AQUIFER TESTS AND WATER-QUALITY ANALYSES OF THE ARIKAREE FORMATION NEAR PINE RIDGE, SOUTH DAKOTA

By Earl A. Greene, Mark T. Anderson, and Darrel D. Sipe

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.06308	liter per second
mile (mi)	1.609	kilometer
inch	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot squared per day (ft^2/d)	0.09290	square meter per day
square mile (mi^2)	2.590	square kilometer

Temperature can be converted to degrees Fahrenheit (°F) or degrees Celsius (°C) by the following equations:

$$°F = 9/5\ (°C) + 32$$
$$°C = 5/9\ (°F-32)$$

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

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ABSTRACT

The Arikaree Formation was studied to determine the hydraulic properties and availability of ground water primarily for irrigation use, at a site 2 miles southeast of Pine Ridge, South Dakota, on the Pine Ridge Indian Reservation. Two production wells and five observation wells were drilled, and several aquifer tests were performed during 1987-89. Two aquifers are present within the Arikaree Formation at the study site. An unconfined aquifer extends to about 140 feet below land surface, with the depth of the water-table at about 42 feet. A confined aquifer extends from about 510 to 830 feet below land surface, with the depth of the potentiometric surface at 37 feet.

Aquifer-tests conducted on the unconfined aquifer were analyzed using the Boulton delayed yield from storage method. This method produced the following estimates of hydraulic properties: Transmissivity (T) = 1,250 feet squared per day (ft^2/d); specific yield (Sy) = 0.03; and horizontal hydraulic conductivity (K) = 13 feet per day (ft/d).

The aquifer tests on the confined aquifer were analyzed based on the assumption that water derived from pumping the well was a combination of water from storage in the aquifer and inside the well bore. The analytical method produced the following estimates of hydraulic properties: T = 300 ft^2/d, storage coefficient (S) = $3x10^{-4}$, and K = 1 ft/d.

The water from each aquifer was analyzed for about 60 water-quality parameters. The unconfined aquifer contains water with the following characteristics: pH = 7.6, specific conductance = 410 microsiemens per centimeter (μS/cm), sodium = 26 milligrams per liter (mg/L) (major cation), bicarbonate = 230 mg/L (major anion), boron = 40 micrograms per liter (μg/L) (trace element), and sodium-adsorption ratio (SAR) = 0.9. The confined aquifer contains water with the following characteristics: pH = 8.1, specific conductance = 458 μS/cm, sodium = 79 mg/L, bicarbonate = 216 mg/L, boron = 110 μg/L, and SAR = 6.

Based on the specific conductance, sodium, boron, SAR values, and other water-quality parameters, the water in the unconfined and confined aquifers is suitable for irrigation. When compared to the U.S. Environmental Protection Agency National Interim Primary Drinking Water Standards, no standard was exceeded for any parameter; therefore, water from the unconfined and confined aquifers is suitable for human consumption.

INTRODUCTION

The Oglala Sioux Tribe proposes to increase agricultural production on the Pine Ridge Indian Reservation by irrigating large areas with center-pivot sprinkler systems. Water for these irrigation systems would be derived from a combination of surface- and ground-water sources. However, the potential of ground-water sources to yield sufficient amounts of water for irrigation on the reservation is unknown. Although regionally important aquifers within the Madison Limestone, Minnelusa Formation, and Inyan Kara Group are reported to exist at various depths (Downey, 1984; Case, 1984) throughout the reservation, no water wells are known to have been completed in these regional aquifers within the reservation. Therefore, information on the hydraulic properties and water quality of these aquifers is unknown.

The Arikaree Formation, a known ground-water source, is exposed at the ground surface over most of the reservation and is extensively used as a domestic and municipal water source by the 13,200 residents of the reservation. Well depths generally are less than 300 ft and the quality of water usually is good enough for human consumption. Very little information exists on the hydraulic and water-quality properties of the Arikaree Formation within the reservation.

Because of these unknowns, the Oglala Sioux Tribe and the U.S. Bureau of Indian Affairs requested the assistance of the U.S. Geological Survey to evaluate the potential of ground water as a source of water for irrigation. Because the near-surface Arikaree Formation appeared to hold the most promise of producing significant water volumes for the proposed crop irrigation, controlled field experiments were designed and conducted at a site located 2 mi southeast of Pine Ridge, South Dakota (fig. 1). Two production wells and five observation wells were completed in the Arikaree Formation, and several aquifer tests were performed from 1987 through 1989.

Purpose and Scope

This report presents the data and results of aquifer tests performed in the unconfined and confined aquifers of the Arikaree Formation southeast of Pine Ridge, South Dakota. Suitable uses of Arikaree Formation water, based on selected water-quality characteristics, also are described.

Drawdown data from each aquifer test were analyzed by techniques based on matching of type curves developed by Boulton (1955, 1963, 1964), Papadopulos and Cooper (1967), and presented by Reed (1980). The resulting estimates of transmissivity, horizontal hydraulic conductivity, specific yield, and storage coefficient provided values to estimate availability of ground water and potential well yields at a study site located 2 mi southeast of Pine Ridge. Water-quality samples were collected from the production wells in the unconfined and confined aquifers and analyzed for about 60 water-quality parameters to determine the suitability of water for irrigation.

Previous Investigations

Geologic and hydrologic investigations of the Pine Ridge Indian Reservation and study site are limited. Darton (1909) was the first to describe the general surface geology of the reservation. The areal geology of the reservation and study site was published as part of a geologic map of South Dakota (Darton, 1951). Gries (1964) briefly discussed the surficial and shallow ground-water resources of the Pine Ridge Indian Reservation. Road logs by Harksen and MacDonald (1969) illustrate the surficial geology along specific highways and roads within the reservation, including State Highways 18 and 87 which are less than 2 mi from the study site.

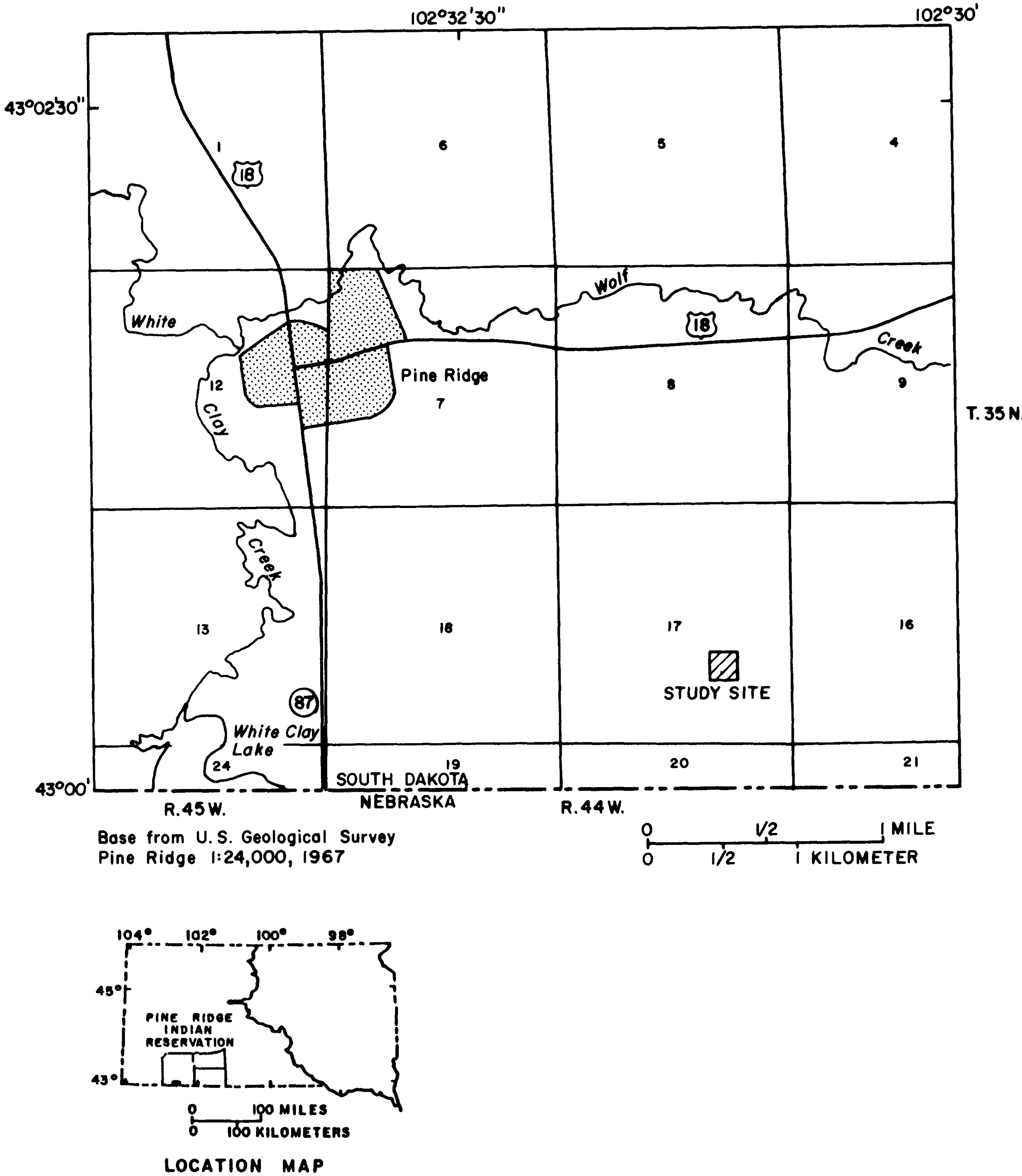


Figure 1.--Location of the study site.

The most comprehensive investigation of the ground-water hydrology of the Pine Ridge Indian Reservation was a reconnaissance study by Ellis and Adolphson (1971). They mapped major geologic units and determined the potential of these units as water sources for domestic and livestock use by analyzing well logs, records of wells and springs, and chemistry of water. Kolm and Case (1983) estimated the hydrologic parameters of the High Plains aquifer, which includes the Arikaree Formation, by using a two-dimensional finite-difference model. The estimated properties include the following range of values: saturated thickness, 0 to 600 ft; hydraulic conductivity, 10 to 160 ft/d; and specific yield, 0 to 0.25. Detailed aquifer characteristics, including the hydraulic properties of the Arikaree Formation at the study site, have not been published.

The quality of water from wells in the Arikaree Formation within the reservation was first described by Adolphson and Ellis (1969). Meyer (1984) summarized the water-quality data for the reservation contained in the U.S. Geological Survey National Water Data Storage and Retrieval System (WATSTORE). Most recently, Heintzman (1988) completed a Master's thesis for the South Dakota School of Mines and Technology which evaluated the water quality of 39 wells distributed throughout the reservation.

Acknowledgments

The authors would like to extend their appreciation to Calvin Clifford of the Indian Health Service and to Sargent Irrigation Company. Mr. Clifford provided assistance with local site conditions, well-field checks, and expertise on wiring of pumps. Sargent Irrigation Company provided equipment and personnel to help complete additional aquifer tests subsequent to expiration of the contract.

GEOHYDROLOGY OF THE STUDY SITE

Geologic Setting

A detailed map describing geology in the vicinity of the study site has not been published. A generalized geologic map and stratigraphic section was published by Ellis and Adolphson (1971) for the entire Pine Ridge Indian Reservation, including the study site. The generalized stratigraphic section describing the geologic units of the study site, based on the work of Harksen (1967), Harksen and MacDonald (1969), and Ellis and Adolphson (1971), is presented in table 1.

The principal geologic units exposed in the vicinity of the study site, in ascending order, are: (1) The Niobrara Formation, (2) the Arikaree Formation, (3) the Ogallala Formation, and (4) alluvial and terrace deposits. A map of these exposed geologic units is shown in figure 2. These geologic units were determined by interpreting driller's logs, cuttings, geophysical logs, and published geologic data by Harksen (1967), Adolphson and Ellis (1969), and Ellis and Adolphson (1971). Site-specific geology was interpreted using borehole geophysics and drill cuttings. A natural-gamma log and a geologist's log from the study site are shown in figure 3. The White Clay fault is located approximately 1 mi to the southwest of the study site (fig. 2) and has approximately 500 ft of vertical displacement (Gutentag and others, 1984).

Table 1.--Generalized stratigraphic section in the vicinity of the study site

[Modified from Harksen, 1967; Harksen and MacDonald, 1969; and Ellis and Adolphson, 1971]

System	Series	Geologic unit and subdivision		Thickness (feet)	Hydrology	Description
Quaternary	Holocene and Pleistocene	Alluvium and terrace deposits		0-180	Saturated alluvium.	Light-brown to gray clay, silt, fine sand, with thin beds of medium to coarse coarse gravel.
Tertiary	Miocene	Ogallala Formation	Upper unit	0-150	Nearly impermeable.	Light-tan to light-gray calcareous, massive sandstone.
			Lower unit	0-200	Water-bearing part of High Plains aquifer.	Light-gray to light olive-green, unconsolidated or poorly consolidated fine to medium sand.
		Arikaree Formation	Unit E	0-235	Units E and B are water-bearing at the study site. Units D and C are nearly impermeable.	Light-tan to brown, sandy clays and silts interbedded with very coarse to fine-grained sandstone.
			Unit D	0-125	Unit A is missing, therefore, water-bearing properties could not be determined at the study site.	Gray, massive, poorly consolidated, siltstone, fine to very fine-grained sandstone. Difficult to distinguish from overlying and underlying beds.
			Unit C	0-150		Gray to buff-colored massive siltstone, well compacted series of clay to sandy silts with volcanic ash. Difficult to distinguish from overlying and underlying beds.
			Unit B	0-375		Pinkish-tan, poorly consolidated silt and very fine-grained silty sandstone.
			Unit A	0-45		White, tan, buff, and reddish-brown silty volcanic ash, interbedded with thin layers of silt. This unit is missing at the study site.
	Oligocene	White River Group	Brule Formation	0-450	Generally too impermeable to serve as a source of ground water.	Gray, yellowish-gray, and buff unconsolidated sandy clays and siltstone, with distinct zones of calcareous concretions.
			Chadron Formation	0-110	Generally too impermeable to serve as a source of ground water.	Pale gray-green bentonitic clay alternating with layers of greenish-gray siltstone.
Cretaceous	Upper Cretaceous	Pierre Shale		0-1,200	Generally too impermeable to serve as a ground-water source.	Dark-gray marine shale and mudstone, containing several zones characterized by bentonitic beds, concretions, or differences in lithology.
		Niobrara Formation		0-325	Normally not a source of ground water.	Upper one-third consists of yellowish-gray to pale-yellow shaly limestone. Lower two-thirds consist of light-grayish-yellow to brownish-yellow, very calcareous shale, that conteins scattered thin interbeds of chalk and limestone.

