Effects of Artificial Recharge on the Ogallala Aquifer, Texas

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By R. F. Brown *and* W. S. Keys

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FIGURES

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

Multiply inch-pound units	By	To obtain metric units
Inch (in)	25.40	millimeter (mm)
Foot (ft)	.3048	meter (m)
Mile (mi)	1.609	kilometer (km)
Mile per hour (mi/h)	1.609	kilometer per hour
Square mile (mi^2)	2.590	square kilometer (km^2)
Acre	4.047×10^3	square meter (m^2)
Cubic foot (ft^3)	2.832×10^{-2}	cubic meter (m^3)
Gallon (gal)	3.785	liter (L)
Gallon (gal)	3.785×10^{-3}	cubic meter (m^3)
Acre-feet (acre-ft)	1.233×10^{-3}	cubic meter (m^3)
Gallon per minute (gal/min)	.0630	liter per second (L/s)
Pound avoirdupois (lb advp)	.454	kilogram (kg)
Part per million (ppm)	[1]1.0	milligram per liter (mg/L)
Pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
Degrees Fahrenheit (°F)	°C=(°F−32)/1.8	degrees Celsius (°C)

[1] For low concentrations.

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Abstract

Four recharge tests were conducted by injecting water from playa lakes through wells into the Ogallala Formation. Injection was by gravity flow and by pumping under pressure. At one site, 34-acre feet of water was injected by gravity and produced a significant increase in yield of the well. At a second site, gravity injection of only 0.58 acre-foot caused a significant decrease in permeability due to plugging by suspended sediment. At two other sites, injection by pumping 6 and 14 acre-feet respectively, resulted in discharge of water at the surface and in perching of water above the water table. Differences in success of recharge were largely due to aquifer lithology and, therefore, the type of permeability; the concentration of suspended solids in the recharge water; and the injection technique.

The injection technique can be controlled and the concentration of suspended solids can be minimized by treatment, but the site for well recharge will accept water most rapidly if it is selected on the basis of a favorable geohydrologic environment. Geophysical logs were used to study the effect of aquifer lithology on recharge and to understand the movement of injected water. Temperature logs were particularly useful in tracing the movement of recharged water. Natural-gamma, gamma-gamma, and neutron logs provided important data on lithology and porosity in the aquifer and changes in porosity and water distribution resulting from recharge. Effective recharge of the Ogallala Formation, using water from playa lakes, is possible where geohydrologic conditions are favorable and the recharge system is properly constructed.

INTRODUCTION

Artificial recharge is extensively used as a means of placing surface water into ground-water storage where it is not subject to evaporation, and where contamination from surface sources is less likely. Where geologic conditions are not suitable for recharge from spreading basins, recharge by injection of water through wells has been used. Commonly, recharge wells have been subject to failure by clogging after a short period of injection, making this system uneconomical for many available surface-water sources.

The economy of the Southern High Plains of Texas is dependent on irrigated agriculture using water pumped from the Ogallala Formation. The average annual pumpage of water in irrigated areas exceeds 1.5 ft/yr, while the average annual recharge under natural conditions is computed to be 0.002 to 0.006 ft/yr (Brown and Signor, 1973, p. 17). As a result, the water table has steadily declined in most areas, and the saturated thickness, which once averaged more than 100 ft, has decreased significantly. The present rate of decline of the water table could result in a decrease in irrigated acreage in the Southern High Plains from approximately 4.3 million acres during 1970 to about 500,000 acres by 2000. The greatest rate of decline is expected to occur before 1990 (Hughes and Harman, 1969, p. 22, fig. 2).

Surface water in the Southern High Plains is available from ephemeral playa lakes. These lakes are present at a density of about one per square mile throughout the Southern High Plains. They receive from 1.8 to 5.7 million acre-ft of water annually that could theoretically be recharged to the Ogallala Formation (Hauser and Lotspeich, 1967, p. 11–15). The playa-lake water contains few dissolved solids but contains much suspended sediment. Therefore, it is chemically suitable for artificial recharge, but, historically, the suspended sediment has clogged the aquifer during artificial recharge through wells and decreased the specific capacity of the wells.

In order to establish design criteria for successful injection of recharge water, it is necessary to understand the movement of water in the aquifer, the chemical reactions that take place, and the deposition of suspended sediment that occurs during injection. In order to determine these hydrologic factors, the tests described in this report were designed to: (1) determine the path of injected water; (2) identify the nature of the clogging that takes place as a result of injecting water containing suspended sediment; (3) document the chemical quality of water present in the aquifer before, during, and after recharge; and (4) develop techniques for identifying lithologic units favorable for recharge and the hydrologic factors affecting recharge.

Two parallel projects were undertaken to obtain relevant information. The first was a comprehensive laboratory project to develop basic concepts of the interaction of injected sediment with an aquifer; the second was a series of field experiments to test hypotheses developed through analysis of the laboratory data.

This report principally describes four injection-recharge tests that were conducted at four sites to determine the relation between clay-size particles in recharge water and the decrease in hydraulic conductivity of an aquifer recharged with water containing this suspended sediment. The locations of the test sites are shown in figure 1, along with a fifth site where prerecharge investigations were carried out.

A section of this report, prepared by Donald C. Signor, describes relevant laboratory-column experiments. These experiments were designed to measure the effects of injection of recharge water that contained clay into a simulated aquifer.

Reports already published describe other specific aspects of the research on artificial recharge (Brown and others, 1978; Brown and Signor, 1973; Keys and Brown, 1971, 1973, 1978; and Wood, 1973).

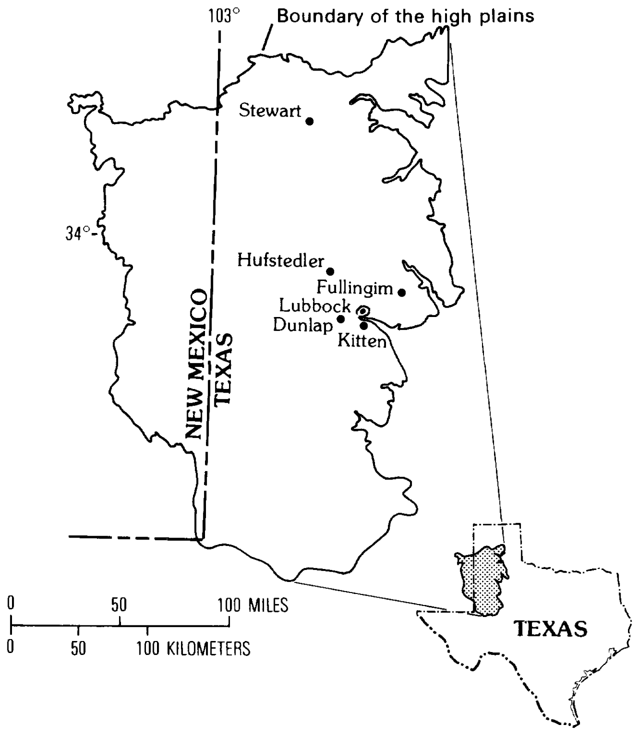


Figure 1. Location of recharge sites.

RECHARGE FLOW AND RELATED LABORATORY TESTS

By Donald C. Signor

Scheidegger (1960) states that the most widely accepted relationship between permeability and geometrical properties of a porous medium is attributable to Kozeny (1927). Kozeny's porous-medium model is an assemblage of channels with cross sections of various sizes, but of definite length. The Navier-Stokes equations are solved simultaneously for all channels passing through a cross section normal to the direction of flow in the medium. The permeability is expressed in terms of the specific surface, which is a measure of the hydraulic radius.

The Kozeny model neglects the effect of conical flow in expansions and contractions of porous-media flow channels by assuming that flow is normal to the cross section where there are no tangential components of the fluid velocity.

The Kozeny equation for permeability is:

$$k=\frac{cp^3}{s^2} \qquad (1)$$

where:

k is permeability, dimensionless,
c is the Kozeny constant, dimensionless,
p is porosity, dimensionless, and
s is specific surface of the tube (surface area per unit volume), L^{-1}.

The Kozeny equation, thus, states that the permeability of a porous medium is inversely proportional to the square of the surface-area-per-unit volume, and directly proportional to the cube of the porosity.

Theoretically, the Kozeny constant "c" varies only slightly, being 0.5 for a circle, 0.5619 for a square, 0.5974 for an equilateral triangle, and 0.667 for a rectangular strip.

A modification of the Kozeny equation (1) was developed by Carman and resulted in the Kozeny-Carman equation (Scheidegger, 1960):

$$k=\frac{p^3}{5\,S^2_o\,(1-p)^2} \qquad (2)$$

where:

S is the surface area exposed to fluid expressed as the surface-per-unit volume of solid material rather than surface-per-unit volume of porous material. Application of equation (2) shows the Kozeny constant to be 0.2 rather than the 0.5 to 0.667 values obtained by theoretical computations. The 0.2 value was in best agreement with laboratory results.

Laboratory Tests

Values of the Kozeny constant were determined in the U.S. Geological Survey's artificial recharge research laboratory at Lubbock, Texas. The data were acquired during a series of tests in which clear water flowed through columns of clean sand, and in one test, glass beads, prior to inflow of a water-clay mixture. Values of the Kozeny constant ranged from 0.16 to 0.89 and averaged 0.35 for coarse sediment where typically a 50-percent size was 500 μm. The constant ranged from 0.14 to 0.34 with an average of 0.23 for finer material where typically the 50-percent size was 170 μm. These Kozeny-constant values are consistent with those previously discussed and indicate a valid flow regime for clogging tests.

Data from a laboratory test in which a water-clay mixture inflow caused clogging are shown in figure 2. These data are from one experiment in which four columns were tested. Each column contained aquifer material of uniform size. The columns were approximately 5 in. in diameter with packed lengths of about 30 in. The four materials were simultaneously subjected to inflow, for 417 minutes, of a prepared mixture composed of water and 500 mg/L of sodium-montmorillonite clay. The relatively small differences in total flow-through were a function of flow-control equipment. The columns clogged fairly uniformly through their lengths. The data in figure 2 show that a small quantity of montmorillonite clay, typically 0.2 to 0.3 percent by weight of the porous medium, can significantly decrease the hydraulic conductivity of the aquifer materials in a short time.

When pressure on the injected mixture was increased, the rate of flow through the column increased,

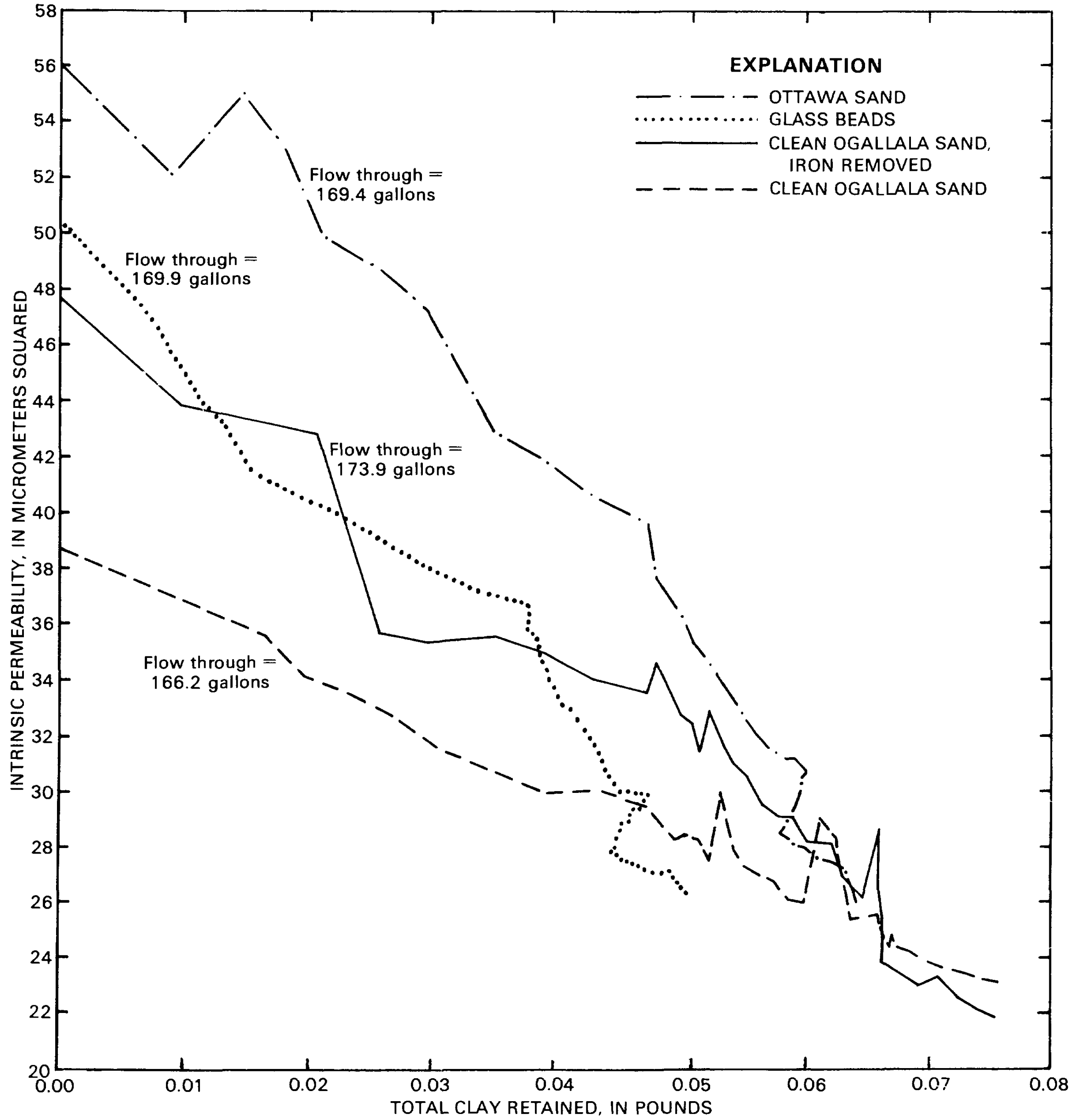


Figure 2. Permeability decrease as a function of clay retained in a porous medium

and the suspended sediment moved at a faster velocity. Therefore, the total volume of water and the volume of suspended sediment that moved through the column was larger at greater injection pressures. In a radial-flow system, this means that increased hydraulic head will result in the suspended sediment moving farther from the point of injection, and the total volume of water and suspended sediment that can be injected will be larger before the matrix clogs.

An attempt was made to remove sediment from the matrix in several columns that had been clogged as a result of injection of sodium-montmorillonite clay. Permeability in the columns had been decreased by 50 percent or more. Attempts to remove the clay by reverse flow of clear water produced no detectable increase in permeability, nor was a measurable quantity of the sediment removed from the matrix.

The data trends in figure 2 show fluctuations that may be due to a variety of secondary factors including temperature, pressure, or a mass of clay breaking loose and flowing out of the column. Irrespective of the possible secondary effects of unmeasured variables, the trend in all tests was a rapid decrease in permeability that was a function of the quantity of clay retained.

Recharge Hydraulics

The field tests described in this report were not analyzed to compare hydraulic response to theoretical prediction. In each test, the U.S. Geological Survey participated as an observer of a recharge process conducted by others. Therefore, prerecharge evaluation of the aquifer by well testing, design and supervision of recharge well construction, control of the recharge test, and comprehensive monitoring for such an analysis was not possible. However, an understanding of the principles of well-recharge hydraulics is necessary to interpret the data obtained in the tests described in this report.

When water is injected into a well for recharge, it forms a conical mound around the well that is virtually the inverse of the cone of depression that is created around a well by pumping. The height of the cone is greatest adjacent to the recharge well and decreases logarithmically with distance from the well depending on permeability and boundary conditions of the aquifer into which the water is being recharged. Where recharge is into an artesian system, the pressure head or potentiometric surface around the recharge well forms an elevated pressure cone comparable to the depressed cone formed in the pressure surface when an artesian well is pumped. The decline in height of the mound following recharge is analogous to recovery in a pumped well.

The shape of the recharge mound is determined by the nature of material suspended in the recharge water, as well as by the hydrologic characteristics of the aquifer system into which it is injected. The presence of both particulate matter and entrained air in the recharge water may alter the permeability of the system and may selectively slow the rate of movement of recharge water through the aquifer. Chemical changes resulting from incompatibility of the recharge water and the natural ground water or the aquifer material may result in selective clogging. Because of these variables, it is not possible to predict the shape of the cone developed during recharge operations as accurately as drawdown can be predicted from application of formulas for an aquifer test. Under idealized conditions, the formulas for analyses are similar, and the constraints on the analyses are essentially the same.

Under many conditions, the Theis equation (Lohman, 1979) may be used to predict the shape and magnitude of the cone produced by the injection of water. This equation and its use and limitations are well described in several references and texts (see for example, Wenzel, 1942; Ferris and others, 1962; or Lohman, 1979).

Because of idealized assumptions, theoretical response to recharge may not match an actual test. A discussion of the practical aspects of well recharge in relation to theory and performance data is presented by Baumann (1963):

> Todd (1959, p. 262) notes "By comparing the discharge equations forpumping and recharge wells, it might be anticipated that the recharge capacity would equal the pumping capacity of a well if the recharge cone has dimensions equivalent to the cone of depression. Field measurements, however, rarely support this reasoning; recharge rates seldom equal pumping rates. The difficulty lies in the fact that pumping and recharging differ by more than a simple change of direction."

The differences are related to the character of the recharge water and the chemical and physical interaction of the recharge water with the native water in the aquifer system. Generally, reactions decrease the volume of water that can be injected into a well system in relation to the volume that might theoretically be injected if the water did not interact with the aquifer. Bear (1979, p. 377) also emphasizes the important differences between pumping and recharging because of the effects of impurities introduced through a recharge well.

GEOHYDROLOGIC SETTING

All recharge tests described in this report were made in the Ogallala Formation of Miocene age. This aquifer is a heterogeneous, alluvial deposit consisting of semiconsolidated clay, silt, sand, and gravel deposited by anastamosing streams flowing at gradients of 8 to 10 ft/mi (Frye, 1970). These deposits have been greatly modified by ground-water solution and deposition, by evaporation, and by soil formation processes. Although the gross hydrologic characteristics of the Ogallala Formation are relatively uniform throughout the 33,000 mi^2 underlying the Southern High Plains of Texas and New Mexico, the permeability characteristics of the aquifer and the response to recharge at each site were unique.

Because of the heterogeneity of the Ogallala Formation, the movement of artificial-recharge water through several different lithologies was examined. Artificial recharge through wells takes place most effectively through coarse-gravel facies, which generally are found near the base of the formation associated with major paleostream channels aligned from northwest to southeast. Artificial recharge is equally effective through wells that are open in facies where secondary porosity occurs in calcium carbonate deposits, locally called caliche. These deposits commonly are associated with old land surfaces and have been reported as occurring dominantly in the upper part of the formation. Calcium carbonate also is found throughout the formation as a cementing material. A discussion of carbonate deposits of this type in soils is given by Gile (1966 and 1975).

Coarse unconsolidated sand, due to its excellent sorting and lack of cementation, generally is a superior medium for artificial recharge. Such sand in open well bores may collapse on redevelopment and permit removal of injected sediments that accumulate in the aquifer near the borehole face of a recharge well.

Laboratory analyses for many physical properties were made on several hundred core samples obtained from the Ogallala aquifer. Porosity values for undisturbed core

Table 1. Comparison of undisturbed and repacked porosities, Stewart and Hufstedler sites

Well No.	Depth (feet)	Undisturbed porosity (percent)	Repack porosity (percent)
S-1	7.5 - 8.0	31.2	47.4
S-1	18.5 - 19.0	33.3	45.1
S-1	20.5 - 21.0	33.7	49.6
S-1	46.5 - 47.0	32.8	51.9
S-1	97.0 - 97.5	29.0 1/	47.5
S-1	104.5 - 105.0	38.1	53.4
H-2	31.5 - 32.0	25.1	46.9
H-2	39.0 - 39.5	30.3	50.2
H-2	78.0 - 78.5	30.3	43.4
H-3	135.5 - 136.0	34.2	53.0
H-3	137.5 - 138.0	30.2	47.8
H-3	142.5 - 143.0	23.8	45.7
H-3	144.0 - 144.5	28.0	45.7
H-3	145.5 - 146.0	27.6	47.0
H-3	147.5 - 148.0	28.6	45.1
H-3	150.5 - 151.0	28.7	46.3

1/Porosity value probably in error, as it is significantly exceeded by volumetric moisture content.

and for repacked materials from several test holes drilled as a part of this project are compared in table 1. The evaluation was made to determine if disturbed samples obtained from auger drilling instead of core could be satisfactorily used to determine porosity. The range in values indicates that repacked porosity measurements are not comparable to values measured on relatively undisturbed drive cores. Furthermore, there is no consistent relationship between the two sets of porosity values. Accordingly, all laboratory analyses in the report were made on undisturbed core samples. This difference has obvious implications with respect to repacking columns with sand for laboratory tests.

RECHARGE OPERATIONS

Recharge Sites

Each of the four tests described in this report was an injection-recharge experiment performed under somewhat different conditions. In each experiment, specific factors were measured to determine their effect on artificial recharge.

The four sites (fig. 1) were selected on the basis of availability of wells suitable for recharge and not on the basis of lithologic character of the aquifer or hydrologic situation. Each of the sites had a unique combination of lithology, recharge techniques, and the quality of water that was recharged. The sites are discussed in the sequence in which the tests were undertaken and are referred to by the name of the owner of the farm containing the site. In sequence, the sites are Hufstedler, Dunlap, Stewart, and Kitten. A fifth site was chosen at Fullingim, and a preliminary evaluation is described in this report; however, the U.S. Geological Survey did not participate in a recharge test at this site.

Investigations at the Hufstedler site were made in cooperation with J. D. Hufstedler, the owner, and with the U.S. Department of Agriculture, Agricultural Research Service, Bushland, Texas. The Agricultural Research Service selected the site and supervised the installation of the recharge well and three observation wells. The remaining observation wells were installed by the U.S. Geological Survey.

The Dunlap and Kitten sites were studied in cooperation with the International Center for Arid and Semi-Arid Land Studies at Texas Tech University. The sites were selected by Philip Johnson and Duane Crawford, Professors in the Department of Petroleum Engineering, and the installation of the recharge wells and several observation wells were under their supervision (Johnson and others, 1976). Additional observation wells and test holes were drilled at the two sites by the U.S. Geological Survey.

The recharge tests. were conducted jointly by the U.S. Geological Survey and Texas Tech University.

The recharge well at the Stewart site was installed under the supervision of Ray Stewart, owner of the farm. The system was modified from a design suggested by the U.S. Department of Agriculture, Agricultural Research Service. Observation wells and test holes were installed, and the recharge test was made by the U.S. Geological Survey.

In this report, observation wells are defined as the drill holes completed with screen so that water levels could be measured. Test holes were cased with pipe, capped on the bottom with no screen or perforations, for temperature logging.

The recharge was into the Ogallala Formation at each site; however, the lithology and degree of cementation varied significantly. Recharge at the Hufstedler site was into coarse sand. Recharge at the Dunlap site was into coarse sand and fine gravel, and during the later part of the test, into calcium carbonate-cemented sand containing secondary-solution openings. Recharge at the Stewart site was into secondary-solution openings, which had developed in partly cemented, relatively fine-grained sandstone. Recharge at the Kitten site principally was into beds of coarse, clean gravel.

Recharge water at the Hufstedler and Stewart sites was transported by gravity flow from a playa lake to the well casing and cascaded to the water surface in the well. Water at the Dunlap and Kitten sites was injected with a pump under pressure ranging from 5 to 85 lb/in^2 during the recharge tests. The Hufstedler, Dunlap, and Kitten wells were gravel packed; the Stewart well was not gravel packed, instead it was finished with torch-slotted casing for its full depth, in partly cemented, relatively fine-grained sandstone.

Water injected at the Hufstedler site contained an average of 600 mg/L of suspended sediment during the recharge test. Water injected at the Dunlap and Stewart sites contained a maximum of 200 mg/L of suspended sediment. The maximum suspended-sediment concentration at the Kitten site was 460 mg/L. The water injected at the Hufstedler site contained more suspended sediment in part because sediment on the playa-lake bottom was resuspended by the effect of a persistant wind during the test. Injection at the other sites took place when wind velocities were much slower which allowed natural settling of suspended sediment in the playa lakes. Analysis of samples from selected playa lakes in the Southern High Plains had a large range in sediment concentration that was not demonstrably correlated to physical properties or chemical characteristics.

Investigative techniques were modified and improved at each successive test. The test was terminated at the Hufstedler site because a rapid rise in water levels indicated a significant decrease in permeability of the aquifer. Tests at the Dunlap and Stewart sites were terminated when all playa-lake water available for recharge had been injected. Injection at the Kitten site was terminated because of the flow of recharged water at the ground surface. A summary of injection conditions during these tests is shown in figure 3.

Data Collection And Instrumentation

Recharge and discharge rates were measured at the Hufstedler and Kitten sites by recording impeller flowmeters. A recording impeller flowmeter was installed at the Dunlap site but was effective only during the latter part of the test, and the total volume of recharge water was calculated from the volume survey of the playa-lake basin. Recharge at the Stewart site was measured intermittently by a Pigmy Price[1] current meter inserted in the recharge pipe through a vertical T-connector pipe. The flow rate was averaged from repetitive measurements of the velocity in the pipe.

