-706	31°46'52"/106°20'38"	46,700	-	146	B

* Texas Water Commission identification number

** Explanation [as defined by Myers (1969)]

B - Hueco Bolson deposits
L - Limestone
SF - Santa Fe deposits
RG - Rio Grande alluvium
NA - not applicable

Table 2. Results of pumping test analyses for the four wells tested.

Permeability (ft/d[m/d])

Well #	Agarwal	Theis	Jacob	Theis Recovery
22	2.8×10^{-1}	2.1×10^{-2}	3.0×10^{-2}	3.1×10^{-2}
	(8.6×10^{-2})	(6.4×10^{-3})	(9.0×10^{-3})	(9.3×10^{-3})
91	3.1×10^{0}	3.0×10^{-2}	2.4×10^{-2}	1.3×10^{-2}
	(9.5×10^{-1})	(9.1×10^{-3})	(7.3×10^{-2})	(5.9×10^{-3})
98	5.9×10^{-1}	3.6×10^{-3}	5.0×10^{-3}	1.3×10^{-2}
	(1.8×10^{-1})	(1.1×10^{-3})	(1.5×10^{-3})	(3.8×10^{-3})
99	1.1×10^{-1}	N/A	3.9×10^{-3}	6.9×10^{-4}
	3.4×10^{-2}	N/A	1.2×10^{-3}	2.1×10^{-4}

Transmissivity (ft^2/d [m^2/d])

Well #	Agarwal	Theis	Jacob	Theis Recovery
22	6.0×10^{0}	4.5×10^{-1}	6.3×10^{-1}	6.6×10^{-1}
	(5.6×10^{-1})	(4.2×10^{-2})	(5.9×10^{-2})	(6.1×10^{-2})
91	2.9×10^{2}	9.1×10^{0}	7.4×10^{0}	5.9×10^{0}
	(2.71×10^{1})	(8.5×10^{-1})	(6.9×10^{-1})	(5.5×10^{-1})
98	5.3×10^{1}	1.9×10^{0}	1.5×10^{0}	3.6×10^{0}
	(4.9×10^{0})	(1.8×10^{-1})	(1.4×10^{-1})	(3.4×10^{-1})
99	7.1×10^{0}	N/A	2.5×10^{-1}	4.3×10^{-2}
	(6.6×10^{-1})	N/A	(2.3×10^{-2})	(4.0×10^{-3})

N/A - not applicable

Table 3. Water wells within 10 mi of proposed site.

I.D.	Owner/operator	Production Equipment	Operational Status	Depth to Water (ft)	Producing Aquifer
22	GLO/BEG	---	Open	592	Cret. Ls.
91	F. Owens	---	Capped	317.25	Cret. Ls.
94	GLO	Windmill	Inactive	---	Cret. Ls.
96	J. Moseley	Subm. Pump	Active	---	Cret. Ls.
97	J. Moseley	Subm. Pump	Active	---	Cret. Ls.
98	GLO/BEG	Subm. Pump	Active	200	Bolson
99	F. MacGuire	---	Open	140	Bolson
106		Thaxton Spring	Active	0	Cret. Ls.
107	Tierra Del Sol	Windmill	Inactive	335	Bolson
108	Fort Hancock Water District	Turbine	Active	93	Bolson
111	F. MacGuire	Windmill	Active	327	Bolson
112	F. MacGuire	Windmill	Active	267	Cret. Ls.
113	S. Wilkey Est.	Pump Jack	Inactive	600	Cret. Ls.
114	S. Wilkey Est.	Subm. Pump	Active	76	Cret. Ls.
115	Gunsight Ranch	Windmill	Active	627	Cret. Ls.
116	F. Owens	Pump jack	Active	300	Cret. Ls.
126	GLO/BEG Pump	Bennett	Active	478.9	Bolson

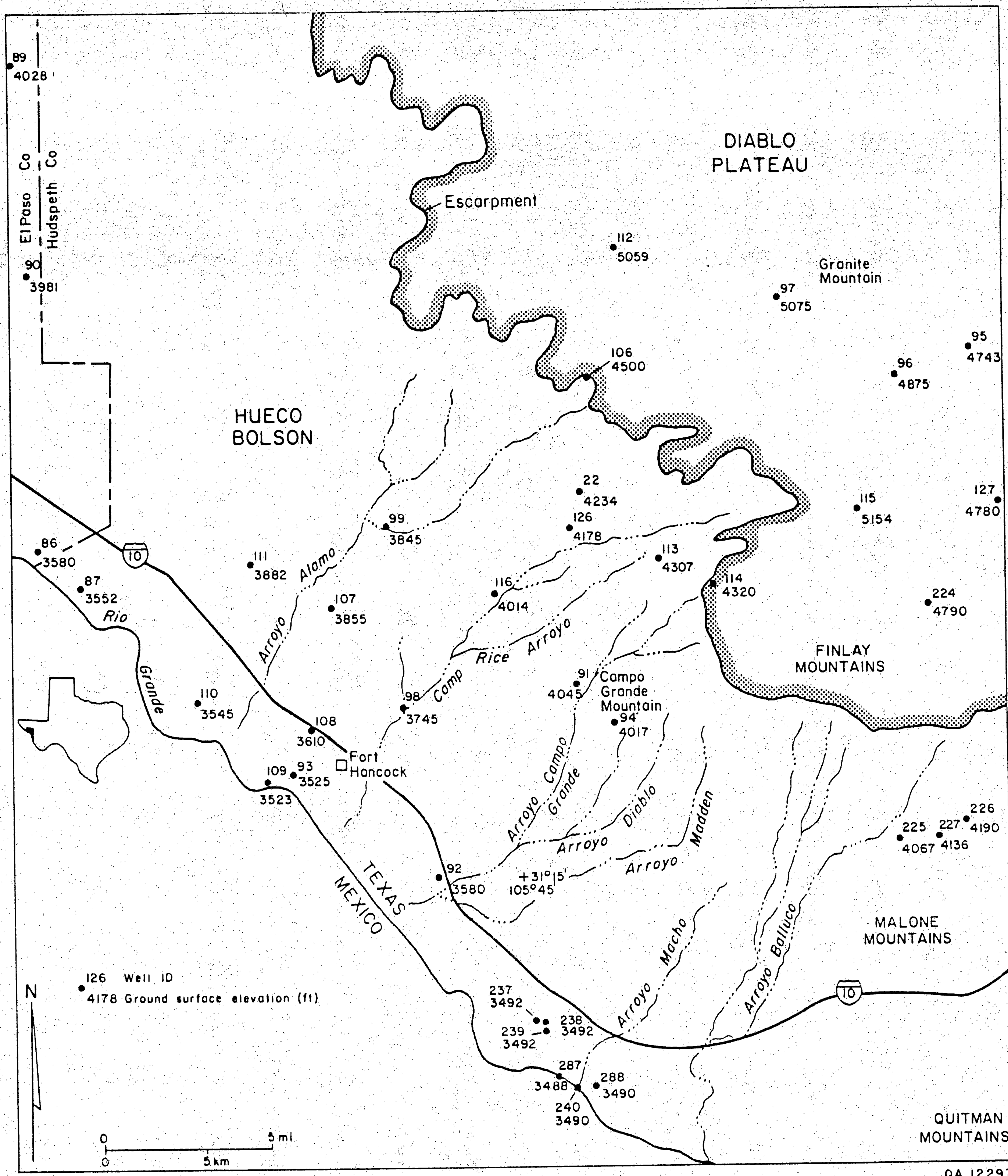

Figure 1. Location of water wells and spring (no. 106) within regional hydrologic study area. Study area includes Rio Grande alluvium aquifer, Hueco Bolson silt and sand aquifer, and Diablo Plateau aquifer systems.

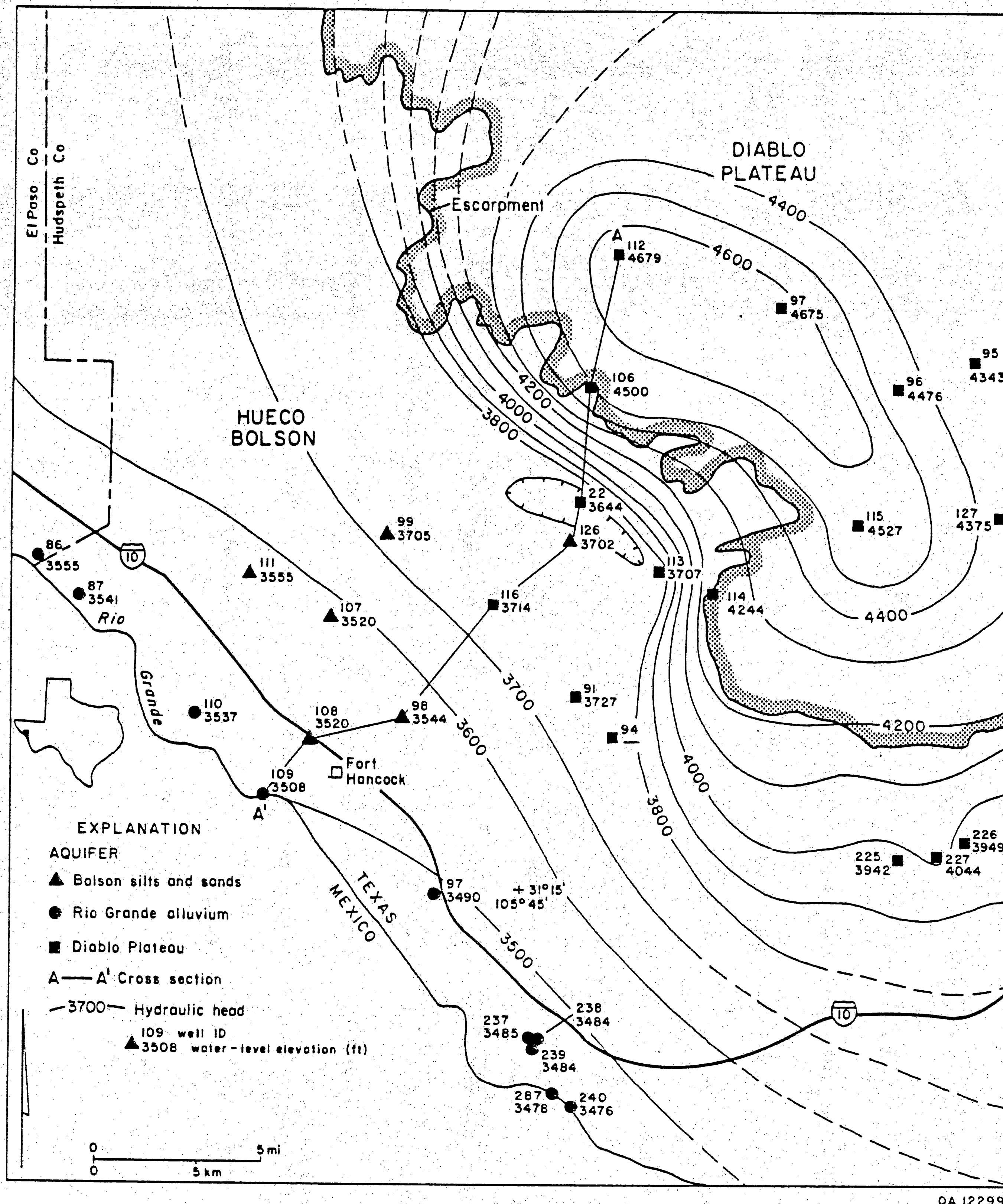

Figure 2. Potentiometric-surface map of the regional hydrologic study area. Efficient hydrologic connection between the different aquifer systems was assumed in the preparation of this map. A - A' is line of cross section illustrated in figure 3.

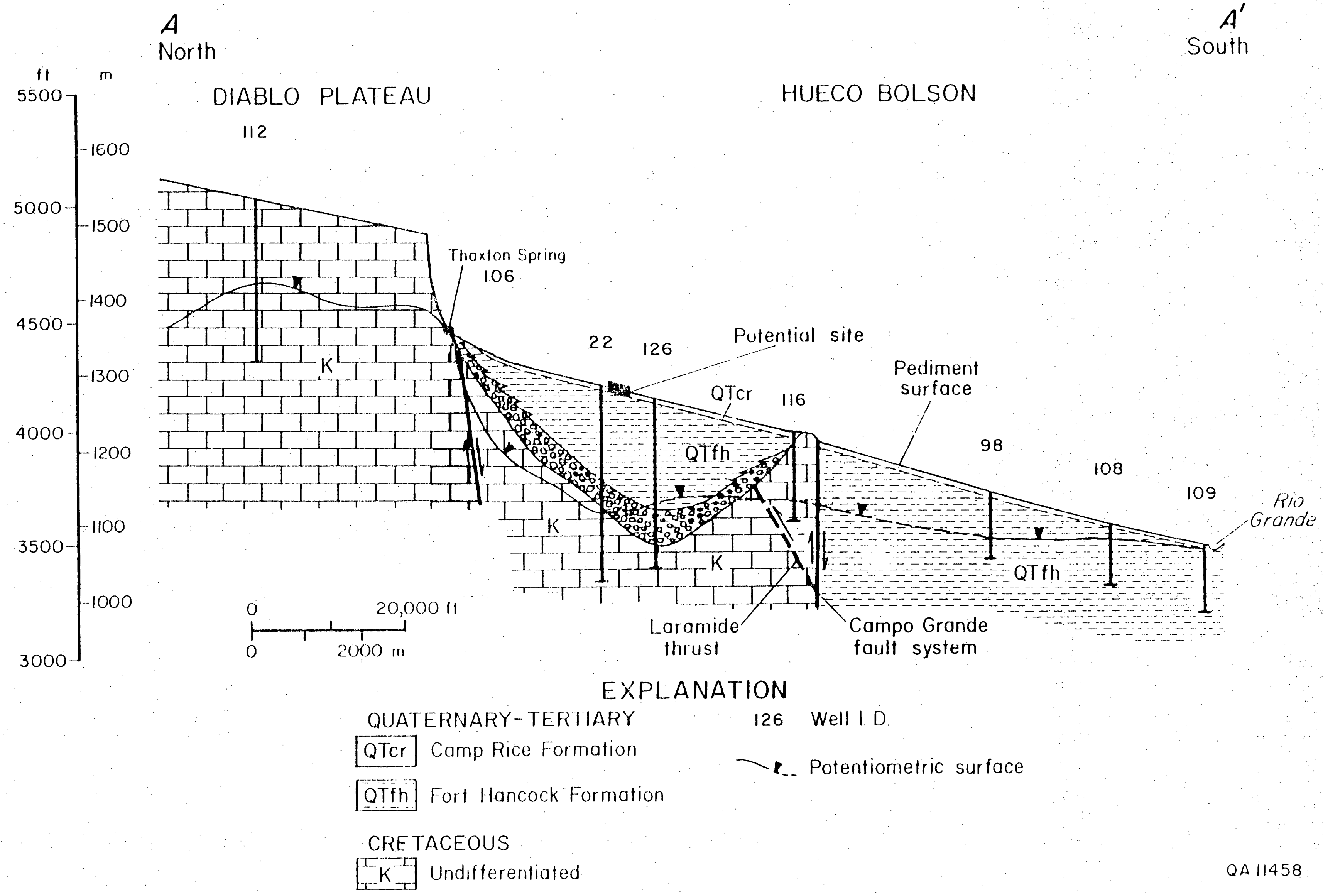

Figure 3. Hydrologic cross section illustrating relationship between potentiometric surface and stratigraphy from the Diablo Plateau to the Rio Grande. Location of cross section shown in figure 2.