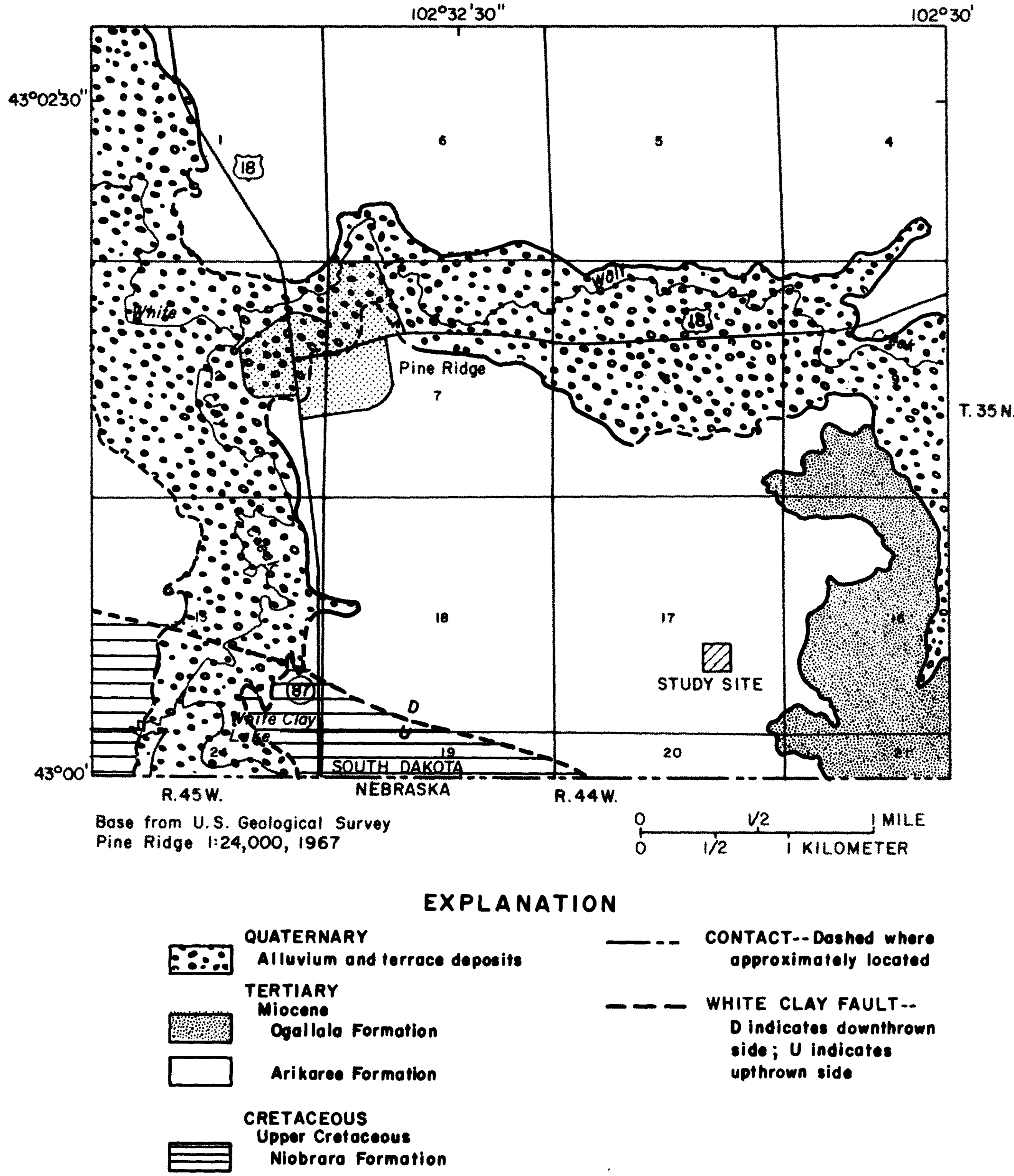
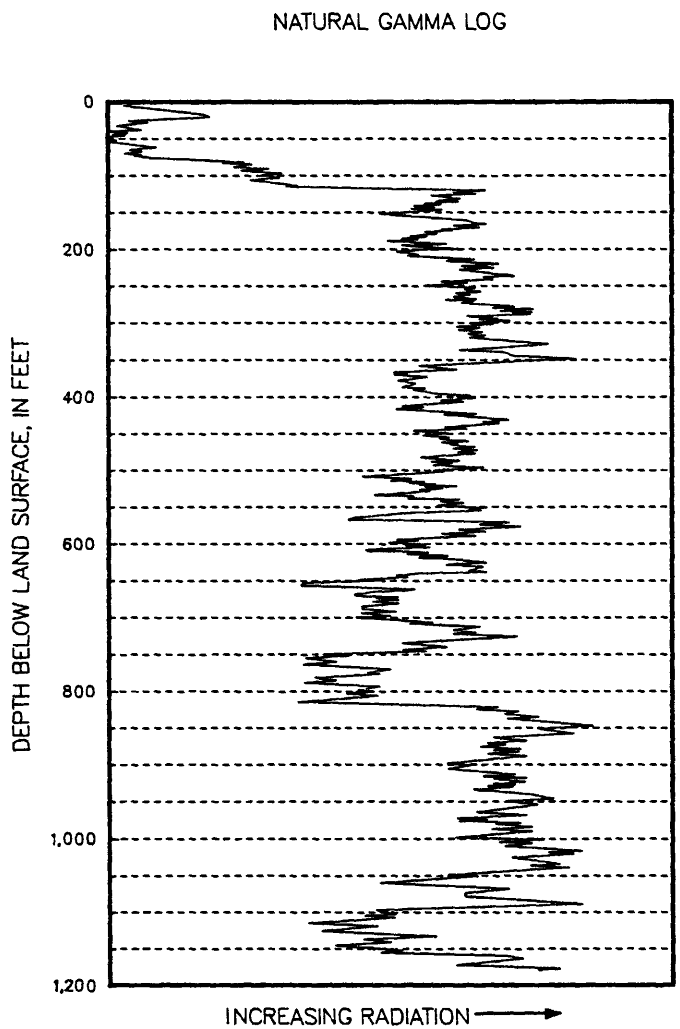


Figure 2.--Generalized geology of the study site and surrounding area (modified from Ellis and Adolphson, 1971, and Harksen, 1967).



GEOLOGIST'S LOG

Depth Below Land Surface (feet)	Description
Arikaree Formation	
Unit E	
0 – 119	Topsoil; sandstone, medium to very coarse-grained, poorly consolidated subrounded to subangular grains, light-brown to buff, contains some white siltstone.
119 – 140	Sandstone, fine to medium-grained, poorly consolidated, subrounded to subspherical grains, calcareous, light-brown to gray, contains some white to buff siltstone.
140 – 190	Sandstone, fine to medium-grained, poorly consolidated, subangular to subspherical, calcareous, light-brown to buff; clayey and contains some white to buff siltstone.
Unit D	
190 – 360	Clay, light brown; siltstone, white to gray; sandstone very fine to fine-grained, light brown to buff; a few disseminated red and yellow chert fragments and traces of calcite fragments are found throughout the interval.
Unit C	
360 – 510	Clay, light brown to gray; siltstone, white to buff; sandstone, very fine to fine-grained, light-brown to buff, calcareous, contains some volcanic ash.
Unit B	
510 – 642	Sandstone, very fine to medium-grained, light brown to buff, poorly consolidated, calcareous; siltstone, white to buff; clay, light brown, with volcanic ash.
642 – 830	Sandstone, fine to medium-grained, poorly consolidated, light brown to buff; clay and siltstone, light brown to buff.
White River Group	
Brule Formation	
830 – 1045	Clay, buff; siltstone, white to buff; sandstone, very fine to fine-grained, light brown to buff, calcareous.
1045 – 1180	Clay, buff; sandstone, very fine to fine-grained, light brown to buff; siltstone, light brown to buff.

Figure 3.--Natural gamma log and geologist's log of observation well E-2 at the study site.

The Niobrara Formation is a calcareous shale interbedded with minor beds of chalk and limestone. The formation has a maximum thickness of about 325 ft in the vicinity of the study site. Southwest of the study site, the Niobrara Formation is in contact at the surface with the Arikaree Formation because of the White Clay fault. The Niobrara Formation, normally overlaid by the Pierre Shale and underlaid by the Carlile Shale, is not considered an important source of ground water in South Dakota.

The White River Group, not exposed at the study site, is the lower confining unit of the Arikaree Formation. The White River Group is divided into two formations; the upper is the Brule Formation and the lower is the Chadron Formation. These formations, composed of unconsolidated shales, siltstones, and sandy clays, cannot be distinguished from each other locally. Geologists' logs and geophysical logs from the study site indicate the thickness of the Brule Formation of the White River Group to be at least 280 ft. The White River Group, which overlies the Pierre Shale, generally is too impermeable to serve as a source of ground-water.

The Arikaree Formation is the major sedimentary deposit exposed at the study site. The Arikaree Formation predominantly is a massive, very fine to fine-grained sandstone with local beds of volcanic ash, silty sand, siltstone, and sandy clay. The Arikaree Formation is underlaid by the Brule Formation and is overlaid by the lower unit of the Ogallala Formation.

The Arikaree Formation is divided into five geologic subdivisions by Ellis and Adolphson (1971). These units, from oldest to youngest, are designated A through E. The South Dakota Geological Survey refers to the Arikaree Formation as the Arikaree Group and has divided the group into a number of formations and formation members. The Rockyford Ash Member of the Sharps Formation corresponds to unit A and an unnamed member of the Sharps Formation corresponds to unit B. The Monroe Creek Formation is equivalent to unit C and the Harrison Formation is equivalent to unit D. The Rosebud Formation corresponds to unit E of the Arikaree Formation (Harksen and MacDonald, 1969).

Unit A of the Arikaree Formation appears to be missing at the study site. This unit caps buttes and tables in the northwestern part of the reservation and is widely but discontinuously exposed.

Unit B of the Arikaree Formation consists of silty sandstone that is massive, poorly consolidated, and contains fine to very fine-grained sand. Layers of channel sand consisting of multi-colored, medium to pebble-sized quartz particles are present throughout the unit. Local beds of volcanic ash, siltstone, claystone, and limestone also are present. Geophysical and drill cutting data (fig. 3) indicate that the unit is about 320 ft thick at the study site. The unit is water bearing where sand layers are present.

Unit C of the Arikaree Formation is a massive, well-compacted series of clay to sandy silts. The unit is uniform in texture and contains a large percentage of volcanic ash. Site-specific data from borehole geophysical and drill cutting data (fig. 3) indicate that the unit is about 150 ft thick, however, gradational contacts make unit C difficult to distinguish from underlying and overlying units. Unit C is characterized by alternating layers of clay and silt, and is nearly impermeable.

Unit D of the Arikaree Formation is composed of clay and silty sands that are massive, moderately consolidated, and fine to very fine-grained sandstone. Channel deposits containing calcareous cement and impure limestones are present at several levels. Borehole geophysical and drill cutting data (fig. 3) indicate that the unit is about 170 ft thick and is nearly impermeable at the study site.

Unit E of the Arikaree Formation is about 190 ft thick and consists of interbedded calcareous sand, silt, and clay layers. Borehole geophysical logs and drill cuttings (fig. 3) show the sands of the unit consist of fine- to medium-grained, permeable sands in the upper 119 ft of the unit. The lower 71 ft of the unit consists of thin, fine- to medium-grained sand layers interbedded with layers of clay and silt. Unit E is adjacent to the Niobrara Formation in the vicinity of the study site because of faulting and is unconformably overlaid by the Ogallala Formation.

The Ogallala Formation near the study site attains a thickness up to 150 ft and is a massive medium-grained sandstone, with poorly sorted sand, gravel, silt, and clay.

The Quaternary units in the vicinity of the study site consist of alluvial and terrace deposits. The alluvium consists of clay, silt, sand, and discontinuous sandy and clayey gravel beds. The terrace deposits are comprised of clay, silt, and fine sand interbedded with discontinuous lenses of medium to coarse gravel.

Hydrologic Setting

The High Plains aquifer underlies about three-fourths of the Pine Ridge Indian Reservation where the Arikaree and Ogallala Formations are present. This aquifer is the principal source of water for irrigation, industrial, municipal, and domestic use in south-central South Dakota. Regionally, the High Plains aquifer is an unconfined (water-table) aquifer consisting of near-surface sand and gravel deposits (Gutentag and others, 1984), but locally some of the permeable beds that make up the aquifer are under confined conditions.

Interpretation of test drilling, borehole geophysical logs, and drill-cutting data obtained at the study site indicated the presence of two aquifers in the Arikaree Formation. The upper aquifer is unconfined at the site, and is saturated from about 42 to 140 ft below land surface. The lower aquifer is confined and extends from about 510 to 830 ft below land surface. Water-level and subsurface data gathered from observation wells show these aquifers are not well connected hydraulically. The upper unconfined aquifer is in unit E of the Arikaree Formation; the lower confined aquifer is in unit B.

Unconfined Aquifer

The unconfined aquifer at the study site comprises the saturated permeable sediments of the upper 140 ft of the Arikaree Formation. The water level in the aquifer measured on November 10, 1988, was about 42 ft below the ground surface. The aquifer has a saturated thickness of about 98 ft and consists of fine to medium, silty sands interbedded with lenses of very fine-grained, calcareous sandstones. A sequence of concretionary sandstone layers interbedded with clay at the base of unit E defines the nearly impermeable base of the aquifer. Near the study site, this aquifer is developed for domestic and agricultural uses. However, until this study, very little was known about its hydraulic properties.

Altitudes of static water levels measured in observation wells at the study site indicate ground-water movement in the unconfined aquifer is northwest towards the city of Pine Ridge. Ground-water flow direction for the unconfined aquifer determined from static water-table altitudes are shown in figure 4.