Turbidity of water samples collected periodically at the Hufstedler and Dunlap sites was determined by use of a laboratory HACH model 2100 turbidity meter. Turbidity at the Stewart and Kitten sites was determined continuously with a HACH model 1861 turbidity meter. Turbidity was related to suspended-sediment concentration by laboratory analyses of samples in which turbidity had been measured.

The suspended-sediment content of samples was determined at the water quality laboratory of the U.S. Geological Survey in Austin, Texas. Mineralogic composition of the suspended sediment was determined by the U.S. Geological Survey. Scanning electron-micrography examinations of lake sediments and core samples from each well site were made at the Emventions Microanalysis Laboratory, Rockville, Maryland.

Water temperature was recorded periodically from observation of a mercury thermometer inserted at the intake of the lake water at the Hufstedler and Dunlap sites. Continuous recording of the temperature of injected water was made using a recording thermistor system through the first week of the test at the Stewart site and intermittently at the Kitten site. The accuracy of the thermistor unit was greater than 0.1°C.

Water levels in the screened observation wells at all sites were measured periodically using an electric tape. Water levels in test holes were estimated from neutron logs. The nature of the recharge systems precluded measurement of water levels in the recharge wells during re-

[1]The use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

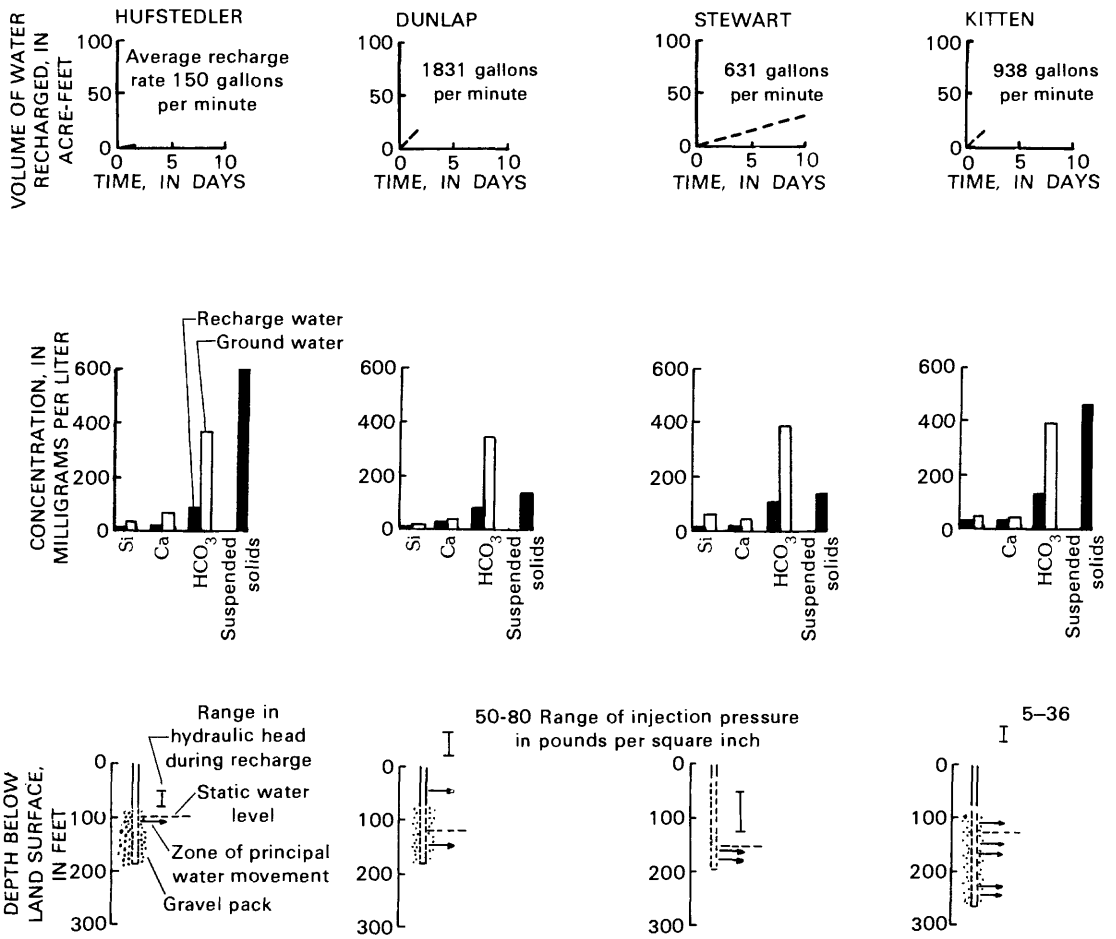


Figure 3. Injection conditions during recharge tests.

charge operations or subsequently in the pressure-injection wells at the Dunlap and Kitten sites.

The chemical quality of the recharge water at all sites was determined from grab samples obtained from the lakes and analyzed at the water quality laboratory of the U.S. Geological Survey. At the Stewart and Kitten sites, continuous recordings were made of specific conductance, and periodic determinations were made of pH, alkalinity, and dissolved oxygen.

Geophysical Logs

Several hundred geophysical-well logs provided important data from the recharge and observation wells and test holes before, during, and after the tests. Most of these geophysical logs were recorded in analog form as a function of depth. Late in the project, digitizing equipment was installed in the logging truck, and logs of the Fullingim core hole were digitized at the site. Other logs were later digitized commercially from the analog record.

The purposes of geophysical logging in the artificial-recharge project were several: to characterize the rocks being studied, to detect changes caused by recharge and pumping, and to trace the movement of the injected water. The long-range objective was to develop both logging and log-interpretation techniques to aid in the selection of recharge sites and in the selection and improvement of recharge techniques.

Geophysical logs obtained from the recharge wells, observation wells, and test holes were natural gamma, gamma spectra, gamma-gamma, gamma-gamma transmittance, neutron, neutron transmittance, caliper, resistivity, temperature, and acoustic televiewer. For a complete description of most of these logs, see Keys and MacCary (1971). Only basic principles and factors unique to artificial-recharge applications will be described herein.

The natural-gamma log is a measure of the total gamma radiation coming from the naturally occurring radioisotopes: uranium, thorium, potassium, and their daughter products. Natural-gamma logs are useful for identifying lithology and for stratigraphic correlation between wells. Borehole gamma-spectrometry records the gamma radiation as a function of energy and permits distinguishing the relative concentrations of different radioisotopes present. Concentrations of these radioisotopes in rock are related to both lithology and redistribution by ground water. Keys and Brown (1971) have shown that ratios of natural radioisotopes are related to calcium carbonate content and lithology in the Ogallala Formation near Lubbock, Texas.

Gamma-gamma probes use a gamma-emitting source shielded from a detector so that most of the radiation measured has traveled through the rock surrounding the borehole. The intensity of radiation recorded is inversely proportional to the bulk density of the rock. Changes in bulk density during recharge are most likely to have been caused by varying moisture content, plugging by entrained material, or subsequent development during pumping.

Single-detector, gamma-gamma logs are particularly susceptible to changes in borehole configuration; therefore, gamma-gamma transmittance logs were tested on the project. In this experimental log, a gamma source and a detector were simultaneously lowered and raised in parallel holes drilled several feet apart. This log was more sensitive to changes in the formation caused by recharge and less affected by borehole diameter and backfill, but drilling parallel holes proved to be difficult.

The neutron probe used during this project has a neutron source shielded and sufficiently far from the detector so that the number of neutrons detected is inversely proportional to the hydrogen content of the surrounding medium. In the Ogallala Formation, most of the hydrogen is in free water, so neutron logs reflect porosity below the water table and moisture content above the water table. Changes in porosity and saturation are, of course, important in recharge studies.

Neutron-transmittance logging is similar to gamma-gamma transmittance logging, and Keys and Brown (1971) have demonstrated that borehole effects are decreased significantly by this technique.

The caliper log displays a continuous record of average hole diameter and provides lithologic information as well as data essential to the correction of other logs.

Multielectrode resistivity logs provide a measure of the porosity of the rocks surrounding a borehole and the salinity of the saturating fluid. Recharge may change either of these characteristics. At the Dunlap and Kitten sites, resistivity logs were made through perforated plastic casing, because uncased holes would not remain open. This technique is only useful for detecting changes, not for quantitatively measuring resistivity.

Temperature logs were used at each of the sites to trace the movement of the recharged water. This technique is described in detail in Keys and Brown (1978). The thermistor-type probe used has excellent resolution, stability, and quick response, but the output is nonlinear. Wood and Erlich (1978) used yeast as a tracer in conjunction with temperature logs at a recharge site at Stanton, Texas. This work substantiates the vertical-permeability profiles derived from temperature logs. They found that the tracer moved faster than the thermal front of injected water. On this basis, the velocities of recharge water given in this report probably are conservative.

The acoustic televiewer was used at the Fullingim site to determine if it would provide superior resolution of lithology and specific information on secondary porosity. The televiewer probe uses a rotating, high-frequency acoustic transducer to produce a log of the reflectivity of the borehole wall. Fractures and other secondary openings and sedimentary contacts can be distinguished clearly in consolidated rocks with this device, and it was used successfully in the Ogallala Formation.

Applying borehole geophysics to recharge tests in the Ogallala Formation presented several problems because the sediments are semiconsolidated. Most holes would not remain open long enough to permit logging before installation of casing. Therefore, few caliper or resistivity logs were obtained. It was necessary to backfill around installed casing or pipe in order to prevent vertical circulation of water in the annulus and to prevent random collapse of the formation against the casing. Backfill material had to be of low permeability for temperature logging, yet provide uniform log response. Cement, clay, chemical grout, and auger cuttings were tried, but dry, fine-to-medium sand seemed to have the most desired characteristics. Even using dry sand, it was difficult to fill the annular space uniformly. Cement was found to take many months to reach a stable moisture content as detected by neutron logs.

Movement Of Recharge Water

This paper deals solely with recharge through wells. Recharge through spreading basins on the Southern High Plains is discussed by Brown and others (1978).

During well recharge, a conical mound of water forms around the injection well and water flows radially under that hydraulic head away from the well. Water may move through primary porosity in unconsolidated sand and gravel or through secondary porosity present as fractures or solution openings. Both types of porosity were found at the recharge sites described here. At the Hufstedler and Kitten sites, the core data indicated that all flow was through primary porosity in clastic material. The most rapid flow apparently occurred through gravel and coarse sand. At the Dunlap site, most flow was through intergranular pore space, but geophysical logs, core samples, and water level measurements indicated that some flow occurred through solution openings in caliche. At the Stewart site, the rapid velocity of flow and the visible solution openings in core samples indicated that most of the flow was through secondary solution openings.

Initial flow from the recharge wells was presumed to be horizontal. However, subsequent flow probably had an upward component and a horizontal-flow component. The vertical component resulted from density differences between the recharge water and the native water, and the upward movement of recharge water that formed the recharge mound. At the Stewart site, for example, the initial ground-water temperature was 15.3°C. Water injected from the lake averaged about 20°C for the first 3 days of the test. Because this water was less dense than the native ground water, there was an apparent upward component of flow subsequent to injection. Similar temperature gradients were present at the Dunlap and Kitten sites, but flow vectors were not as precisely delineated. Horizontal flow only was detected at the Hufstedler site. This was probably due in part to the short duration of the test and to the relatively low permeability.

At both the Stewart and Kitten sites, biological contamination was found in samples collected during the recharge tests from observation wells at least 15 ft from the recharge well. Some of the biota identified in samples collected at Stewart site were macroscopic and thus large enough to further confirm the presence of large, secondary, interconnected openings not due to primary porosity. The samples indicate that there is a possibility of foreign material from playa lakes reaching potable water-supply wells and causing a degradation of quality. This possibility increases the importance of studies that determine the rate and direction of movement of recharge water.

Solution Openings

Interconnected solution openings are present in some zones in the Ogallala Formation. Core obtained from a test hole at the Stewart site contained numerous conspicuous solution openings at several depths, and similar openings were present in core from several depths at the Fullingim site. Test drilling at the Lubbock Municipal Airport and trenches at Stanton in the Southern High Plains of Texas penetrated zones containing openings caused by solution. The playa lake at Stanton drained through these openings.

The Ogallala Formation includes deposits of calcareous silt, sand, and gravel. Concentrations of calcium carbonate are found in zones near paleo-land surfaces. Subsequent leaching resulted in solution of some of the calcium carbonate and its removal from the system by ground water. The environmental conditions that resulted in removal of the calcium carbonate are not known, but, on the basis of the widely spaced areas of solution, they must have been effective throughout much of the Southern High Plains. It is probable that the depressions in which the playa lakes formed are largely the result of selective solution removal of calcium carbonate.

The solution openings range in appearance from a spongelike texture to prominent fractures that are widened by solution to an estimated 0.125 in or more. Cylindrical openings with diameters as large as 0.25 in and irregularly shaped interconnected channels of approximately the same width have been observed in core samples (fig. 4). Laboratory analysis of core samples determined that there is little calcium carbonate in the aquifer matrix where the solution openings are present, but that there is significant calcium carbonate in the aquifer matrix above and below these permeable zones. The documented occurrence of these solution openings indicates that some of the reportedly successful well-recharge operations on the Southern High Plains injected water into sections of the Ogallala Formation that had well-developed interconnected solution openings (Brown and Signor, 1973, p. 46–49).

HUFSTEDLER SITE

Location

The Hufstedler site is approximately 2.5 mi northwest of the community of County Line (fig. 5). A total of 0.58 acre-ft of water from an adjoining playa lake was injected into the Hufstedler well during the recharge test. The test is described in detail by Schneider and others (1971).

Recharge And Monitoring System

The recharge system at the Hufstedler site consisted of a floating intake in the playa lake connected to an 8-in diameter pipe to the side of the injection-well casing (fig. 6). Water from the lake flowed by gravity to the well and cascaded from the inlet to the water level in the injection well. No specific effort was made to prevent air entrainment of the recharge water. A gate valve was used to maintain a relatively constant rate of recharge.

The well was drilled 24 in. in diameter and 185-ft deep. It was lined with 82.5 ft of 13.375-in diameter casing and 100 ft of 13.375-in diameter mill-slotted screen. The gravel pack in the recharge well was emplaced by use of a tremie pipe, through which a slurry of gravel and water was pumped under pressure into the annulus around the well casing. In order to prevent hydraulic separation of the gravel particles, the lower end of the tremie pipe was kept below the level of the gravel that had already been emplaced in the annular space around the well casing.

Two observation wells, ARS–2 and ARS–3, were drilled to the same depth as the recharge well and cased with slotted 6-in pipe. Observation wells H–1 through H–4 were drilled with a 4-in auger and cased with 2-in pipe

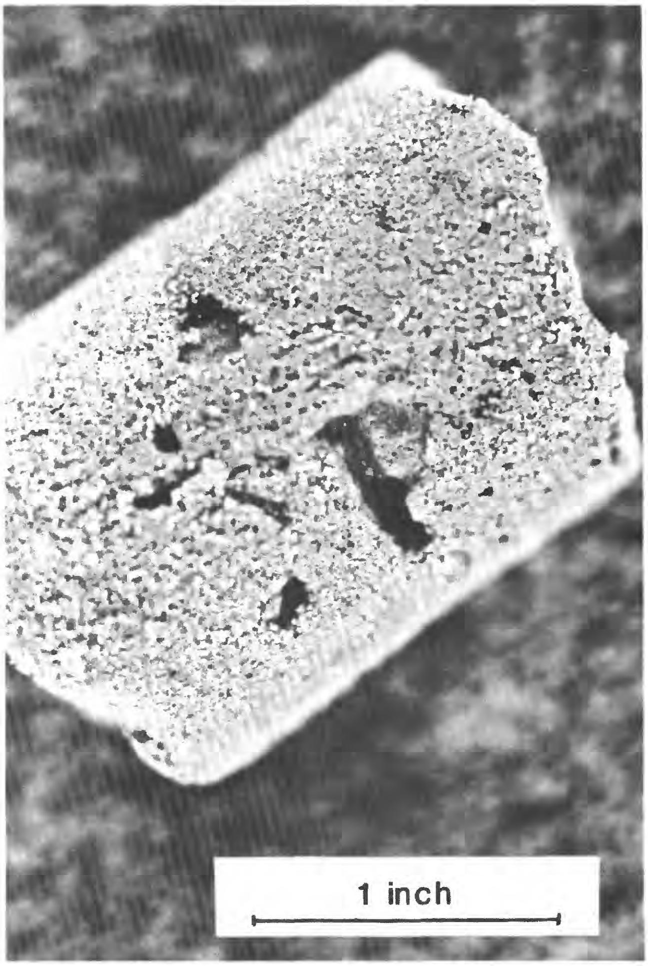


Figure 4. Solution openings in core, Stewart site.

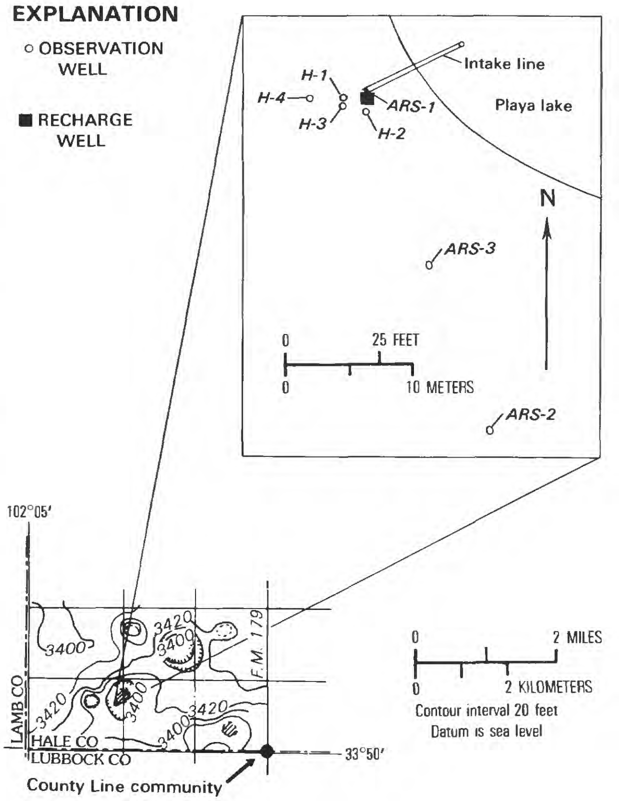


Figure 5. Location of recharge well, observation wells, and playa lake, Hufstedler site.

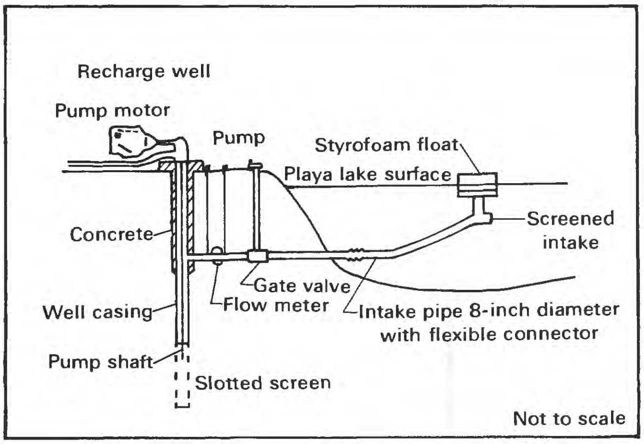


Figure 6. Recharge system, Hufstedler site.

with 2-ft well points. A 2-in observation well with a 2-ft well point was spot welded to the exterior of the casing of recharge well ARS–1 to permit measurements of water level and geophysical logging during recharge. Well construction is shown diagramatically in figure 7.

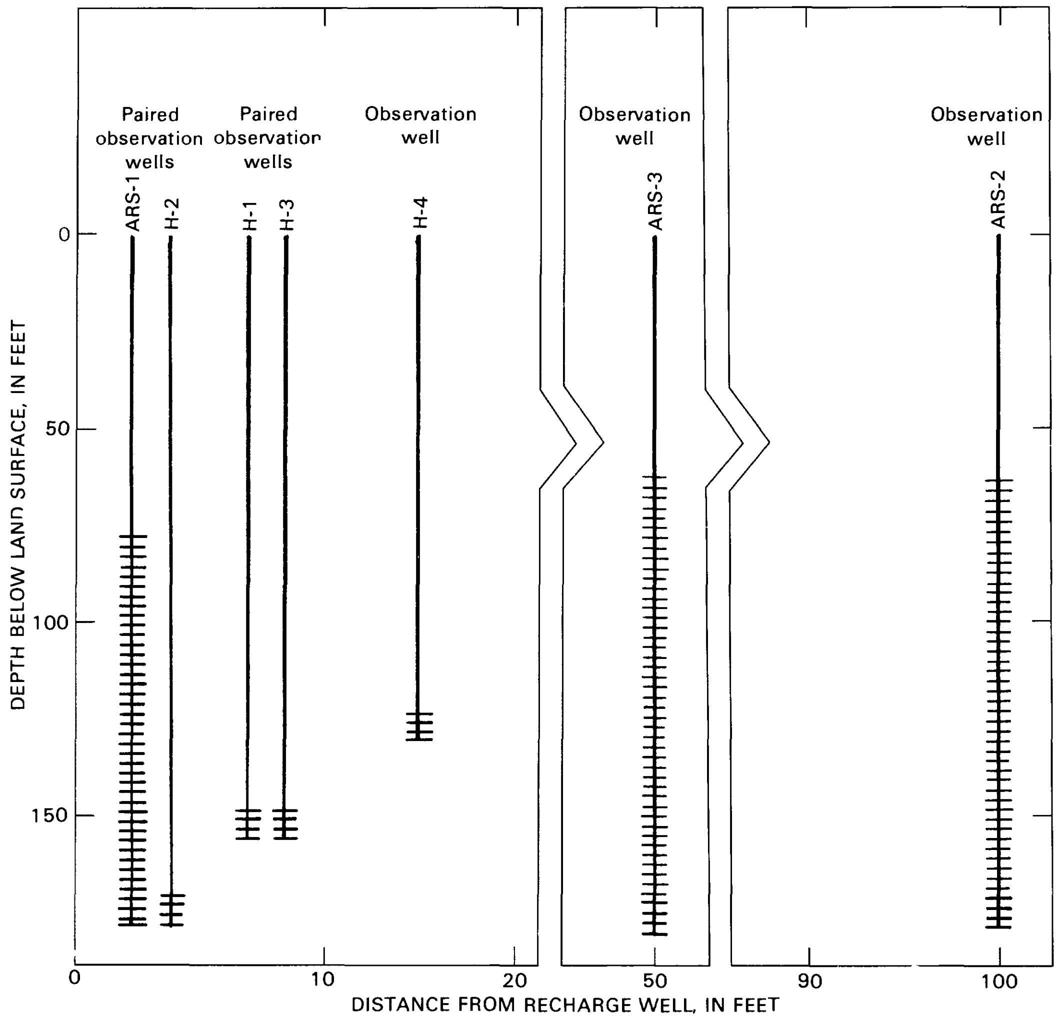
Geohydrology

Core Data

Drive cores were obtained at the Hufstedler site, but because they were not continuous, most changes in lithology were determined from cuttings. A summary of the particle-size analyses of cores is shown in figure 8. Most of the section above a depth of 110 ft was logged as fine sand with 10- to 30-percent silt and clay. Below a depth of 110 ft, the gravel content increased significantly to a maximum of 45 percent. The depth interval from 90 to 110 ft contains generally less than 15-percent clay and silt and is distinguished by low radioactivity on the natural-gamma log. This interval has a relatively large porosity and hydraulic conductivity as determined from core analysis (figs. 9 and 10) and transmitted most of the recharge water.

Geophysical Logs

Natural-gamma logs of the test holes at the Hufstedler site indicatesignificant vertical changes in lithology. A natural-gamma log is compared with temperature logs



EXPLANATION

SCREENED INTERVAL

OBSERVATION WELLS—2-inch-diameter steel pipe
ARS-2,3 : 6-inch-diameter steel pipe

OBSERVATION WELL SCREENS—2-foot V slot
wire wrap ARS-2,3 : 3-foot mill slot

RECHARGE WELL—ARS-1 : 13.4-inch-diameter steel pipe

RECHARGE WELL SCREEN—100-foot-long mill slot
0.125 X 2.75 inch; 80 slots per foot

Figure 7. Construction of recharge well and observation wells, Hufstedler site.

made during recharge in observation well H–3 in figure 11. The intervals of least gamma radiation are in the coarser sediments, and the greater radiation was measured in the clays. This figure indicates that the interval of least gamma radiation is sand, but data presented by Schneider and others (1971) from observation well H–1 indicate that gravel also may be present in the interval of least gamma radiation. Stratigraphic correlation between the test holes based on natural-gamma logs showed that the major lithologic units have lateral continuity in the area drilled.