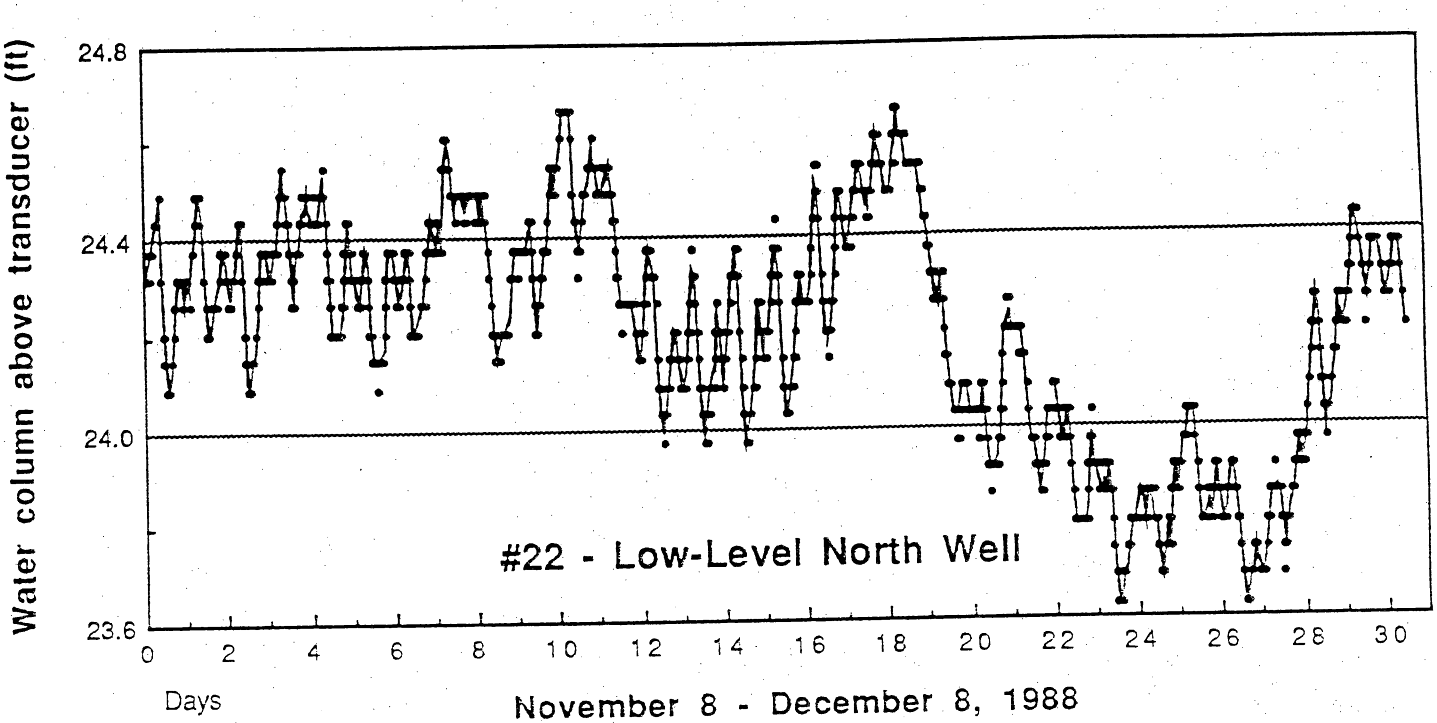

Figure 4A. Fluctuations in water levels recorded in well no. 22 from November 8 to December 8, 1988.

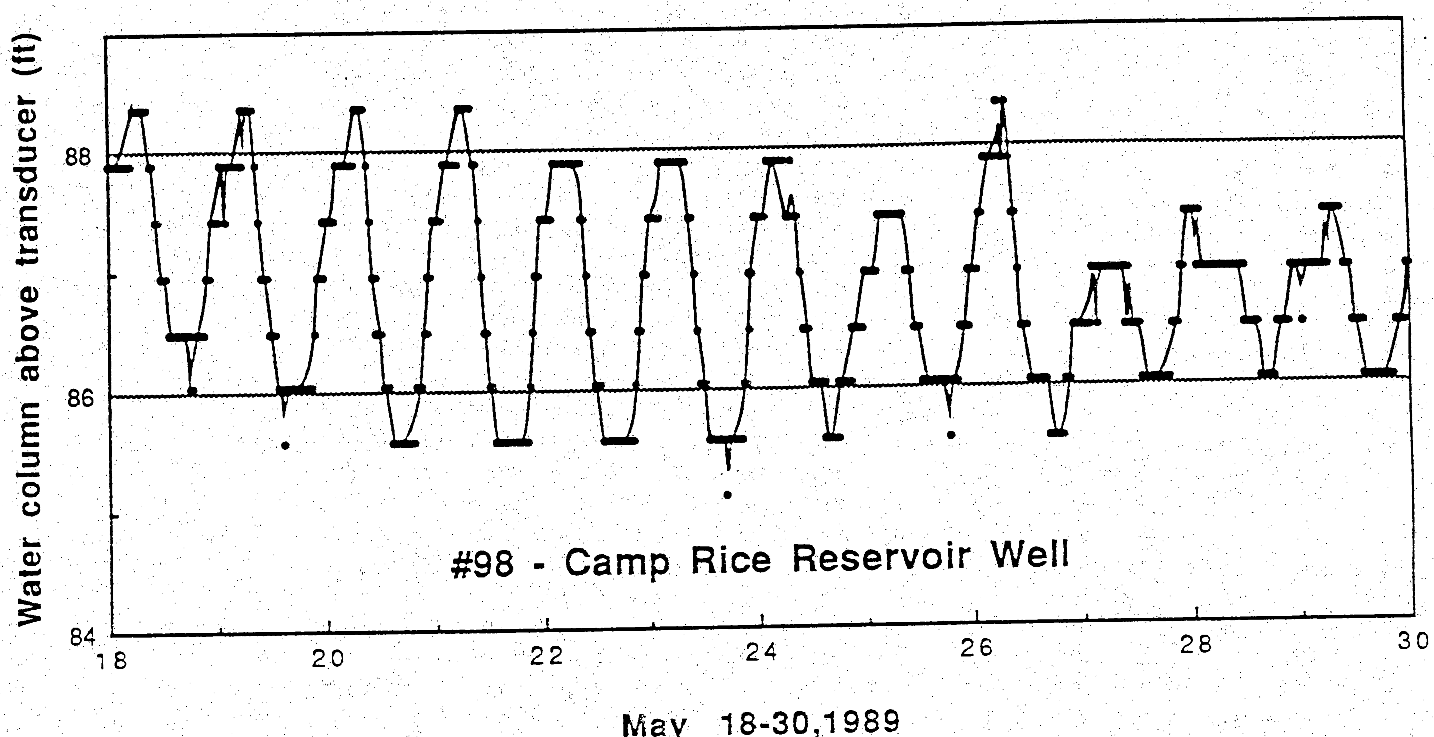

Figure 4B. Fluctuations in water levels recorded in well no. 98 from May 18 to May 30, 1989.

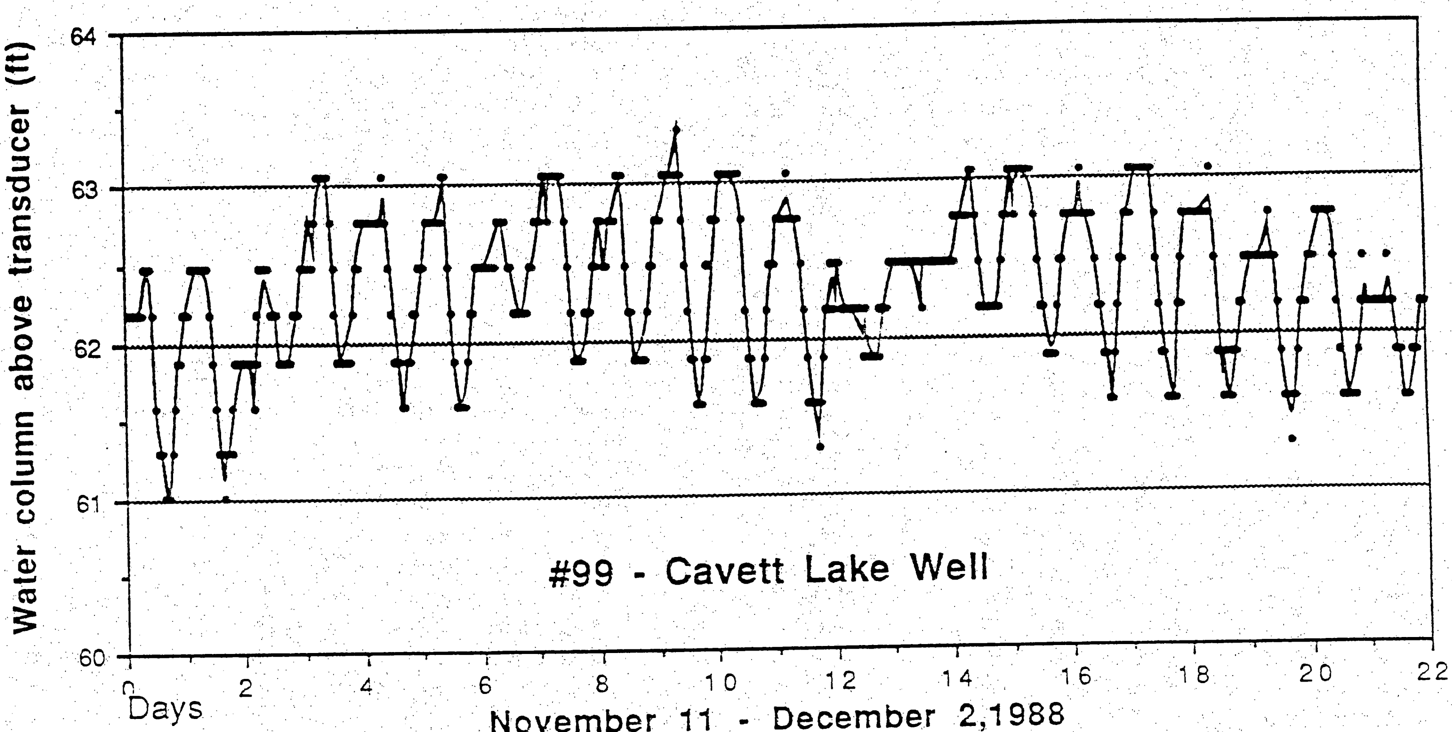

Figure 4C. Fluctuations in water levels recorded in well no. 99 from November 11 to December 2, 1988.