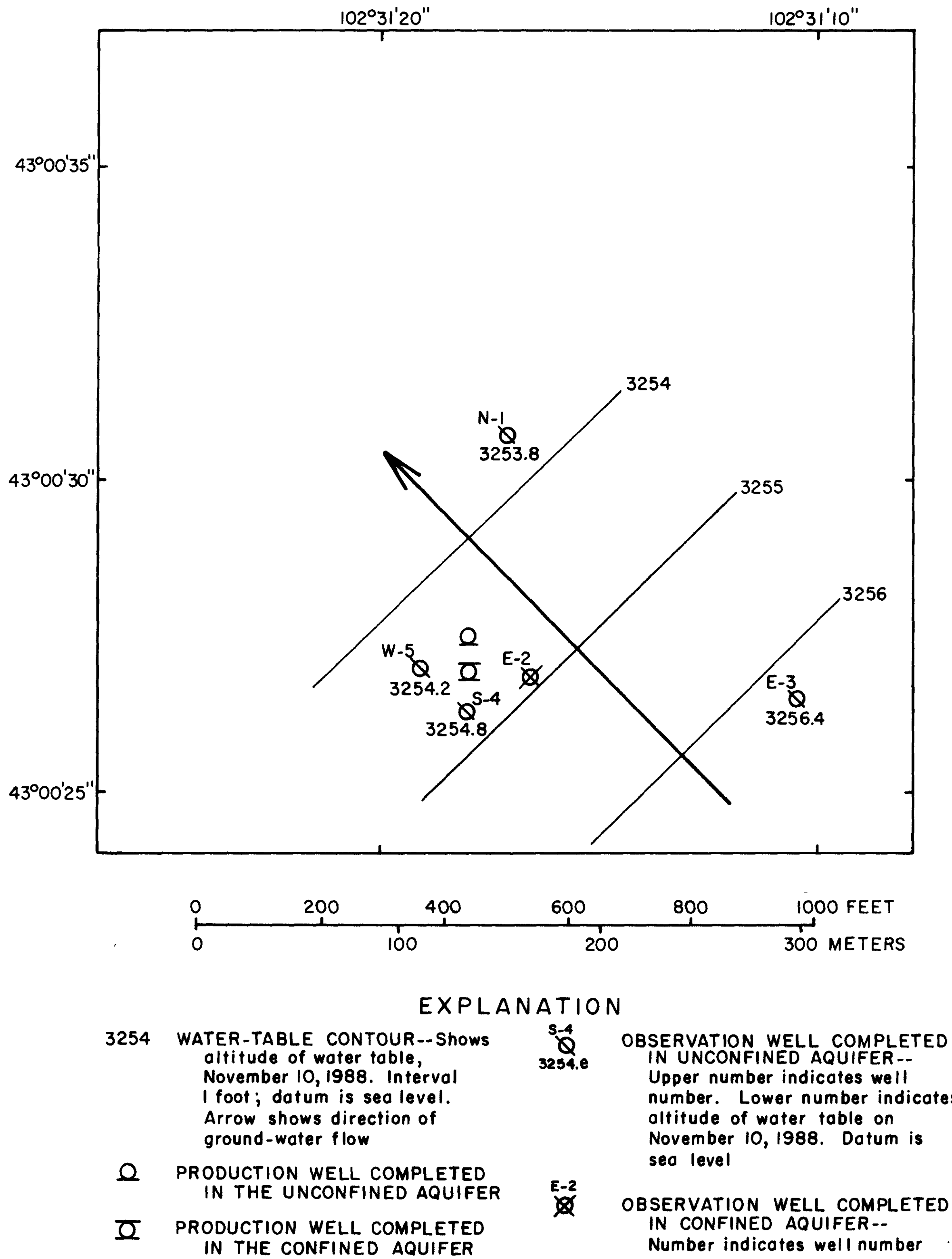


Figure 4.--Areal design of the well field and direction of ground-water flow in the unconfined aquifer at the study site located in the SE¼ of section 17, T. 35 N., R. 44 W.

Confined Aquifer

The confined aquifer at the study site is in unit B of the Arikaree Formation. Unit B comprises about 320 ft of stratified sediments containing permeable sand lenses interbedded with lenses of silt and clay from 510 to 830 ft below land surface. Based on test drilling, borehole geophysical logs, and drill cuttings, the aquifer contains about 170 ft of permeable sand.

The top of the lower confining unit is at 830 ft, and consists of the shales and siltstones of the Brule Formation of the White River Group. The upper confining unit from 360 to 510 ft below the surface is composed of the clay and sandy silts of unit C of the Arikaree Formation. The potentiometric surface in the confined aquifer is about 37 ft below the ground surface, about 5 ft above the water table at the study site.

DESCRIPTION OF WELLS

Production wells and observation wells were drilled and installed by private contractors from July 1986 to September 1987. The relative locations of the wells at the study site are shown in figure 4. The relation of well depths and screened intervals to the geohydrologic system at the study site is shown in figure 5. The distance of observation wells from the corresponding production well and position of well screens for all wells are given in table 2.

The production well in the unconfined aquifer originally was cased with 16-inch diameter steel casing from 0 to 60 ft and screened with slotted steel casing from 60 to 180 ft in depth. The well annulus was packed with 1/4- to 3/8-inch washed pea gravel. After experiencing difficulties in developing the well and with excessive production of sand during the first aquifer test on October 13, 1987, the well was lined with a 12-inch diameter casing from the surface to a depth of 60 ft, and a 12-inch diameter galvanized wire-wrapped steel screen with 0.025-inch openings from 60 to 140 ft which included about 83 percent of the saturated thickness of the aquifer. The annulus between the 12- and 16-inch casing was then packed with Luther Maddox type "C" well gravel that had a mean diameter of 0.0625 inches. A schematic of the construction details of the production well in the unconfined aquifer is shown in figure 6.

Table 2.--Data on position of well screens and distance of observation wells from the corresponding production wells

Production well	Observation well	Distance of observation well from production well (feet)	Depth of screened interval below land surface (feet)
Unconfined	--	--	60-140
	N-1	337	39- 90
	E-3	536	48- 80
	S-4	111	44-213
	W-5	88	43-100
Confined	--	--	[1]505-835
	E-2	100	[1]505-835

[1]180 feet of screen alternating with 150 feet of blank casing.

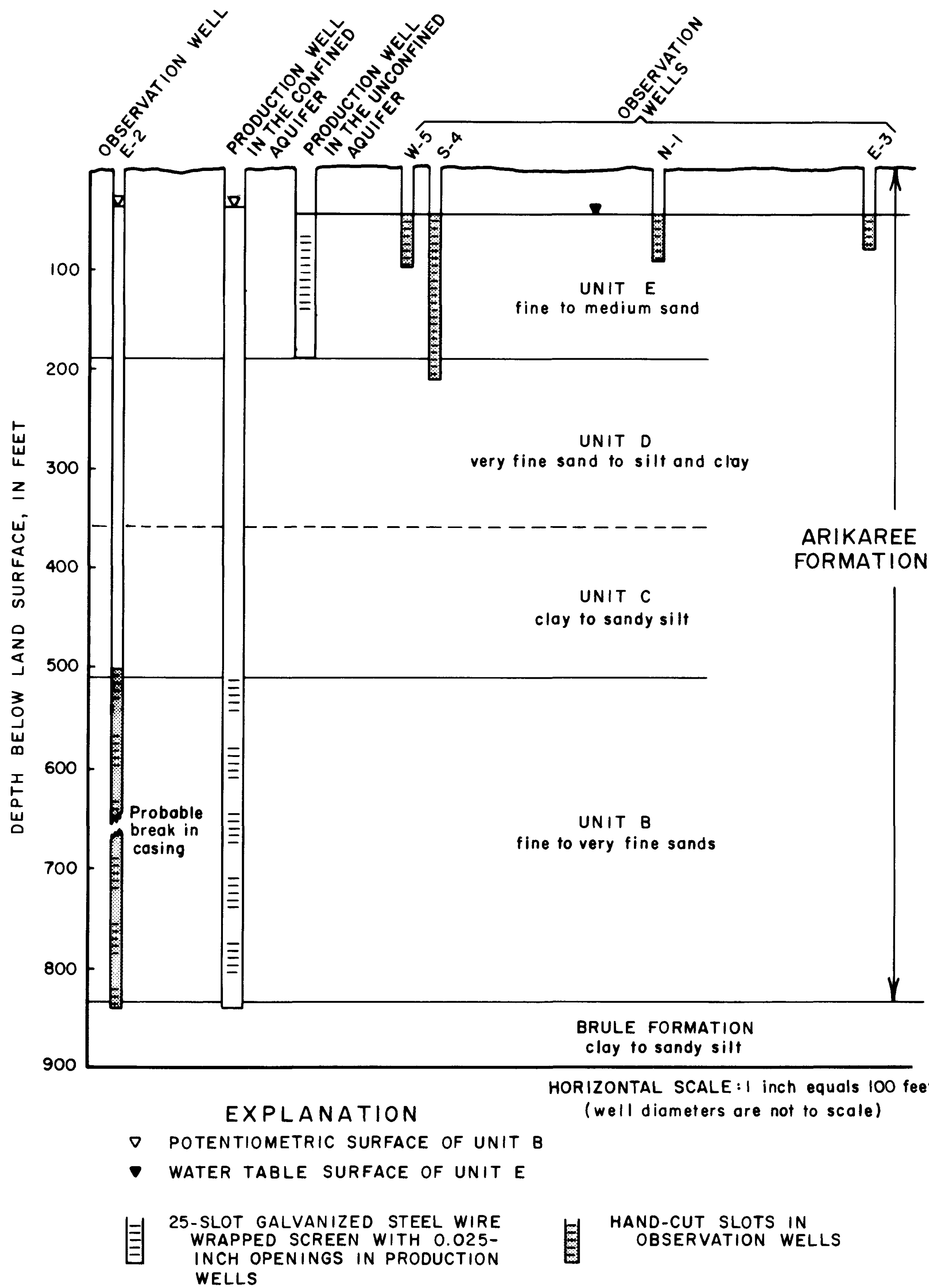


Figure 5.--Relation of well depths and screened intervals to the geohydrology of the study site.

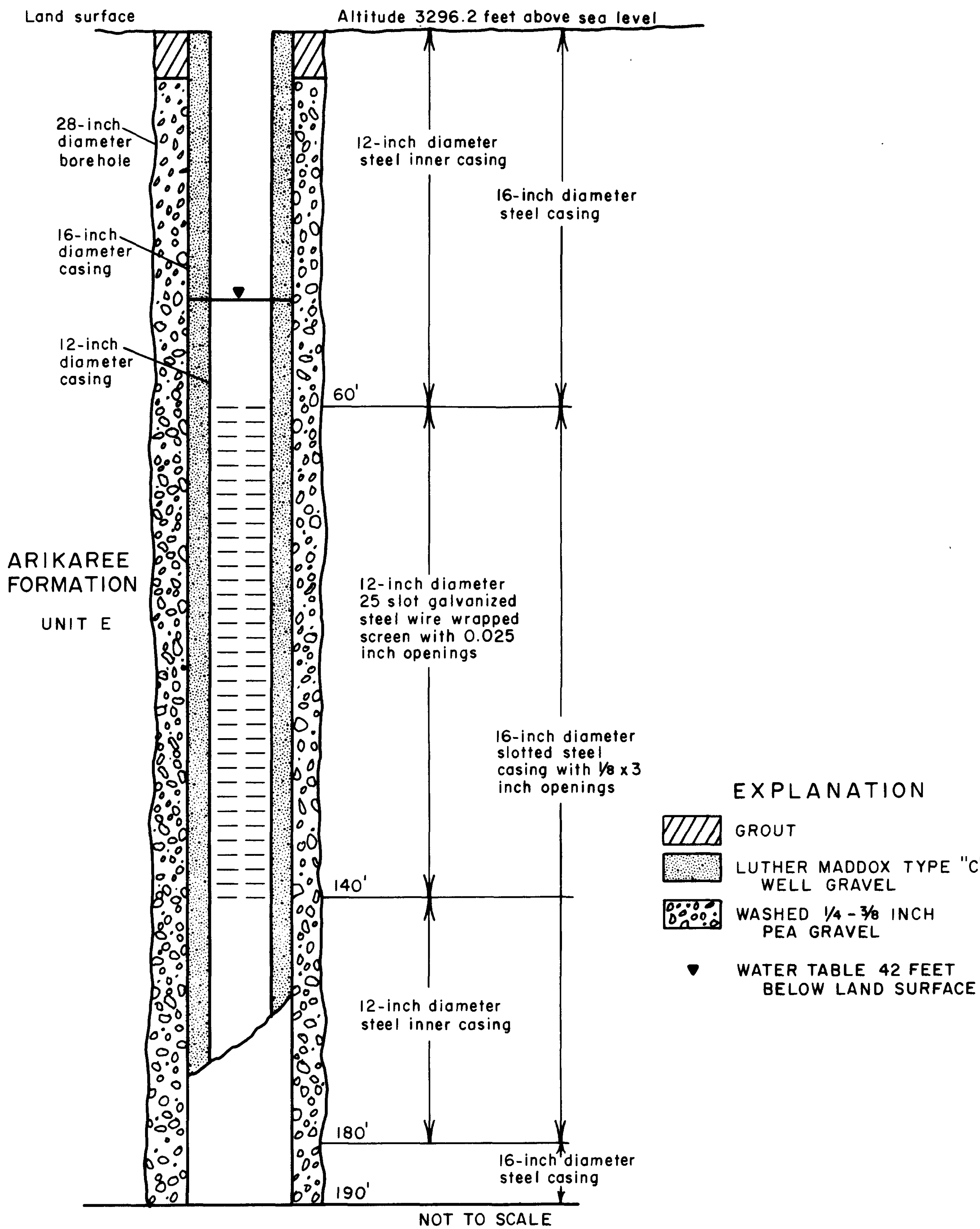


Figure 6.--Vertical cross section of the production well in the unconfined aquifer showing construction details.

The production well in the confined aquifer was cased with 12-inch diameter steel casing from the land surface to 505 ft. From 505 to 835 ft, the well was cased with alternating sections of 8-inch diameter steel casing and 8-inch diameter galvanized wire-wrapped steel screen with openings of 0.025 inch. The screen intervals of the well total 180 ft and were installed adjacent to the more permeable sandy zones of the aquifer. The well annulus was packed with Luther Maddox type "C" well gravel. A schematic of the construction details of the production well in the confined aquifer is shown in figure 7.

Four 2-inch diameter observation wells were installed in the unconfined aquifer in a radial pattern around the production well in the unconfined aquifer to provide information on the shape of the cone of depression. All four wells were cased with 2-inch PVC plastic pipe and were slotted with a hand saw. Slotted intervals in the observation wells extend from the static water table to the bottom of the well. Observation wells W-5, N-1, and E-3 partially penetrate the unconfined aquifer, whereas observation well S-4 fully penetrates the unconfined aquifer, as shown in figure 5.

Observation well E-2 was drilled initially as a test hole to a depth of 1,180 ft to determine the thickness of the Arikaree Formation. The hole was cased with 505 ft of 2-inch schedule 40 PVC plastic pipe and screened from 505 to 835 ft with alternating screened intervals and blank casing using a total of 180 ft of plastic screen. The same intervals were screened as the production well in the confined aquifer. Prior to aquifer testing, well E-2 was sounded to a maximum depth of only 660 ft, indicating a probable break in the casing at this point.

AQUIFER-TEST DATA AND ANALYSIS

Aquifer tests were conducted on various occasions during 1987, 1988, and 1989 on units E and B of the Arikaree Formation near Pine Ridge. The aquifer tests were designed to determine the hydraulic properties of transmissivity (T), specific yield (Sy) in the unconfined aquifer, storage coefficient (S) in the confined aquifer, and hydraulic conductivity (K) of the water-bearing units of the formation.

During all tests, data were collected according to the standards for aquifer-test data collection and analysis (Stallman, 1971). Production-well pumping rates were maintained within 10 percent of the design pumping rate, water levels in observation wells were measured to within 0.01 ft, elevations of measuring points were measured to 0.1 ft, and the distances from production wells to observation wells were measured to within 1 ft. Water discharged from the production wells was removed from the well field area in a plastic-lined trench to prevent recharge to the aquifers during the tests. Precipitation was measured during all aquifer tests.

Monthly water-level data were collected in all observation wells to establish antecedent conditions of water-level trends in the aquifers. Water-level trends from September 1987 to July 1989 for the unconfined and confined aquifers are shown in figure 8.