Prerecharge Aquifer Test

The recharge well was pumped for 72 hours to establish the prerecharge capacity of the well. It produced 200 gal/min with 43.5 ft of drawdown for a specific ca-

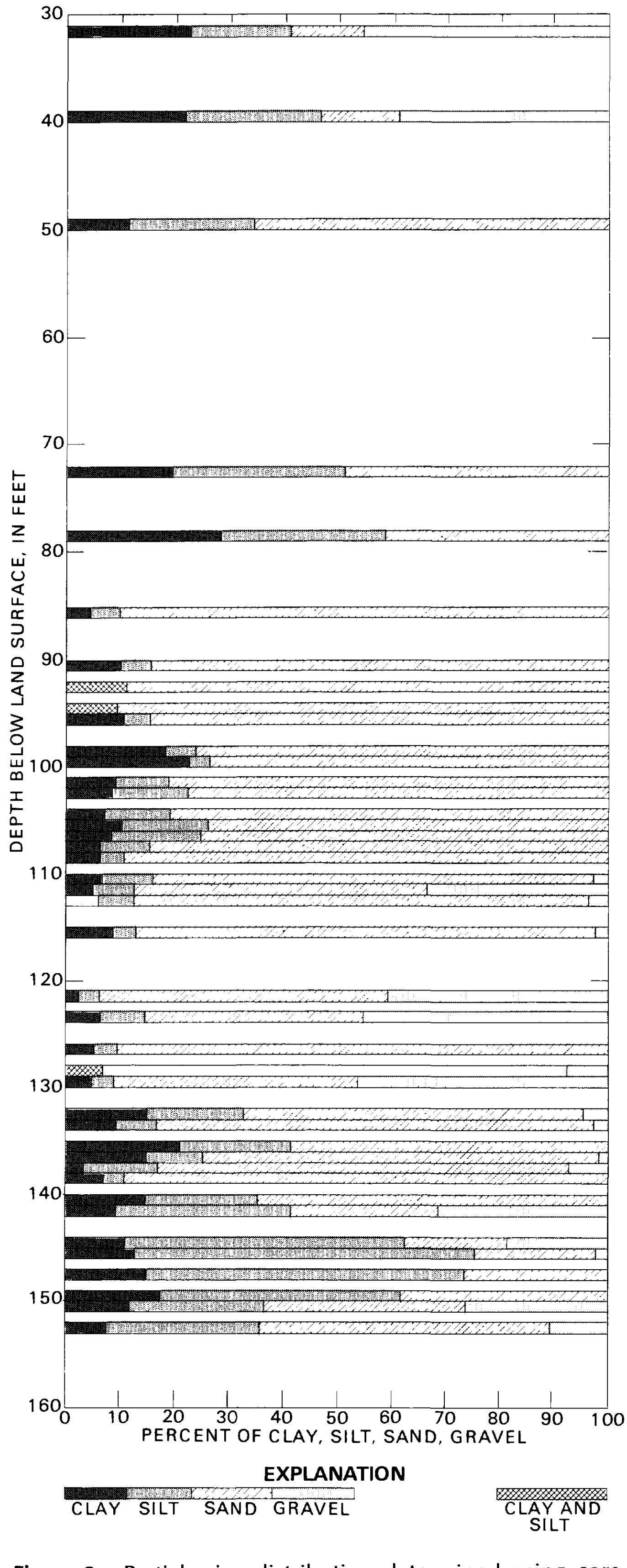


Figure 8. Particle-size distribution determined using core samples, observation well H–2, Hufstedler site.

pacity of 4.6 (gal/min)/ft. After 1 day of an earlier 10-day test, the specific capacity was 5.7 (gal/min)/ft, which decreased to 4.5 (gal/min)/ft at the end of the test (Schneider and others, 1971). Drawdown greater than 30 ft caused no increase in yield, which indicated that the Ogallala Formation produced water mostly from the water table to a depth of about 130 ft.

Water Chemistry

Water was pumped from the recharge well prior to recharge to obtain a sample for determining the pretest water quality. The concentration of dissolved constituents in the sample is typical of ground water from the Ogallala Formation, very high in calcium and magnesium bicarbonate and having dissolved solids in excess of 450 mg/L (table 2).

As further shown in table 2, water from the playa lake at the Hufstedler site is also high in calcium and magnesium bicarbonate, but dissolved solids are only about one fourth of the concentration found in the sample of ground water that was obtained by pumping the recharge well. Because the water from the playa lake is so low in dissolved solids, recharge of the water to the aquifer resulted in dilution of the native ground water and apparently did not cause precipitation of any constituent.

The playa-lake water contained an average of about 600 mg/L of suspended sediment. The large concentration of sediment was due in part to a persistant wind with velocities estimated at 20 to 30 mi/h, that occurred for several days prior to and during the test. No mineralogic analysis was made of sediment at the Hufstedler site; however, analyses were made of sediments obtained from the Dunlap and Kitten sites. The sample from the Dunlap site is believed to be similar to lake sediment at the Hufstedler site because of similar physiographic location. The Dunlap sample contained about 80-percent clay minerals, dominantly montmorillonite, and 12-percent quartz and calcite. A sample from the Kitten playa lake contained only 10-percent clay minerals and more than 60-percent quartz and calcite. The wind that prevailed during the Hufstedler test would tend to increase the percent of quartz and calcite relative to clay that was in suspension.

The temperature of the playa-lake water was about 22°C when recharge was started. Ground-water temperature averaged 17.2°C.

Recharge Operation

Recharge was started at 1600 hours on May 21, 1969, and continued at an average rate of 150 gal/min for 21 hours. After recharge was completed, the well was redeveloped by pumping and surging for 2.1 hours at rates ranging from 200 to 150 gal/min. The total volume of water injected was 0.58 acre-ft.

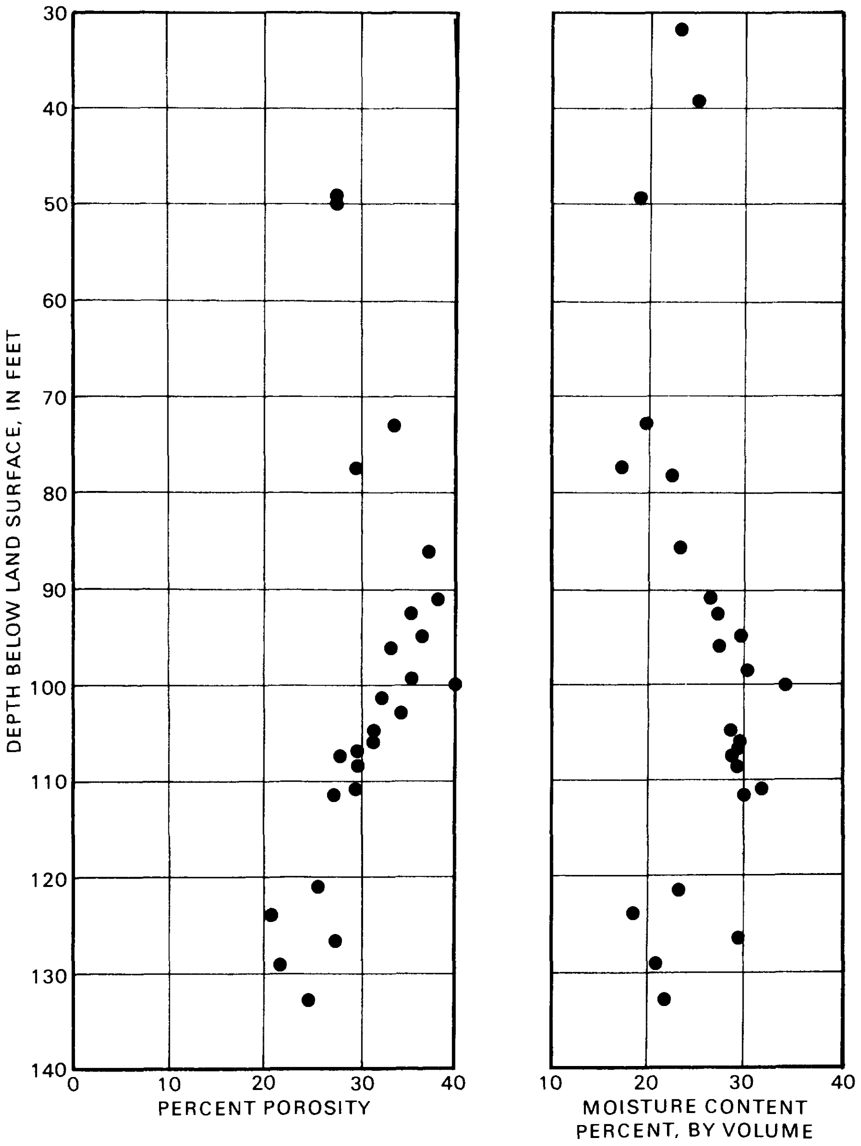


Figure 9. Laboratory values for porosity and moisture content determined using core samples, observation well H–2, Hufstedler site.

Analysis Of Recharge Test

Movement Of Recharge Water

The test at the Hufstedler site was the first in the Ogallala Formation for which temperature logs were used to trace movement of the water (Keys and Brown, 1973). A series of temperature logs made in the test holes immediately after start of recharge showed rapid lateral movement of water through a depth interval centered on 105 ft (fig. 11) and increasing vertical distribution throughout the test. In general, temperature logs indicated that the recharge water moved horizontally at relatively rapid velocity in thin vertical intervals rather than being uniformly distributed throughout the section. Some of the recharge water moved above the prerecharge water level as the injection cone developed. At 1030 hours on the second day, recharge water had reached a depth of 135 ft in observation well H–3, which is approximately the top of a clay interval. The test was terminated before velocities under quasi-steady state conditions could be measured.

Injected Sediment

Approximately 950 lb of sediment was injected. During 2.1 hours of postrecharge pumping, approximately 190 lb or 20 percent of the silt and clay injected was recovered. The remainder was deposited in the aquifer in pore space both above and below the initial water table.

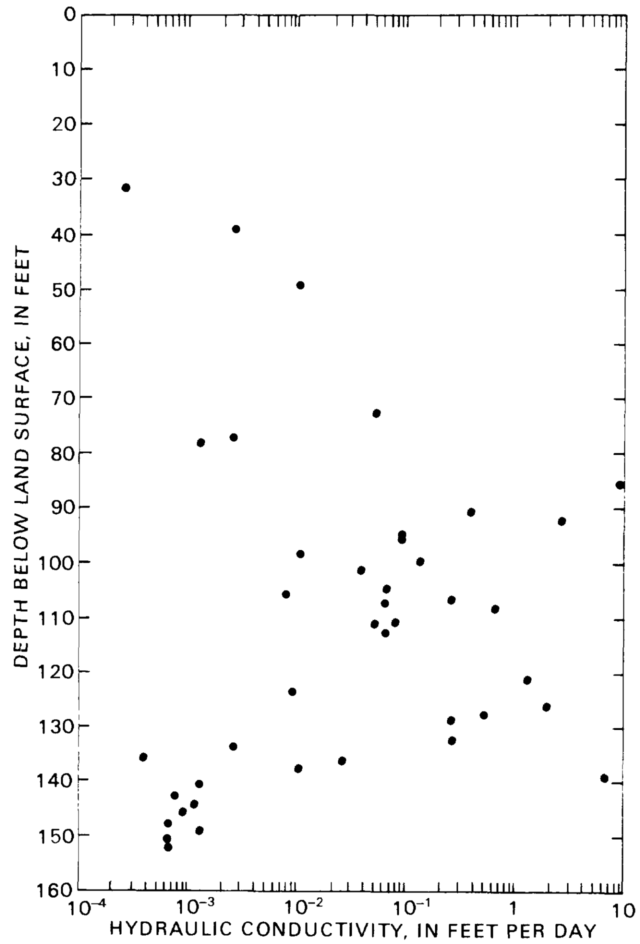


Figure 10. Laboratory values for vertical hydraulic conductivity determined using core samples, observation well H–2, Hufstedler site.

Changes In The Aquifer

The Hufstedler test was the first where gamma-gamma transmittance logs were applied to locate depth intervals where aquifer porosity was changed due to recharge and subsequent pumping. Gamma-gamma transmittance logs were made between observation wells H–1 and H–3, and between observation well H–2 and the recharge well. One problem inherent in this technique is apparent in figure 12; it is difficult to drill two parallel holes. When the source and detector converge in nonparallel holes that approach each other, the count rate increases until detector saturation is reached. When the holes diverge with depth, the count rate decreases and sensitivity is decreased. The pairs of logs in figure 12 were made less than an hour after recharge was completed, and after a short period of pumping for redevelopment. Note that the pairs of logs are closely comparable except for the depth interval immediately below and above the prerecharge water table. The logs show a decrease in bulk density probably due to an increase in porosity in the depth interval above the original water table. This interval could not be developed before recharge but was developed by pumping the well after recharge. Redevelopment caused a detectable increase in porosity only in the interval near the top of the cone of injection. The gamma-gamma transmittance logs show an apparent increase in bulk density for the interval that is 10 to 15 ft below the postrecharge water level.

In the section of this report on laboratory studies, Signor shows a decrease in permeability in laboratory sand-column tests that resulted from injection of a sodium-montmorillonite clay in suspension (fig. 2). The injected clay constituted 0.2 to 0.3 percent by weight of

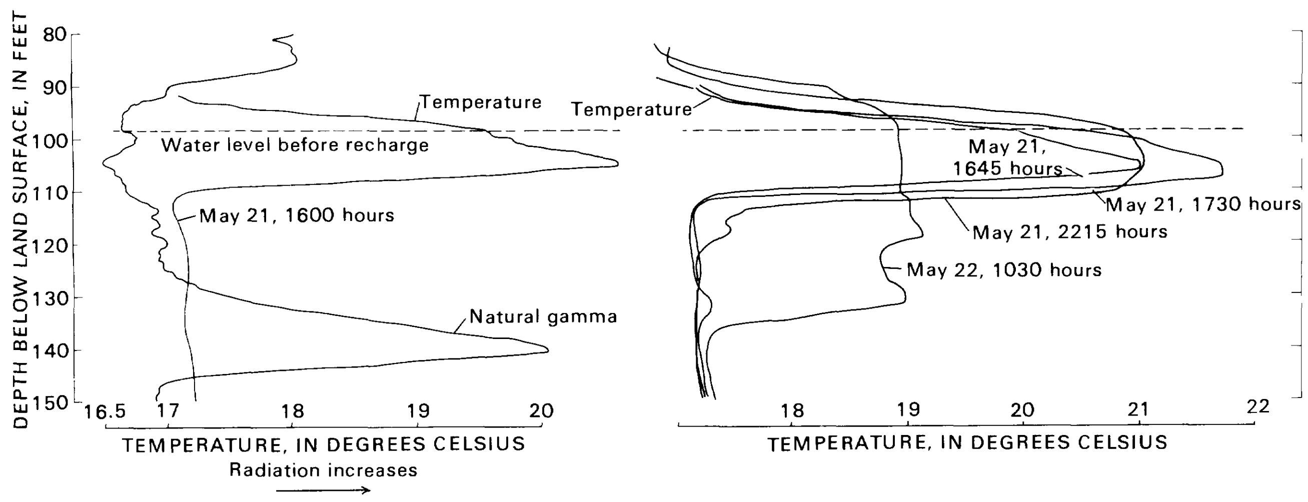


Figure 11. Natural-gamma log and temperature logs, observation well H–3, Hufstedler site.

Table 2. Chemical analyses of native ground water, injected recharge water, and water of reaction, Hufstedler site

Constituents and properties	Concentration (milligrams per liter, except as indicated)		
	Prerecharge ground water from injection well	Lake water	Postrecharge ground water from injection well
Silica, dissolved (SiO_2)	38	13	16
Iron, dissolved (Fe)	.06	.08	.02
Manganese, dissolved (Mn)	.08	.00	.00
Calcium, dissolved (Ca)	66	21	25
Magnesium, dissolved (Mg)	43	4.4	6
Sodium, dissolved (Na)	21	3.9	4.9
Potassium, dissolved (K)	11	7.9	8
Bicarbonate, dissolved (HCO_3)	364	85	105
Carbon dioxide, dissolved (CO_2)	0	0	0
Sulfate, dissolved SO_4)	36	9.8	11
Chloride, dissolved (Cl)	36	3.2	4.3
Flouride, dissolved (F)	2.7	.8	1
Nitrate, dissolved (NO_3)	18	4.2	3.5
Phosphate, dissolved (PO_4)	.9	.59	.46
Dissolved solids (sum)	451	110	132
Hardness (Ca+Mg)	342	70	87
Specific conductance (μmho/cm at 25° C)	719	179	214
pH	8.1	7.4	7.9

the porous medium. The sediment injected into the Hufstedler well probably consisted of montmorillonite and mixed-layer clays plus quartz and calcite that was held in suspension by wave action in the shallow playa lake. Because the gamma-gamma transmittance logs showed a clear and repeatable increase in bulk density after recharge, both above and below the prerecharge water level, it is possible that the change was the result of emplacement of injected sediment. A standard gamma-gamma log can be used to detect changes in bulk density of about 0.01 g/cm^3. It is not known whether the gamma-gamma transmittance log is more sensitive to changes in bulk density or whether the density change in the Hufstedler test was greater than that measured in the laboratory columns. Laboratory tests (fig. 2) showed considerable flow-through of sodium-montmorillonite clay under typical injection-well pressure. Because of the larger size of quartz and calcite clastics, they tend to be filtered out and remain in pore space relatively close to the injection well. The greater density of quartz and calcite relative to clay would result in a large increase in bulk density where they are deposited. Additional testing of the gamma-gamma transmittance log is needed to measure the sensitivity of response and to develop quantitative relations for changes in bulk density that occur as a result of recharge of sediment-laden water.

Well Yield

An attempt was made to redevelop the recharge well and regain the specific capacity measured prior to the recharge test (Schneider and others, 1971). Redevelopment was undertaken by a series of short periods of pumping. Although the water table near the well had risen 7 ft, the specific capacity immediately following recharge was 3.8 (gal/min)/ft. On July 25, 2 months after recharge, the specific capacity was 4.6 (gal/min)/ft. An aquifer test started March 9, 1970 showed that specific capacity had increased to 4.8 (gal/min)/ft. It is possible that the gradual increase in specific capacity during that time was due principally to a decrease in air binding that occurred as a result of air entrainment in the recharge water. The 1970 test was continued for 9 days in an attempt to redevelop the aquifer further; however, the specific capacity decreased from 4.8 to 4.1 (gal/min)/ft at the end of the test.

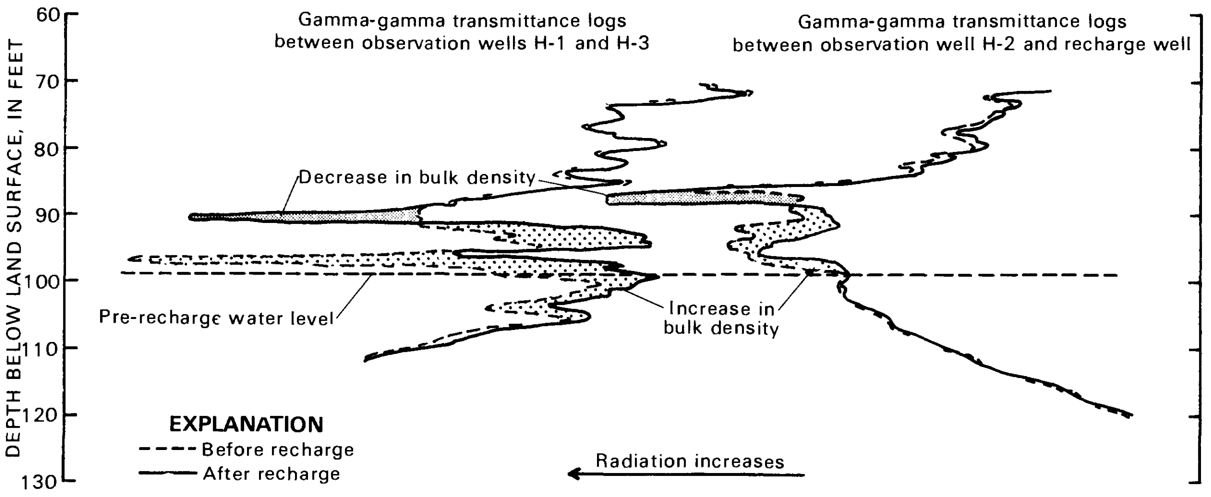


Figure 12. Gamma-gamma transmittance logs showing changes in bulk density induced by recharge of playa-lake water, Hufstedler site.

In the laboratory experiments previously described, an attempt was made to remove the injected clay and increase hydraulic conductivity by backflushing, which involved a backflow of clear water through the matrix. No measurable quantity of clay was removed by this process, and there was no increase in hydraulic conductivity. During redevelopment at the Hufstedler site, flow during pumping was radial and, therefore, the water velocity through the clogged formation was less than in the laboratory tests. The limited redevelopment that occurred shows that, like reverse flushing in the laboratory experiments, pumping the aquifer after recharge did not increase permeability.

Effect Of Well Construction On Recharge

The gravel pack in the recharge well resulted in adequate yield for an irrigation well during prerecharge testing. The quantity of injected sediment removed from the aquifer by postrecharge redevelopment was not sufficient to attain yield or specific-capacity values comparable to those obtained in the prerecharge tests. Thus, the gravel pack did not filter injected sediment as was initially anticipated and did not allow removal of the sediment by redevelopment. Apparently, some of the sediment was deposited at the gravel-pack formation interface where flow velocities generated by pumping are slower than adjacent to the well screen. Thus, this test indicates that the limited redevelopment capacity of gravel-pack recharge wells may result in a less effective recharge system than in naturally developed wells.

Chemical Changes

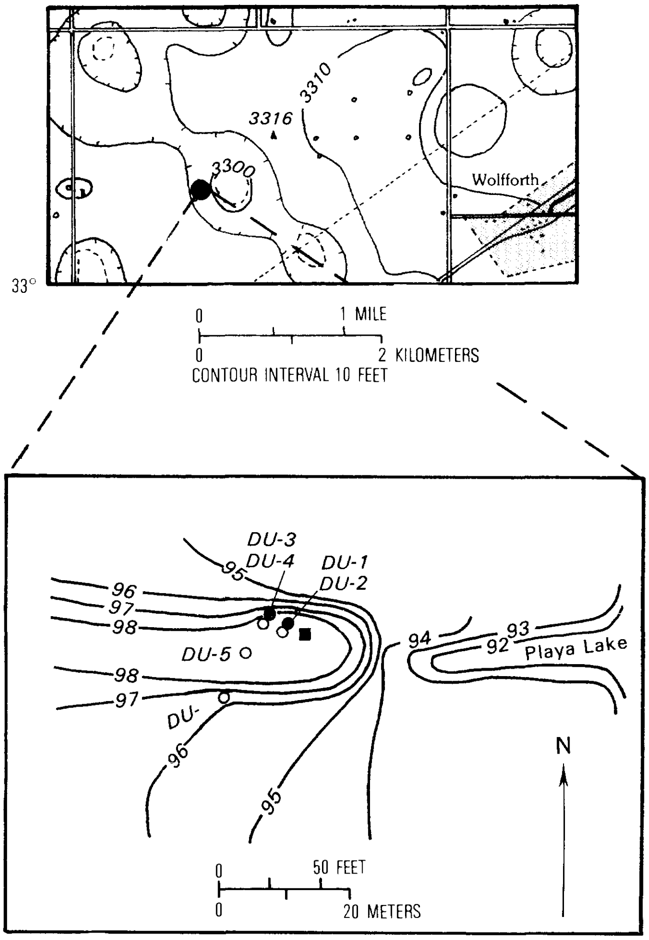
After recharge, the well was pumped and the discharge water was analyzed to determine which characteristics had been changed by the mixing of playa-lake water and native ground water. Table 2 lists values that resulted from mixing.

A comparison of this analysis with the lake-water analysis, and the Ogallala ground-water analysis, (table 2), shows that the repumped water is dominantly playa-lake water, but has an increased concentration of dissolved solids apparently due to mixing with ground water.

DUNLAP SITE

Location

The Dunlap site is 1¼ mi west of Wolfforth, Texas, on the Dunlap ranch. Figure 13 shows the location of the site, the recharge well, and the test holes.



EXPLANATION

——95—— LAND-SURFACE CONTOUR—Shows altitude of the land surface. Contour interval 1 foot. Datum is arbitrary

■ RECHARGE WELL

● *DU-2* OBSERVATION WELL

○ *DU-4* TEST HOLE

Figure 13. Location of recharge well, observation wells, test holes, and playa lake, Dunlap site.