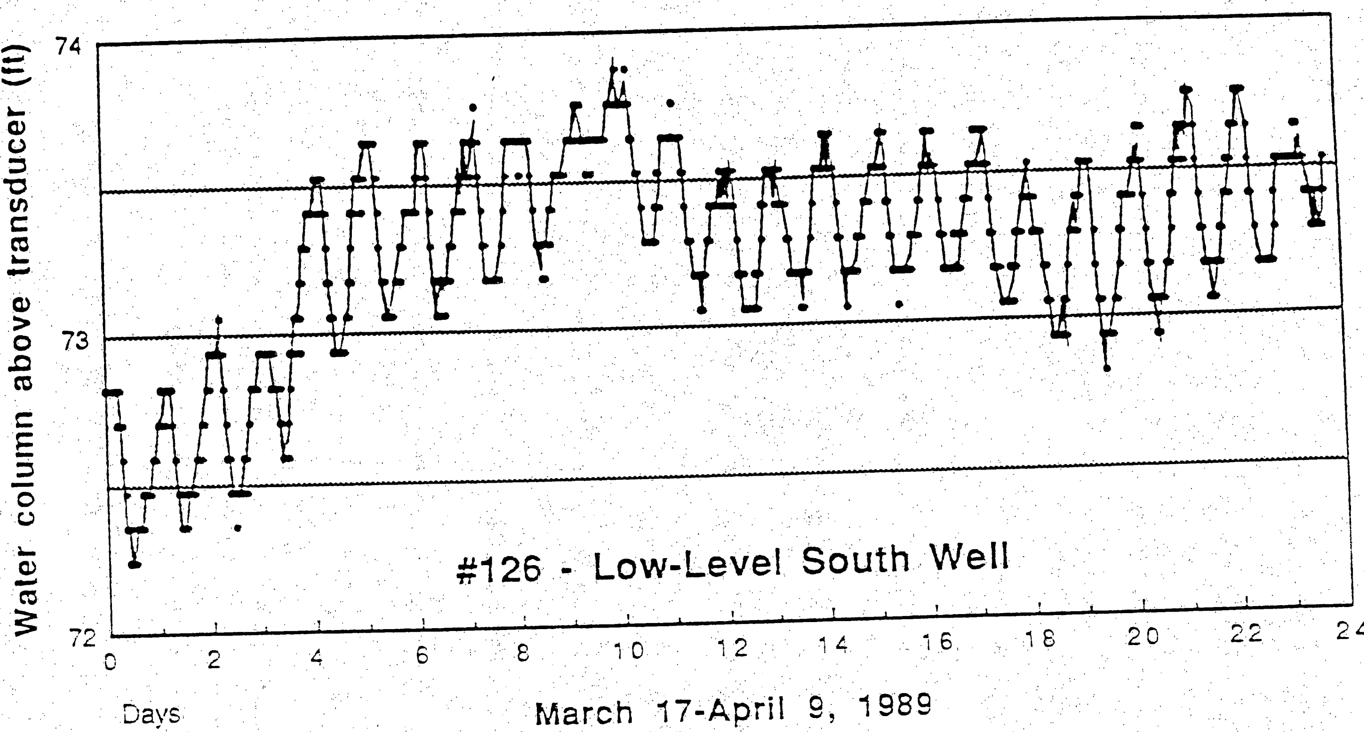

Figure 4D. Fluctuations in water levels recorded in well no. 126 from March 17 to April 9, 1989.

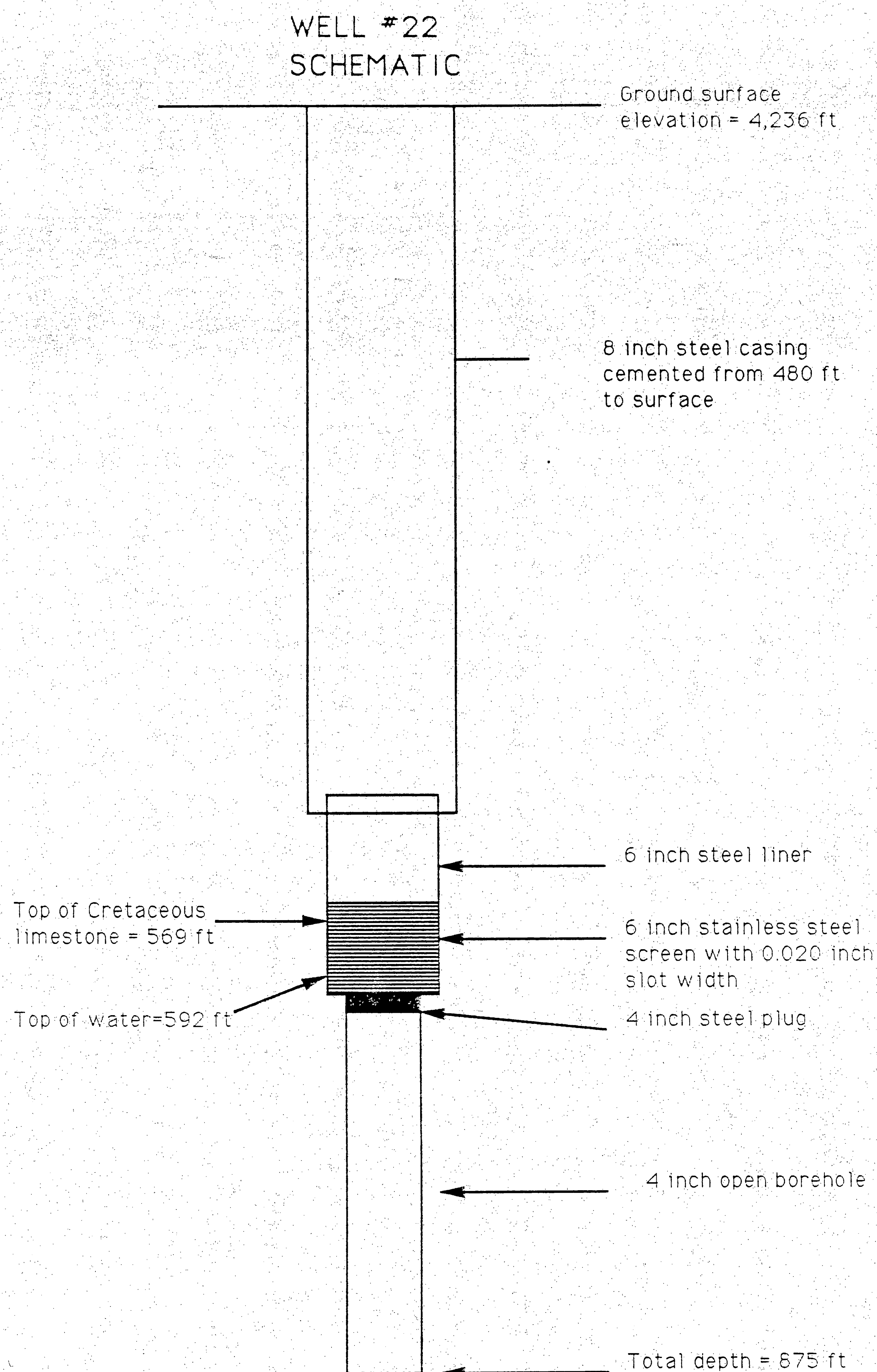

Figure 5. Schematic drawing of well no. 22 design during pumping test conducted October 5, 1988.

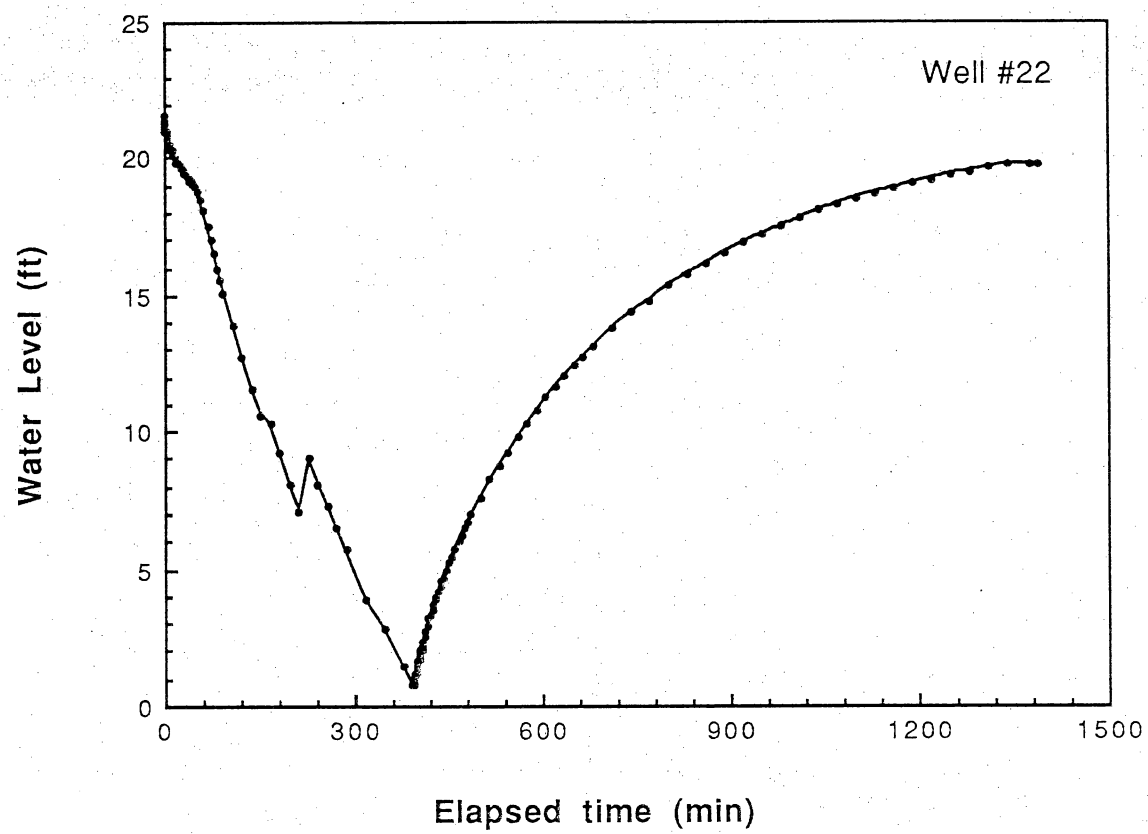

Figure 6. Drawdown and recovery curves for pumping test conducted in well no. 22.

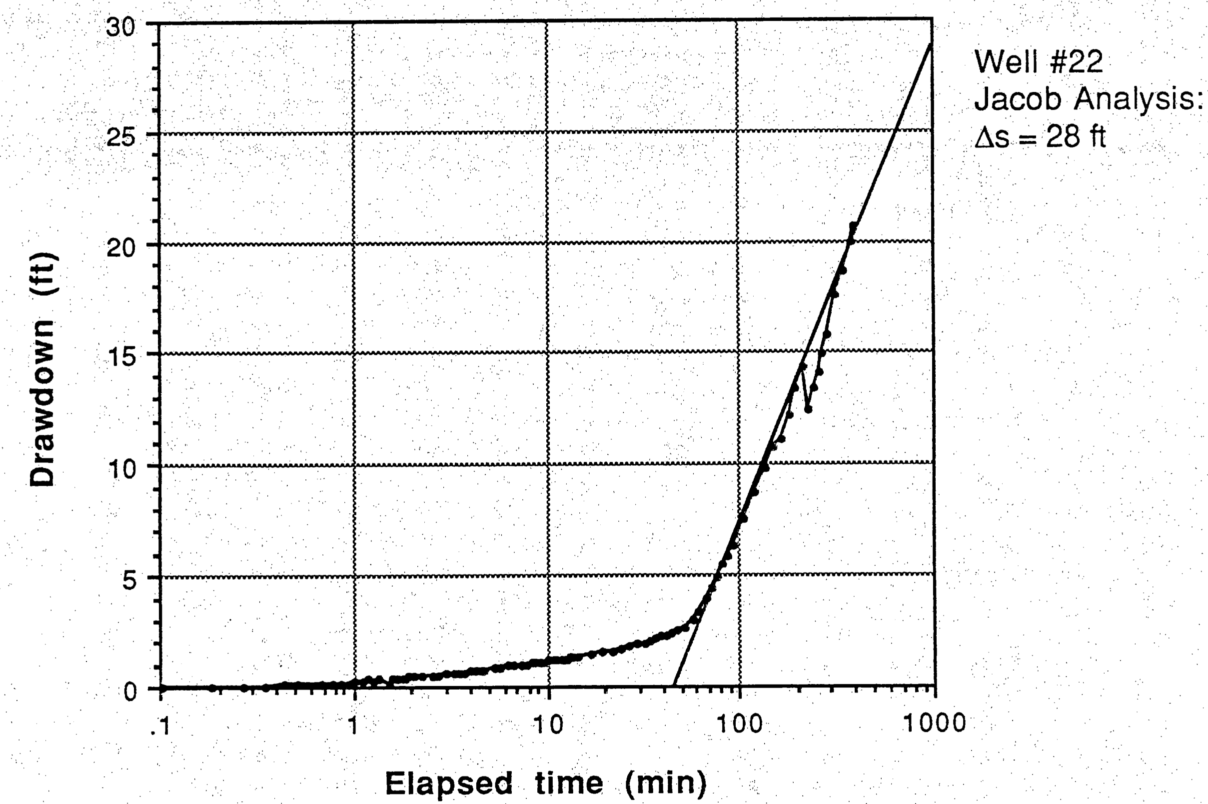

Figure 7. Plot of hydrologic test data during drawdown phase of pumping test on well no. 22. This semilogarithmic presentation used for Jacob's method of analysis. For this and subsequent figures, transmissivity and permeability values determined from this method are given in table 2.

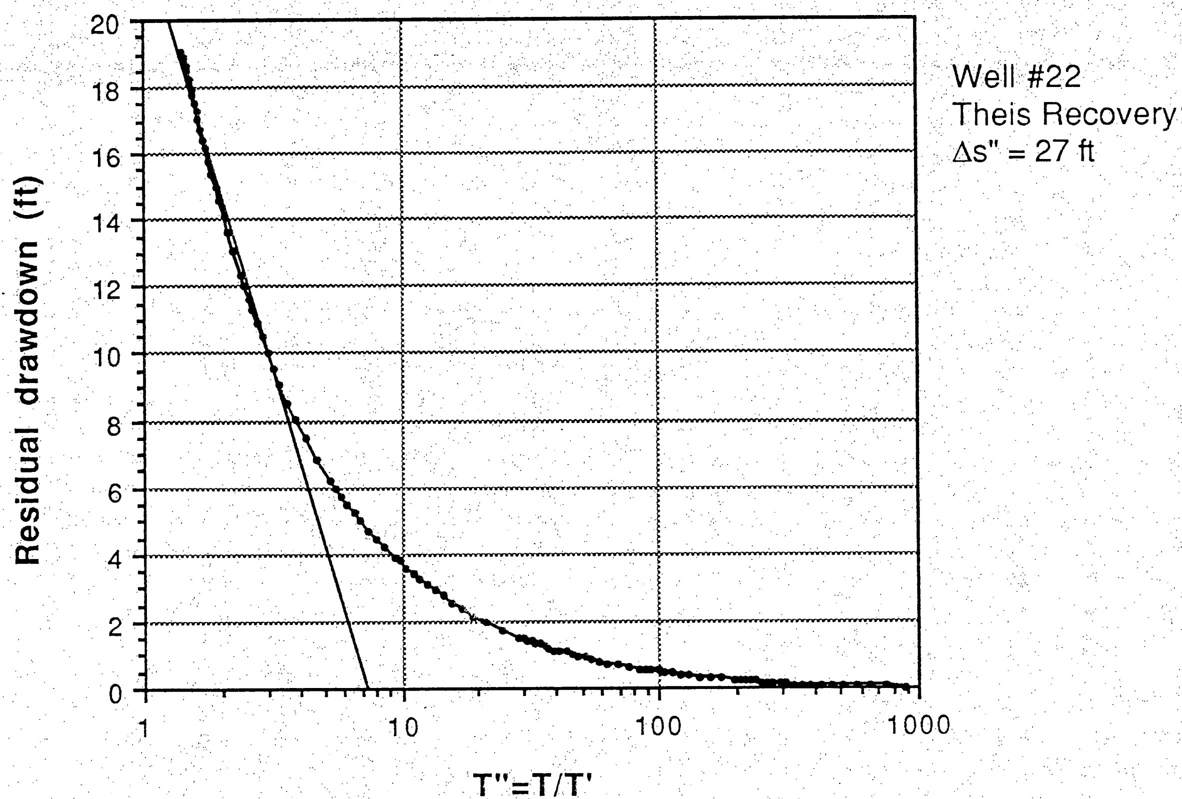

Figure 8. Plot of hydrologic test data during recovery phase of pumping test on well no. 22. This semilogarithmic presentation used for Theis's method of analysis.