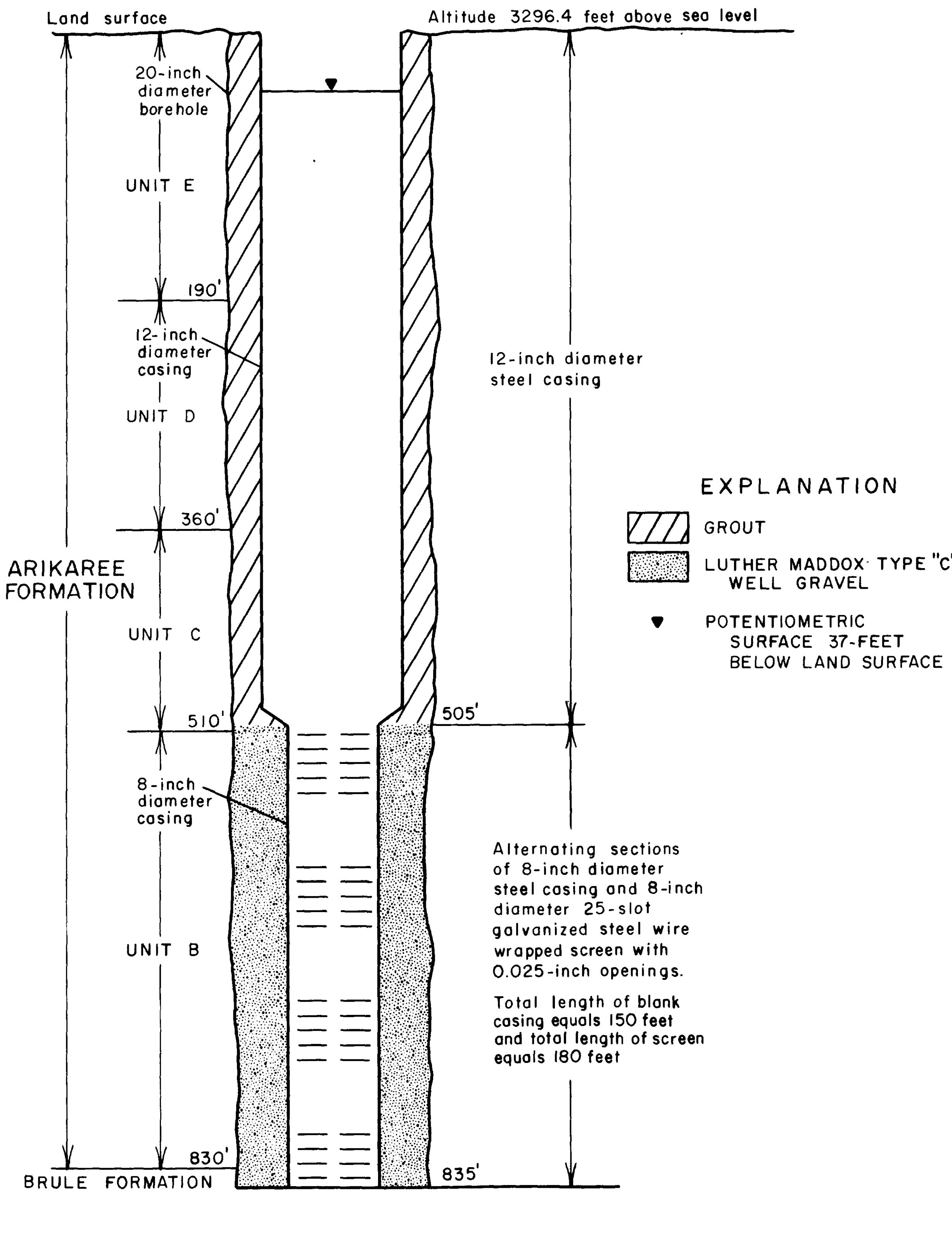


Figure 7.--Vertical cross section of the production well in the confined aquifer showing construction details.

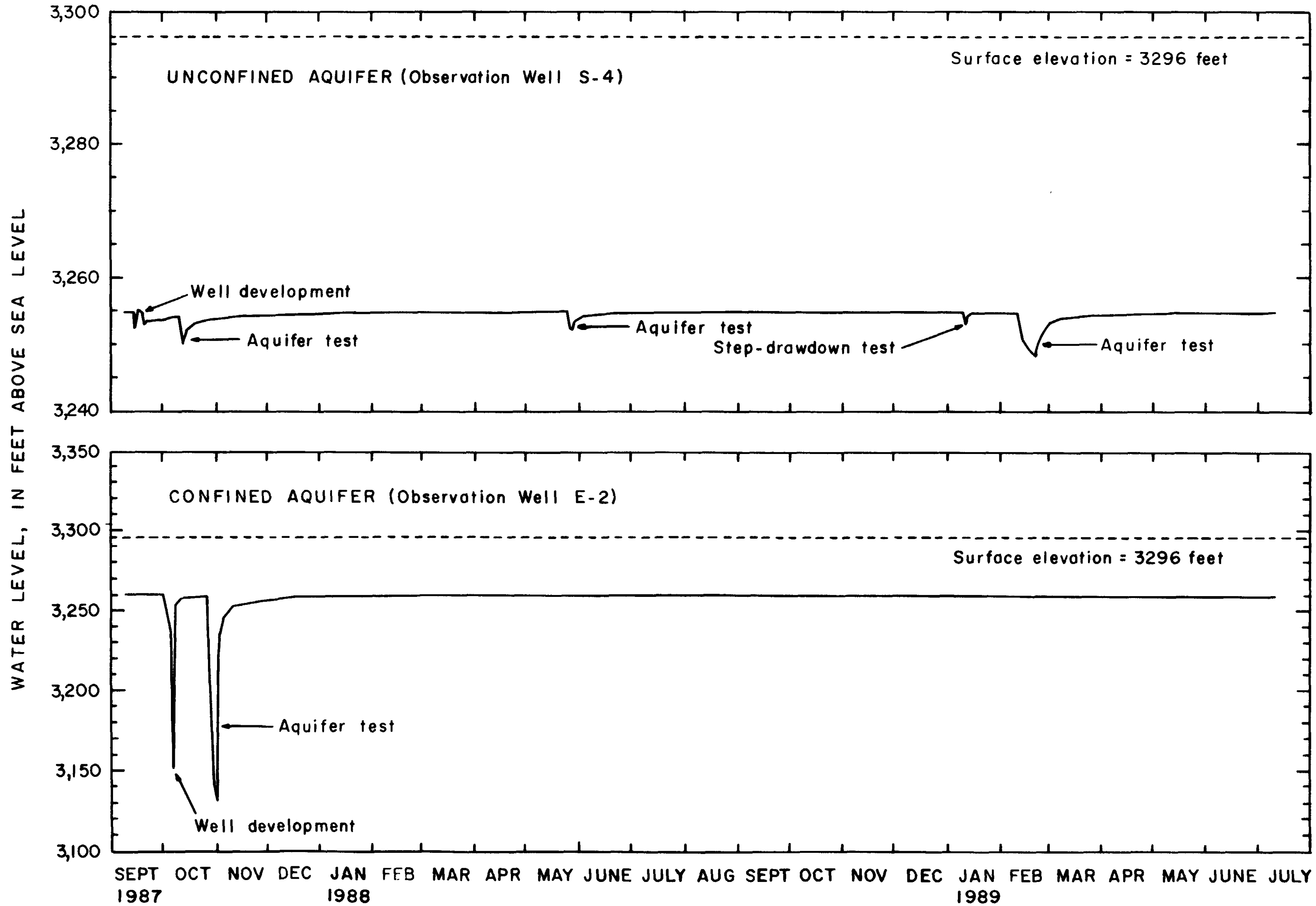


Figure 8.--Water-level trends at the study site for the unconfined and confined aquifers of the Arikaree Formation.

Unconfined Aquifer

Four aquifer tests were conducted on the unconfined aquifer to determine its hydraulic properties. The following is a brief description of each of the tests.

Data Collection

The first aquifer test began on October 13, 1987, and the production well was pumped for 51 hours at a rate of 190 gal/min. During the test, the well produced excessive amounts of sand, and the pumping rate varied by more than 10 percent due to an unstable power source. The coarse gravel pack and screen were determined to be responsible for the sand production, and the well was retrofitted with galvanized screen and Luther Maddox type "C" gravel pack as shown in figure 6. The data obtained from the first test were not used in the calculation of hydraulic properties of the unconfined aquifer.

On May 27, 1988, a second test of the unconfined aquifer (referred to as the 1988 aquifer test) was begun. A 5-horsepower submersible pump powered by a portable generator was used to pump the production well at a rate of 90 gal/min. Discharge remained within 5 percent of 90 gal/min throughout the first 42 hours of the test. Between 42 hours and 44.5 hours of pumping, discharge varied as much as 13 percent due to generator problems. Drawdown in the production well was measured with an air line, and recovery was measured with an electric water-level indicator. Measurements in the observation wells were taken with electric water-level indicators and steel tapes. During the test, the production well in the confined aquifer and the observation well (E-2) in the confined aquifer were monitored for changes in water level. The aquifer-test data (table 5, Supplemental Data section at the end of this report) from this test were used to determine the storage and transmissivity values of the aquifer.

Because lining the production well in the unconfined aquifer might have caused a large increase in frictional head loss in the well, a step-drawdown test of the production well was made on January 13, 1989. The step-drawdown test can be used to calculate head losses (water-level declines) caused by turbulent flow in the well bore and to determine aquifer transmissivity.

The step-drawdown test consisted of 4 steps at pumping rates of 43, 58, 78, and 87 gal/min. The test lasted for 445 minutes and drawdown in the production well in the unconfined aquifer was measured with an electronic data logger and a pressure transducer. Data obtained with the data logger and pressure transducer were checked with electric water-level indicators. Aquifer-test data for the step-drawdown test are presented in table 6 of the Supplemental Data section.

The last test of the unconfined aquifer (referred to as the 1989 aquifer test) was started on February 13, 1989, to measure aquifer response to a larger pumping rate and to obtain drawdown data for longer pumping periods. Aquifer-test data for this test are presented in table 7, Supplemental Data section. After 47.5 hours, the constant-rate aquifer test was stopped because variations in the pumping rate exceeded 10 percent of 115 gal/min. Data loggers and pressure transducers were installed and used to monitor drawdown in the production well and observations wells W-5 and S-4. Measurements made by data loggers and pressure transducers were checked with electric water-level indicators or steel tapes. Water levels in observation wells N-1 and E-3 were measured with electric water-level indicators.

In all tests of the unconfined aquifer, drawdowns in observation wells N-1 and E-3 were too small for analysis. Drawdown in observation wells W-5 and S-4 were sufficient for analysis.

Drawdown Corrections

In application of analytical techniques to determine the hydraulic properties of an aquifer under unconfined conditions, measured values of drawdown must be corrected for the decrease in saturated thickness (dewatering) of the aquifer (Jacob, 1963). The dewatering adjustment equation ($s-(s^2/2b)$, where s is measured drawdown and b is aquifer thickness) was applied to all test data. Because the maximum adjustment was only 0.12 feet, dewatering effects in the unconfined aquifer during the tests were minimal.

In addition to adjusting drawdown values for dewatering, drawdown data also must be adjusted for partial penetration of the pumping (production) and observation wells. If a pumped well only partially penetrates an unconfined aquifer, then the cone of depression is distorted and the measured drawdowns in observation wells will be different from theoretical values. Because the production well is screened throughout the bottom 83 percent of the aquifer, this well was assumed to be fully penetrating for analysis purposes. Neuman (1975) used the same assumption when analyzing data from an aquifer test in an unconfined aquifer where the pumping well had a similar large percentage of penetration (82 percent) through the aquifer.

Drawdown in unconfined aquifers is affected by the curvature of the water table near the pumping well, resulting in curvature of flow lines. Because of this curvature in flow lines, drawdown throughout the aquifer may be different at the base of the aquifer than near the water table (Jacob, 1963; Weeks, 1969).

Observation well W-5 penetrates the upper 58 percent of the saturated thickness of the aquifer. Therefore, drawdown in this partially penetrating observation well may not be representative of drawdown that would occur in a fully penetrating well. However, Babbitt and Caldwell (1948) and Weeks (1969) state that the effects of this curvature on flowlines are small when drawdown in the pumped well is less than 0.2 times the saturated thickness of the aquifer. Drawdown data for the 1988 and 1989 aquifer tests in the unconfined aquifer were less than 0.2 times the saturated thickness of the aquifer. Therefore, the effect of partial penetration of observation well W-5 on drawdown is minimal; well W-5 was assumed to be representative of a fully penetrating well.

Boulton Delayed-Yield Analysis

The analytical method applied to determine the hydraulic properties of the unconfined aquifer was based on the work of Boulton (1955, 1963, 1964). Boulton showed that drawdown in unconfined aquifers often depends upon delayed yield of water from storage. Boulton theorized that water levels near a pumping well may decline at a slower rate than predicted by the Theis equation, because the water in the aquifer is not released from storage instantaneously, as assumed by Theis, but is released more slowly because of gravity drainage in fine sediments. Boulton developed an empirical parameter called the "delay index" to represent this effect. In order to apply Boulton's analytical method, the following basic assumptions must be adhered to. The aquifer must be unconfined and areally extensive. During the test, the production well must be pumped at a constant rate. All the wells must be fully penetrating, and horizontal permeability of the aquifer must be greater than the vertical permeability.

Boulton's type curves account for the delay in yield to the well that occurs in unconfined aquifers during the interval between early-time drawdown (similar to artesian conditions), and later-time drawdown (similar to water-table conditions) (Boulton, 1963). The basic theory of Boulton's type curves may be summarized as follows: at early time, a few minutes after pumping begins, the time-drawdown data will follow the Theis curve; at intermediate time, the effects of gravity drainage become significant and the time-drawdown data simulates a "leaky-artesian aquifer type curve;" and at late time, after a long period of pumping, the effects of gravity drainage predominate and the time-drawdown data merges with the Theis curve for a storage coefficient equal to the specific yield (Boulton, 1963).

Equations for solving tests of aquifers under water-table conditions, where the effects of delayed yield are present, are based on the relation of the delay index parameter and the materials in which gravity drainage takes place (Prickett, 1965). Boulton (1963) produced two families of nonsteady-state type curves based on the expression $W(\mu_{AB}, r/B)$, which is the well function for water-table aquifers. The first family of curves are termed "Type A," and are used to analyze early-time drawdown data. The second family of type curves are termed "Type B," and are used to analyze later-time data. After the appropriate match points are determined from the type curves, the following equations are used to determine the values of transmissivity, specific yield, and storage coefficient. Notations of the equations used to solve for the hydraulic properties of the aquifer are those of Boulton (1963) and Lohman (1972).

$$s = \frac{Q}{4\pi T} W(\mu_{AB}, r/B)$$

where under early-time conditions:

$$\frac{1}{\mu_A} = \frac{4Tt}{Sr^2}$$

under later-time conditions (Type B):

$$\frac{1}{\mu_B} = \frac{4Tt}{S_y r^2}$$

and where:

$$\mu_B = \mu_A(\eta - 1)$$

$$\eta = \frac{(S + S_y)}{S}$$

where in the above equations:

- s = drawdown in observation well, in feet;
- r = distance from production well to observation well, in feet;
- Q = pumping rate, in cubic feet per day;
- t = time after pumping started, in days;
- T = transmissivity, in square feet per day;
- S = storage coefficient (volume of water instantaneously released from storage), dimensionless;
- S_y = specific yield (total volume of delayed yield from storage), dimensionless;
- η = ratio of coefficient of storage plus specific yield divided by coefficient of storage, dimensionless.