Recharge And Monitoring System

The recharge well is 20 in. in diameter, gravel packed, with 10-in casing, mill slotted (3/16- by 2¾-in slots) and has 16 perforations per foot from 80 to 181 ft. During construction, the well was gravel packed to the surface, then bailed until the gravel settled to about 30 ft. The well was cemented from that depth to the surface, but leakage at the surface during recharge indicated that the cement seal was not competent because water moved vertically through the annulus. The screened inter-

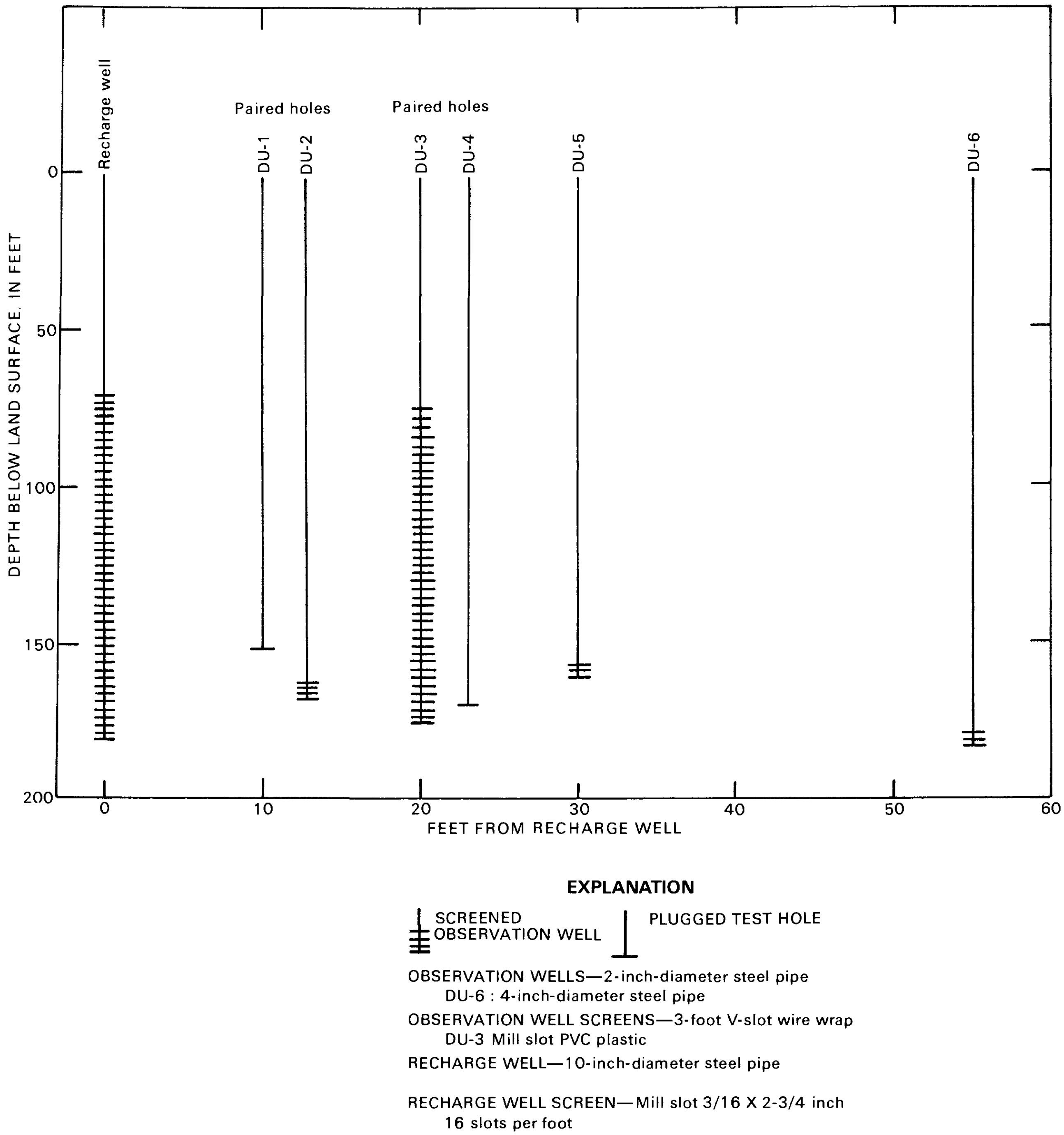


Figure 14. Construction of recharge well, observation wells, and test holes, Dunlap site.

vals in the recharge and observation wells are shown in figure 14. The recharge well was installed under the direction of Duane Crawford and Philip Johnson, Department of Petroleum Engineering, Texas Tech University. Figure 15 is a schematic of the recharge system. No pump was installed in the well, so no aquifer tests could be made.

The observation wells and test holes were located and constructed to yield the maximum information on changes that occurred as a result of recharge. The placement and design was based on the analysis of recharge data obtained at the Hufstedler site. Holes DU–1 and DU–2 were intended to be drilled parallel to each other, 29 in apart. The attempt to drill parallel holes was made by leveling the drill rig and by very slow drilling to avoid drift of the bit. In spite of these efforts, logging indicated that holes DU–1 and DU–2 diverge with depth, preventing

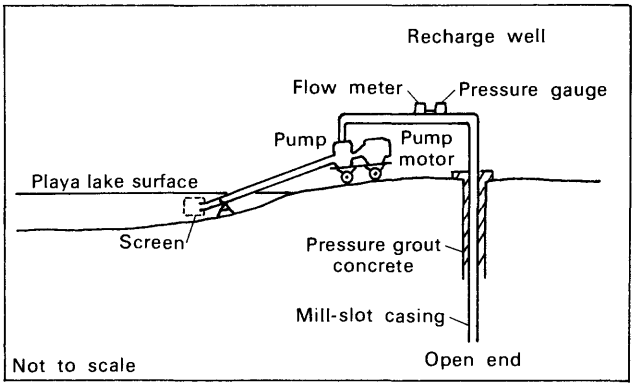


Figure 15. Recharge system, Dunlap site.

meaningful gamma-gamma transmittance logging in the zone affected by recharge. Test hole DU–2 was lined with capped 2-in steel pipe for use in temperature logging. Observation well DU–1 was screened at the bottom with a 3-ft section of V-notch wire-wrap screen; thus, measured water levels represent hydraulic head at that depth. Observation well DU–3 and test hole DU–4 are 3.5 ft apart. Attempts to drill them parallel failed, the wells converged and actually crossed near the bottom, thus preventing their use for gamma-gamma transmittance logging. Observation well DU–3 is cased with 2-in steel pipe to a depth of 74 ft and finished with 100 ft of 2-in saw-slotted, plastic screen. Plastic screen was used to permit resistivity logging and to permit measurement of water levels representative of average head conditions throughout the recharged zone. The casing in hole DU–4 is capped on the bottom to permit temperature logging. DU–5 is screened with a 3–ft section of 2-in diameter, V-notch wire-wrap screen. Observation wells DU–6, DU–7, and DU–8 are located 183 ft, 938 ft, and 1,360 ft, respectively from the recharge well, and are cased with 4-in steel pipe with a 3-ft screen on the bottom.

Geohydrology

Core Data

The geology at the Dunlap site is typical of the Ogallala Formation in the Southern High Plains; the lithology consists of detrital sediment with widely differing particle sizes, and parts of the section have high calcium carbonate content (fig. 16).

Test hole DU–2 was drilled at the site using a split-tube, wire-line core device and hydraulic rotary methods. Because the coring technique used drilling fluid, samples were analyzed for porosity and hydraulic conductivity, but not for moisture content.

Particle size and calcium carbonate content are shown in figure 17. The particle-size-distribution graph shows that for most of the intervals analyzed, there is a uniform range of particle size from clay and silt through coarse sand. The interval from 67 to 70 ft contains chert nodules. Similar zones of high silica content are visible in exposures throughout the Southern High Plains. Laboratory analyses of this interval were not available because chert pebbles jammed and rotated in the core barrel and prevented entry of other material on each core run.

Because the injection well could not be pumped, all pretest values for permeability were measured on core samples. A plot of hydraulic conductivity measured on samples from observation well DU–1 is shown in figure 18. The hydraulic conductivities range over five orders of magnitude. The distribution does not agree with data obtained from the recharge test and could not have been used to predict the movement of injected water.

The section of Upper Triassic Santa Rosa (?) Sandstone from 147 to 157 ft consists of permeable, clean, medium-fine to fine sand. The uniform sand cored in this section was visually judged to have the highest intrinsic permeability of any that was penetrated. The depth interval from 50 to 80 ft had a high calcium carbonate content and extensive secondary solution openings. Although this interval was above the initial water table, the well was screened above the water table and gravel packed so that recharge water entered that section under pressure-injection conditions.

Geophysical Logs

The lithology of the Ogallala Formation at the Dunlap site is markedly different than at the Hufstedler site. Several conglomerate beds with chert nodules and igneous and metamorphic pebbles cemented by calcium carbonate are present at the Dunlap site. These are interbedded with beds of fine-grained sand with abundant calcium carbonate as cement and nodules. The geophysical logs distinguished most of these lithologic units and demonstrate that they are continuous within the area drilled.

The natural-gamma logs show that the calcareous conglomerate beds have the highest radioactivity, and that those with chert nodules are more radioactive than the beds with igneous and metamorphic pebbles. The gamma-emitting radioisotopes may be concentrated in the calcareous cement inasmuch as an interval of high calcium carbonate content is also quite radioactive. The conglomerate layers are also clearly distinguished on the neutron logs by a low porosity response in the interval 109–125 ft (figs. 16 and 19). The conglomerate with igneous and metamorphic pebbles appears to have the lowest porosity of all the units penetrated. In contrast, the fine-grained sand has the highest apparent neutron porosity.

The underlying Santa Rosa (?) Sandstone is characterized by a relatively low gamma response and high apparent neutron porosity. This high apparent porosity may

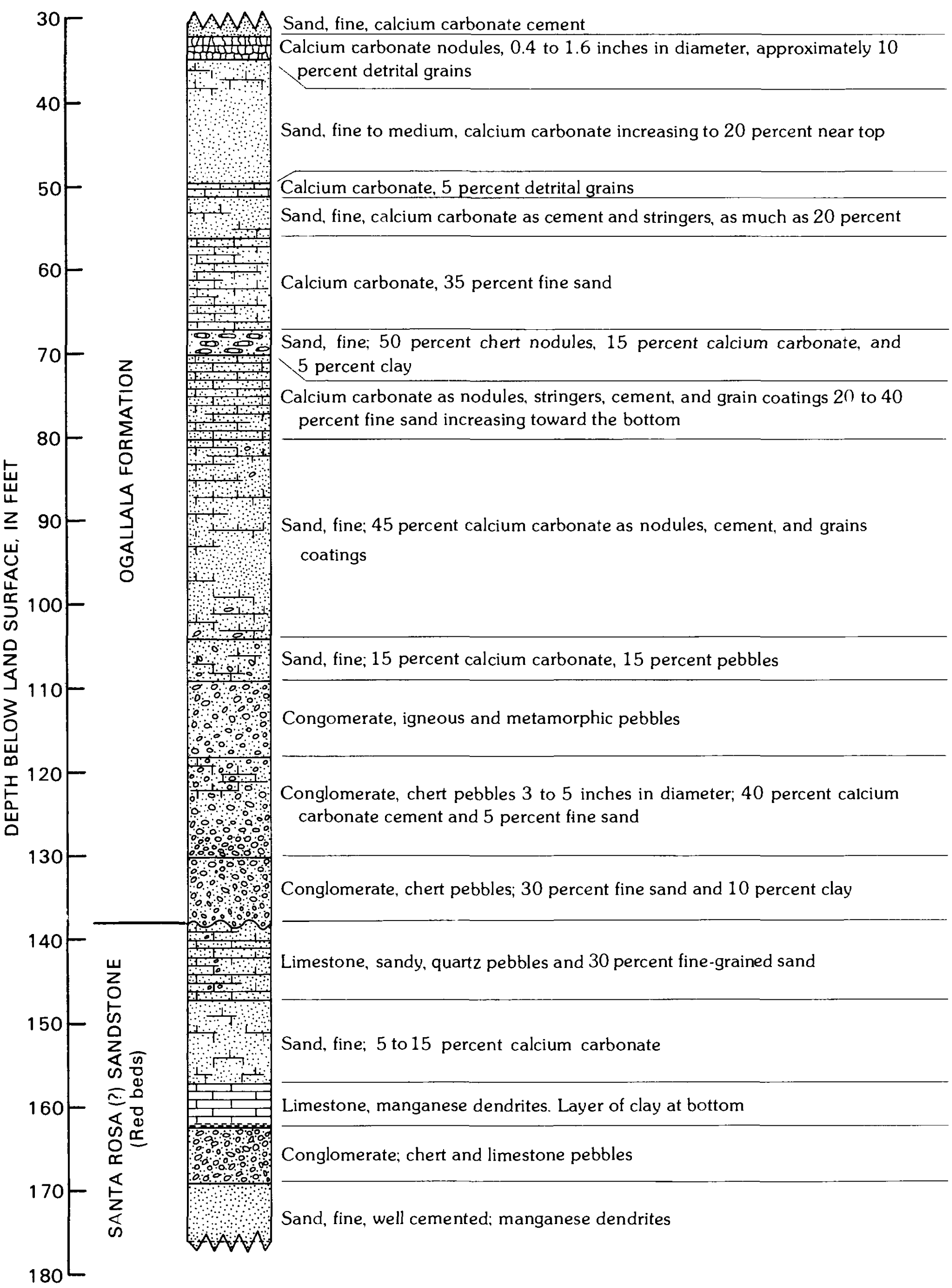


Figure 16. Lithologic log, test hole DU–2, Dunlap site.

be partly due to the presence of water in gypsum which is prevalent elsewhere in the Santa Rosa (?) Sandstone.

Water Chemistry

Water for recharge was obtained from a shallow playa lake adjacent to the wells. Temperature of the water was diurnally pulsed by solar heating and night cooling and was considerably warmer than the prerecharge ground water which averaged 18°C. The maximum temperature range of the recharge water was from slightly less than 19°C to 34°C, and similar diurnal cycles persisted throughout the test (fig. 20). The water in the playa lake was not significantly agitated by wind action during the test, but still contained approximately 137 mg/L of suspended solids. An X-ray diffraction analysis of the suspended solids in the lake water showed that clay minerals comprised approximately 80 percent, quartz approximately 10 percent, and calcite 2 percent. The clay minerals consisted of mixed-layer illite and montmorillonite and appeared to have considerable interlayer material.

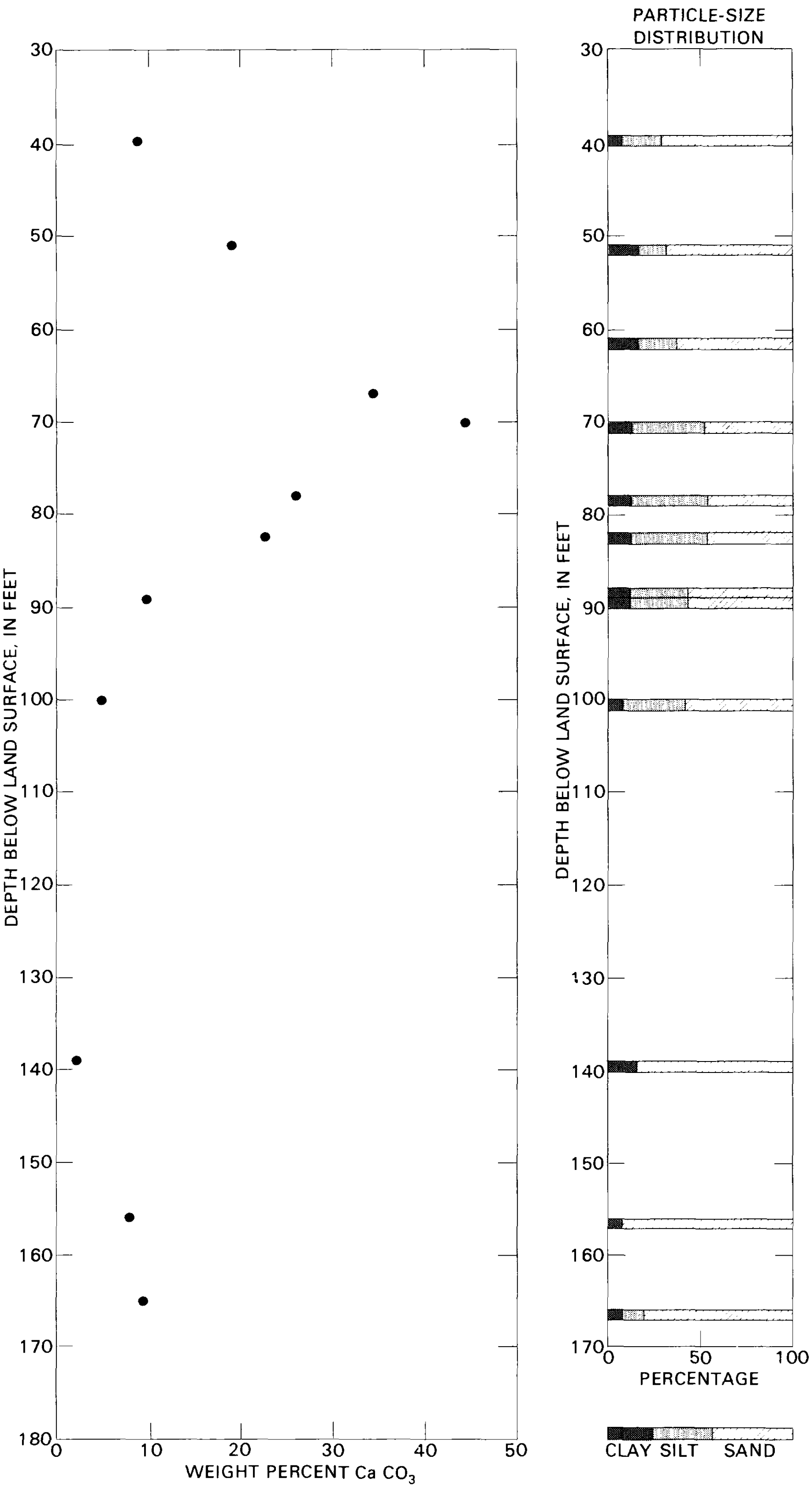


Figure 17. Calcium carbonate content and particle-size distribution, test hole DU–2, Dunlap site.

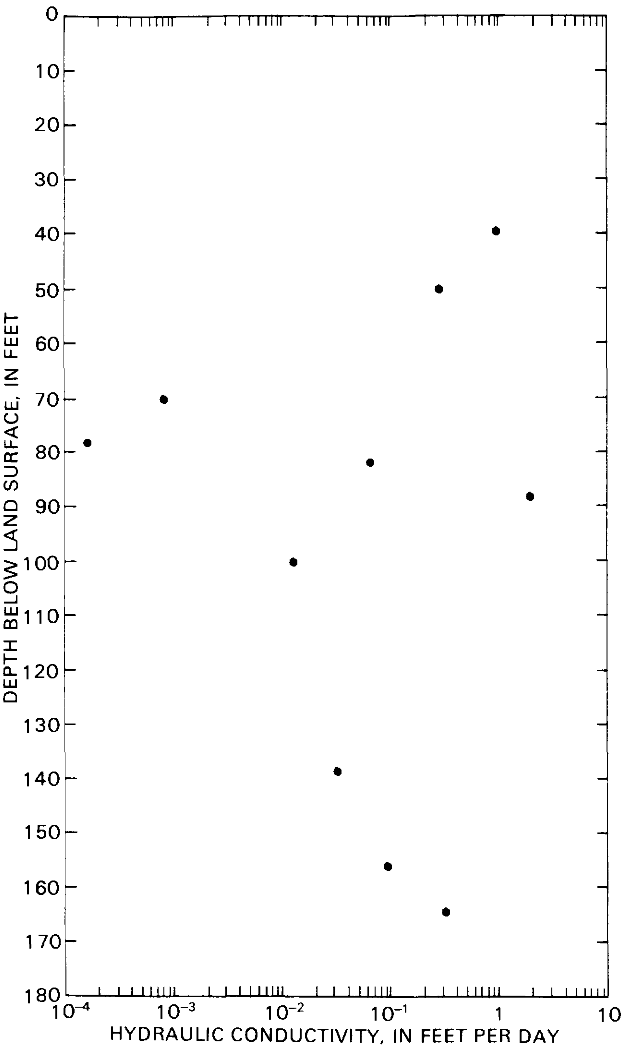


Figure 18. Laboratory values for vertical hydraulic conductivity determined using core samples, test hole DU–2, Dunlap site.

A chemical analysis of a sample of the lake water collected July 14, just prior to recharge, is typically low in total dissolved solids as compared to ground water (table 3).

Recharge Operation

The recharge test was conducted at the Dunlap site from 1500 hours, July 16, to 1730 hours, July 18, including several stops required because of equipment malfunction. The total recharge time was 50.5 hours. Total recharge for the test is estimated at 4.5 million gallons, or 14 acre-ft.

Water was pumped from a canal connected to the playa lake (fig. 21). It passed through an 8-in pipe coupled directly to the top of the casing in the recharge well. Pump-engine speed varied between 1,800 and 2,200 revolutions per minute, resulting in a range of injection pressure at the wellhead from about 50 to 85 lb/in^2. Particularly detrimental to quantitative analyses of the test were several shutdowns during the first hour of recharge July 16, when leaks developed and were repaired in the injection line. Recharge also stopped from 0800 hours to 0900 hours and from 1313 hours to 1610 hours on July 17. Late in the recharge test, surface springs developed between the injection well and the playa lake.

Analysis Of Recharge Test

Movement Of Recharge Water

As in the Hufstedler test, the flow of recharge water through the aquifer was monitored by measurement of temperature. Temperature of recharge water was measured periodically at the intake of the recharge system and by temperature logs of test holes DU–2 and DU–4, and observation wells DU–1, DU–3, and DU–5. Approximately 75 temperature logs were run during the test; these were replotted as temperature versus time for those depths at which significant movement of recharge water occurred.

Figure 22 shows three temperature logs of test hole DU–2, prior to recharge, while water was moving below the water table, and later in the test when all movement was above the prerecharge water table. The prerecharge log shows minor temperature anomalies due to residual water from rotary drilling. The log made after 8 hours of recharge shows that a significant amount of recharge water had arrived in the interval from 135 to 150 ft and very little had arrived in the shallow zones. The log made the day after the test was terminated shows that most of the warmer recharge water was in the depth interval from 30 to 90 ft.

An example of the diurnal-temperature fluctuations of the recharge water and at three depth intervals in test hole DU–2 is shown in figure 20. The maximum and minimum temperature of the input water could be correlated with thermal peaks of the recharge water as it moved past test holes. No temperature effects of recharge were seen in observation wells DU–6, DU–7, and DU–8.

Analysis of the movement of the diurnal-temperature pulses through the aquifer at test hole DU–2 shows that the most permeable zones were at depths of 35 to 50 ft, 60 to 92 ft, and 138 to 155 ft (fig. 20). The first arrival of recharge water was probably in the shallowest zones in test hole DU–2 (fig. 23). Ground-water velocities were higher than predicted, and it was not possible to log all the holes fast enough to record the initial arrivals of thermal anomalies. The logs of test hole DU–2 also indicate that little flow took place in the deeper zones

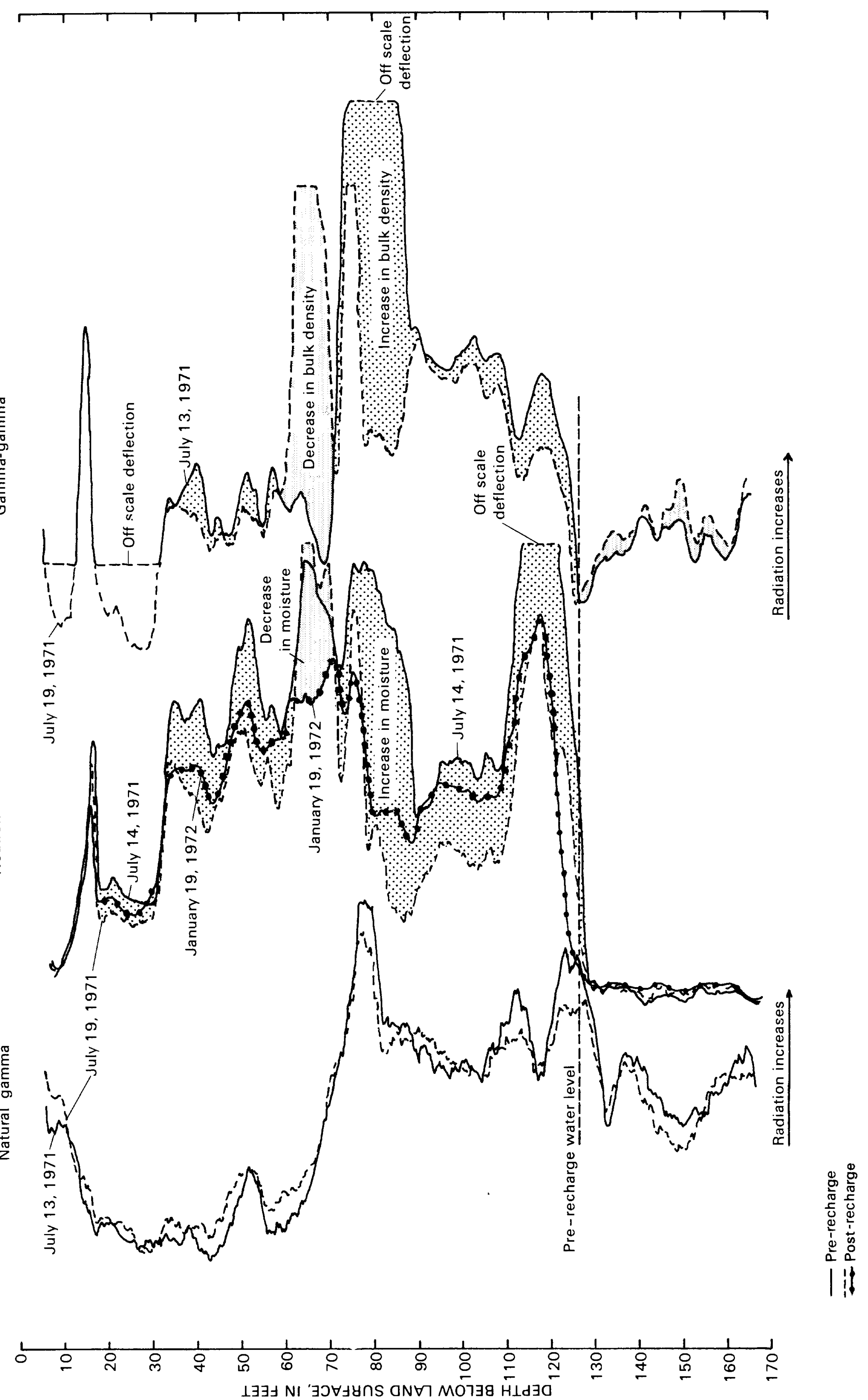


Figure 19. Natural-gamma, neutron, and gamma-gamma logs, test hole DU-2, Dunlap site.