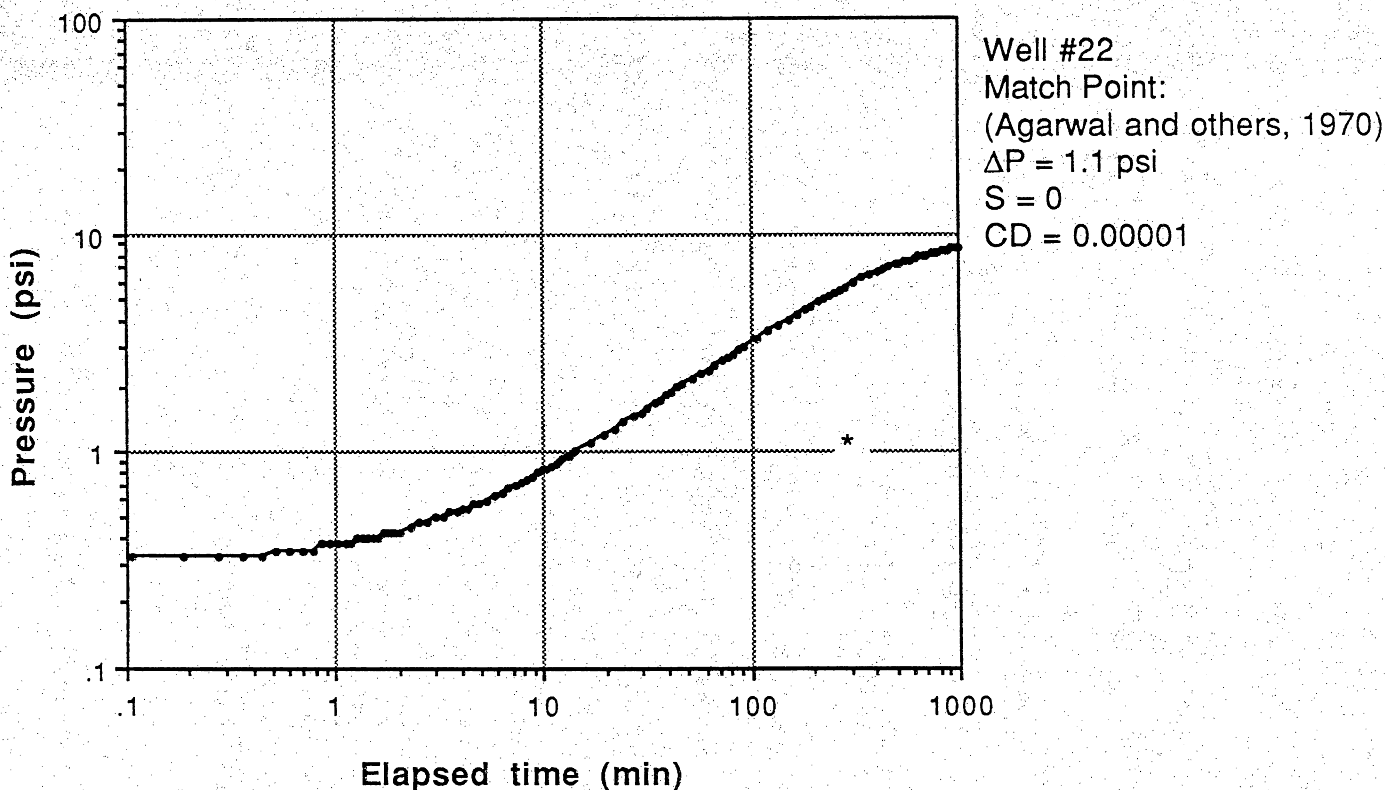

Figure 9. Plot of hydrologic test data during recovery phase of pumping test on well no. 22. This logarithmic presentation used for matching test data with Agarwal's type curves.

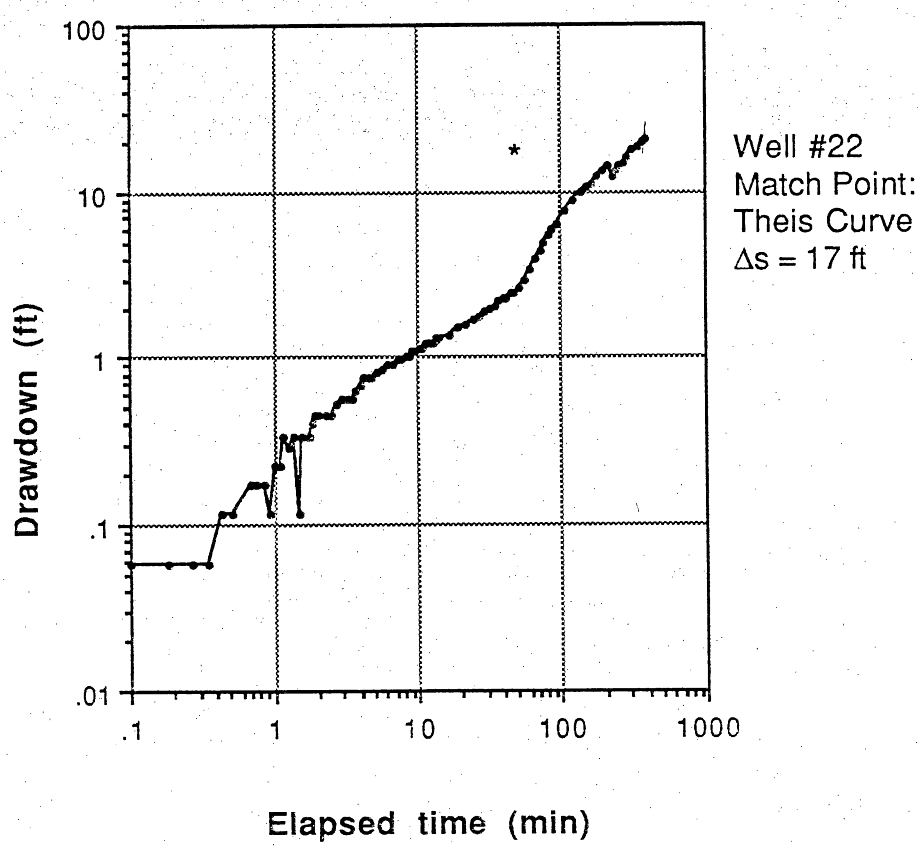

Figure 10. Plot of hydrologic test data during drawdown phase of pumping test on well no. 22. This logarithmic presentation used for matching test data with Theis' type curves.

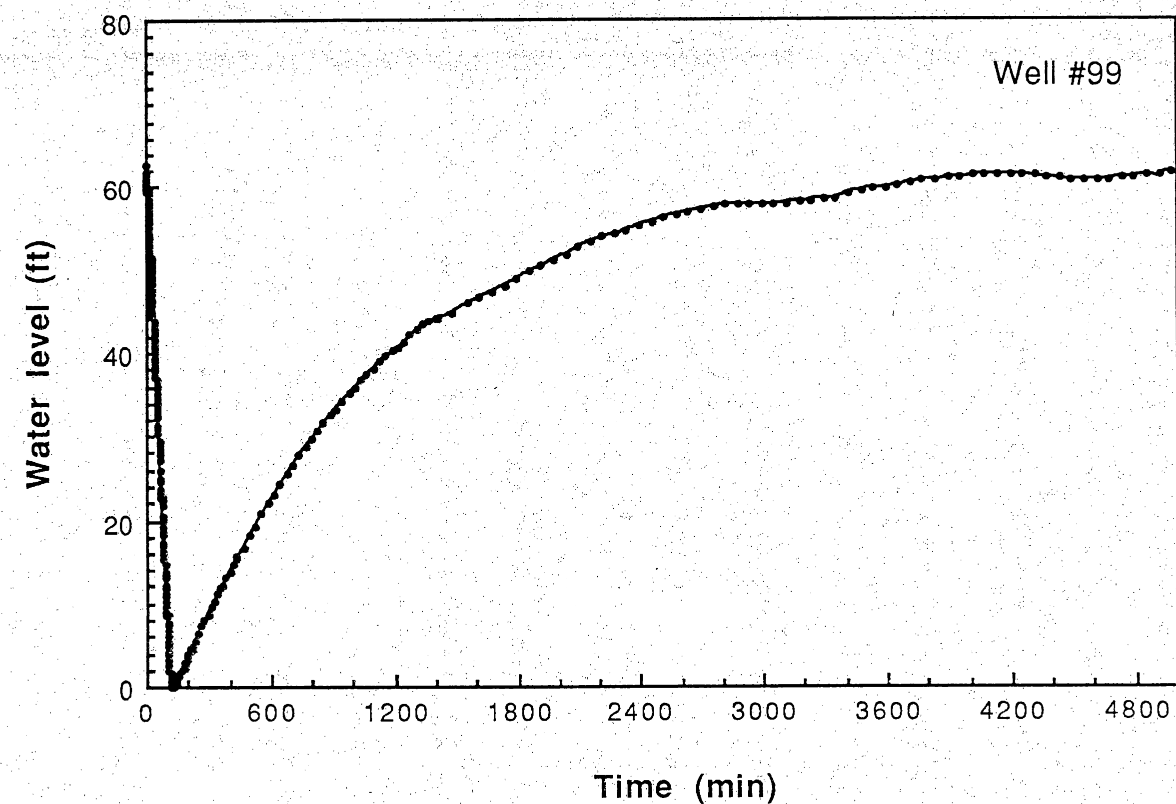

Figure 11. Drawdown and recovery curves for pumping test conducted in well no. 99.

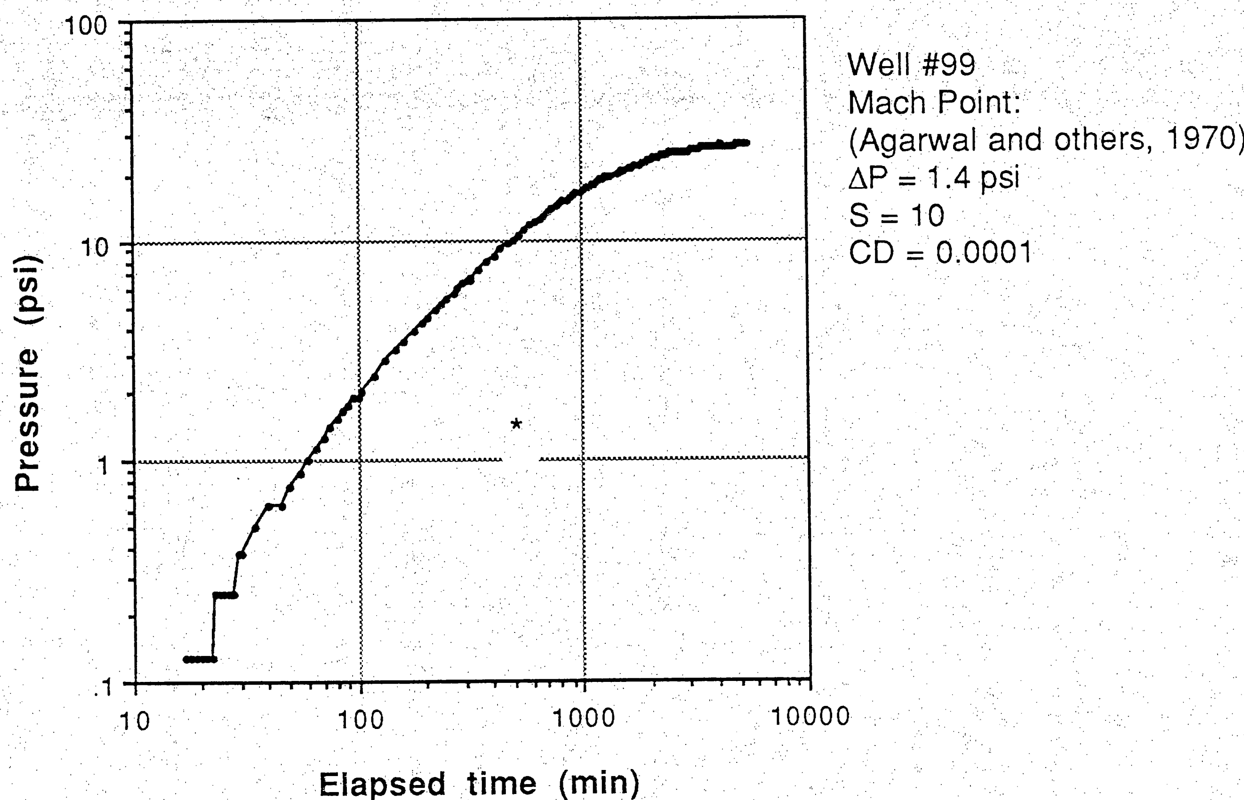

Figure 12. Plot of hydrologic test data during recovery phase of pumping test on well no. 99. This logarithmic presentation used for matching test data with Agarwal's type curves.