Figure 9 presents the drawdown versus time divided by radius squared and corresponding match points for early and late data from the 1988 aquifer test in the unconfined aquifer. The 1989 aquifer test was analyzed using the same analytical method and procedure. Values of T, S (early), Sy (late), and horizontal hydraulic conductivity (K) were calculated for each test. The hydraulic properties of the aquifer derived by the Boulton's delayed-yield analysis within the cone of depression for the 1988 aquifer test are presented in fig. 9.

Separation of the effects of delayed yield from storage between wells W-5 and S-4 is so small that two distinct r/B curves cannot be matched (fig. 9). The data plots of wells W-5 and S-4 match r/B curves close to 1.5 (fig. 9).

Values of T, S, Sy, and K calculated for the 1989 aquifer test were similar to the 1988 aquifer test. These calculated values for the 1989 aquifer tests were T = 1,250 ft^2/d, S = $7x10^{-3}$, Sy = 0.03, and K = 13 ft/d.

Specific yields of unconfined aquifers range from 0.01 to 0.30, though for most aquifers values of 0.1 to 0.3 are more normal (Freeze and Cherry, 1979). Both aquifer tests in the unconfined aquifer produced values of specific yield equal to 0.03. The small value of specific yield calculated from the aquifer test may be partially explained by drill cuttings which showed the aquifer to be composed of medium to fine sands with large amounts of silt and clay.

Step-Drawdown Analysis for Well Loss

A 445-minute step-drawdown test was conducted on January 13, 1989, to determine well-loss coefficients and estimate the efficiency of the production well in the unconfined aquifer. The two well screens and two gravel packs in the production well were suspected of causing a large well loss component of drawdown (turbulent flow) during pumping.

Jacob (1947) suggested that drawdown in a well may be expressed as the sum of the first-order laminar (aquifer) flow component of drawdown and a second-order turbulent (flow) component of drawdown. The equation that represents this relation is:

$$s_w = BQ + CQ^n$$

where:

s_w = drawdown in the production well, in feet;
BQ = laminar flow component (aquifer loss), in feet;
CQ^n = turbulent flow component (well loss), in feet, n usually = 2; and
Q = pumping rate, in cubic feet per day.

Figure 10 presents the drawdown versus time plot for each corresponding step change in pumping rate on the production well in the unconfined aquifer. Coefficients B and C were calculated by a graphical method after Bierschenk and Wilson (1961), as shown in figure 11. The analytical results of the step-drawdown test are summarized in table 3.

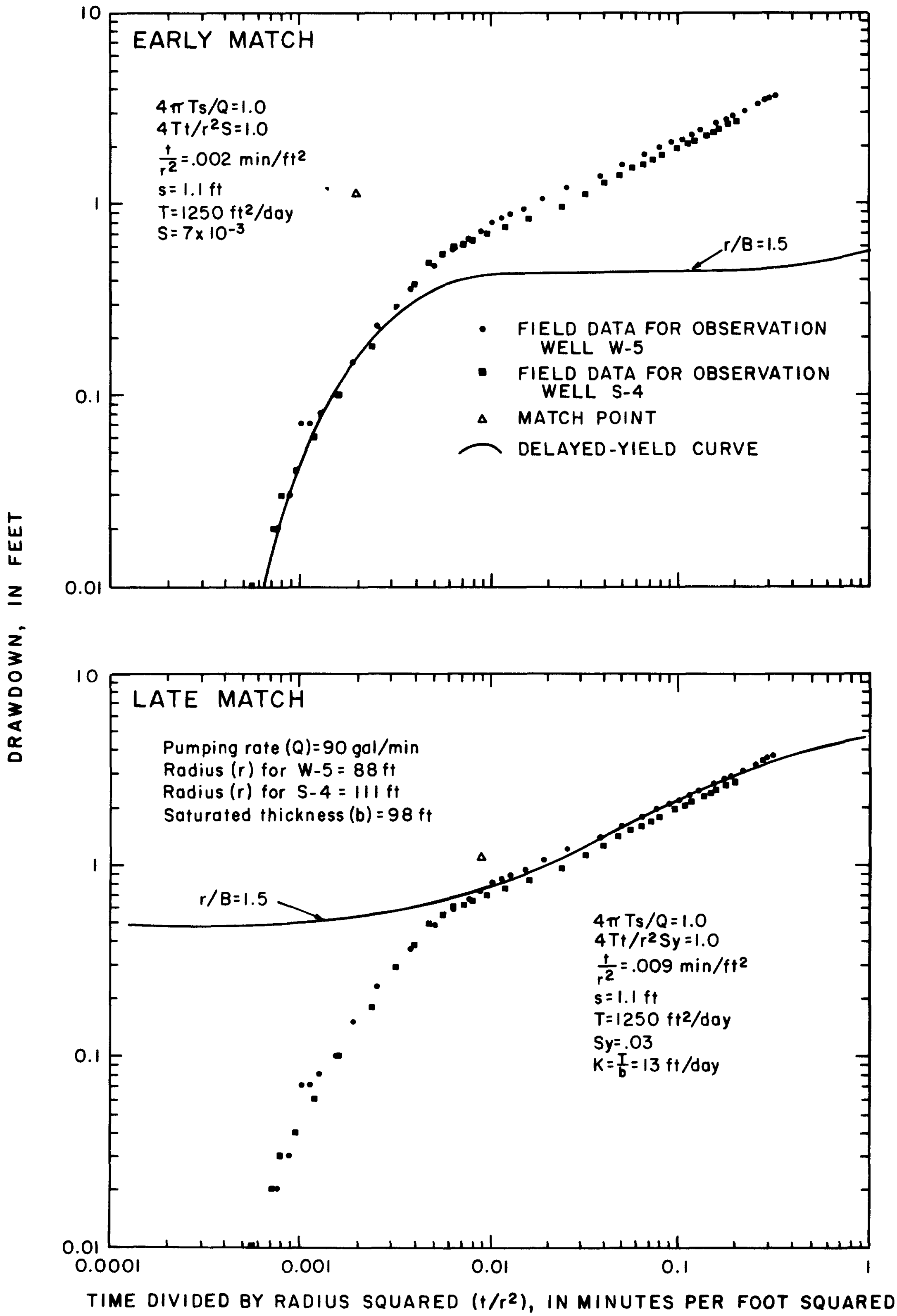


Figure 9.--Logarithm of drawdown versus the logarithm of time divided by radius squared and corresponding match points for early and late data from the 1988 aquifer test of the unconfined aquifer.

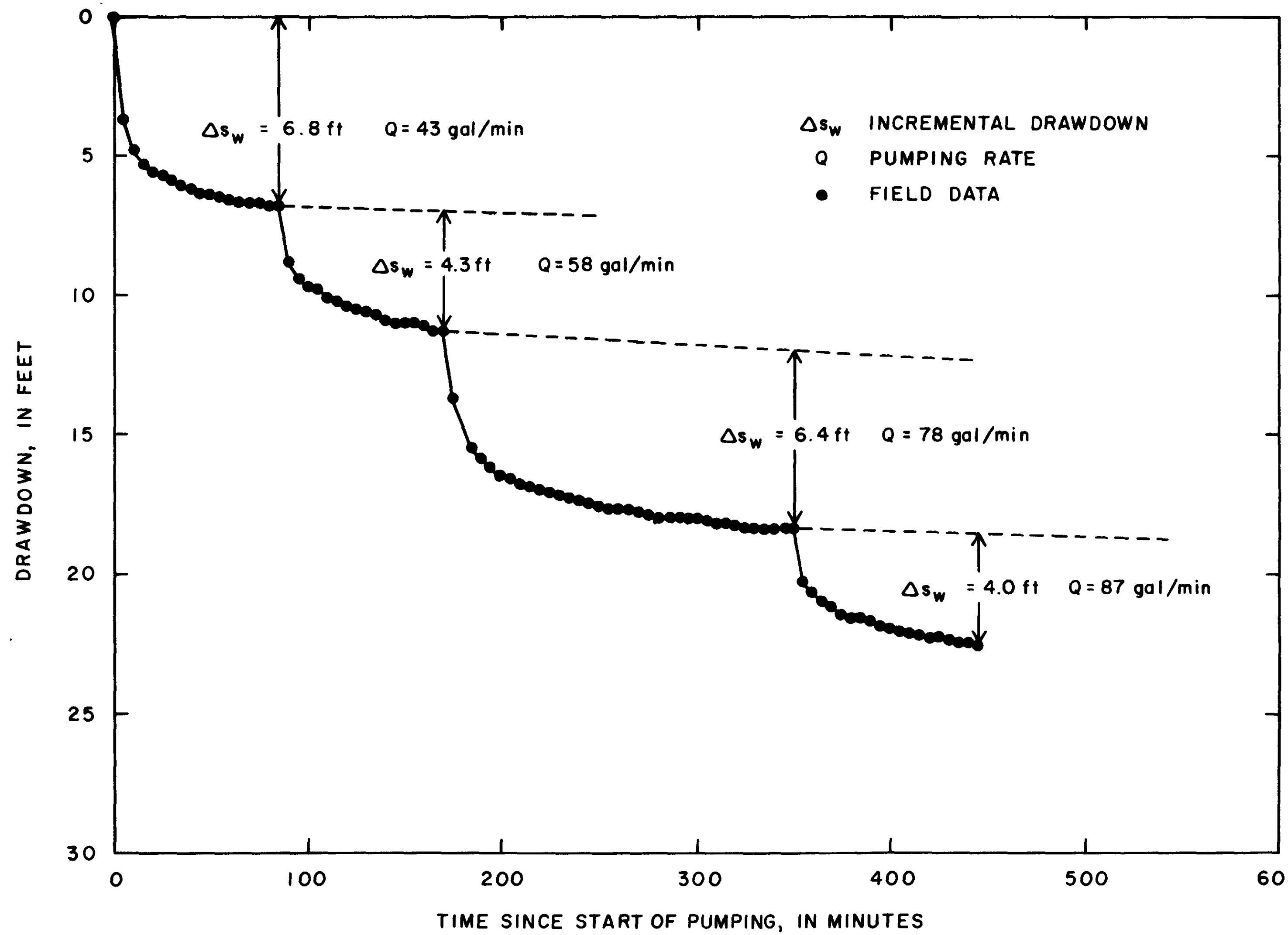


Figure 10.--Drawdown versus time for the January 13, 1989, step-drawdown test conducted on the production well in the unconfined aquifer.

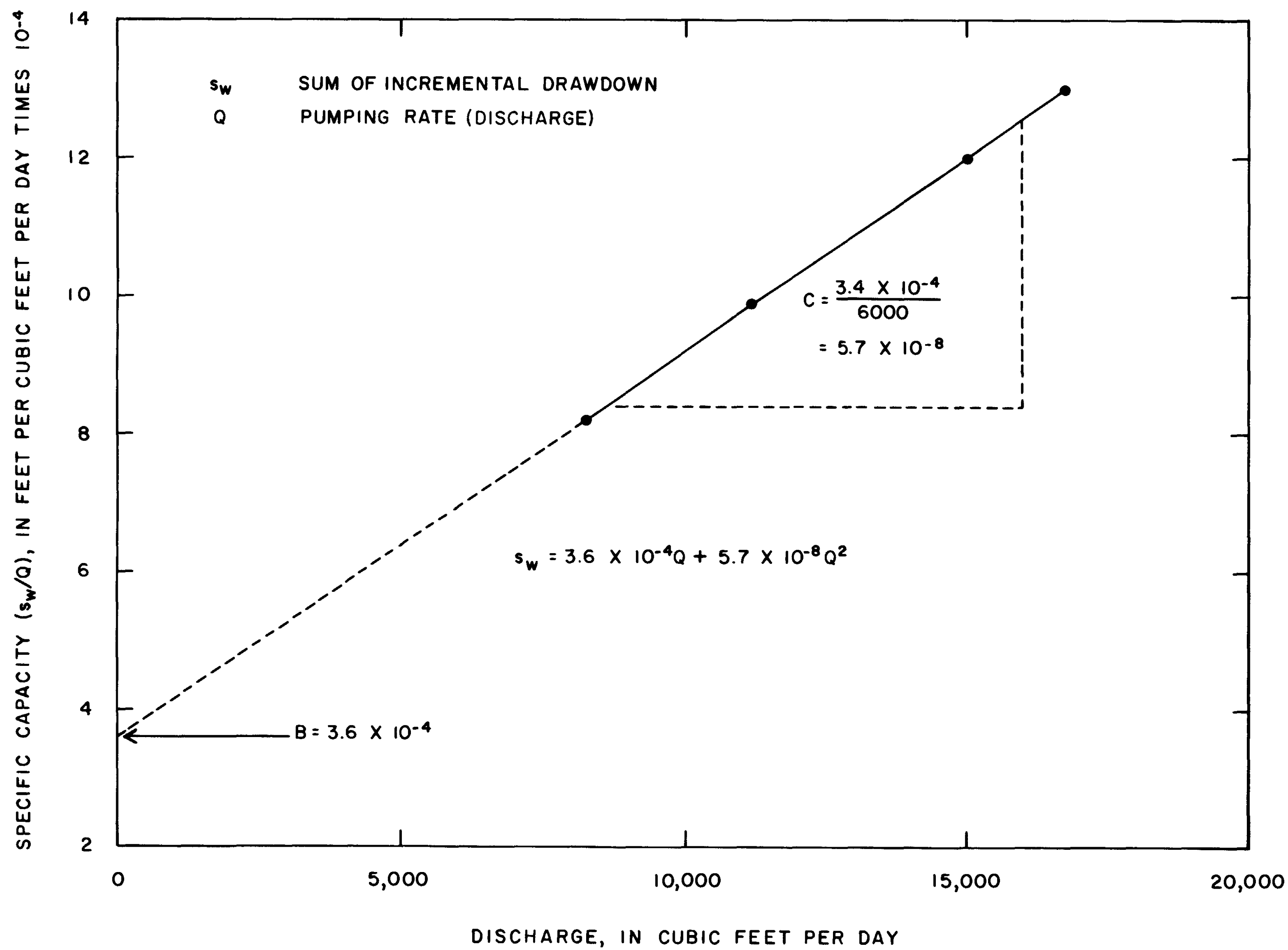


Figure 11.--Graphical determination of coefficients B and C for the January 13, 1989, step-drawdown test on the production well in the unconfined aquifer.

Table 3.--Analytical results of the step-drawdown test conducted on January 13, 1989, for the production well in the unconfined aquifer

[ft, feet; gal/min, gallons per minute; ft^3/d; cubic feet per day; $ft/(ft^3/d)$, feet per cubic feet per day]

Step	Incremental drawdown (Δs_w) (ft)	The sum of incremental drawdown (s_w) (ft)	Pumping rate (Q) gal/min	Pumping rate (Q) ft^3/d	$\frac{s_w}{Q}$ $(ft/(ft^3/d))$	(CQ^2)[1] (ft)
1	6.8	6.8	43	8,285	8.2×10^{-4}	3.9
2	4.3	11.1	58	11,175	9.9×10^{-4}	7.1
3	6.4	17.5	78	15,028	12×10^{-4}	12.9
4	4.0	21.5	87	16,762	13×10^{-4}	16.0

[1]Theoretical well loss component, $C = 5.7 \times 10^{-8} \frac{ft\text{-}d^2}{ft^6}$.