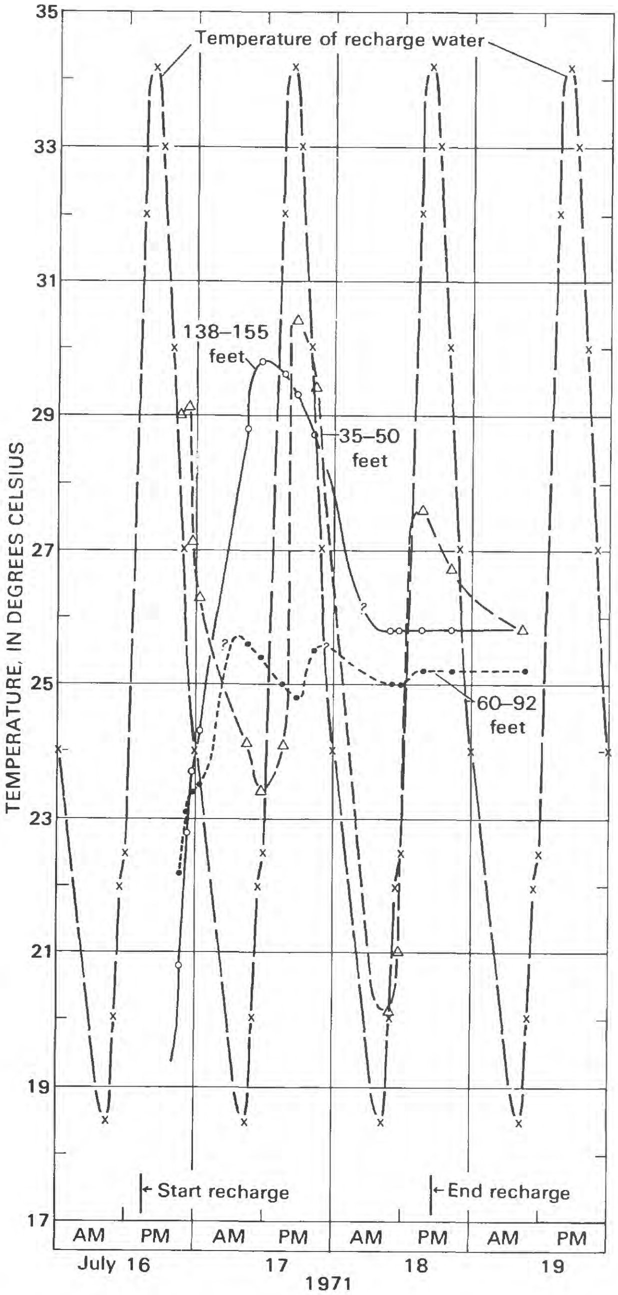


Figure 20. Temperature changes in recharge water and in three-depth intervals, test hole DU–2, Dunlap Site.

after the initial arrival of recharge water. In contrast, recharge water continued to move through the interval from 35 to 50 ft.

Temperature logs show that it took several hours for the recharge water to arrive at test hole DU–2 in the interval from 135 to 150 ft. Diurnal-pulse arrivals were not clearly detected for the interval below the prerecharge water table; however, velocity of the thermal front was apparently from 2 to 4 ft/h. This previously saturated portion of the Ogallala Formation transmitted only the initial

Table 3. Chemical analysis of water from the playa lake collected before the recharge test, Dunlap site

Constituents and properties	Concentration (milligrams per liter, except as noted)
Silica, dissolved, (SiO_2)	10.
Calcium, dissolved, (Ca)	30
Magnesium, dissolved (Mg)	3.4
Sodium, dissolved (Na)	3.4
Potassium, dissolved (K)	6.9
Bicarbonate, dissolved (HCO_3)	8.5
Sulfate, dissolved (SO_4)	7.8
Chloride, dissolved (Cl)	13.0
Flouride, dissolved (F)	0.4
Nitrate, dissolved (NO_3)	3.2
Boron, dissolved (B)	0.09
Total dissolved solids	122
Suspended solids	137
Turbidity (JTU)	80
pH	7.5

Figure 21. Recharge operations, showing details of pressure recharge system, Dunlap site.

thermal pulse and then apparently plugged. In contrast, sharp and continued pulse arrivals were recorded in the interval 35 to 50 ft (fig. 20). The timing of the first arrival of recharge water in this zone gave an average thermal front velocity of 2.2 ft/h in observation well DU–1 and test hole DU–2. On the second day, the thermal pulse moved in this interval with a velocity of 2.5 ft/h. The increase in velocity may have been caused by a combination of several effects—the zone had become saturated, some development had taken place near the recharge well, and the deepest zone had plugged.

The presence of an intermediate, less permeable zone from 60 to 92 ft is indicated by temperature logs (fig. 23). Thermal fluctuations in this interval are either considerably reduced or, as in test hole DU–4, water tem-

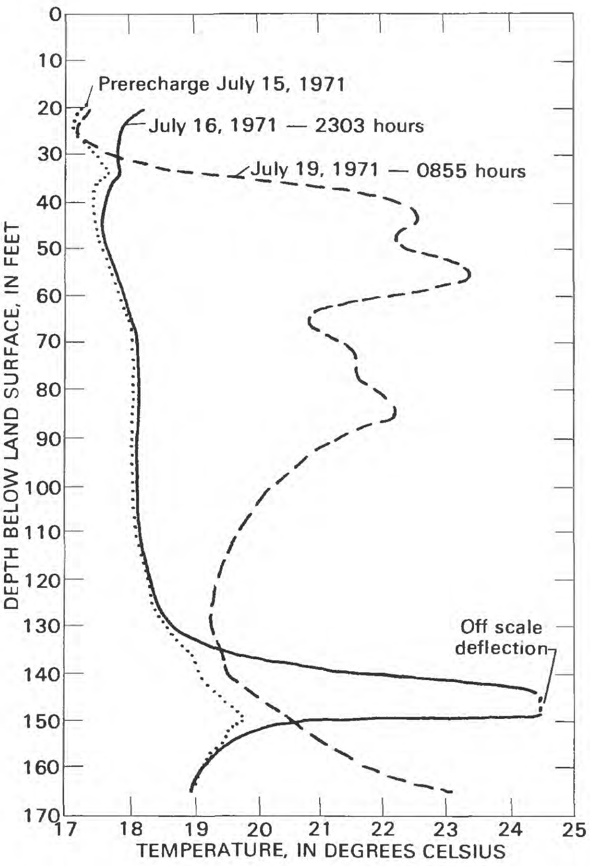


Figure 22. Temperature logs resulting from recharge of warm playa-lake water, test hole DU–2, Dunlap site.

perature gradually increased during the test. These logs suggest that this zone was gradually becoming saturated by recharged water, mostly by downward movement.

A comparison of prerecharge and postrecharge neutron and gamma-gammalogs shows a significant increase in moisture content above the prerecharge water table (fig. 19). No calibration data were available for the logs, but by extrapolation of data from a site near Lubbock, Texas, the change in moisture content ranged from 1 percent to 19 percent, with an average of approximately 14 percent. The thickness of zones of significant moisture change was 88 ft in observation well DU–5, 85 ft in test hole DU–2, 80 ft in test hole DU–4, and an anomalous 111 ft in observation well DU–3. Although the porosity values may be in error, it is obvious that a very large amount of water was stored in this upper zone. The rate of acceptance of recharge was high in this zone, and as shown on figures 16 and 17, the upper zone has a high calcium carbonate content. It is likely that secondary porosity is well developed and extends throughout the test area. A large increase in moisture in this zone was measured by neutron logs of the wells close to the recharge well. Neutron logs showed no detectable moisture change in test hole DU–6 during recharge. From calculations based on one half the volume of recharge water injected and assuming a 20-ft-thick, permeable interval through which water moved, the radius of formation to be affected would be about 130 ft, which is beyond observation well DU–6. Water may have flowed in secondary openings that did not intersect observation well DU–6. The declining water level in the observation wells (caused by distant pumping) indicates that very little recharge water entered the aquifer below the water table and that most of the recharged water entered the permeable upper zone.

Successive neutron logs of test hole DU–2 showed that rapid drainage took place in the interval from 34 to 61 ft in the 160 minutes following cessation of recharge. However, neutron and gamma-gamma logs made on January 19 of the following year showed that much of the water still remained above the prerecharge water table (fig. 19). The fact that water levels in the observation wells continued to decline after only a short period of rise also indicates that a significant part of the recharged water was perched above the water table (fig. 24) and was not immediately available for pumping.

Injected Sediment

The water injected into the Dunlap recharge well contained an average suspended sediment concentration of 137 mg/L. In the 4.5 million gallons of water injected, the total weight of sediment was about 5,100 lb. The volume of space in the gravel pack (annulus between 10-in slotted well casing and the 20-in drill hole) is about 50 ft^3. Laboratory studies of flow of sediment through sand columns (described previously) resulted in 0.2 to 0.3 weight percent retention of clay before hydraulic conductivity was reduced about 50 percent. If it is assumed that the concentration of clay minerals retained in the gravel pack was comparable, less than 40 lb of suspended sediment was retained in the gravel pack. Thus, by far the greatest amount of the sediment was deposited in those zones of the Ogallala Formation that accepted water at a maximum rate; the remainder was deposited in the gravel pack and concentrated on the face of the well bore. There was no observed clogging effect from either air entrainment or bacteria. However, data on bacteria concentration were not collected.

Changes In The Aquifer

Temperature logs suggest that plugging of the 135- to 155-ft zone occurred early in the test. Differences between the prerecharge and the postrecharge neutron and gamma-gamma logs are not sufficient to demonstrate a significant change in porosity due to plugging of that interval (fig. 19). It is possible that low permeability resulted in too small an inflow of sediment to be detected,

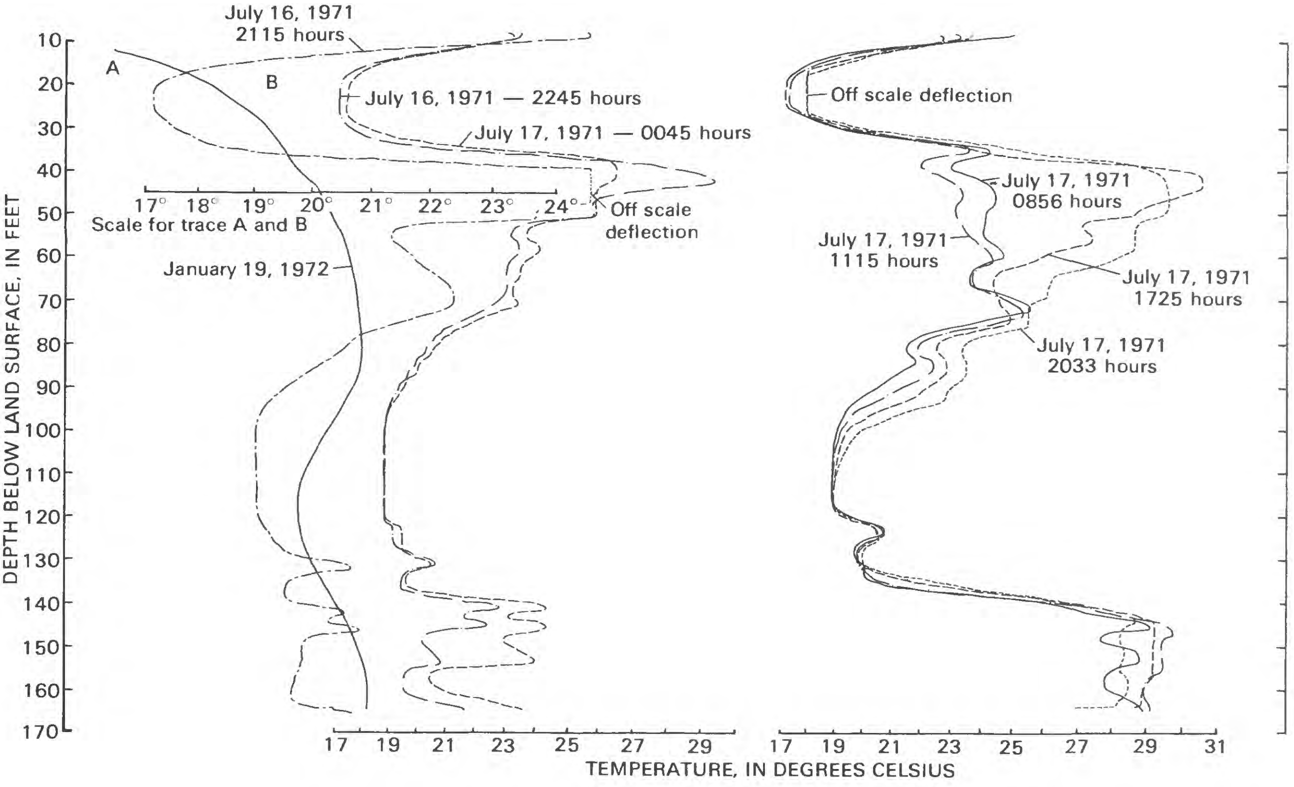


Figure 23. Temperature logs, test hole DU–2, Dunlap site.

or that most of the plugging took place in the immediate vicinity of the recharge well; thus the total volume plugged was not sufficient to measurably affect the density 10 to 20 ft from the recharge well. Furthermore, the conventional gamma-gamma logs that had to be used at the Dunlap site are not as sensitive to bulk density changes distant from a drill hole as the gamma-gamma transmittance technique used at the Hufstedler site.

Normal electrode resistivity logs of observation well DU–3 were made to investigate possible changes in the aquifer. The logs, made through plastic screen, are shown in figure 25. The 64-in normal curve represents resistivity of a relatively large volume of material, and the increase in resistivity on this curve after recharge is attributed to the lower dissolved solids of the playa-lake water. The decrease in resistivity on the 16-in normal curve, a measurement of a smaller volume of material near the borehole, is probably due to development in the annulus around the screen.

The plastic screen in observation well DU–3 served as a short circuit for intra-aquifer flow. Late in the test,

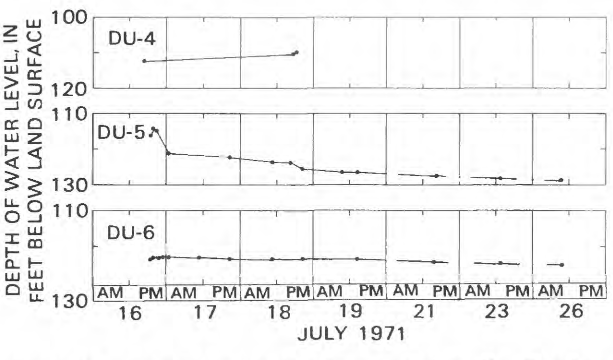


Figure 24. Water levels in observation wells, Dunlap site.

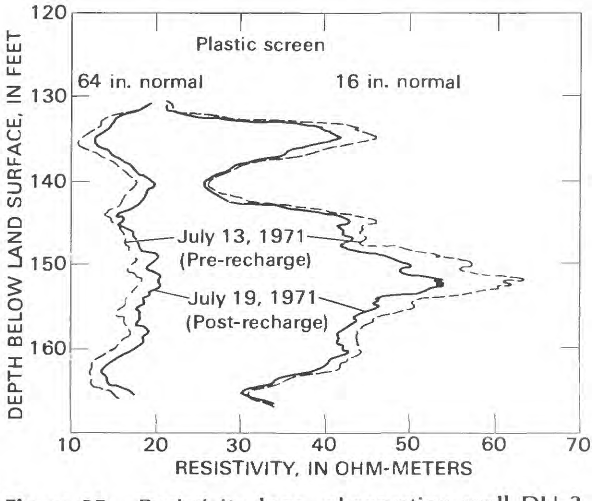


Figure 25. Resistivity logs, observation well DU–3, Dunlap site.

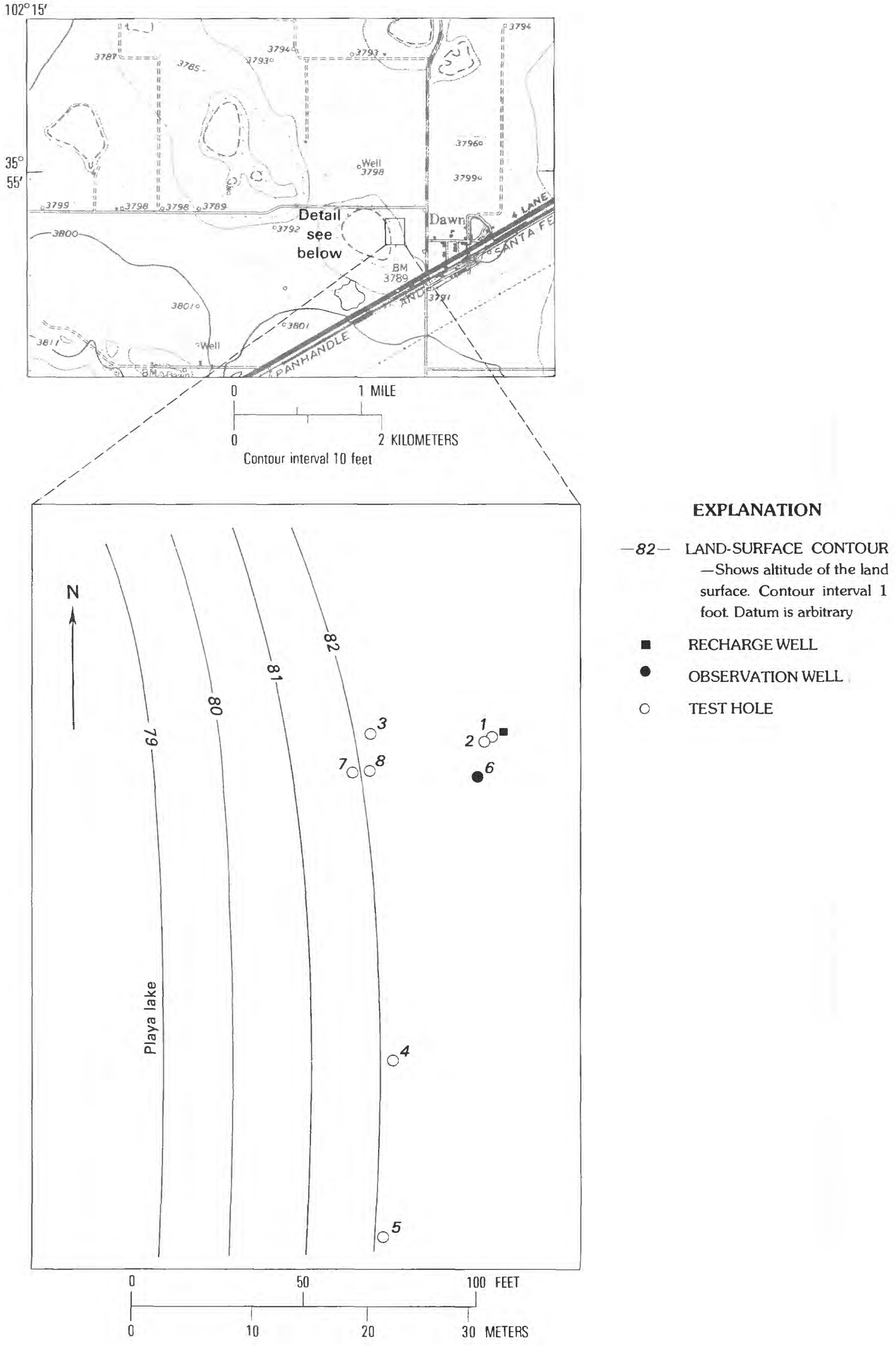


Figure 26. Location of recharge well, observation well, test holes, and playa lake, Stewart site.

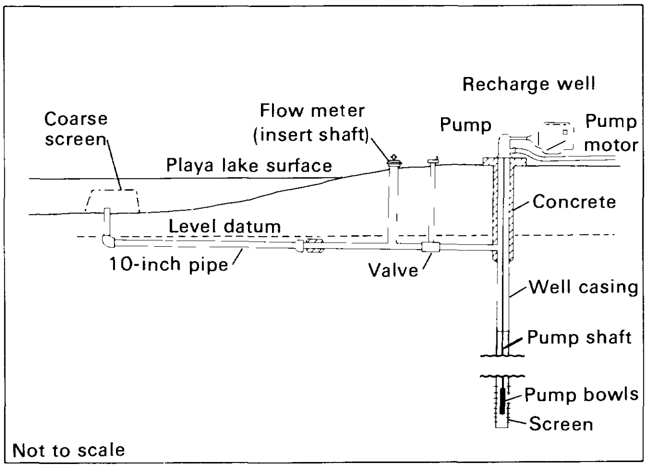


Figure 27. Recharge system, Stewart site.

water cascaded through the screen from an upper zone to the water table. Water-level measurements in observation well DU–3 are very likely in error. This is a problem inherent in observation wells that are screened continuously between two or more permeable intervals.

STEWART SITE

Location

The Stewart site is 14 mi northeast of Hereford, Texas, one-fourth mile west of the community of Dawn, Texas. The configuration of the recharge and test holes is shown in figure 26.

The site was selected for artificial-recharge tests by the Agricultural Research Service, Bushland, Texas, and the first test hole was drilled and sampled under their supervision. Samples of cuttings consisted dominantly of

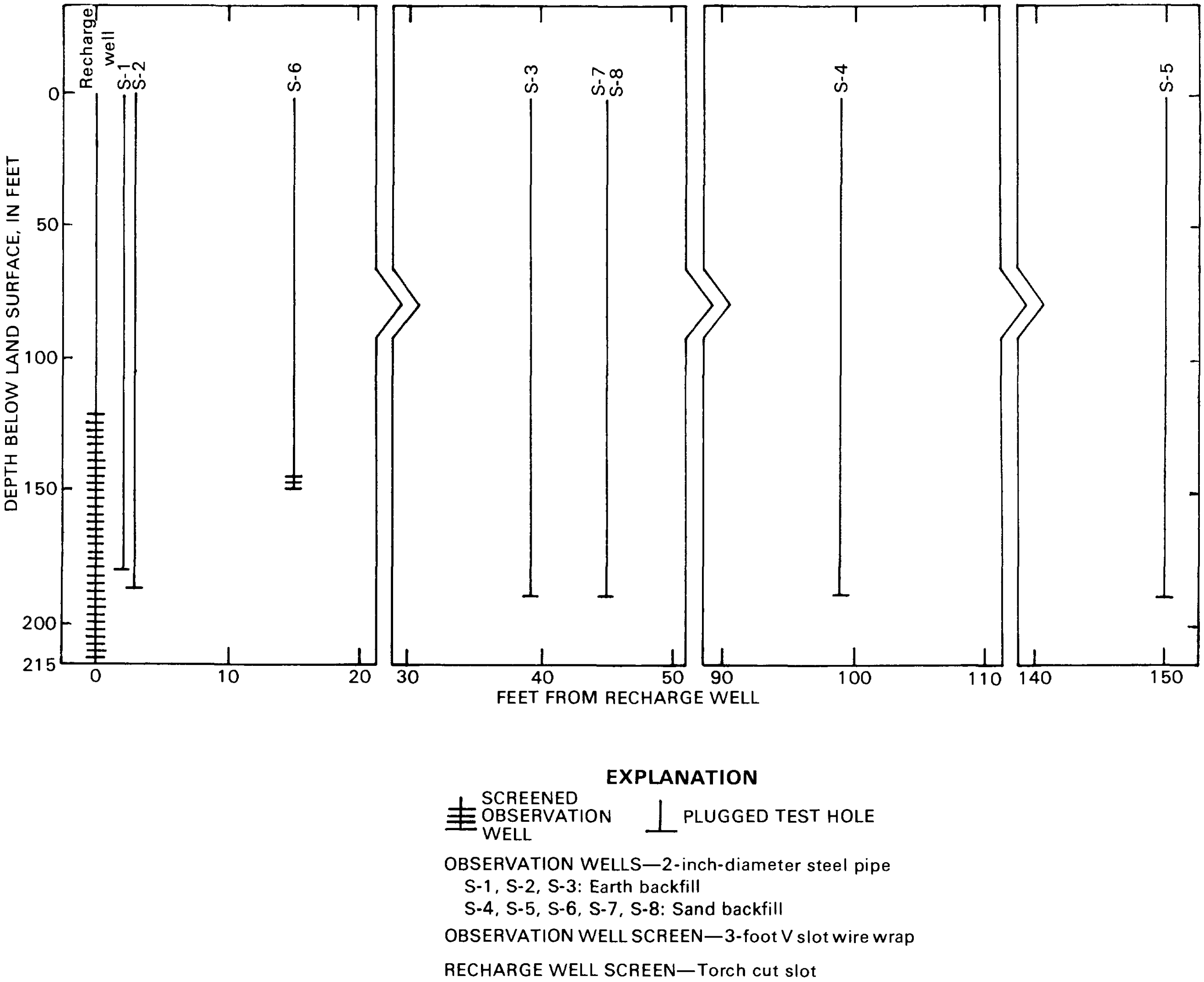


Figure 28. Construction of recharge well, observation well, and test holes, Stewart site.