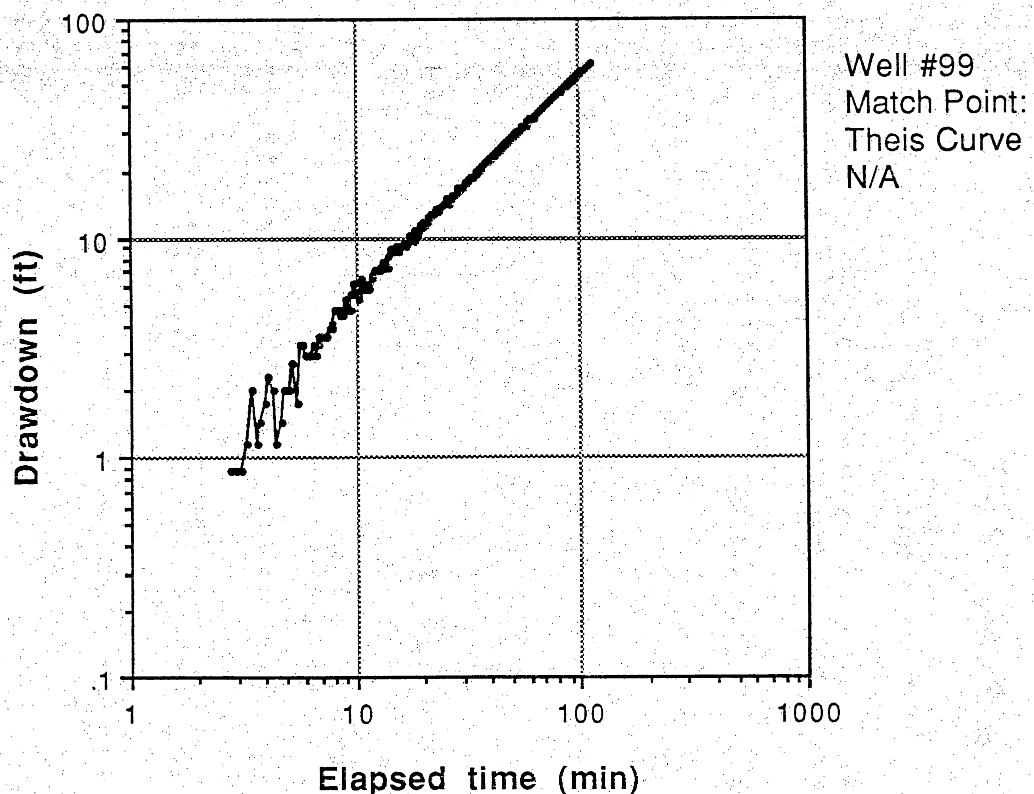

Figure 13. Plot of hydrologic test data during drawdown phase of pumping test on well no. 99. This logarithmic presentation used for matching test data with Theis's type curves.

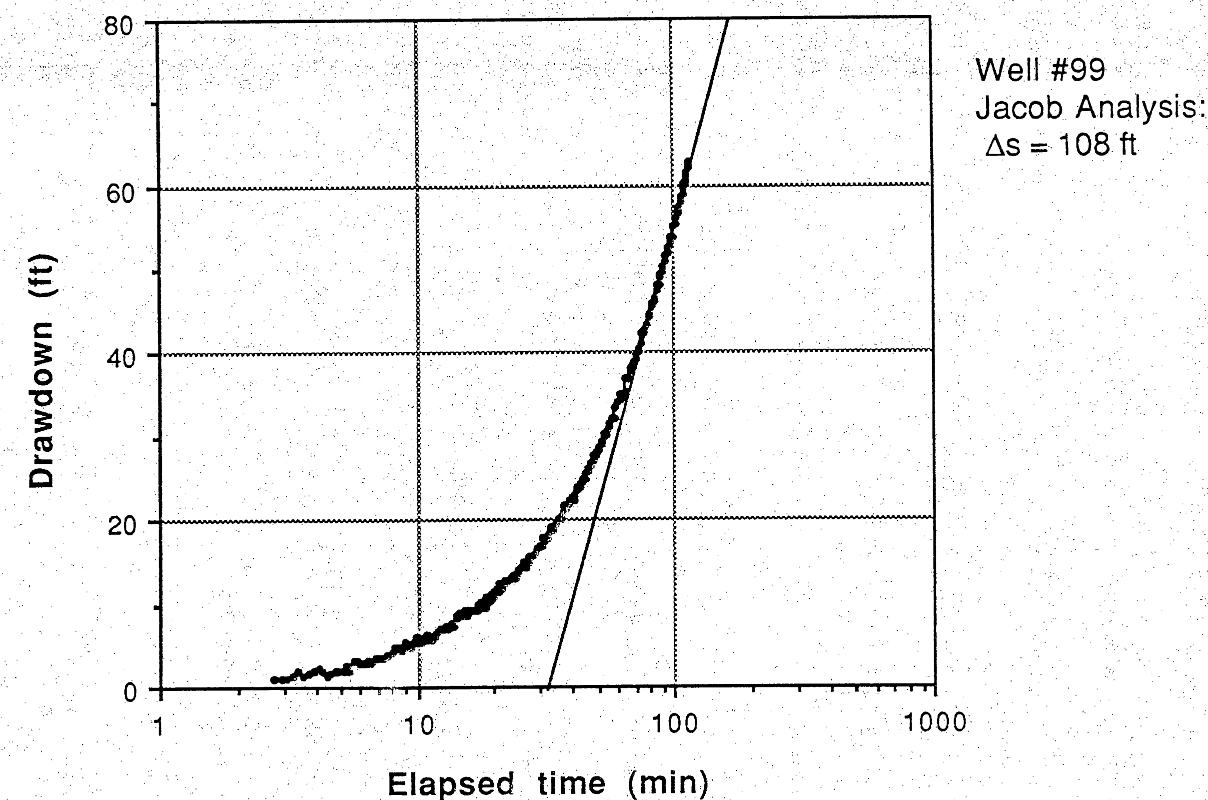

Figure 14. Plot of hydrologic test data during drawdown phase of pumping test on well no. 99. This semilogarithmic presentation used for Jacob's method of analysis.

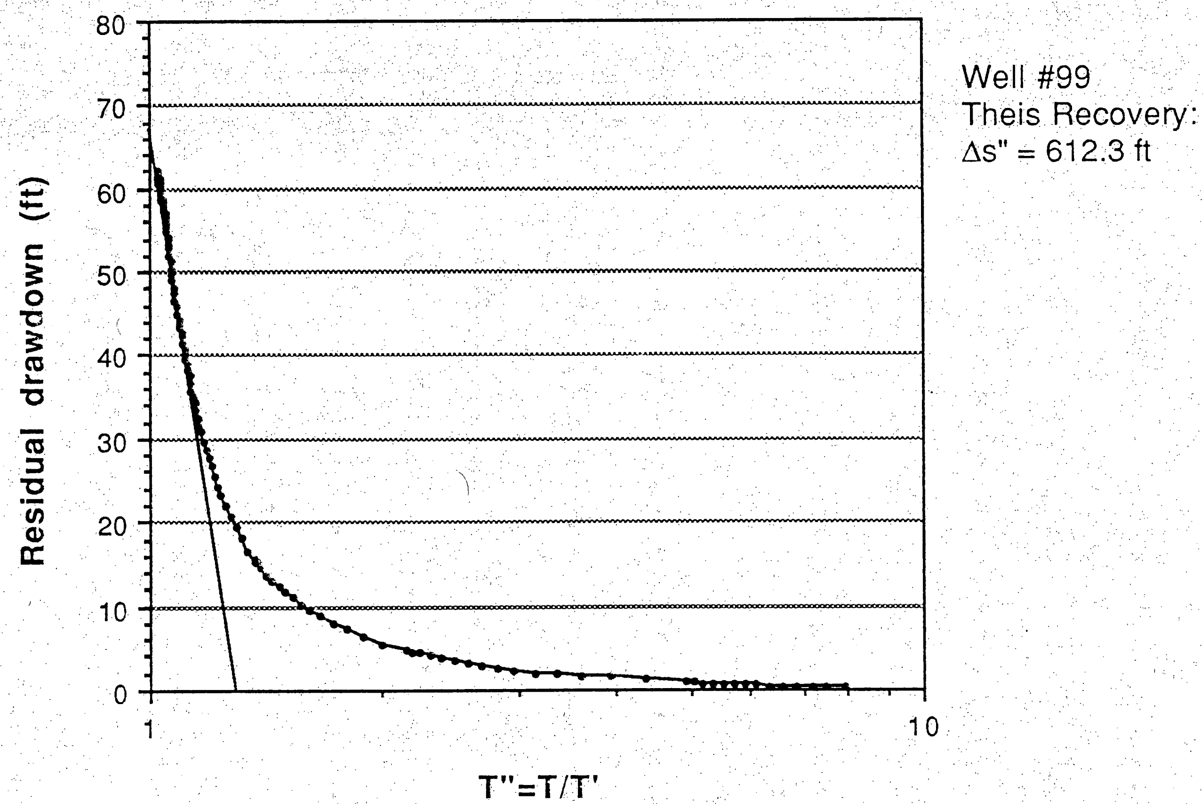

Figure 15. Plot of hydrologic test data during recovery phase of pumping test on well no. 99. This semilogarithmic presentation used for Theis's method of analysis.

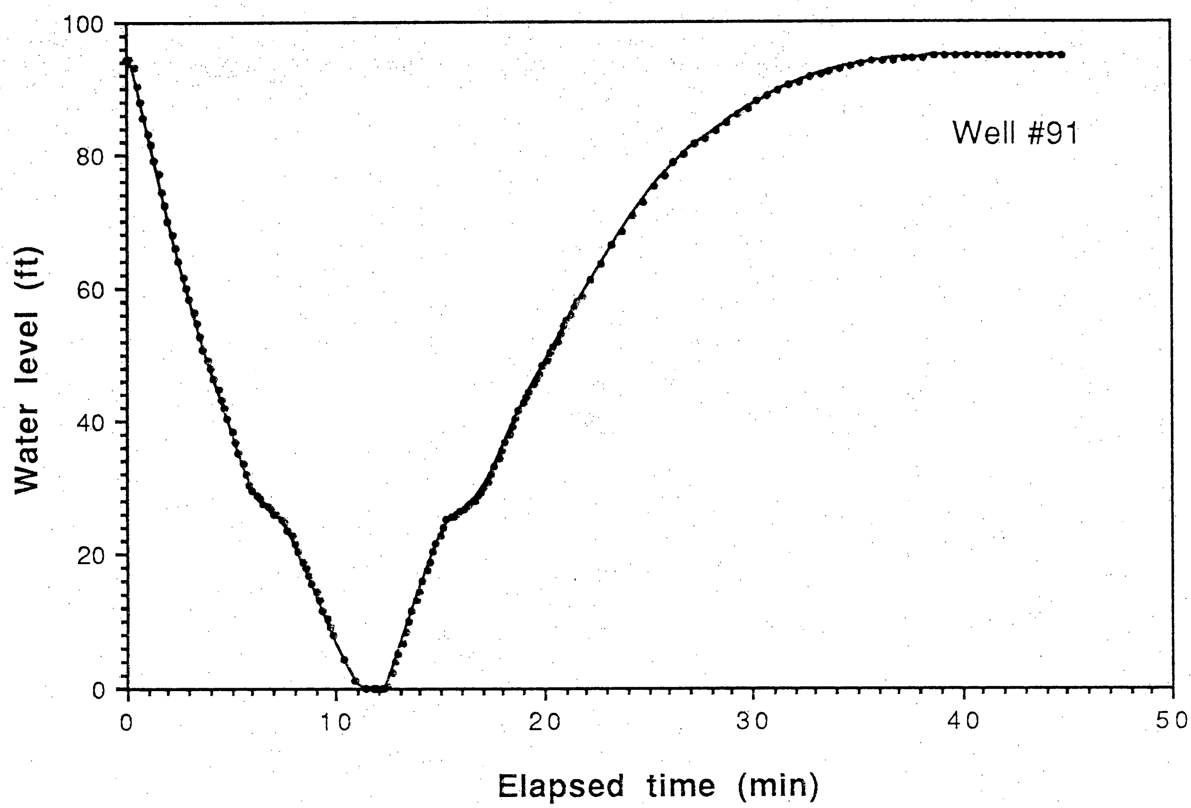

Figure 16. Drawdown and recovery curves for pumping test conducted in well no. 91.