The well-loss constant C is empirically derived and will depend on the number and size of the well screen or perforation openings, screen condition, and effectiveness of well development (Bierschenk, 1964). The effectiveness of well development is evaluated by the relation of C/B x 100: where values less than 0.1 are "excellent" developed wells; 0.1 to 0.5 indicate "good" developed wells; 0.5 to 1.0 suggest "fair" development; and values greater than 1.0 indicate "poor" well development (Bierschenk, 1964). The value of C/B x 100 for the production well in the unconfined aquifer is 0.016, which indicates "excellent" well development.

Confined Aquifer

Data Collection

An aquifer test on the confined aquifer (referred to as 1987 aquifer test) began on October 29, 1987. The production well in the confined aquifer was pumped with a shaft-driven turbine pump powered by a diesel engine. Pumping rate was maintained within 3 percent of 405 gal/min. The test ended 98 hours later, on November 2, when the pump bowls separated. Recovery data were collected for 10 days (November 2-12) after pumping ended. Data from this aquifer test are presented in table 8, Supplemental Data section. During the aquifer test, water levels were measured in the production well with an air line and in the observation wells with electric water-level indicators and steel tapes. Pumping rate from the production well was measured with a 120° V-notch weir equipped with a continuous recorder. A manometer and an orifice plate were used as a supplemental system to measure discharge in case of failure of the weir or continuous recorder.

Analysis Considering Well Bore Storage

The analytical method used to evaluate the drawdown and recovery data from the aquifer test on the confined aquifer is based on the assumptions that the aquifer is isotropic, homogeneous, areally extensive, and fully confined. In addition, pumping rate is constant and water derived from the well is a combination of water from storage in the aquifer and from inside the well bore (Papadopulos and Cooper, 1967; Reed, 1980).

The method of analysis uses a type curve developed by Papadopulos and Cooper (1967) and presented in Reed (1980). The equations used to determine drawdown in and around a well of finite diameter, taking into consideration the large storage capacity of the well, are:

$$s = (Q/4\pi T)F(\mu,\alpha,\rho)$$

and

$$\mu = r^2S/4Tt$$

$$\alpha = r_w^2S/r_c^2$$

$$\rho = r/r_w$$

where:

- T = aquifer transmissivity, in feet squared per day;
- Q = pumping rate, in cubic feet per day;
- r = distance of observation well from pumping well, in feet;
- s = drawdown, in feet;
- S = storage coefficient, dimensionless;
- t = time since pumping began, in days;
- r_c = radius of well casing in the interval over which the water level declines, in feet; and
- r_w = effective radius of well screen or open hole, in feet.

The graph of the logarithm of drawdown versus the logarithm of time divided by radius squared for observation well E-2 is shown in figure 12. The overlay of the type curve $F(\mu,\alpha,\rho)$ versus $1/\mu$ determined for observation well E-2 also is shown in figure 12. It is apparent from figure 12 that $F(\mu,\alpha,\rho)$ approaches $W(\mu)$, the Theis solution, as time becomes large.

The hydraulic properties for the confined aquifer, determined from the 1987 aquifer test were T = 300 ft^2/d, S = 3 x 10^{-4}, and K = 1 ft/d. Horizontal hydraulic conductivity (K) calculations were based on a saturated thickness of 320 ft and not on the amount of screen, which is 180 ft. Results of the aquifer test did not indicate the presence of the White Clay fault or any other boundaries during the 98-hour test.

GROUND-WATER AVAILABILITY

The hydraulic properties determined for the unconfined (unit E) and confined (unit B) aquifers may be used to compute theoretical drawdowns within the aquifers of the Arikaree Formation at the study site for various distances and well pumping rates using the Theis equation. These predicted drawdowns then may be used to determine availability of ground water for beneficial uses in the area, including domestic, livestock, or irrigation use.

Drawdown versus distance plots are presented for the unconfined aquifer (fig. 13) and confined aquifer (fig. 14) for various pumping rates after 10 days of pumping. Drawdowns in the figures were computed by the method shown in Lohman (1972) and are based on the values of transmissivity (T) and storativity (Sy,S) determined for each aquifer.

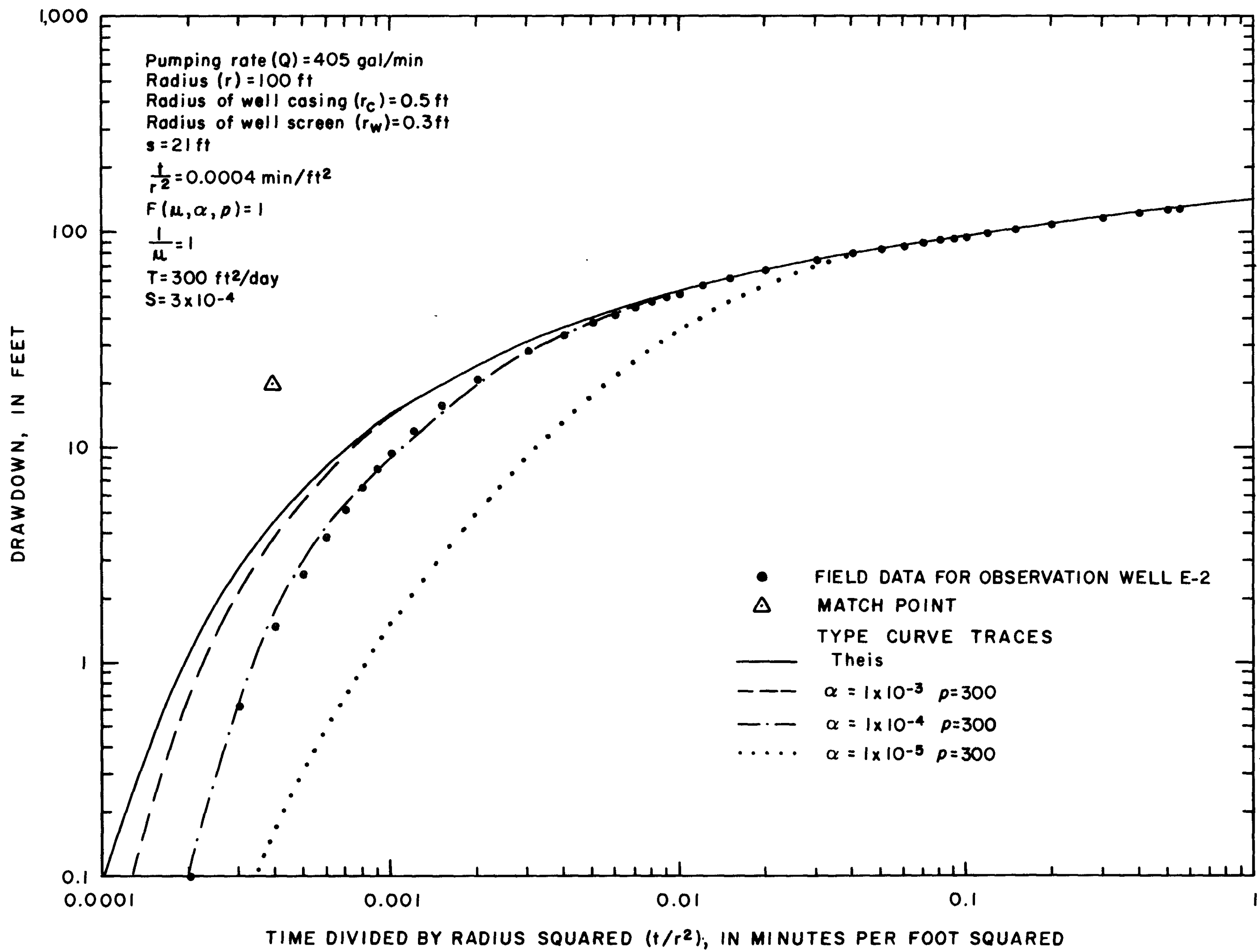


Figure 12.--Logarithm of drawdown versus the logarithm of time divided by radius squared and corresponding match point for the 1987 aquifer test of the confined aquifer.

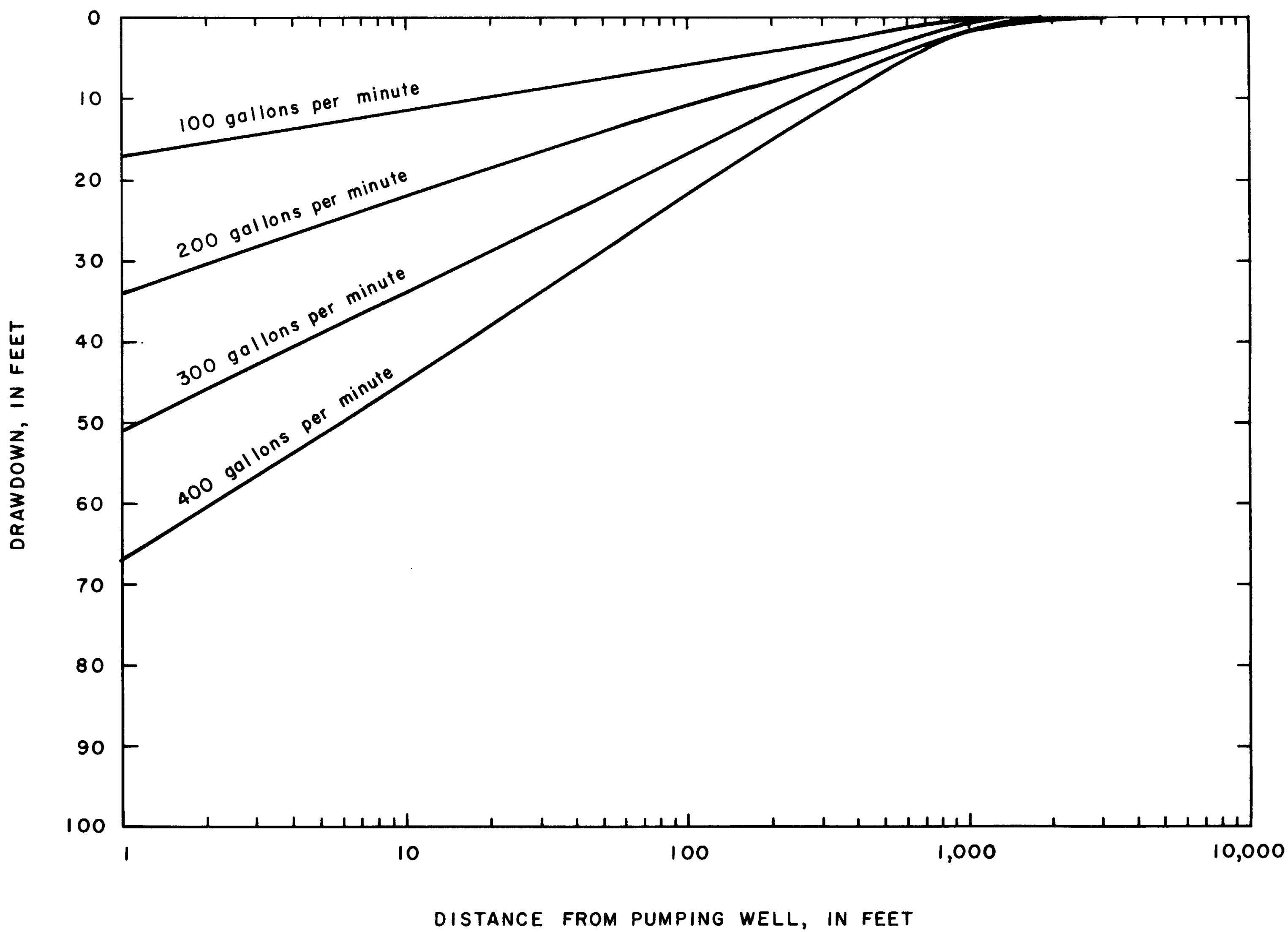


Figure 13--Theoretical drawdown versus distance for the unconfined aquifer at various rates of pumping after 10 days (for transmissivity = 1,250 ft^2/d and specific yield = 0.03).

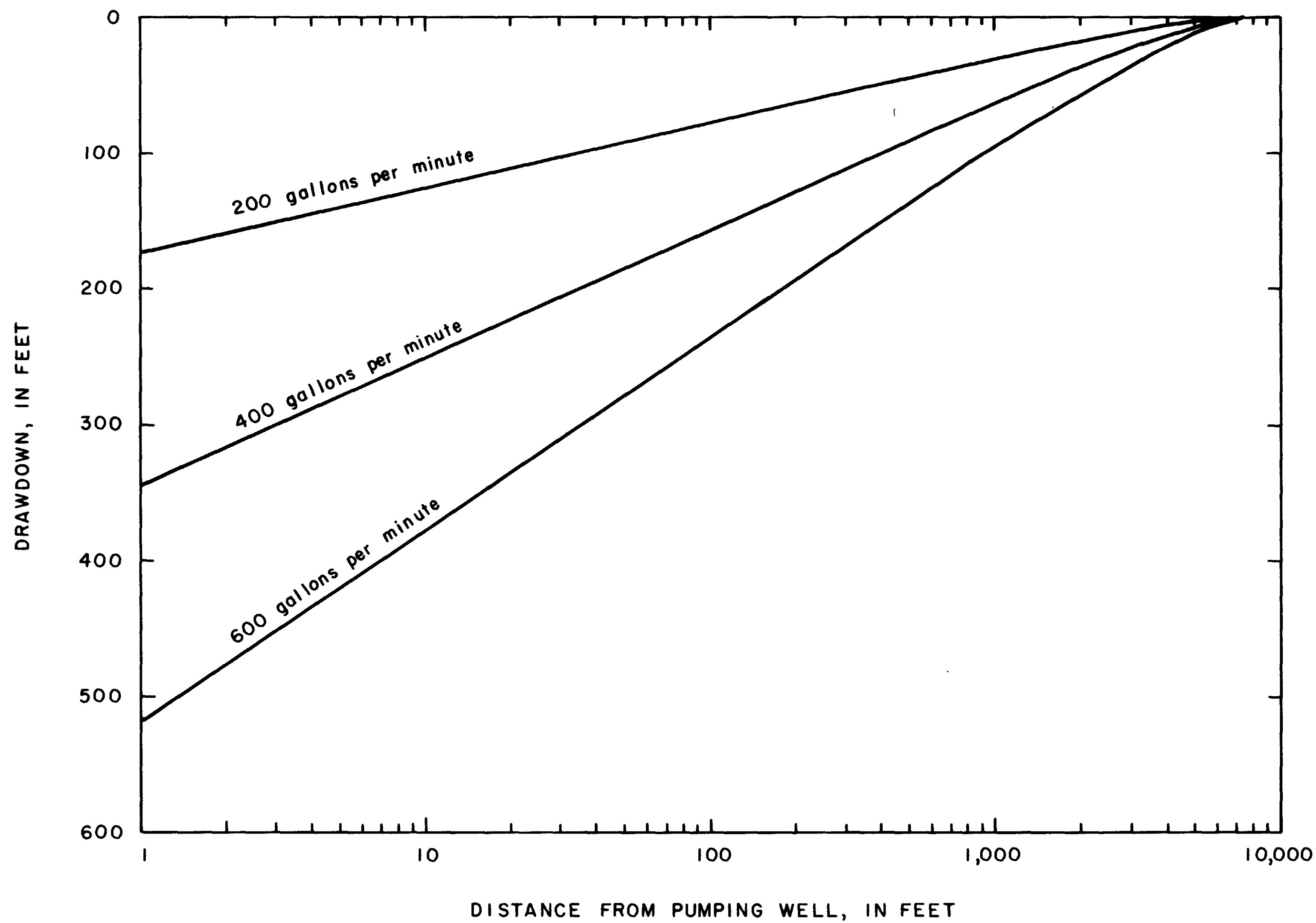


Figure 14.--Theoretical drawdown versus distance for the confined aquifer at various rates of pumping after 10 days (for transmissivity = 300 ft^2/d and storage coefficient = 3×10^{-4}).