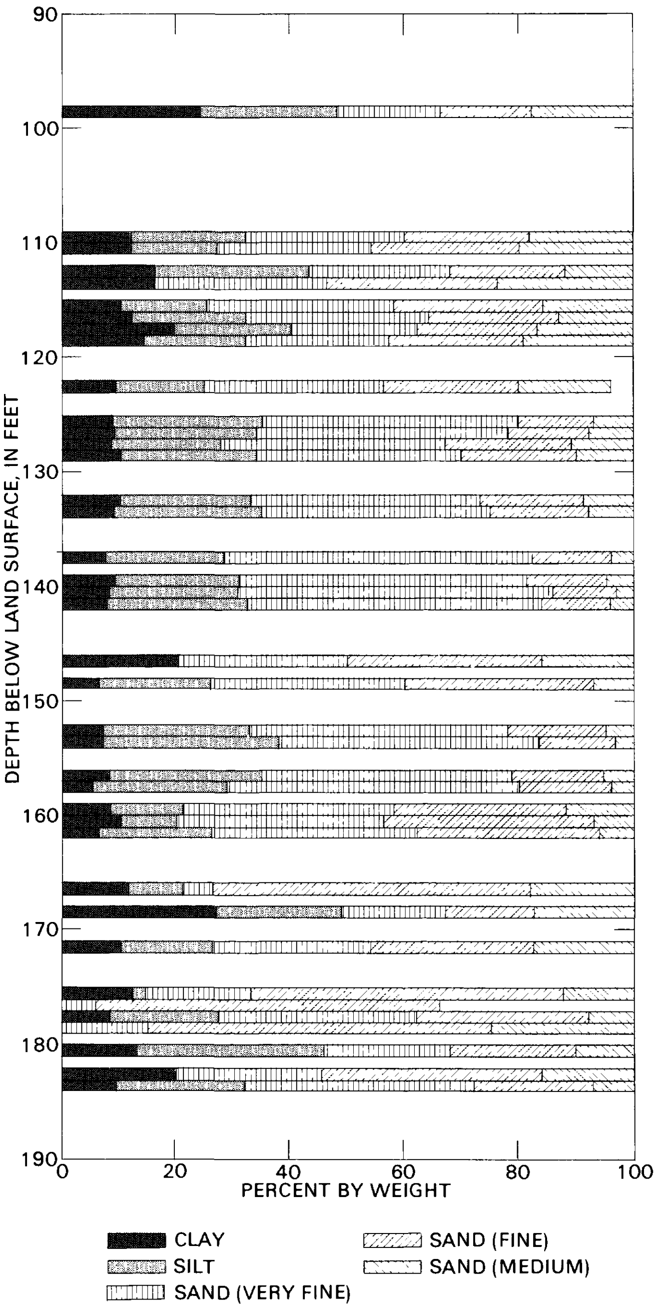


Figure 29. Particle-size distribution in core samples, test hole S–7, Stewart site.

fine and medium sand. Because of the apparent low permeability of the aquifer at this site, the Agricultural Research Service withdrew from further tests. However, the owner of the site, Ray Stewart, completed the recharge well and water conductance-system in accordance with Agricultural Research Service specifications, modified to reduce the effect on farm operations. Subsequently, the U.S. Geological Survey was granted permission to construct test holes and measure hydrologic parameters during recharge.

Recharge And Monitoring System

The recharge well at the Stewart site consists of a 14-in diameter hole in which 10-in casing was inserted from the surface to a depth of 219 ft. The casing was torch slotted from 123 to 219 ft. The well was developed naturally by high-speed bailing and was additionally developed by pumping. No gravel pack was added. The friable-sand aquifer probably collapsed against the casing. Cement grout was placed only at the surface. A deep-well, line-shaft turbine pump was installed, operated by a natural-gas engine (fig. 27).

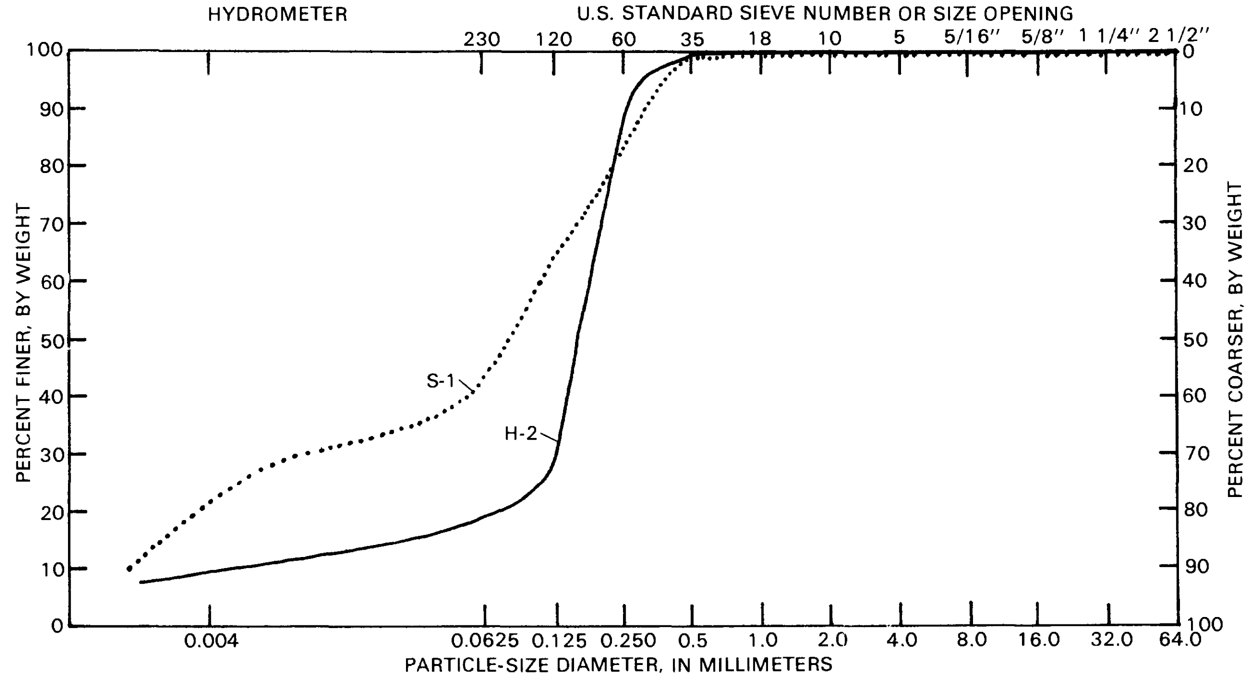
Average discharge rate from the well during the previous irrigation season was estimated by Mr. Stewart at 150 gal/min, from an initial static water level of about 152 ft. However, during test pumping immediately prior to the recharge test, the pump broke suction and the well yield was not measurable.

Water for recharge was obtained from the playa lake adjacent to the recharge well. Water was conducted by gravity flow from a screened inlet near the center of the playa to the well casing (fig. 27). Lake water cascaded from the casing inlet pipe to the water level in the well.

Holes in the pump and pump base were plugged to minimize air entrainment, but large volumes of air still entered the system. A gate valve was used to control the rate of inflow, but excessive changes in the valve setting resulted in large fluctuations in flow for a short time. The rate of flow was measured by use of a small rotating-cup current meter. Debris inside the screened enclosure intermittently altered the rate of flow and distorted measurements.

Test holes S–1, S–2, and S–3 were augered prior to recharge, cased with 2-in iron pipe, and screened at the bottom. In order to fill the pipes with water so the holes could be used for temperature logging, rubber stoppers were pushed into the casing to a point just above the screen. Holes S–4 and S–5 were drilled during the test to monitor the extent of movement of the recharge water beyond the pre-existing holes. Observation well S–6 was drilled to 150 ft and screened at the bottom to yield water samples for quality analysis.

Test holes S–7 and S–8 were drilled subsequent to the test to obtain postrecharge core samples and gamma-spectral logs of the lithologic units at the site. Hole S–7 was cored using a split-spoon drive sampler. Hole S–8 was cored using a Dennison core barrel. The poorly consolidated core was collected in 3-in diameter, brass-core barrel liners, and core samples were extruded from these liners by action of a hydraulic piston. The distance of test holes from the recharge well and the hole construction are shown on figure 28.



Hufstedler site, Hole H-2, 10[1] feet below land surface			PERCENT OF SIZE	Stewart site, Hole S-1, 121 feet below land surface		
CLAY 9.5		Very fine 10.7		CLAY 21.0		Very fine 21.3
SILT 9.6	SAND	Fine 57.5		SILT 22.1	SAND	Fine 18.8
		Medium 12.3				Medium 15.7
		Coarse 0.4				Coarse 0.9
						Very Coarse 0.2

Figure 30. Particle-size distribution determined using core samples, test hole S–1 and observation well H–2, Stewart and Hufstedler sites.

Geohydrology

Core Data

Plots of particle size distribution, and calcium-carbonate content were constructed using data derived from core samples from test holes S–7 and S–8. Hydraulic conductivity was measured on cores from test hole S–8. The graph of particle-size distribution shows that the section consists of remarkably uniform fine and medium sand with consistent amounts of clay and silt (fig. 29). Particle-size distribution curves also have very similar shapes. Typical distribution at the Stewart site and the Hufstedler site are compared in figure 30. Some intervals were completely unconsolidated and no gravel or coarse sand was present in the section that was cored.

The aquifer at the Hufstedler site contained less fine material and was of more uniform particle size than at the Stewart site; yet, because the secondary openings associated with calcium carbonate were not present, the permeability at the Hufstedler site was much less than at the Stewart site.

The most significant change in the vertical lithology of the Stewart section was the variation in calcium carbonate content. Figures 31, 32, and 33 show that the calcium carbonate content of measured samples ranges from less than 1 percent to more than 60 percent. In general, the most permeable zones, defined by the temperature logs of injected recharge water, are those having low calcium-carbonate content. Microscopic examination of cores showed that secondary porosity resulting from solution is present in zones of low calcium carbonate content. Above and below these permeable zones, calcium carbonate content was greater, and permeability existed principally through primary openings between grains. In these less permeable zones, most pore space was filled with calcium carbonate. Porosity ranged from 20 percent to more than 60 percent, but these values did not correlate well with either hydraulic conductivity or the distribution of calcium carbonate.

Vertical hydraulic conductivities are shown in figure 34. The scatter of values illustrates the difficulty in predicting movement of water through the Ogallala Formation from laboratory analyses, particularly where samples

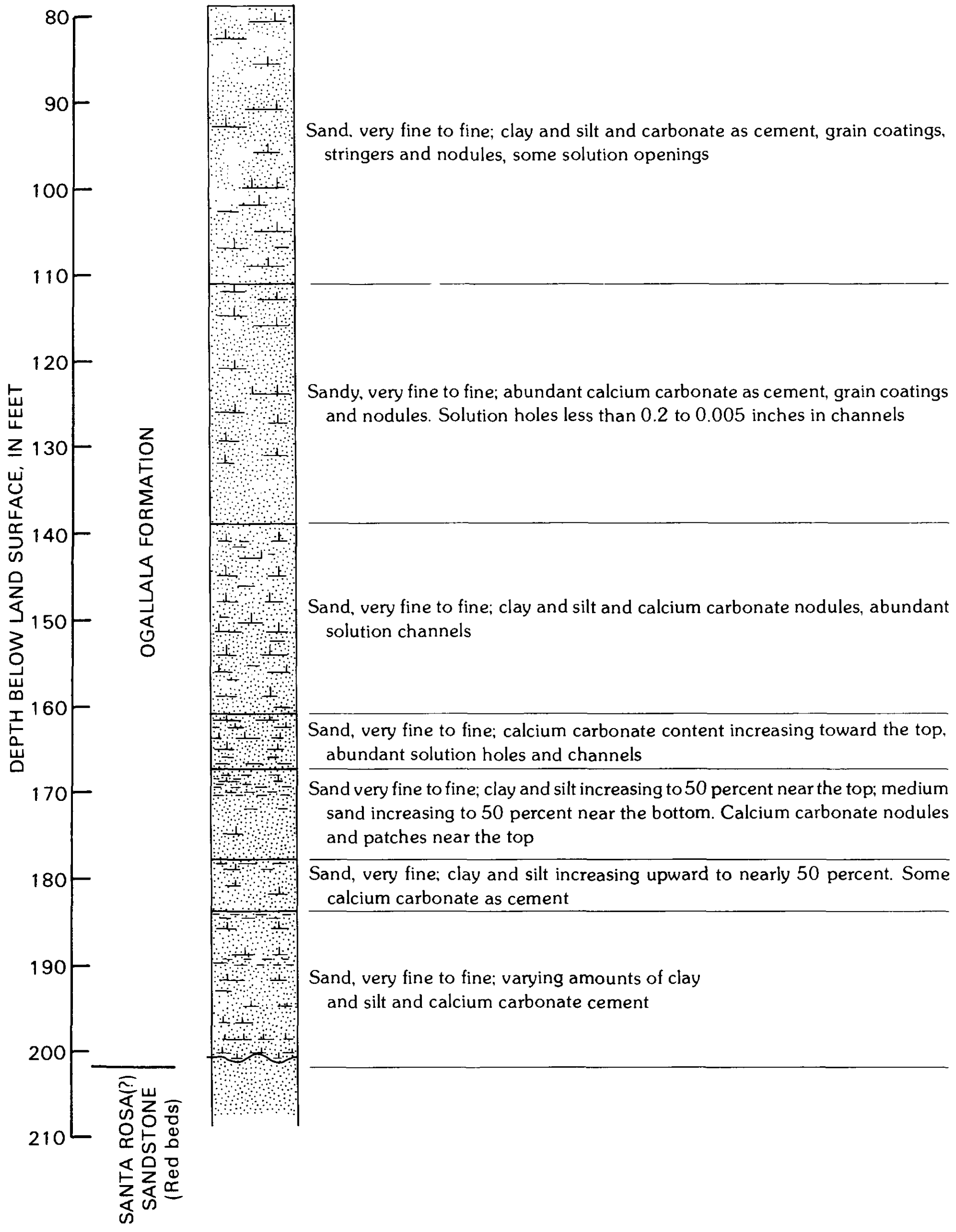


Figure 31. Lithologic log, test hole S–7, Stewart site.

that exhibit secondary porosity were not adequately tested. Hydraulic-conductivity values were generally greater at the Stewart site than at the Dunlap and Hufstedler sites, but not as great as indicated by measured thermal-pulse velocity.

Temperature logs were the first data obtained that indicated that intervals having very large values of permeability might be present at the Stewart site. The temperature logs led to the use of special coring techniques that produced cores of the unconsolidated sand. These core samples provided the first documentation of secondary solution openings in the sand facies of the Ogallala Formation (fig. 4).

Following is a description of the petrography determined on thin sections made from selected samples from test hole S–7:

153 ft

Quartz	85 percent
Clay	10 percent
Calcite	1 to 2 percent
Opaques	1 to 2 percent
Hornblende	trace
Epidote	trace

Well rounded and sorted quartz grains—0.1 to 0.2

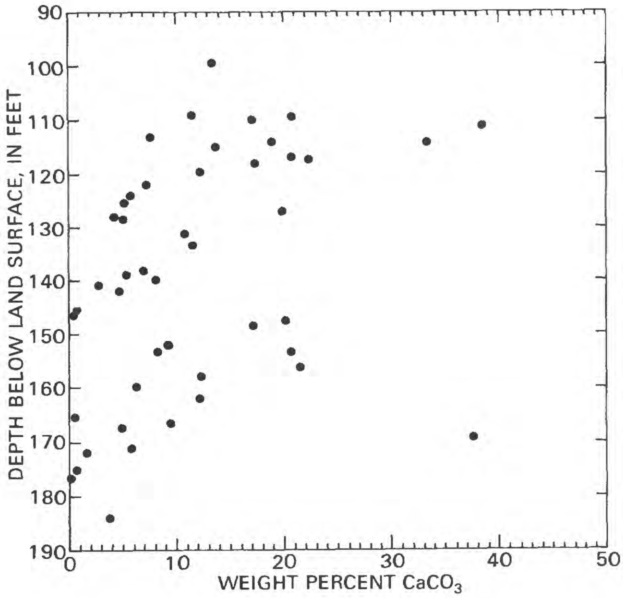


Figure 32. Calcium carbonate content determined using core samples, test holes S–7 and S–8, Stewart site.

mm; Clay occupies "pore" space and contains 1- to 3-mm clumps of carbonate cemented grains.

155 ft

Quartz	95 percent
Calcite	<5 percent
Clay	<5 percent
Feldspar	1 percent
Epidote	trace
Staurolite	trace
Opaques	trace

Fairly well rounded and sorted quartz grains; Average grain size—0.1 mm; Grains coated with a thin selvedge of clay.

163 ft

Quartz	85 percent
Calcite	5 percent
Feldspar	<5 percent
Clay	<5 percent
Epidote	trace
Opaques	trace

Fairly well rounded grains, sorting fairly good; Average grain size—0.1 mm, occasional grains to 1 mm; Most grains coated with selvedge of clay and/or calcite; One quarter of pore space between grains, filled with calcite.

Samples for thin-section analyses were taken at selected depths where high values of permeability were

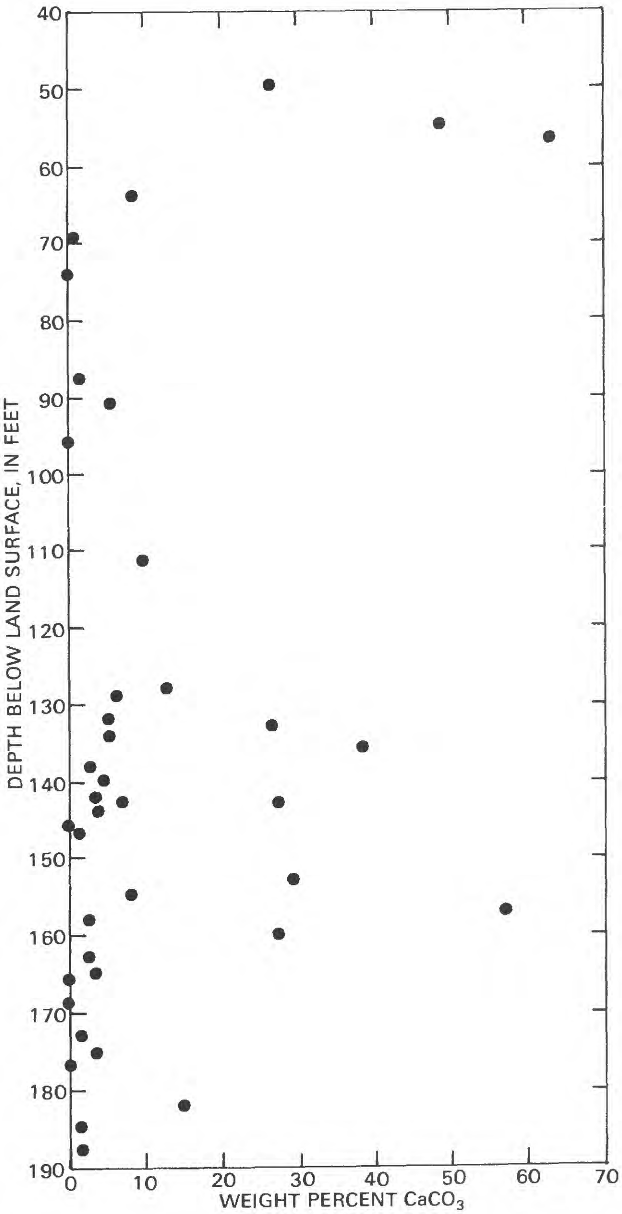


Figure 33. Calcium carbonate content determined using core samples, test hole S–1, Stewart site.

indicated by analysis of temperature logs. The analyses were made to identify the physical characteristics that controlled permeability. In general, samples showing secondary porosity were so poorly cemented that they disintegrated before thin sections could be ground. Samples that were successfully ground to thin sections displayed solution openings between quartz grains, and the edges of the grains were commonly selvedged with calcite and clay. Scanning electron microscopy of solution openings in selected core samples showed that the openings were lined with calcite crystals (fig. 35).

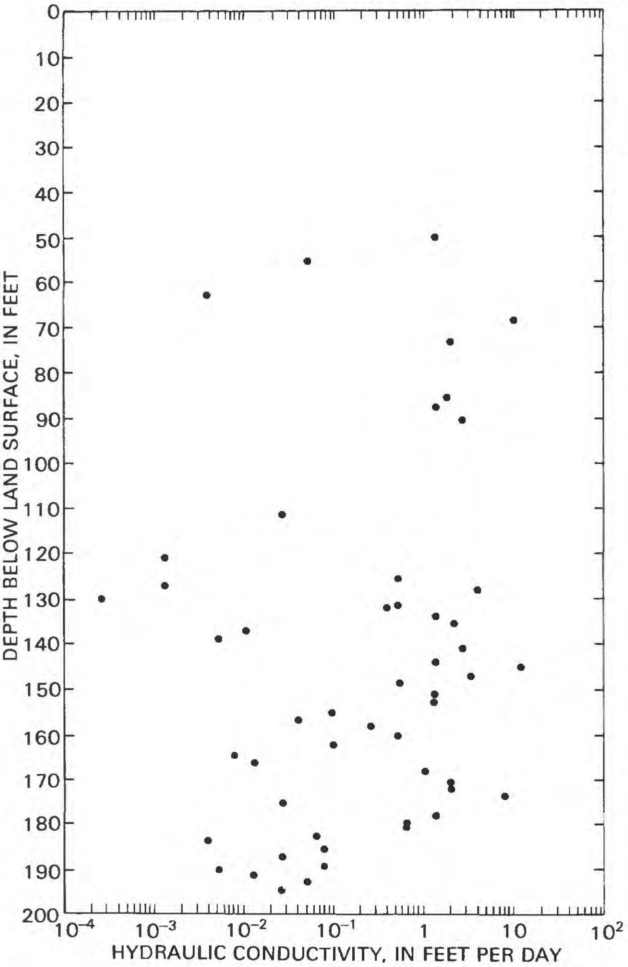


Figure 34. Laboratory values for vertical hydraulic conductivity determined using core samples, test hole S–1, Stewart site.

Geophysical Logs

Natural-gamma, gamma-gamma, neutron, and temperature logs of test holes S–1, S–2, and S–3 were made before, during, and after recharge. These same logs were also made of test holes S–4 to S–8 after drilling was completed. The natural-gamma logs at the Stewart site indicated that there is lateral continuity of lithologic units but that some units are not uniform in depth and thickness (fig. 36). The interval that appears from core studies to have the largest permeability (140 to 162 ft) is characterized by the greatest gamma radioactivity in the hole. Temperature logs made during recharge indicated the most permeable interval is just below that radioactive zone. Another interval of greater than average radioactivity occurs at 105 to 115 ft. A comparison of figure 37 with figures 32 and 33 indicates that high radium-potassium ratios correlate well with most intervals having larger concentrations of calcium carbonate, as was the case in samples collected at the Lubbock spreading site (Keys and Brown, 1971). Figure 38 shows a clear decrease in potas-

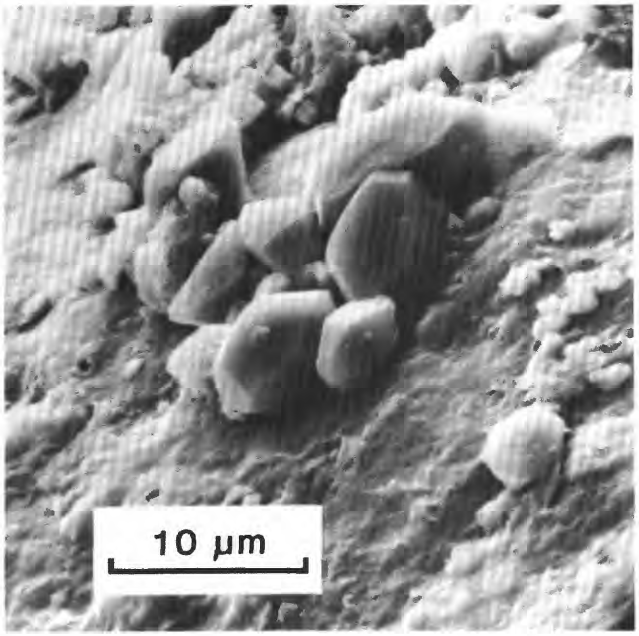


Figure 35. Calcite crystals lining solution opening in core, test hole S–7, Stewart site.