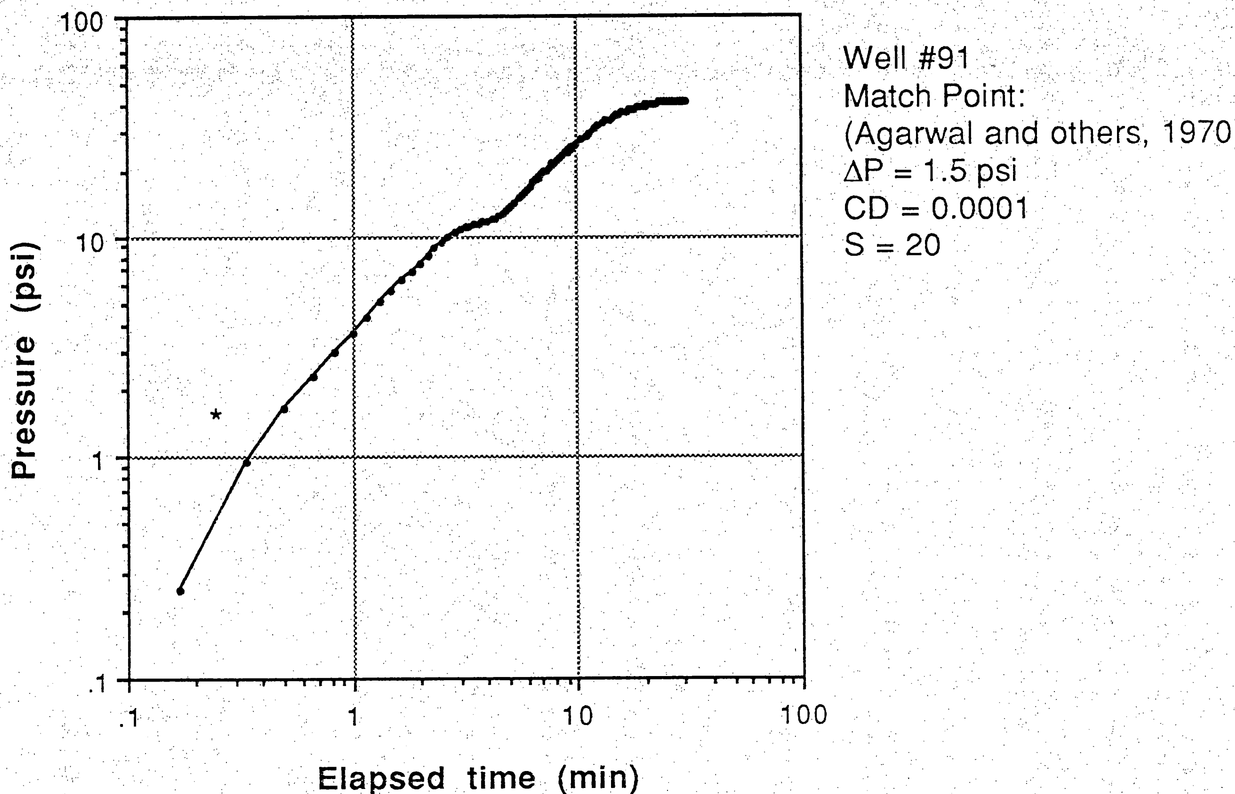

Figure 17. Plot of hydrologic test data during recovery phase of pumping test on well no. 91. This logarithmic presentation used for matching test data with Agarwal's type curves.

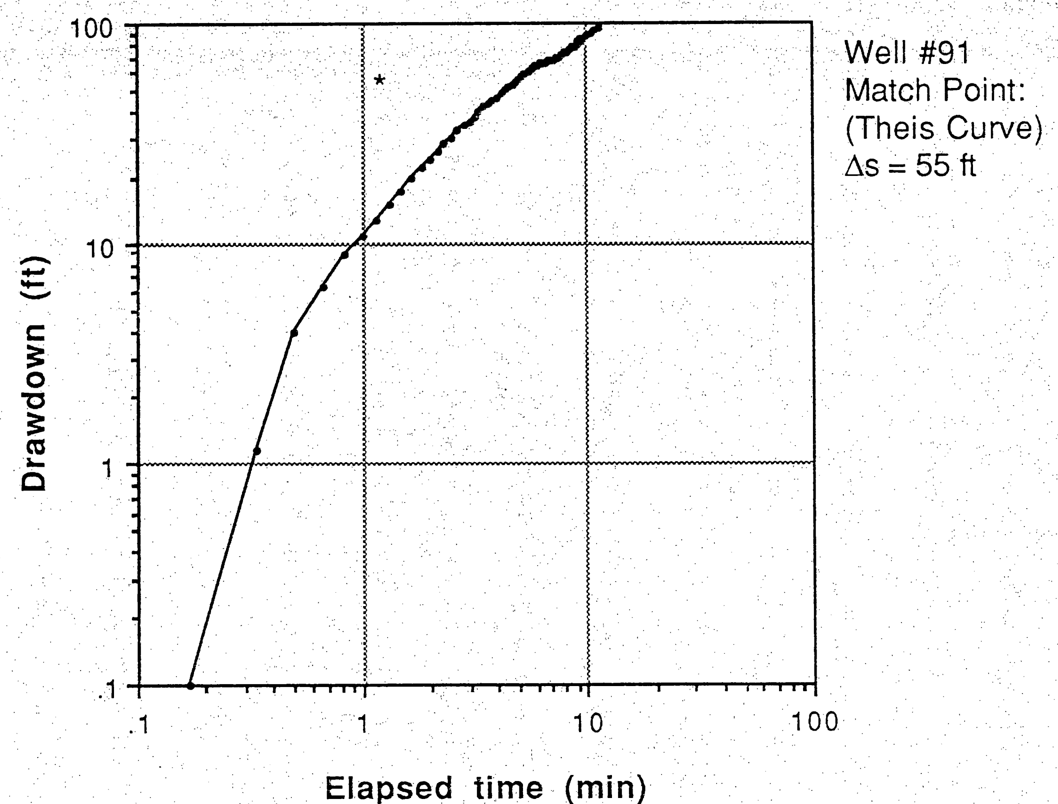

Figure 18. Plot of hydrologic test data during drawdown phase of pumping test on well no. 91. This logarithmic presentation used for matching test data with Theis's type curves.

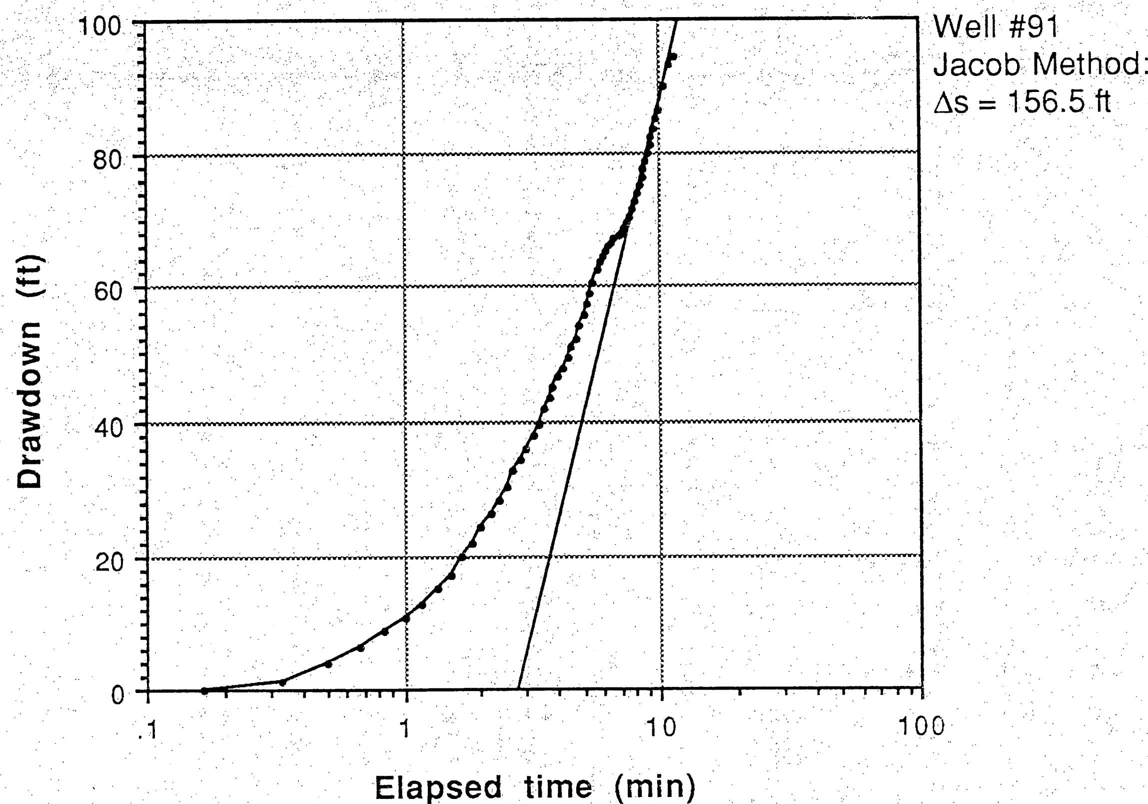

Figure 19. Plot of hydrologic test data during drawdown phase of pumping test on well no. 91. This semilogarithmic presentation used for Jacob's method of analysis.

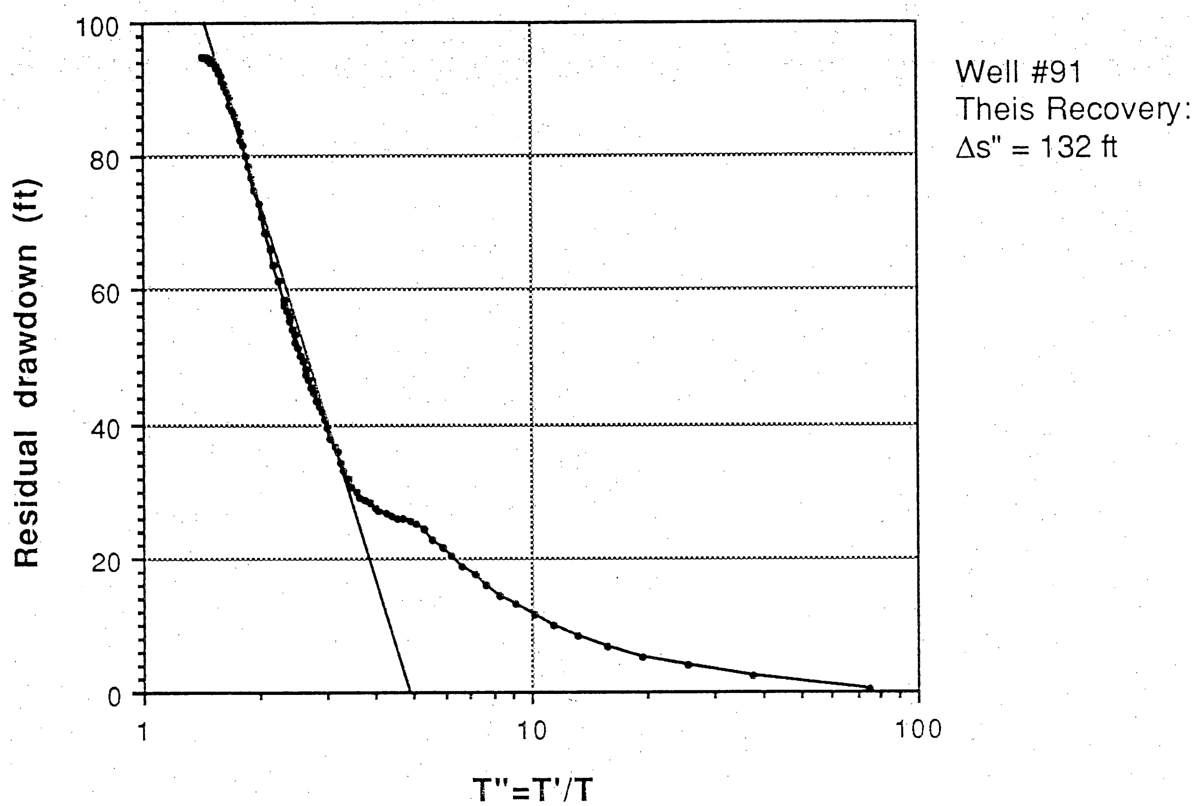

Figure 20. Plot of hydrologic test data during recovery phase of pumping test on well no. 91. This semilogarithmic presentation used for Theis's method of analysis.

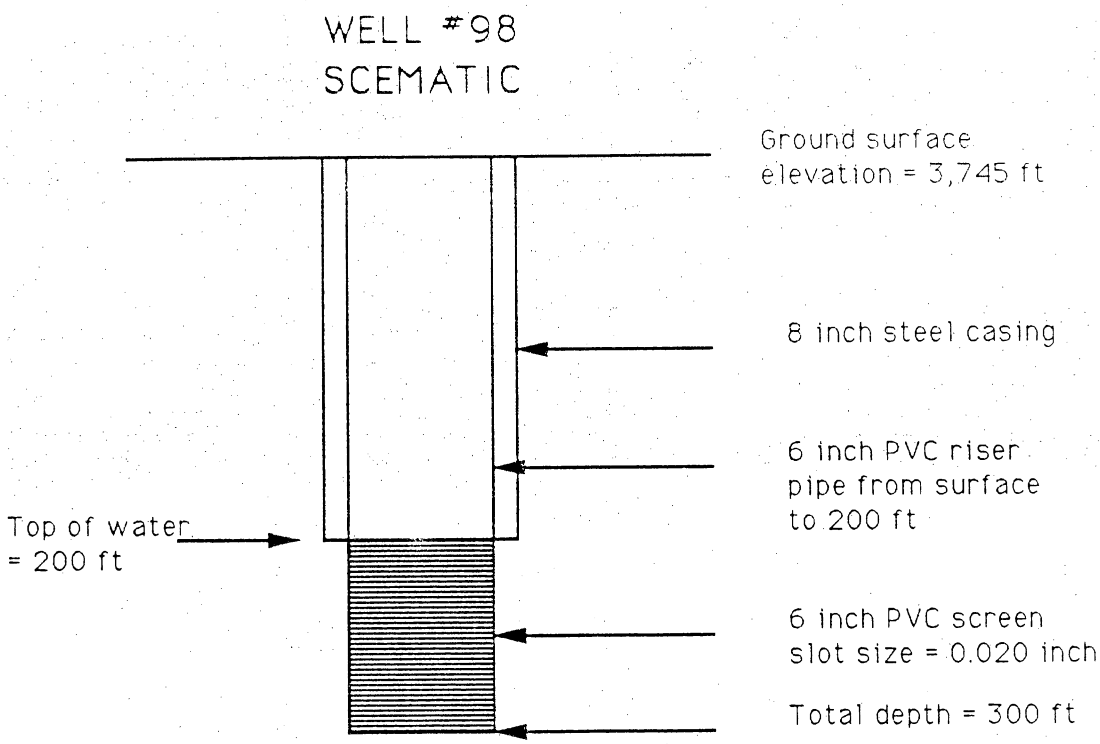

Figure 21. Schematic drawing of well no. 98 design during pumping test conducted in May 1989.