Pumpage rates greater than 400 gal/min for 10 days in the unconfined aquifer may dewater the saturated thickness of the aquifer at the study site (fig. 13). Drawdown versus distance values obtained from figure 13 should be used with care, because the equation does not take into account changes in saturated thickness of an unconfined aquifer due to dewatering of the aquifer. In the confined aquifer, pumpage rates greater than 600 gal/min for 10 days will pull the potentiometric head below the top of the aquifer (fig. 14).

Areal extent of the unconfined and confined aquifers is unknown beyond the study site. Additional test drilling will need to be conducted in the Arikaree Formation to determine the extent of the aquifers.

WATER QUALITY

Water samples were collected from the unconfined aquifer on September 21, 1987, February 14 and 22, 1989, and from the confined aquifer on November 1, 1987, and again on March 29, 1989. Samples were analyzed for selected water-quality parameters by the U.S. Geological Survey Central Laboratory in Arvada, Colorado, and the results are listed in table 4.

Water from the unconfined and confined aquifers is suitable for drinking when compared to U.S. Environmental Protection Agency (1986b) recommended maximum contaminant levels (table 4). The water contained in the unconfined aquifer is a calcium bicarbonate type and water from the confined aquifer is a sodium bicarbonate type (fig. 15). The predominance of sodium and potassium ions in water from the deeper confined aquifer may occur as the result of ion exchange in which calcium and magnesium ions are replaced by sodium and potassium. The occurrence of sodium and potassium indicates a longer residence time or path of travel for water in the confined aquifer as compared to the unconfined aquifer.

Suitability of water for irrigation depends upon salinity, which is indicated by specific conductance; the sodium content of the water, which is indicated by percent sodium; and concentration of boron. Sodium is an undesirable constituent in irrigation water because the ion will replace the divalent cations of calcium and magnesium in the soil. Calcium and magnesium are necessary in the soil to maintain soil permeability and tillage. Irrigation water containing too much sodium causes deflocculation of soil particles which, in turn, reduces permeability and creates "hard pan" areas which are common throughout the Northern Great Plains.

The relation between sodium, calcium, and magnesium is referred to as the sodium-adsorption ratio (SAR), which is defined by the U.S. Department of Agriculture (1954) and computed by the formula:

$$SAR = \frac{(Na^{+})}{\sqrt{\tfrac{1}{2}\left[(Ca^{2+}) + (Mg^{2+})\right]}}$$

where:

SAR = sodium adsorption ratio, dimensionless;
Na^{+} = concentration of sodium, in milliequivalents per liter;
Ca^{2+} = concentration of calcium, in milliequivalents per liter; and
Mg^{2+} = concentration of magnesium, in milliequivalents per liter.

Table 4.--Water-quality characteristics of the unconfined and confined aquifers at the study site

[All units in milligrams per liter unless otherwise noted. µS/cm, microsiemens per centimeter at 25 °Celsius; °C, degrees Celsius; NTU, National turbidity units; µg/L, micrograms per liter; pCi/L, picocurie per liter; --, not analyzed; -, no criteria available; <, less than detection limit; U-238, uranium isotope with mass number 238; Cs-137, cesium isotope with mass number 137]

Parameter	Unconfined (Unit E)	Confined (Unit B)	Drinking water maximum contaminant levels[1]
Date of sample	Feb. 14, 1989	Nov. 1, 1987	
Properties			
Specific conductance (µS/cm)	410	458	-
pH field (pH units)	7.6	8.1	-
pH lab (pH units)	7.7	8.3	-
Temperature (°C)	13.0	22.0	-
Turbidity (NTU)	0.70	1.2	-
Hardness (as $CaCO_3$)	160	37	-
Noncarbonate hardness (as $CaCO_3$)	0	0	-
Alkalinity (as $CaCO_3$)	190	176	-
Dissolved solids			
Sum of constituents	307	340	-
Residue at 180 °C	299	348	-
Major ions (dissolved)			
Calcium	52	13	-
Magnesium	7.2	1.1	-
Sodium	26	79	-
Sodium-adsorption ratio (SAR)	0.9	6	-
Percent sodium	25	76	-
Potassium	8.8	14	-
Bicarbonate	230	216	-
Carbonate	0	0	-
Sulfate	26	46	-
Chloride	4.6	4.0	-
Fluoride	0.3	--	[2]1.4-2.4
Silica (as SiO_2)	68	81	-
Nutrients (dissolved)			
Nitrite (as N)	<0.01	<0.01	-
Nitrate (as N)	1.00	<0.10	-
Nitrite plus nitrate (as N)	1.00	<0.10	10
Nitrogen, ammonia (as N)	<0.01	--	-
Nitrogen, organic (as N)	0.30	--	-
Nitrogen, ammonia plus organic (as N)	0.30	--	-
Phosphorous (as P)	<0.01	0.01	-
Phosphorous, orthophosphate (as P)	0.004	--	-

Table 4.--Water-quality characteristics of the unconfined and confined aquifers at the study site--Continued

Parameter	Unconfined (Unit E)	Confined (Unit B)	Drinking water maximum contaminant levels[1]
Trace elements (μg/L, dissolved)			
Antimony	<1	2	-
Arsenic	5	7	50
Barium	93	60	1,000
Boron	40	110	-
Cadmium	<1	<1	10
Chromium	2	1	50
Cobalt	--	<3	-
Copper	<1	2	1,000
Iron	15	220	300
Lead	<5	5	50
Manganese	2	22	50
Mercury	<0.1	<0.1	2
Nickel	--	1	-
Selenium	2	2	10
Silver	--	<1	50
Zinc	99	15	5,000
Radiation, radionuclides, and isotopes			
Gross alpha, dissolved (μg/L as U-238)	12 [4]8.2	5.30	-
Gross alpha, suspended (μg/L as U-238)	--	0.80	-
Gross beta, dissolved (pCi/L as Cs-137)	19 [4]19	16.00	-
Gross beta, suspended (pCi/L as Cs-137)	--	<0.40	-
Radium-226, dissolved (pCi/L)	<0.1	[4]<0.1	[6]5
Radium-228, dissolved (pCi/L)	--	[4]<1.0	[6]5
Tritium (Tritium units)	[3]1.4	[4]0.2	-
Deutrium/hydrogen (ratio per milliliters)	[3]-109 [5]-106	-107	-
Oxygen-18/oxygen-16 (ratio per milliliters)	[3]-14.4 [5]-14.2	-14.1	-
Uranium, dissolved (μg/L as μ)	[5]12	--	-
Organic compounds			
Cyanide, dissolved	<0.01	--	-
Cyanide, total	<0.01	--	-
Bacteria (colonies per 100 milliliters)			
Fecal coliform	0	--	<1
Fecal streptococcus	0	--	<1

[1]U.S. Environmental Protection Agency (1986a).
[2]Dependent on mean daily maximum temperature.
[3]Sampled on September 21, 1987.
[4]Sampled on March 29, 1989.
[5]Sampled on February 22, 1989.
[6]Combined emissions from Radium-226 and Radium-228.

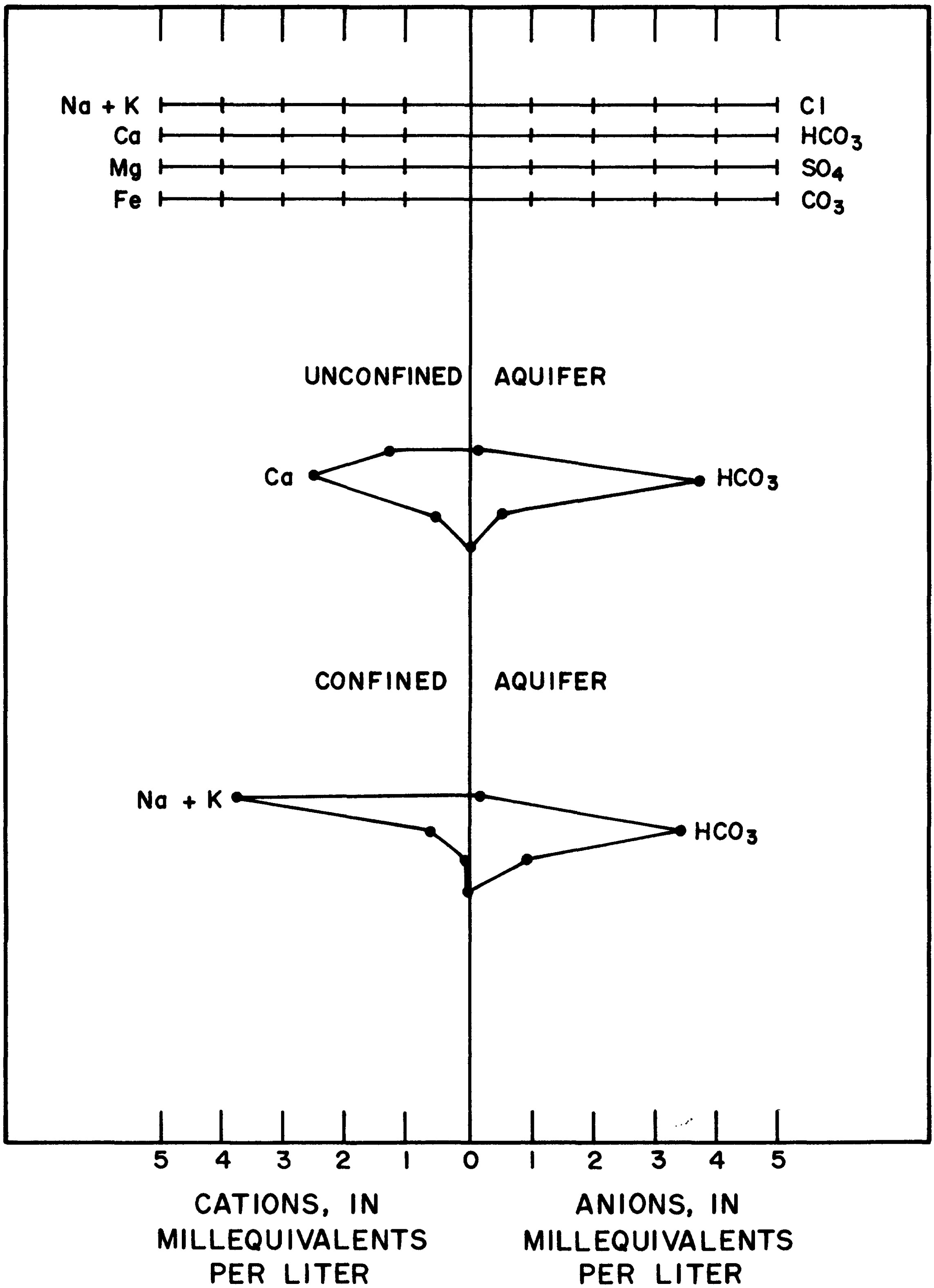


Figure 15.--Stiff diagram for samples of water from the unconfined and confined aquifers at the study site.

The concentration of boron in water from the unconfined and confined aquifers is less than 750 µg/L (micrograms per liter) which is the recommended maximum concentration for irrigation waters (U.S. Environmental Protection Agency, 1986b). The water from the unconfined and confined aquifers is low in sodium hazard and medium in salinity hazard (fig. 16); therefore, these waters should not cause detrimental effects to the soils proposed for irrigation.

Water temperature in the unconfined and confined aquifers is notably different. The water in the unconfined aquifer is 13.0 °C while the confined aquifer is 22.0 °C, or 9 °C warmer. Typically, the temperature of the earth increases (geothermal gradient) with depth at a rate of 0.5 to 0.6 °C per 100 ft (Keys, 1988). The water in the confined aquifer is about 5.5 °C warmer than expected based on a geothermal gradient of 0.6 °C per 100 ft. This departure from the expected geothermal gradient suggests the water in the confined aquifer may consist of upward leakage from underlying aquifers. The tritium values of 1.4 (unconfined) and 0.2 (confined) tritium units (Tu) suggest that the water of the confined aquifer probably is at least older than 100 years, while the water of the unconfined aquifer contains some modern water which has infiltrated since the advent of atmospheric nuclear weapons testing in the late 1950's to early 1960's (Robert Michel, U.S. Geological Survey, oral commun., 1990). The 95-percent confidence interval for these tritium measurements is ±1.0 Tu for the unconfined and ±1.2 for the confined aquifer, which reduces somewhat the certainty of these relative age determinations.

The concentrations of iron, manganese, and boron are considerably higher in the confined aquifer than in the unconfined aquifer because of the warmer water temperature and lower pH. Overall, the water in both aquifers is of suitable quality for any anticipated use.

SUMMARY AND CONCLUSIONS

The Arikaree Formation was studied to determine the hydraulic properties and availability of ground water for irrigation use at a site 2 mi southeast of Pine Ridge, South Dakota, on the Pine Ridge Indian Reservation. At the study site, the Arikaree Formation extends from land surface to a depth of about 830 ft. This is the greatest reported thickness of the Arikaree Formation on the Pine Ridge Indian Reservation.

The Arikaree Formation is composed of five geologic units, designated A through E. Unit E extends from land surface to a depth of about 190 ft. An unconfined aquifer, within unit E, is about 98 ft thick, and the water-table is about 42 ft below land surface. A confined aquifer under artesian pressure was identified within unit B of the Arikaree Formation. This represents a significant discovery for water-supply potential within the Pine Ridge Indian Reservation, even though the transmissivity of the aquifer is relatively small for large-scale water production. Unit B, about 320 ft thick, extends from about 510 to 830 ft below land surface. The potentiometric surface of the confined aquifer is 37 ft below the ground surface, which is 5 ft above the water table in the unconfined aquifer.

Four aquifer tests were conducted over a period of 3 years (1987-89) to determine the hydraulic properties of transmissivity (T), specific yield (Sy), storage coefficient (S), and horizontal hydraulic conductivity (K) of the unconfined and confined aquifers. Aquifer-test data were analyzed by using several analytical techniques to estimate hydraulic properties and to determine the existence of boundary conditions within the aquifer systems.