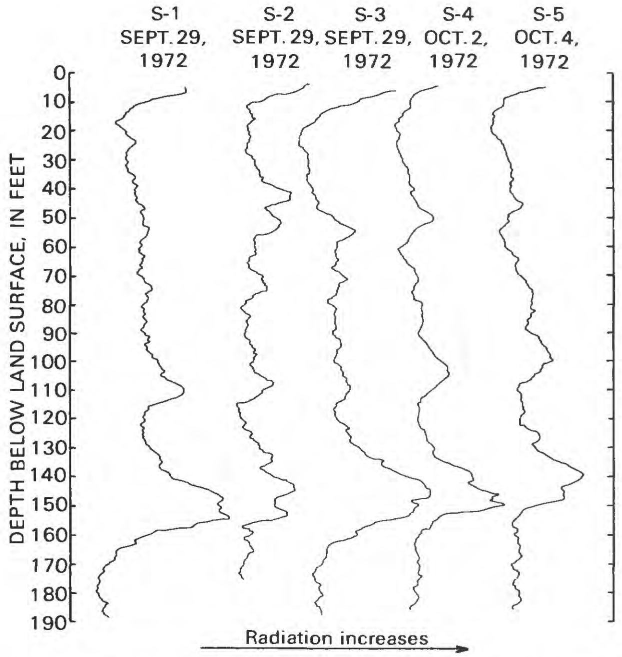


Figure 36. Natural-gamma logs of test holes, Stewart site.

sium at depths with larger concentrations of calcium carbonate at the Stewart site. This may be due to a lower clay content in these intervals.

The gamma-gamma logs in figure 39 show an interval of low bulk density (large porosity) between 150 and 160 ft in test holes S–1, S–2, and S–3. This corresponds to part of the permeable interval indicated by other logs

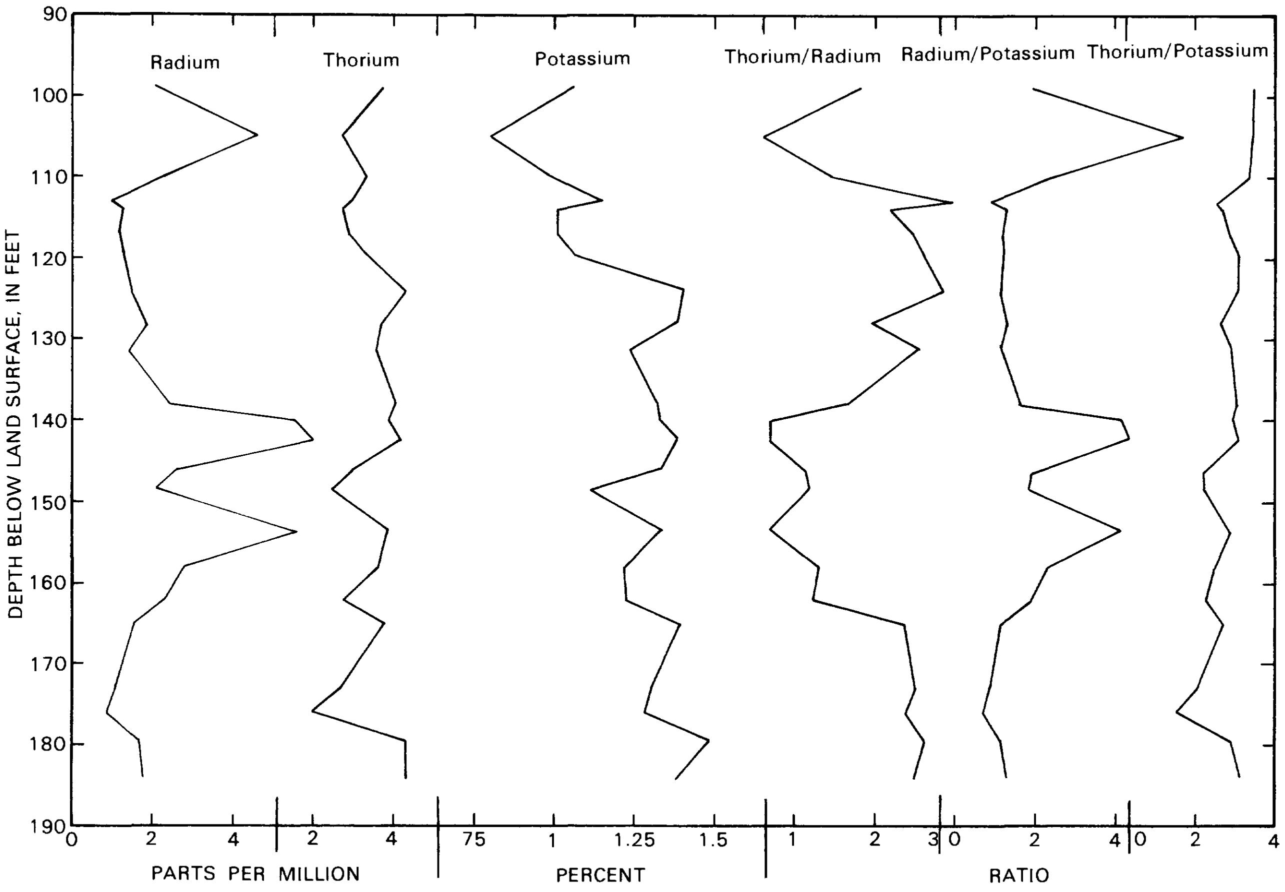


Figure 37. Radiometric analyses determined using core samples, test hole S–7, Stewart site.

and core studies. A thinner, more porous zone is shown on the gamma-gamma logs of test holes S–1 and S–3, at a depth of approximately 180 ft. The neutron logs in figure 40 clearly define the intervals of highest porosity between 150 and 160 ft in test holes S–1, S–2, and S–3,

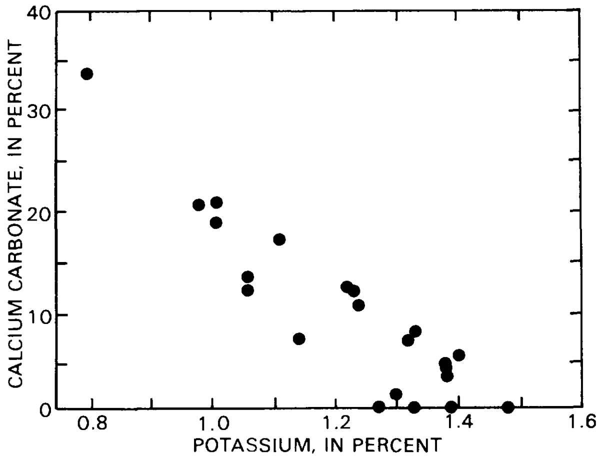


Figure 38. Calcium carbonate versus potassium content, test hole S–7, Stewart site.

and the ones made in September 1972 show that this same interval, which was above the water table at the time, had drained more completely than adjacent sediments. Thus, the specific yield of this interval is measurably larger than other zones in the aquifer.

Gamma-gamma transmittance logs in figure 41 were made of core in brass tubes. These logs show the greatest variability in intervals of largest permeability. The variability in gamma attenuation is due to the presence of solution openings.

Water Chemistry

The turbidity values determined using samples of playa-lake water indicated little difference in sediment content of water between the inlet and the surface. Most of the lake water was from precipitation in late September, 1971 (fig. 42). Accumulation of water in the playa-lake occurred because of the amount of soil moisture that was residual from heavy August rains. These antecedent conditions also decreased the sediment inflow to the lake from the late September precipitation. Weather conditions were stable through the test period and the wind was calm except for late on October 2 during pas-

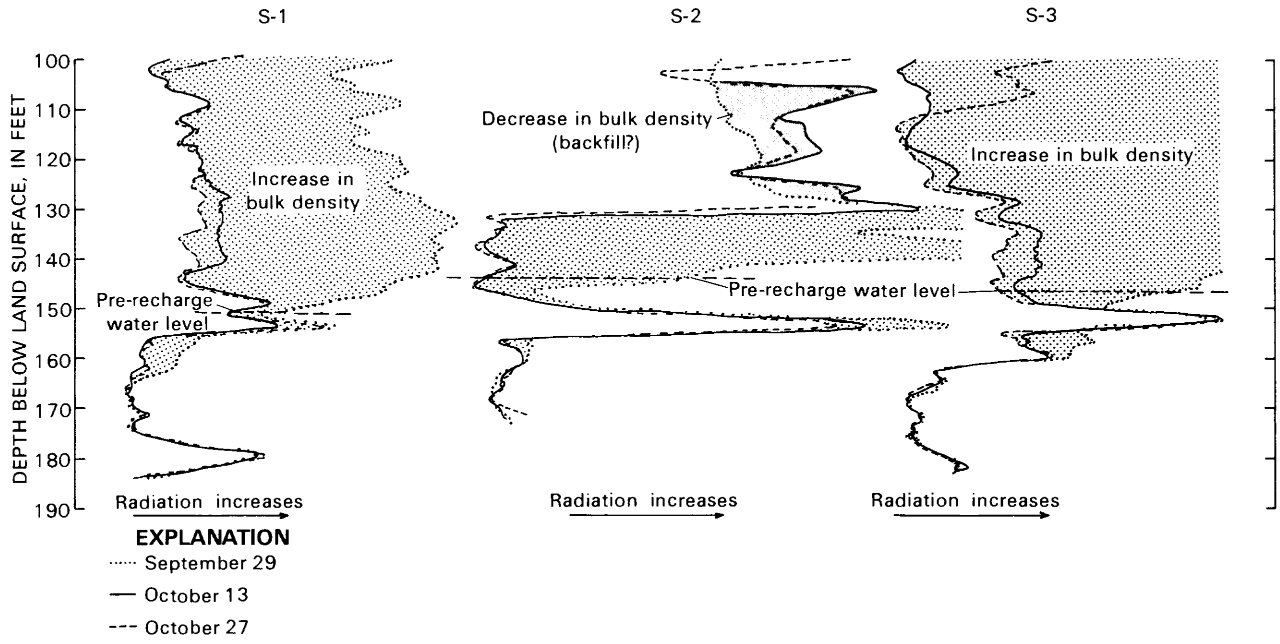


Figure 39. Gamma-gamma logs, test holes S–1, S–2, and S–3, Stewart site.

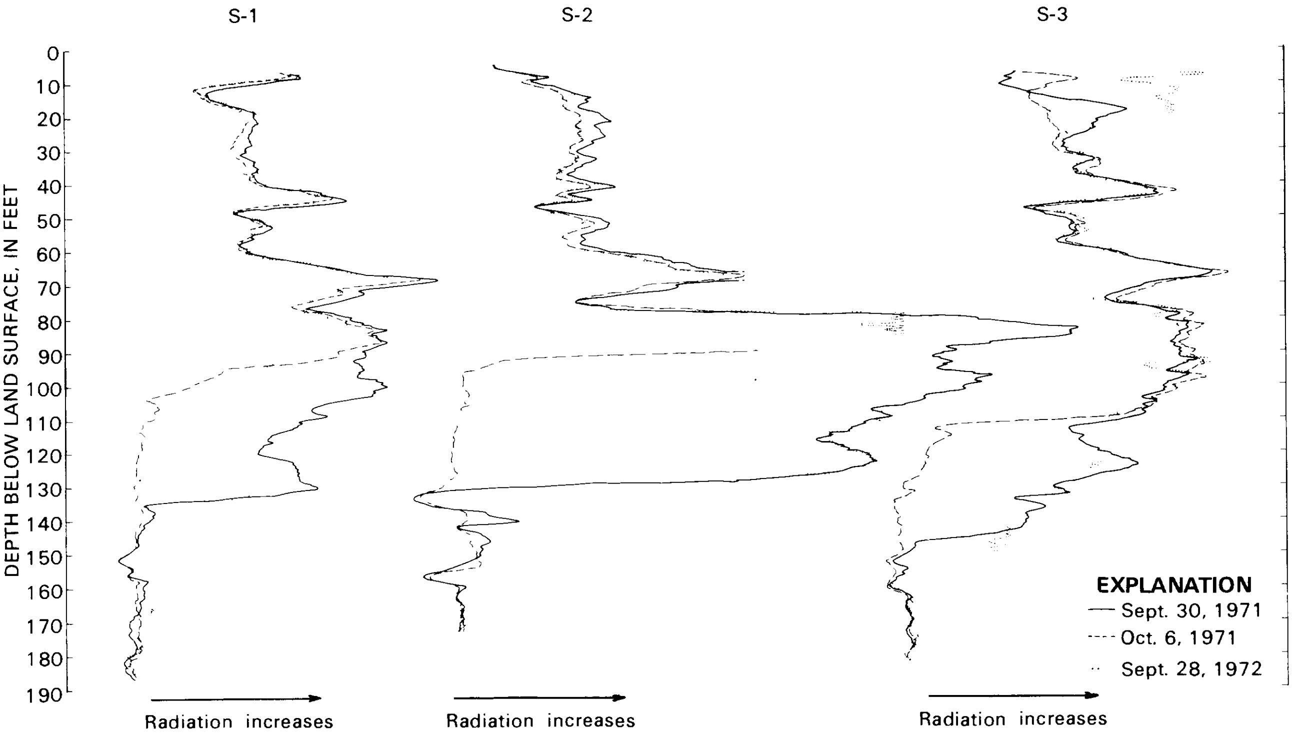


Figure 40. Neutron logs, test holes S–1, S–2, and S–3, Stewart site.

sage of a cold front, which was accompanied by higher winds and lower temperatures. No measurable precipitation occurred at the test site during the recharge test described in this report.

Continuously monitored values of playa-lake turbidity ranged from 50 to 100 Jackson Turbidity Units. Corresponding suspended solids were approximately 30 to 170 mg/L. The rate of sediment injection into the recharge well is shown on figure 43. The daily average weights of injected suspended solids are shown in figure 44.

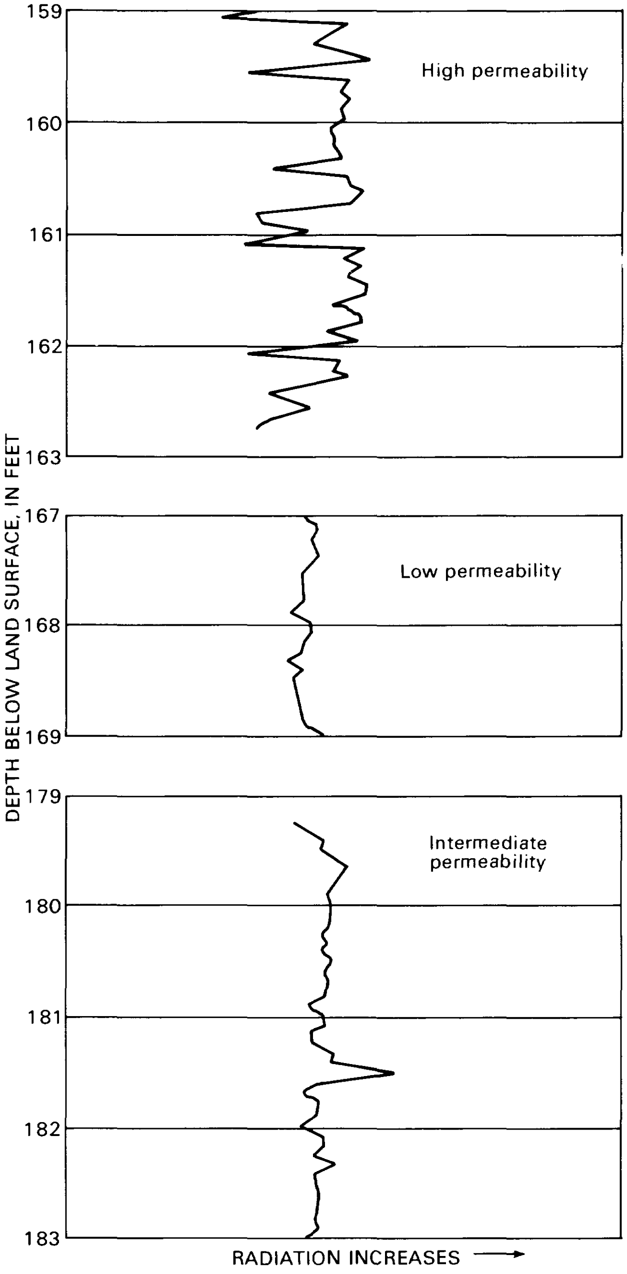


Figure 41. Gamma-gamma transmittance measurements through core, test hole S–7, Stewart site.

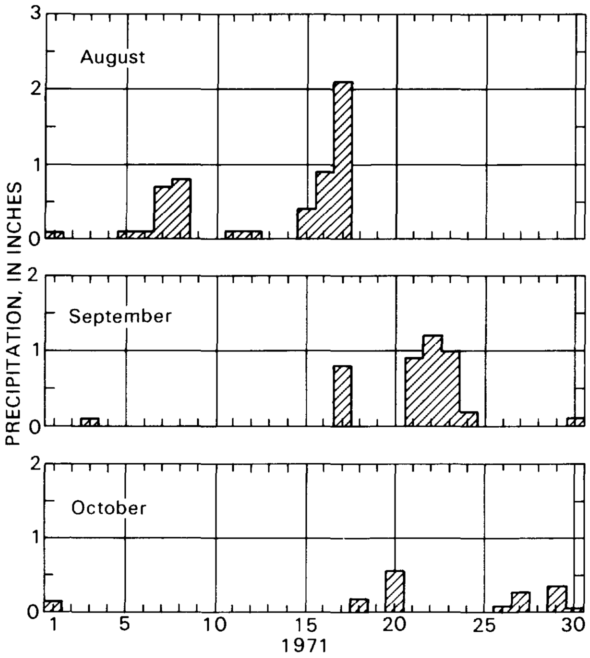


Figure 42. Precipitation at Hereford, near the Stewart site.

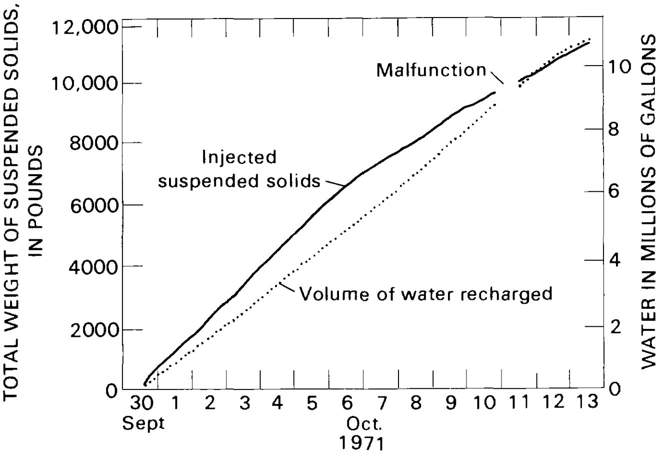


Figure 43. Injection rate of suspended solids, Stewart site.

The initial concentration of sediment in a playa is determined principally by vegetative cover, soil condition, antecedent moisture, and the intensity and duration of the precipitation that fills the playa. Subsequent variations in suspended solids result largely from variations in wind speed, although temperature, solar radiation, and related biologic activity may have a minor effect. Increased wind velocity is believed to be the dominant cause of the increase in injected solids shown for October 3 through 6 in figure 44. The lower average values later in the test are attributed to gradual settling of the sediments after wind velocities declined to an estimated velocity of less than 5 mi/h. The average sediment content of injected water was somewhat less at the Stewart site than in than in other tests described in this report (fig. 3).

The bacteria content of the lake was variable (fig. 45). There is no evidence that the well was physically plugged by bacteria and macrobiota, although bacteria from the playa lake did move through the aquifer to observation well S–6.

A chemical analysis of ground water taken from the injection well prior to recharge is given in table 3 in the section on chemical changes (p. 23). Calcium, magnesium, and bicarbonate are the dominant ions, which are typical of ground water from other areas in the Ogallala Forma-

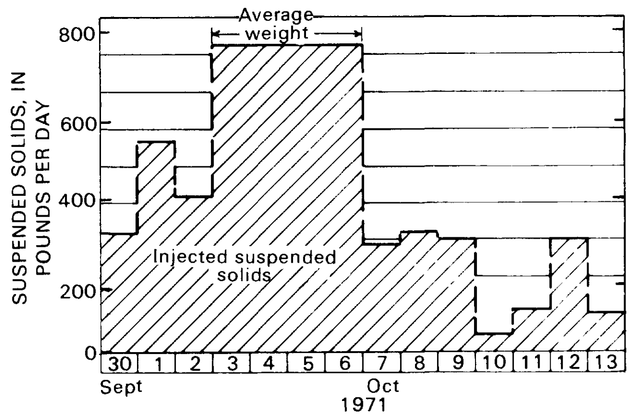


Figure 44. Weight of suspended solids injected into recharge well, Stewart site.

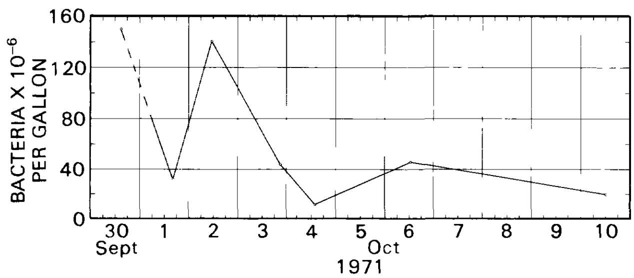


Figure 45. Bacteria content of injected water, Stewart site.

tion in the Southern High Plains (Cronin, 1964). Chemical analysis of the playa-lake water at the Stewart site is also given in table 3. Calcium, potassium, and bicarbonate are dominant which is typical of the quality of playa-lake water in the Southern High Plains (Lotspeich and others, 1969; Wells and others, 1971; and Brown and others, 1971).

Recharge Operation

Recharge was started at 1231 hours, September 30, at a rate of 270 gal/min. This was gradually increased to 640 gal/min at 1338 hours, and the rate was maintained between 550 and 600 gal/min through October 8. Flow was erratic from October 8 through 1200 hours, October 13, because of difficulties in maintaining a constant rate through the gate valve at the prevailing lake stage. The flow gradually decreased from 1200 hours, October 13, to the end of the day because the stage in the lake was declining (fig. 46). The total volume of water injected was approximately 34 acre-ft.

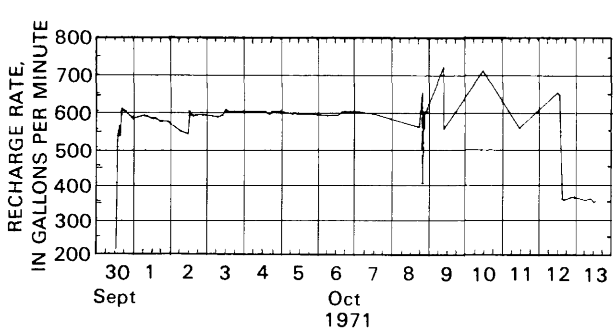


Figure 46. Injection rate of recharge water, Stewart site.

Analysis Of Recharge Test

Movement Of Recharge Water

Water temperature in the playa lake varied diurnally and as a result of passage of a major weather system. The shift in the daily-temperature range resulting from the passage of the weather front was used as an additional marker for the determination of flow rate through the system. Because recharge was continuous for 13.5 days, changes in the rate of movement of the recharge water could be estimated from observed shifts with time of diurnal-temperature pulses. A detailed analysis of the temperature fluctuations measured during this test is given by Keys and Brown (1978).

Average ground-water temperature prior to recharge was 15.3°C, and temperature of the recharge water from the playa lake fluctuated between 13°C and almost 23°C during the first 7 days of the test. Temperature of the recharge water was monitored continuously, and temperature and neutron logs were made at frequent intervals in the water-filled, 2-in test holes. A series of logs was made in rapid sequence in test holes S–1 through S–5 for most of each 24-hour period during the first 7 days of the test. For short intervals, the temperature probe was stationed at a specific depth of interest, and the strip chart recorder was operated on time drive.

Figure 47 shows part of the series of temperature logs made in test hole S–3 during the first week of recharge, September 30 to October 7. The relative temperature scale is the same for each log but displaced to show time. The bottom-hole temperatures are approximately 15°C on each log. The bulge, at a depth of 160 ft in the first log on September 30, indicates the arrival at that depth of warm water injected during the afternoon from the playa-lake source. Arrival of the first warm water in test hole S–3 occurred less than 4 hours after beginning of recharge. The subsequent upward expansion of the bulge indicates the continuing arrival of warmer water and

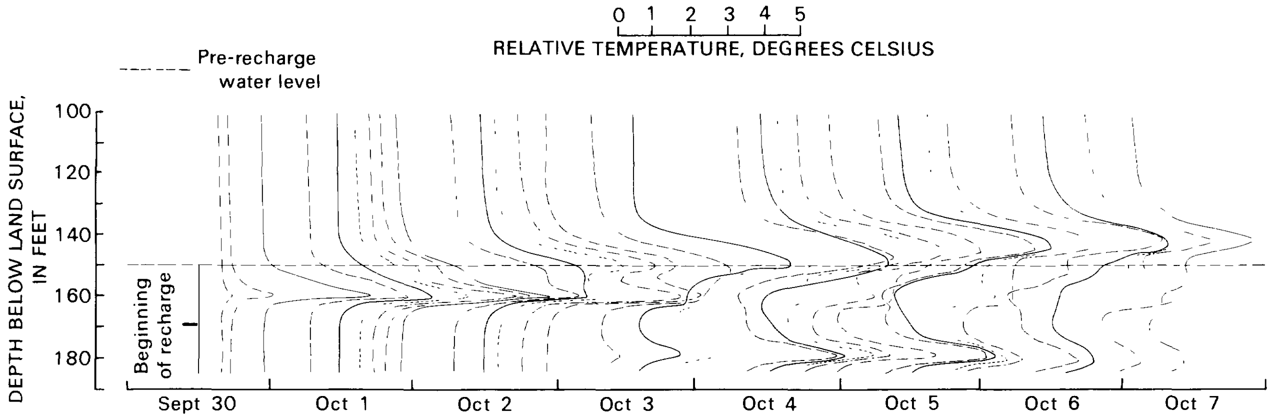


Figure 47. Temperature logs, test hole S–3, Stewart site.

a rise in water level. Diminution of the bulge occurred when low temperature water, cooled in the playa lake during the night, was injected.