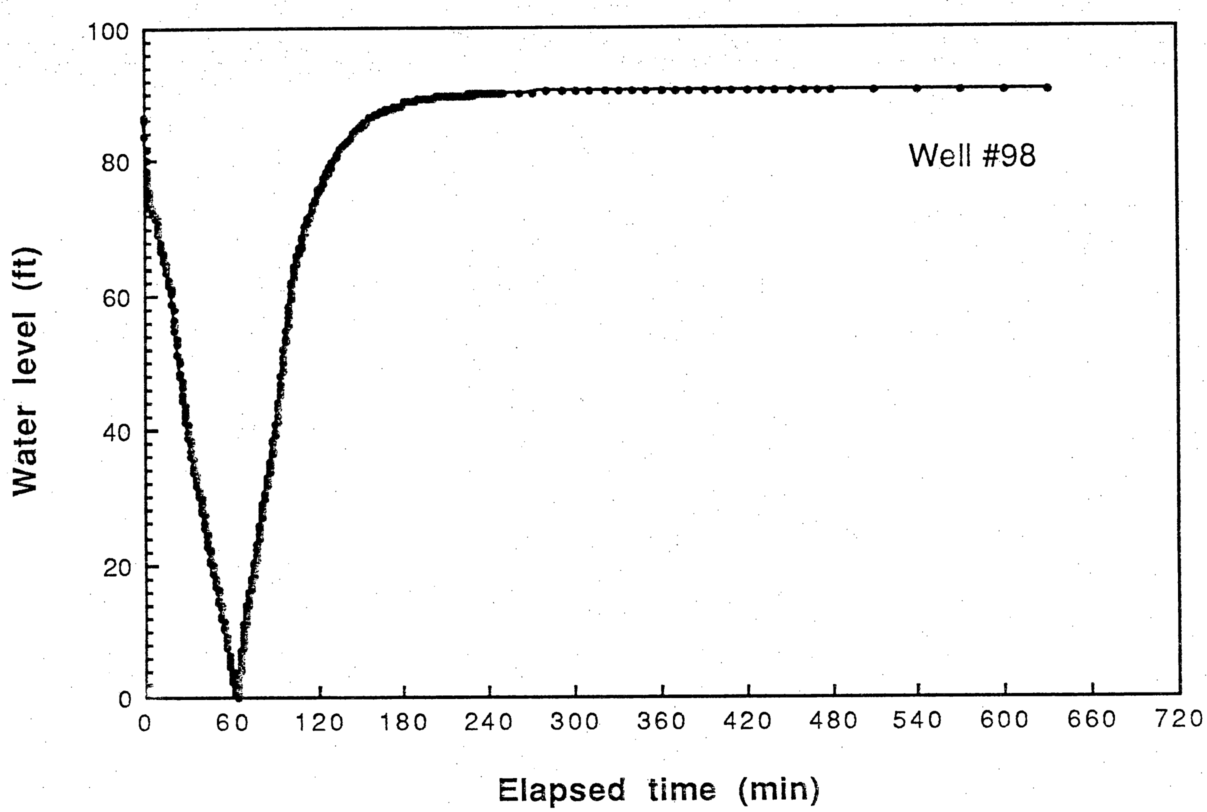

Figure 22. Drawdown and recovery curves for pumping test conducted in well no. 98.

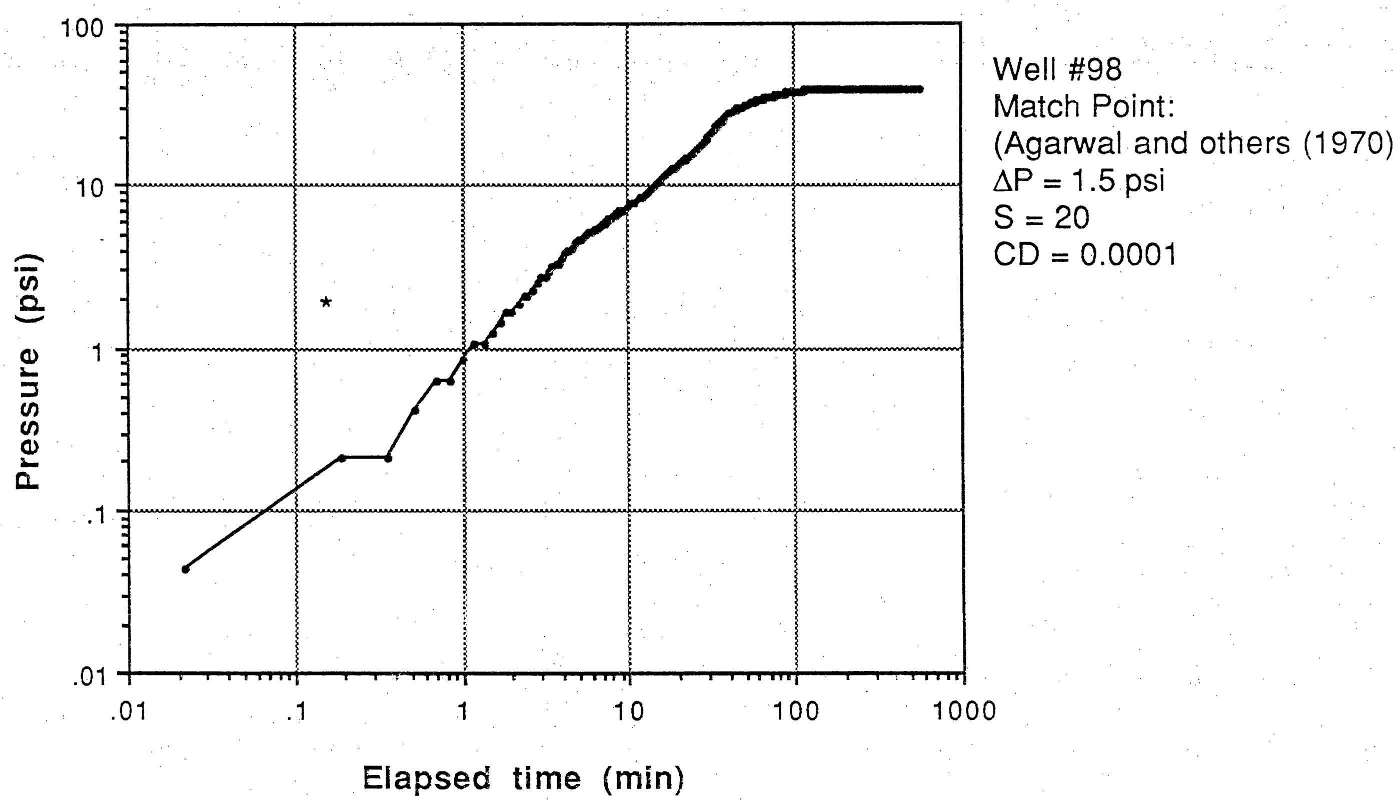

Figure 23. Plot of hydrologic test data during recovery phase of pumping test on well no. 22. This logarithmic presentation used for matching test data with Agarwal's type curves.

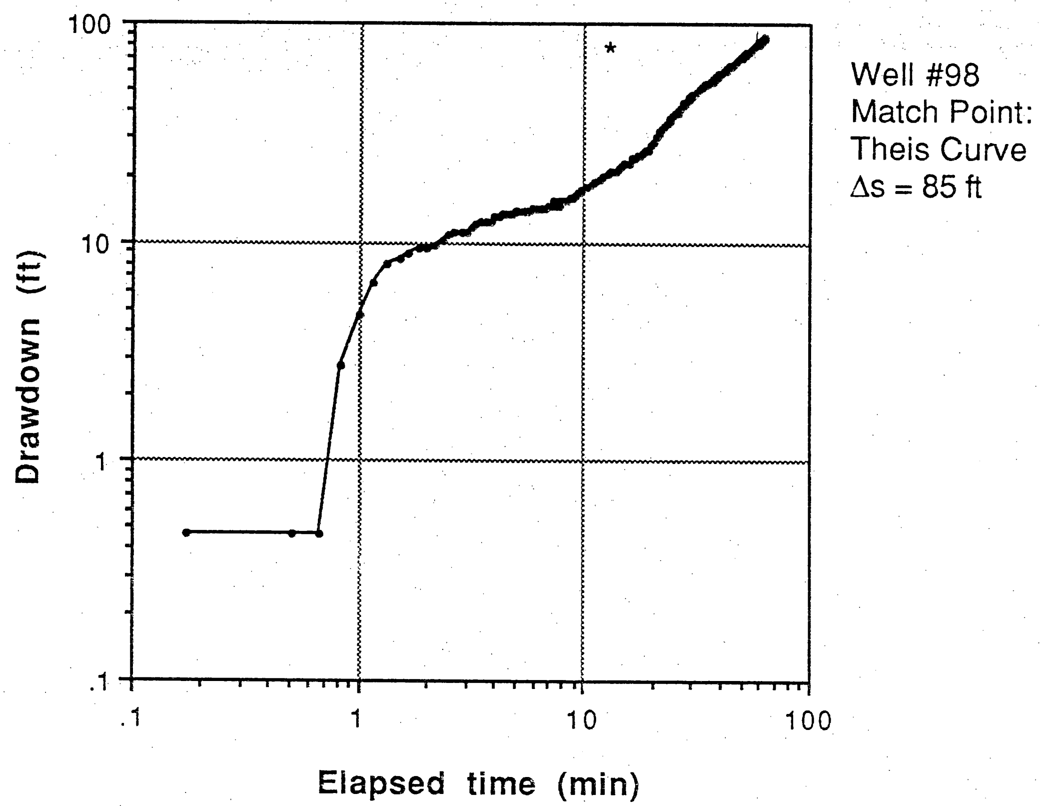

Figure 24. Plot of hydrologic test data during drawdown phase of pumping test on well no. 98. This logarithmic presentation used for matching test data with Theis's type curves.

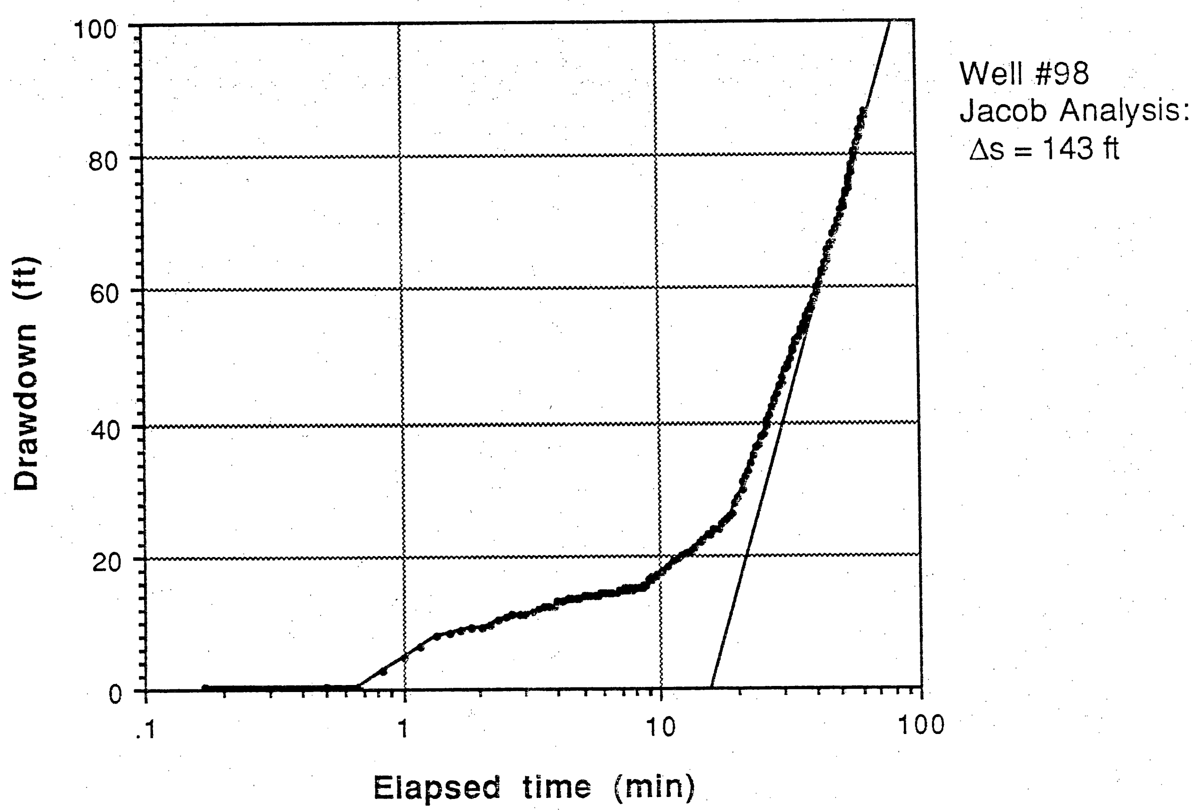

Figure 25. Plot of hydrologic test data during drawdown phase of pumping test on well no. 98. This semilogarithmic presentation used for Jacob's method of analysis.