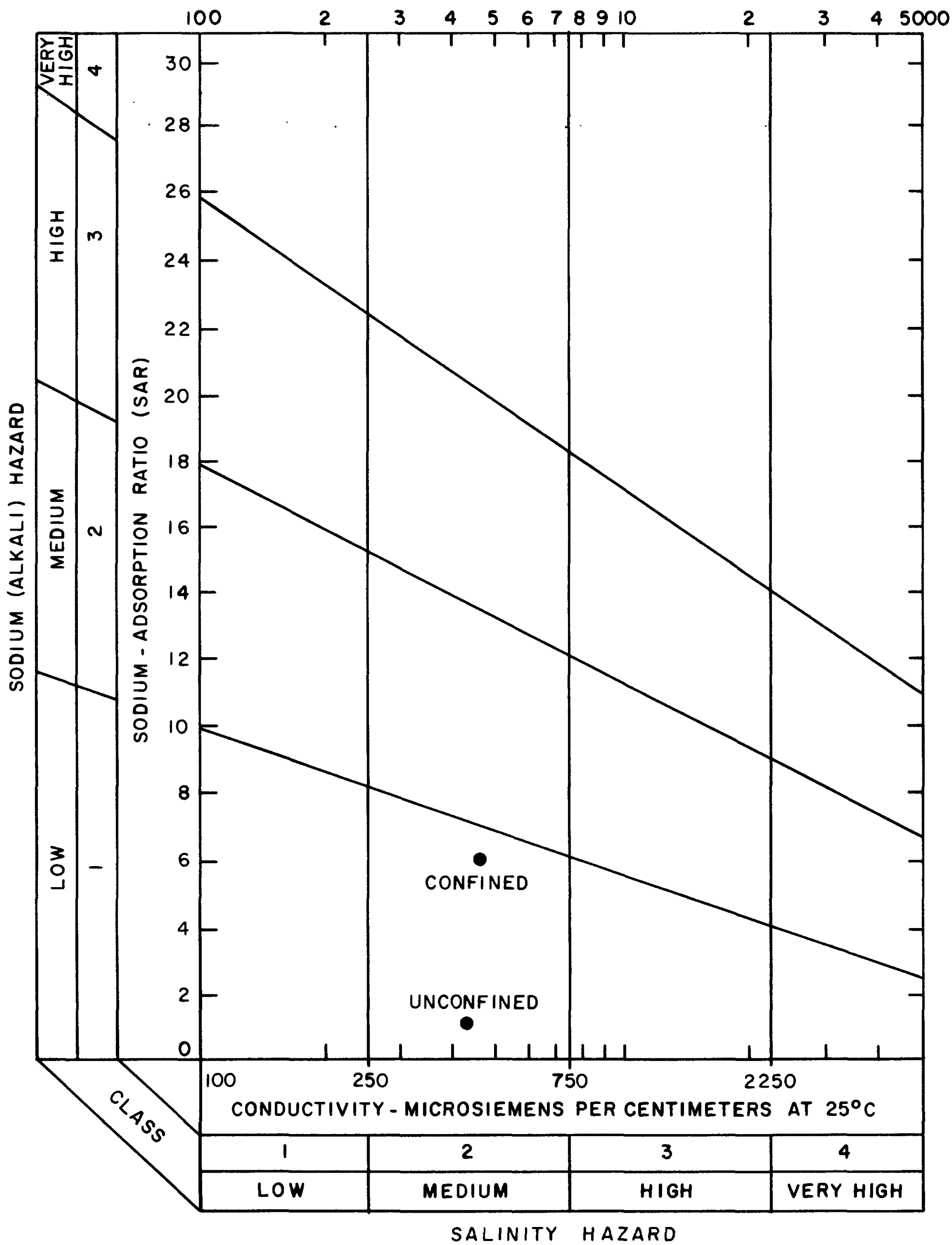


Figure 16.--Classification of water for irrigation use from the unconfined and confined aquifers at the study site (diagram from U.S. Department of Agriculture, 1954).

The analytical method used to determine the hydraulic properties of the unconfined aquifer was based on Boulton's delayed yield from storage. The application of Boulton's analytical method produced the following estimates of hydraulic properties: T = 1,250 ft^2/d, Sy = 0.03, and K = 13 ft/d. A small value of specific yield was calculated for the unconfined aquifer, probably because the aquifer is composed of medium to fine sands with large amounts of silt and clay.

A step-drawdown test was conducted on the production well in the unconfined aquifer to determine the loss of head (well efficiency) caused by the construction of the well. The step-drawdown test analysis showed that the production well in the unconfined aquifer is an "excellent" developed well.

The analytical method used to evaluate the drawdown and recovery data from the 1987 aquifer test conducted on the confined aquifer was based on the assumption that water derived from the well was a combination of water from storage in the aquifer and inside the well bore. The analytical method produced the following estimates of hydraulic properties: T = 300 ft^2/d, S = 3×10^{-4}, and K = 1 ft/d. The presence of the White Clay fault had no detectable effect on the 98-hour aquifer test.

Theoretical drawdown versus distance curves were developed for the unconfined and confined aquifers for various distances and well-pumping rates. These predicted drawdowns can be used to determine local availability of ground water for beneficial uses, including domestic, livestock, or irrigation use.

Water-quality samples collected from each production well during aquifer testing were analyzed for about 60 parameters. Additional samples were collected from each well at a later date and analyzed for selected parameters. The unconfined aquifer contains water with the following characteristics: pH = 7.6, specific conductance = 410 μS/cm, sodium = 26 mg/L (major cation), bicarbonate = 230 mg/L (major anion), boron = 40 μg/L (trace element), and sodium-adsorption ratio (SAR) = 0.9. The confined aquifer contains water with the following characteristics: pH = 8.1, specific conductance = 458 μS/cm, sodium = 79 mg/L, bicarbonate = 216 mg/L, boron = 110 μg/L, and SAR = 6.

Based on the specific conductance, boron, and SAR values, the water in both aquifers is suitable for irrigation; however, water in the unconfined aquifer is better. When compared to the U.S. Environmental Protection Agency (1986a) drinking water standards, no exceedances were found in the water from either aquifer; therefore, water from both aquifers is suitable for human consumption.

Other water-quality characteristics indicate the water in the unconfined and confined aquifers is probably of different origin or flow paths. Because of the departure from the expected geothermal gradient in the confined aquifer, temperature data indicate that water in the confined aquifer may consist of upward leakage from underlying aquifers.

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SUPPLEMENTAL DATA

Table 5.--Aquifer-test data for the 1988 aquifer test conducted on the unconfined aquifer

Production well		Observation well S-4		Observation well W-5	
Pumping rate (Q) = 90 gallons per minute		Distance from production well (r) = 111 feet		Distance from production well (r) = 88 feet	
Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown (feet)
0	0	0	0	0	0
1	3.7	7	.01	6	.02
2	5.1	9	.02	7	.03
3	6.0	10	.03	8	.07
4	6.9	12	.04	9	.07
5	7.4	15	.06	10	.08
6	7.8	20	.10	12	.10
7	8.3	30	.18	15	.15
8	8.8	40	.29	20	.23
9	9.2	50	.38	30	.36
10	9.7	60	.49	40	.48
12	10.2	70	.55	50	.58
15	10.2	80	.59	60	.66
20	10.6	90	.62	70	.72
30	11.5	100	.65	80	.80
40	12.0	120	.70	90	.84
50	12.5	150	.76	100	.88
60	13.2	200	.84	120	.94
70	13.4	302	.97	150	1.06
80	13.6	400	1.13	200	1.21
90	14.1	504	1.28	300	1.39
100	14.3	605	1.42	390	1.60
120	14.5	705	1.54	506	1.79
150	14.8	806	1.60	607	1.96
200	14.3	905	1.70	707	2.08
300	15.2	1,008	1.80	809	2.17
366	16.4	1,215	1.97	907	2.30
400	17.1	1,382	2.07	1,010	2.43
475	18.0	1,496	2.14	1,218	2.65
499	18.2	1,729	2.29	1,380	2.79
566	18.9	1,886	2.37	1,498	2.90
600	19.4	2,020	2.47	1,727	3.09
700	20.1	2,255	2.62	2,024	3.35
800	20.3	2,497	2.73	2,200	3.52
897	21.5			2,320	3.60
964	21.7			2,500	3.72
998	21.9				
1,208	22.8				
1,360	22.4				
1,495	22.6				
1,725	23.1				
1,972	23.5				
2,099	24.0				
2,148	24.4				
2,520	24.5				

Table 6.--Aquifer-test data for the January 13, 1989, step-drawdown test conducted on the production well in the unconfined aquifer

	Production well	
Pumping rate (Q) (gallons per minute)	Time since start of pumping (minutes)	Drawdown (feet)
43	0	0.0
	5	3.7
	10	4.8
	15	5.3
	20	5.6
	25	5.7
	30	5.9
	35	6.1
	40	6.2
	45	6.4
	50	6.4
	55	6.5
	60	6.6
	65	6.7
	70	6.7
	75	6.7
	80	6.8
	85	6.8
58	90	8.8
	95	9.4
	100	9.7
	105	9.8
	110	10.1
	115	10.2
	120	10.4
	125	10.5
	130	10.6
	135	10.7
	140	10.9
	145	11.0
	150	11.0
	155	11.0
	160	11.1
	165	11.3
	170	11.3
78	175	13.7
	185	15.5
	190	15.9
	195	16.2
	200	16.5
	205	16.6
	210	16.8
	215	16.9
	220	17.0
	225	17.1
	230	17.2

Table 6.--Aquifer-test data for the January 13, 1989, step-drawdown test conducted on the production well in the unconfined aquifer--Continued

Pumping rate (Q) (gallons per minute)	Production well: Time since start of pumping (minutes)	Production well: Drawdown (feet)
78 (Cont.)	235	17.3
	240	17.4
	245	17.5
	250	17.6
	255	17.7
	260	17.7
	265	17.7
	270	17.8
	275	17.9
	280	18.0
	286	18.0
	291	18.0
	295	18.0
	300	18.0
	305	18.1
	310	18.2
	315	18.2
	320	18.3
	325	18.4
	330	18.4
	335	18.4
	340	18.4
	346	18.4
	350	18.4
87	355	20.3
	360	20.7
	365	21.0
	370	21.2
	375	21.5
	380	21.6
	385	21.6
	390	21.7
	395	21.9
	400	22.0
	405	22.1
	410	22.2
	415	22.2
	420	22.3
	425	22.3
	430	22.4
	435	22.5
	440	22.5
	445	22.6

Table 7.--Aquifer-test data for the 1989 aquifer test conducted on the unconfined aquifer

Production well Pumping rate (Q) = 115 gallons per minute		Observation well S-4 Distance from production well (r) = 111 feet		Observation well W-5 Distance from production well (r) = 88 feet	
Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown (feet)
0	0	0	0	0	0
1	1.8	8	.01	5	.01
2	4.6	9	.02	6	.02
3	6.6	10	.03	7	.02
4	8.4	11	.04	8	.03
5	9.9	12	.05	9	.04
6	11.0	13	.07	10	.05
7	12.0	14	.08	11	.06
8	13.1	15	.10	12	.07
9	14.2	16	.12	13	.08
10	15.2	17	.14	14	.09
11	16.3	20	.22	15	.11
12	17.2	30	.62	20	.17
13	18.1	40	.80	30	.32
14	18.8	50	.92	40	.51
20	23.7	60	1.00	50	.66
30	27.0	70	1.05	60	.78
40	29.3	80	1.10	70	.87
50	31.7	90	1.13	80	.97
60	29.4	100	1.17	90	1.06
70	29.3	120	1.24	100	1.13
80	28.8	140	1.31	120	1.25
90	29.1	160	1.37	140	1.36
100	29.5	180	1.43	160	1.46
120	30.0	200	1.48	180	1.55
140	30.3	220	1.53	200	1.63
160	30.6	240	1.58	220	1.70
180	30.9	260	1.63	240	1.76
200	31.2	280	1.67	260	1.82
220	32.3	300	1.71	280	1.87
240	32.9	350	1.82	300	1.93
260	33.3	400	1.90	350	2.05
280	33.5	510	2.07	400	2.16
300	34.2	550	2.13	440	2.25
350	35.9	600	2.19	510	2.41
400	36.6	650	2.25	600	2.57
440	37.2	700	2.32	700	2.74
510	38.2	800	2.42	800	2.88
550	38.7	900	2.51	900	3.01
600	39.2	1,000	2.59	1,000	3.14
650	39.8	1,200	2.77	1,100	3.27
700	39.3	1,400	2.92	1,200	3.41

Table 7.--Aquifer-test data for the 1989 aquifer test conducted on the unconfined aquifer--Continued

Production well		Observation well S-4		Observation well W-5	
Pumping rate (Q) = 115 gallons per minute		Distance from production well (r) = 111 feet		Distance from production well (r) = 88 feet	
Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown (feet)
800	42.7	1,600	3.04	1,300	3.54
900	44.0	1,800	3.17	1,400	3.64
1,000	44.2	2,000	3.29	1,500	3.73
1,200	44.9	2,200	3.43	1,600	3.83
1,400	45.1	2,400	3.52	1,700	3.92
1,600	45.9	2,600	3.68	1,800	4.02
1,800	47.1	2,850	3.92	2,000	4.19
2,000	48.6			2,200	4.35
2,200	51.3			2,400	4.49
2,400	51.6			2,600	4.68
2,600	56.2			2,850	4.95
2,850	61.5				

Table 8.--Aquifer-test data for the 1987 aquifer test conducted on the confined aquifer

Production well Pumping rate (Q) = 405 gallons per minute		Observation well E-2 Distance from production well (r) = 100 feet	
Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown (feet)
0	0	0	0
1	73.8	2	0.10
1.2	83.1	3	0.62
1.5	94.6	4	1.48
2	113.0	5	2.57
3	143.0	6	3.84
4	162.6	7	5.12
5	180.0	8	6.54
6	193.8	9	7.94
7	201.9	10	9.38
8	207.6	12	11.94
9	211.1	15	15.68
10	215.7	20	20.87
12	228.4	30	28.31
15	235.3	40	33.53
20	241.8	50	38.29
30	249.2	60	42.03
40	256.1	70	45.38
50	269.5	80	48.08
60	271.8	90	50.38
70	273.4	100	52.59
80	276.4	120	56.81
90	281.5	150	61.42
100	283.8	200	66.95
120	293.0	300	74.58
150	298.8	400	79.86
200	305.7	500	83.50
300	313.8	600	87.11
360	316.1	700	89.96
400	318.4	800	91.67
500	323.0	900	93.13
600	327.6	1,000	94.43
700	329.9	1,200	99.12
800	329.9	1,500	103.65
900	329.9	2,000	108.90
1,000	329.9	3,000	117.16
1,200	340.3	4,000	123.40
1,500	342.8	5,000	127.35
2,000	347.0	5,500	128.35
3,000	357.1		
4,000	357.4		
5,000	370.5		
5,670	371.0		

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