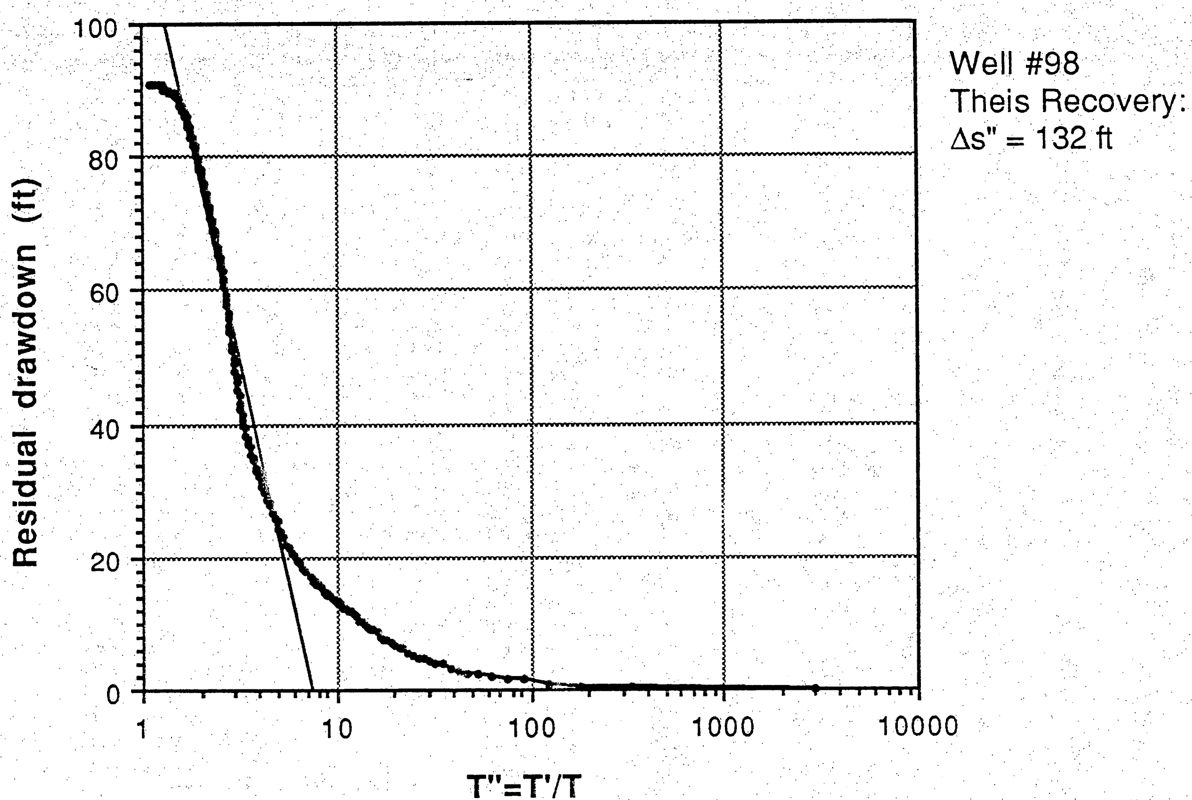

Figure 26. Plot of hydrologic test data during recovery phase of pumping test on well no. 98.

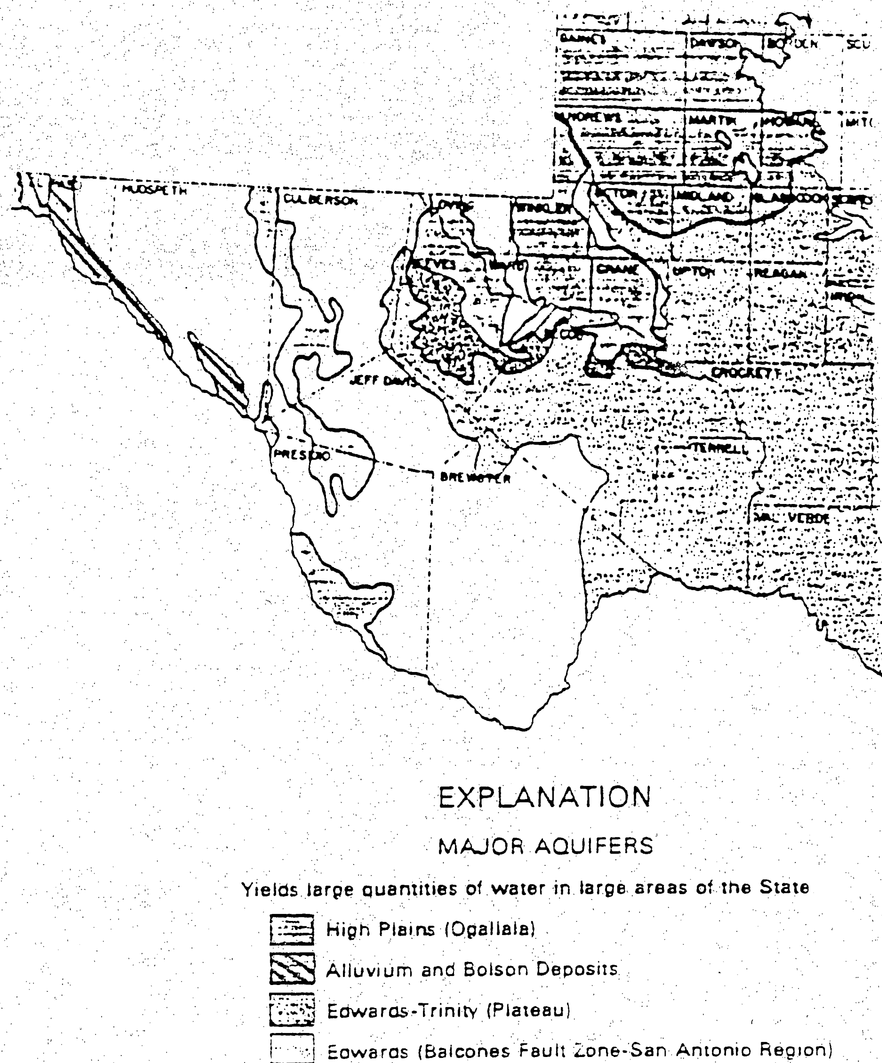

Figure 27. Texas Department of Water Resources (1984) map delineating major aquifer systems of West Texas.

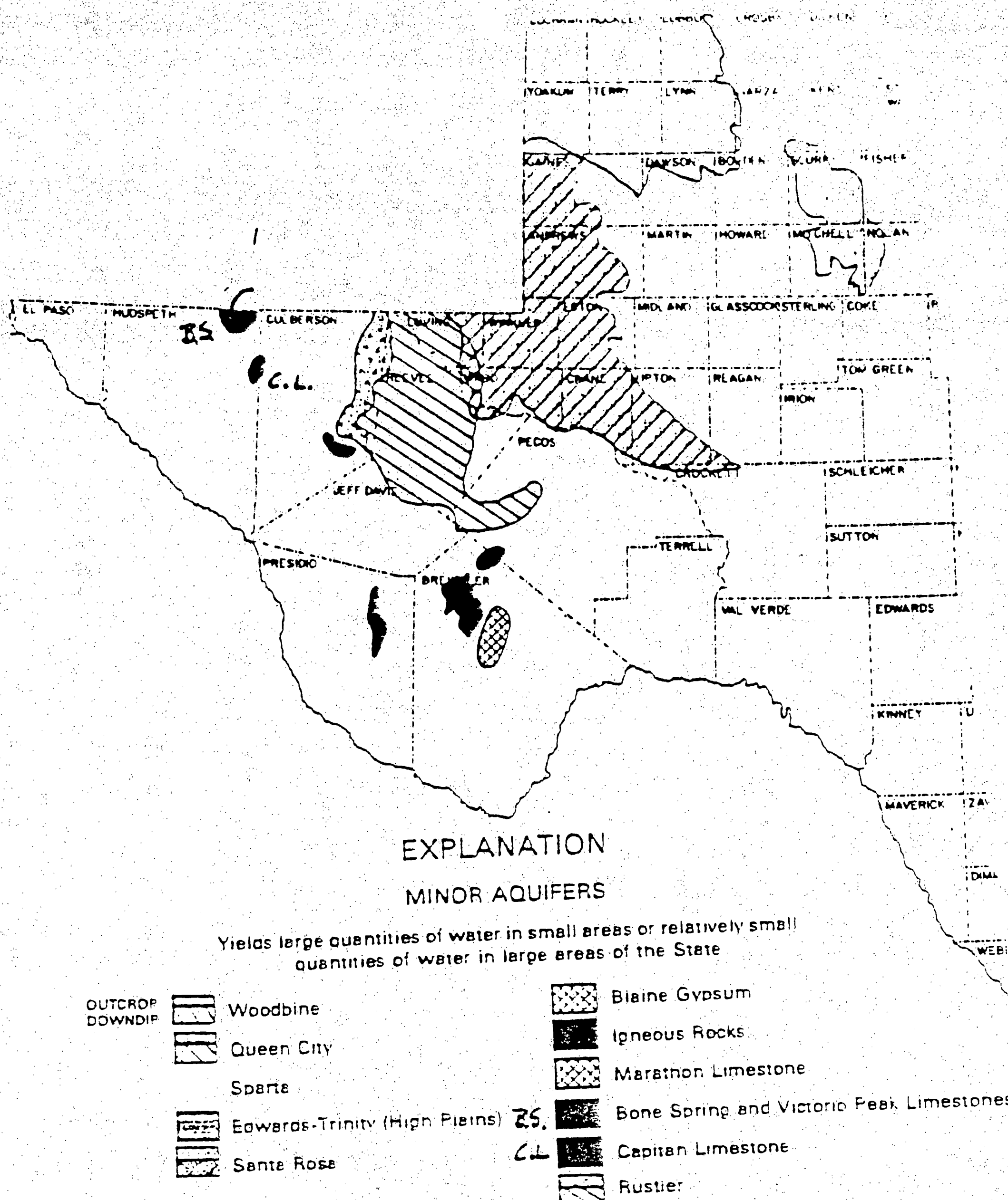

Figure 28. Texas Department of Water Resources (1984) map delineating minor aquifer systems of West Texas.

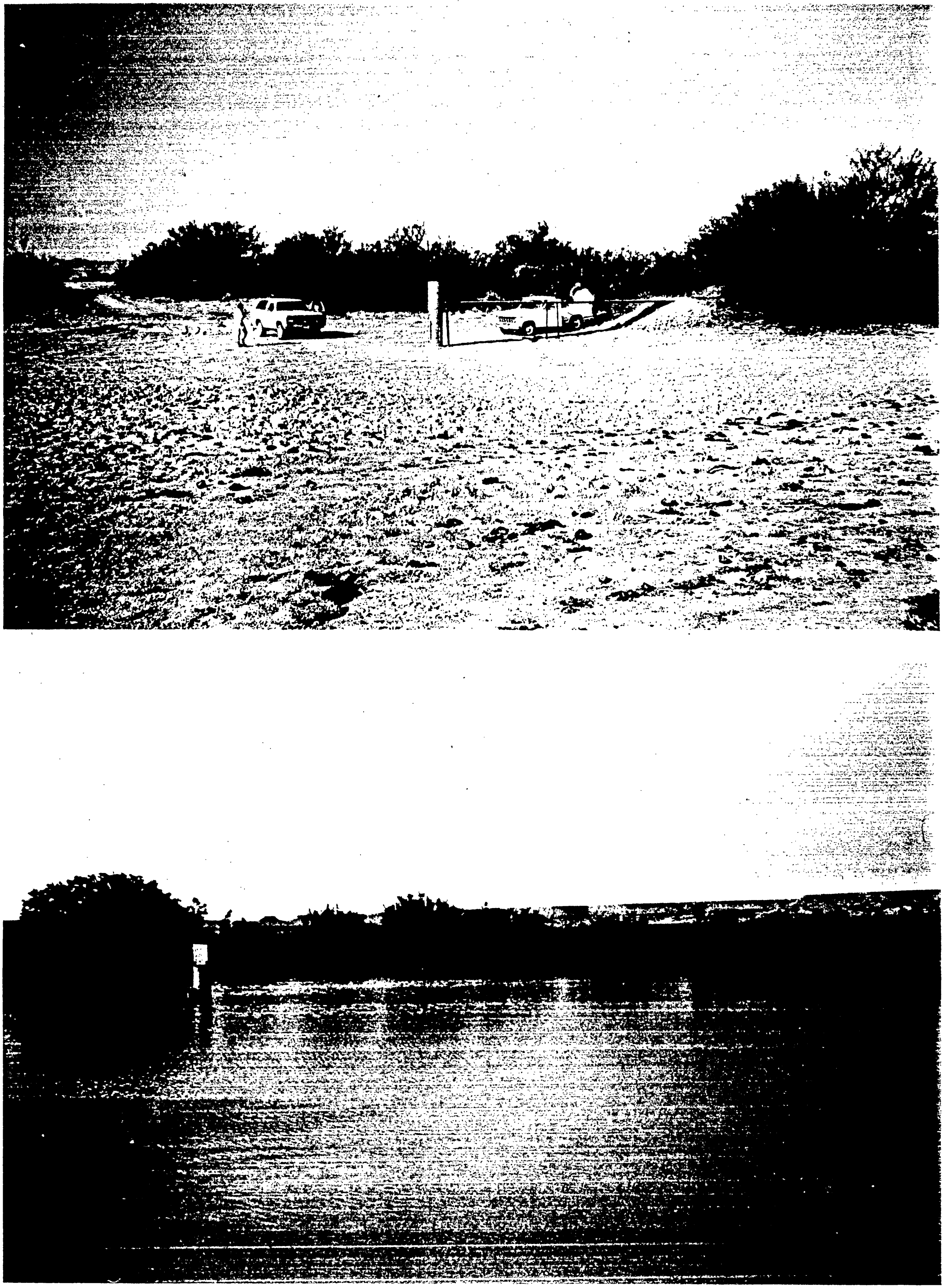

Figure 29. Photographs (A) and (B) of dirt tank located west of study area were taken immediately before and after rainfall event in July 1988.