In contrast to the rapid arrival at a depth of 160 ft, the first arrival of injected water at a depth of 178 ft was not until October 3. Subsequent temperature fluctuations occurred at 178 ft, but because of the lower permeability at this depth, the range of temperature was not as great.

Permeability at other depths was so low that arrival of thermal pulses could not be positively identified. However, the logs clearly show that the warmer water moved upward as an injection cone developed.

Changes in the temperature of the recharge water with time and changes in the temperature of the water in test hole S–3, at depths of approximately 152, 161, and 178 ft with time are shown in figure 48. The large diurnal-temperature fluctuations of the input water were recognizable in the water that arrived at test hole S–3. The shape of the thermal waves arriving at test hole S–3 was determined by constructing smooth curves through temperatures at each depth taken from numerous logs. Following arrival of a cold front on October 3, the temperature of the playa-lake water decreased to 13°C. This change is clearly seen in figure 48.

The delay time or transit time required for the thermal wave to travel from the recharge well to test hole S–3 is plotted as the time between centers of both the warm and cold thermal waves in the upper part of figure 48. Travel time derived from temperature logs in this way is mainly a function of the velocity of water movement, which is related to porosity, hydraulic conductivity, and head. In the permeable zones, at 152, 161, and 178 ft, flow rates gradually increased after the second day of recharge and decreased from the fifth day. The decrease in travel time of the thermal front during the second day of recharge is probably due to dissipation of air that was previously trapped behind the advancing wetting front in the unsaturated zone. This would result in increased hydraulic conductivity. The increase in travel time during the latter 3 days may be due to the accumulation of sediment which decreased the hydraulic conductivity.

The rate of flow measured at test hole S–3 at the 178-ft depth was consistent with the arrival time of the temperature pulse at test holes S–4 and S–5. Thus, permeability through this zone must have been reasonably constant in the early part of the test. Changes in velocity of the pulses at the 161-ft depth probably indicated changes in permeability, but the changes could not be well defined by the highly attenuated thermal pulses in test holes S–4 and S–5 (fig. 49). Accordingly, the hydrology of the flow system is interpreted principally from the record in test hole S–3 at the 161-ft depth.

The rate of water movement at a depth of 161 ft is considerably higher than would be expected from hydraulic conductivities determined using core samples. These high rates support the theory that movement of recharge water is principally through secondary porosity. Core samples with visible secondary porosity were so poorly consolidated that undisturbed hydraulic conductivities could not be measured. The highest hydraulic conductivity measured on core from test hole S–7 was 11 ft/day at a depth of 166.5 to 166.7 ft. Computed hydraulic conductivities from the data in figure 48 are in the range of 165 to 325 ft/day, depending principally on values chosen for head difference, thickness of the permeable zone, and porosity (Keys and Brown, 1978).

Visual examination of the core showed secondary solution openings in samples taken at several depths. Macroscopic openings ranged in width up to 0.3 in. None of the openings observed were visually continuous through the core; however, many were interconnected to form longer conduits. Large secondary openings were observed at depths of 140 ft, 160 ft, and 180 ft. The most conspicu-

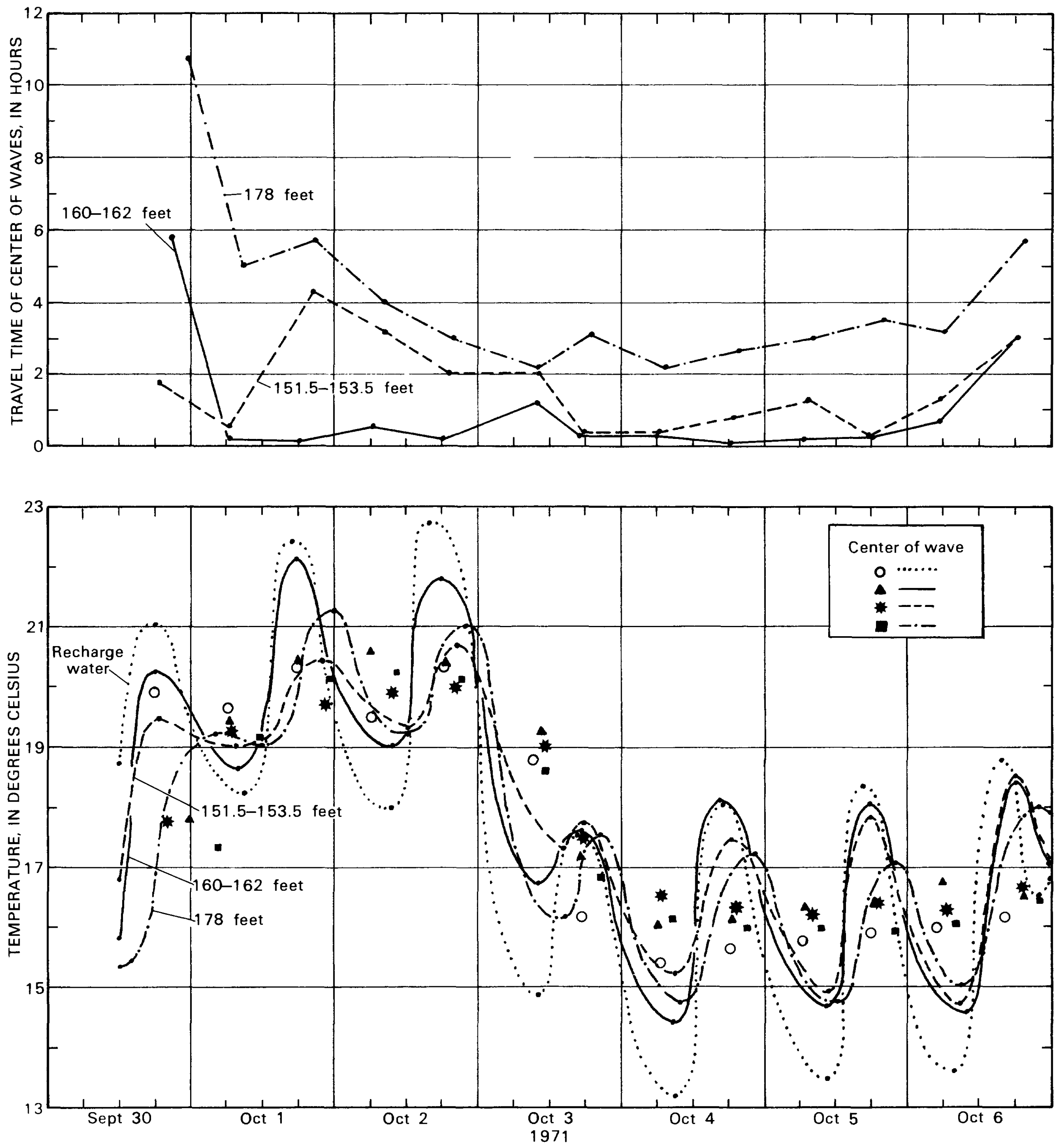


Figure 48. Travel time for recharge water to move from injection well to indicated depths, and changes in temperature of the recharge water at three depths, test hole S–3, Stewart site.

ous openings were in samples from a depth of 160 ft; this corresponds with the depth of maximum velocity shown by temperature logs. Figure 4 shows the surface of a core section that has secondary porosity. The interior surface of an opening is shown in figure 35.

Changes In The Aquifer

The Stewart recharge operation was successful because of the extensive occurrence of secondary porosity due to solution openings. Temperature logs indicated that these permeable zones were not significantly plugged by

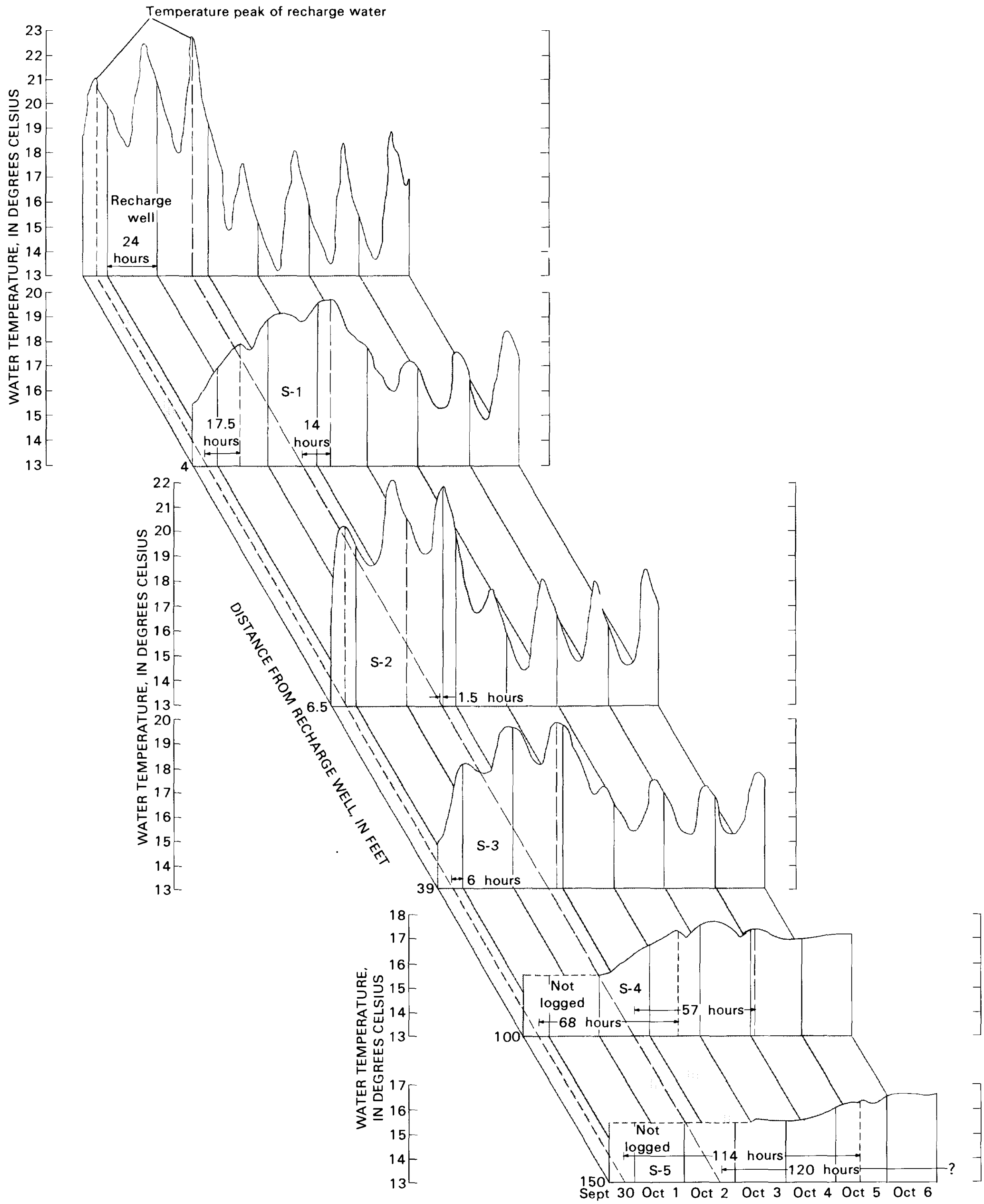


Figure 49. Attenuation of diurnal-temperature fluctuations at a depth of 160 feet, Stewart site.

sediment injected during recharge. The moderate clay and silt content of the Ogallala Formation and the dominance of uniform fine sand restricted flow through primary pore space, which probably became plugged during the test.

Well Yield

Yield of the Stewart well before recharge was reported by Ray Stewart to be 150 gal/min. However, immediately before recharge, the well was pumped at this

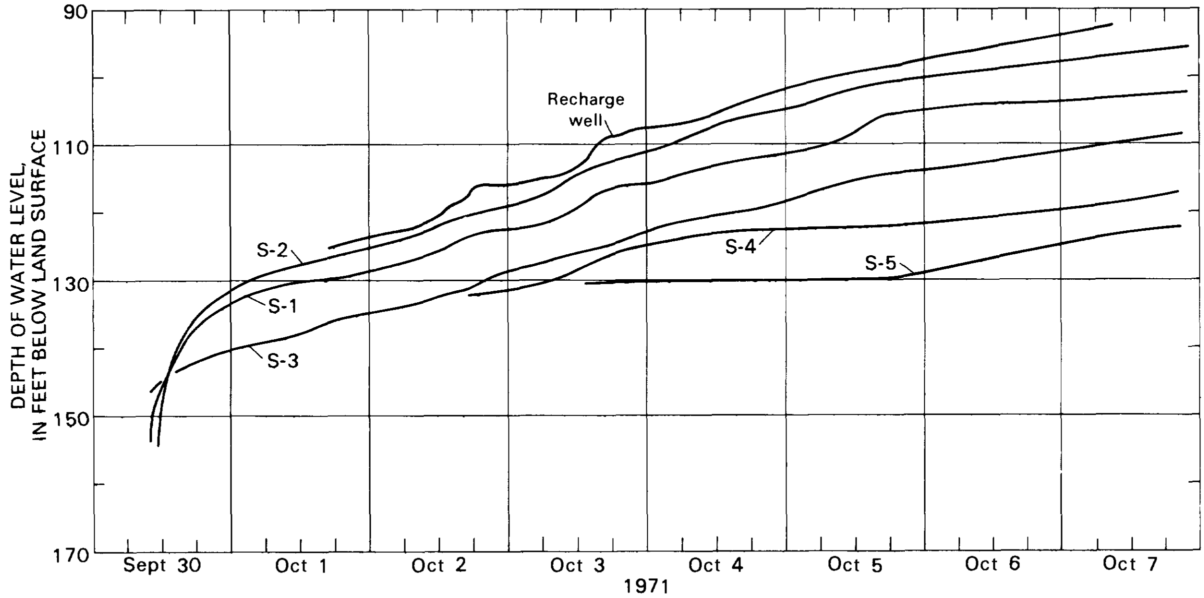


Figure 50. Water levels measured in the recharge well and interpreted from neutron logs, test holes S–1 to S–5, Stewart site.

rate and broke suction in 14 min. Immediately after recharge ceased, the pump was started and pumped at an initial rate of 350 gal/min. This rate was gradually increased to a maximum of 440 gal/min during a 90-min period. Subsequently, the well yield at the same engine speed decreased to 380 gal/min after 22 hours of pumping. This was probably due to the developing cone of depression and increased lift required as the water level in the well declined. During this 22-hour test, the water level in observation well S–6, which is 15 ft from the recharge well, dropped 29 ft. At that time, pump testing was terminated. Although well yield was not measured, Ray Stewart reported that yield was increased, and that the well continued to produce more than 150 gal/min during the following spring and summer. This increase over prerecharge yield was largely due to the higher water level caused by recharge (fig. 50) and possibly to a minor development of the aquifer by solution of calcium carbonate which increased porosity. This was the only recharge well tested that showed an increase in yield following recharge.

Effect Of Well Construction On Recharge

The Stewart well was the only recharge well of the four tested that was not gravel packed. Because it utilized casing with slots, approximately ⅛ in wide, severe sand pumping and rapid plugging of the well by the injected sediment was anticipated. The data show that plugging did not occur, and the subsequent yield of the well was enhanced by recharge. The well did not pump measurable sand either before the test or after regular irrigation pumping resumed. The performance of the well indicates that the construction used enhanced recharge and that in some beds of the Ogallala Formation a gravel-packed recharge well may not be advantageous.

Chemical Changes

Calculations based on thermodynamic principles indicate that native ground water from the injection well is near equilibrium with respect to calcite and supersaturated with respect to dolomite. The water is undersaturated with respect to the other common carbonate and sulfate minerals but supersaturated with respect to silica (table 4). In contrast, the water from the playa lake is undersaturated with respect to all common carbonate and sulfate minerals, and supersaturated with respect to silica.

The permeable zones consist of generally uncemented sands that have acquired secondary porosity by the apparent selective solution of calcium carbonate. However, some calcium carbonate remains in the major injection zones, usually as small nodules and intergranular cement. The sand grains in several core samples from test hole S–7 consist of approximately 82-percent quartz, 2-percent potassium feldspar, 12-percent plagioclase feldspar, and 3-percent heavy minerals consisting mainly of magnetite, limonite, garnet, and epidote. Calcium carbonate and amorphous silica are the major cementing material; they occur also as nodules and discrete layers at several depths.

The water sample from test hole S–6 (Tables 4 and 5, 3rd column) was taken just below the prerecharge water table, 6 days after injection began. Hundreds of pore volumes of injected water passed through the zone prior to sampling. Therefore, the chemical quality of this sample should represent reaction of the injected water only with

Table 4. Chemical analyses of native ground water, injected recharge water, and water of reaction, Stewart site

Constituents and properties	Concentrations (milligrams per liter, except as noted) Prerecharge ground water from injection well	Lake water	Water from observation well S-6 after 6 days of recharge
Silica, dissolved (SiO_2)	59	16	12
Aluminum, dissolved (AL) (μg/L)	0	--	30
Iron, dissolved (Fe) (μg/L)	30	--	0
Manganese, dissolved (Mn) (μg/L)	30	--	80
Calcium, dissolved (Ca)	53	22	48
Magnesium, dissolved (Mg)	45	6.7	18
Sodium, dissolved (Na)	19	5.6	8.1
Potassium, dissolved (K)	7.6	14	16
Lithium, dissolved (Li)	.14	--	--
Strontium, dissolved (Sr)	1.200	--	.390
Bicarbonate, dissolved (HCO_3)[1/]	390	107	244
Sulfate, dissolved (SO_4)	33	4.0	18
Chloride, dissolved (Cl)	7.6	3.4	6.0
Fluoride, dissolved (F)	2.6	.5	1.6
Nitrate, dissolved (NO_3)	1.4	3.0	.0
Phosphate, dissolved (PO_4)	.10	--	.00
Boron, dissolved (B)	.23	--	.10
Dissolved oxygen	0	1.6	--
Specific conductance (μmho/cm at 25°C)	639	191	427
pH[1/]	7.45	7.19	7.50
Temperature (°C)	17.25	17.5	18
Eh	+0.335 volts	--	--

[1/] Field measurement

Table 5. Mineral saturation index for common minerals calculated from chemical analyses of the indicated waters, Stewart site

Constituents and properties	Concentrations (milligrams per liter, except as noted) Prerecharge ground water from injection well	Lake water	Water from observation well S-6 after 6 days of recharge
Calcite, dissolved ($CaCO_3$)	0.89	0.088	0.70
Aragonite, dissolved ($CaCO_3$)	.63	.062	.50
Dolomite, dissolved ($CaMg(CO_3)_2$)	1.21[1/]	.0039	.32
Magnesite, dissolved ($MgCO_3$)	.77	.026	.26
Strontianite, dissolved ($SrCO_3$)	.19	--	.052
Siderite, dissolved ($FeCO_3$)	.0055	--	–
Rhodochrosite, dissolved ($MnCO_3$)	.027	--	.059
Gypsum, dissolved ($CaSO_4\ 2H_2O$)	.0054	.00074	.0046
Anhydrite, dissolved ($CaSO_4$)	.0029	.00041	.0026
Fluorite, dissolved (CaF_2)	.015	.00030	.0058

[1/] All values, except dolomite, indicate undersaturation in the prerecharge ground water.

Table 6. Differences between injected water and that sampled at observation well S-6 based upon a reaction model for the injected water, Stewart site

Constituents and properties	Concentrations (milligrams per liter except as noted)
Silica, dissolved (SiO_2)	-4
Calcium, dissolved (Ca)	26
Magnesium, dissolved (Mg)	11
Sodium, dissolved (Na)	2.5
Potassium, dissolved (K)	2.0
Bicarbonate, dissolved (HCO_3)	137
Sulfate, dissolved (SO_4)	12
Chloride, dissolved (Cl)	2.6
Flouride, dissolved (F)	1.1
Nitrate, dissolved (NO_3)	-3.0
Dissolved solids	122
Specific conductance (μmho)	236

aquifer material, and not mixing of formation water with recharge water.

Table 6 illustrates the losses and gains of individual ions in the injected water based on reaction with the aquifer material. Calcium, magnesium, and bicarbonate ions show the greatest gains, and silica and nitrate show losses. The gains are expected because the recharge water is undersaturated with respect to the calcium and magnesium carbonate minerals in the aquifer and would be expected to dissolve them. The mineral equilibria for the water sampled in observation well S–6 are given in table 5, and as expected, are much closer to saturation for all common minerals than was the lake water. This analysis assumes equilibrium conditions with no kinetic controls. This is probably not a valid assumption, but the equilibrium is so closely approximated as to suggest that these reactions are quite rapid.

The weight of material taken into solution from the aquifer by the injected water is slightly greater than the average suspended sediment in the injected water, on a weight-per-volume basis. However, this net loss in material from the aquifer did not result in a significant change in either permeability or porosity during the test. The suspended sediment had a greater volume than an equal weight of calcium carbonate because of a difference in density. Therefore, it is possible that the suspended material could plug pore space at the well-aquifer interface faster than solution could take place. Injected suspended material tends to concentrate adjacent to the well face, whereas solution occurs over a broad area.

KITTEN SITE

Location

The Kitten recharge site is 16 mi southeast of Lubbock, Texas. The position of the recharge well and test holes is shown on figure 51. Hydrologic measurements were made during the test by the U.S. Geological Survey and Texas Tech personnel.

Recharge and Monitoring System

The recharge well at the Kitten site is similar in construction to the well at the Dunlap site and was designed and constructed specifically to recharge the Ogal-

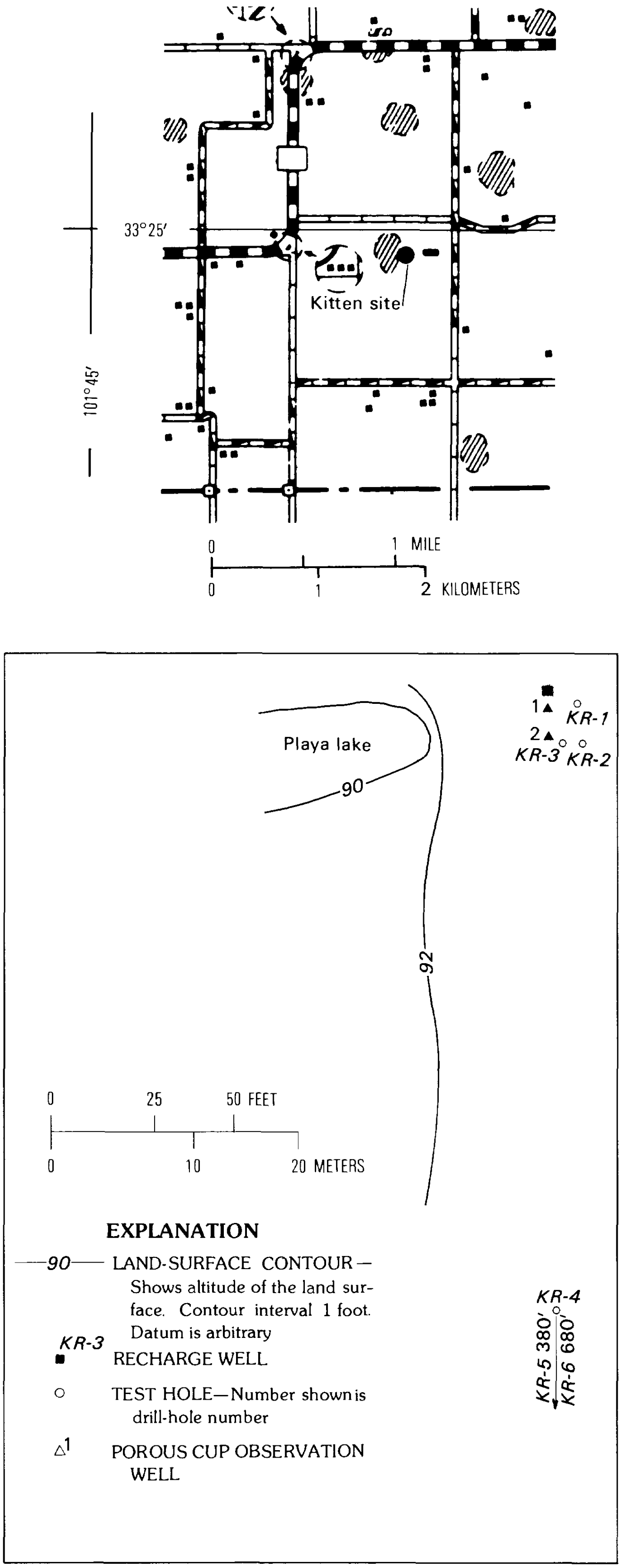


Figure 51. Location of recharge well, observation wells, test holes, and playa lake, Kitten site.

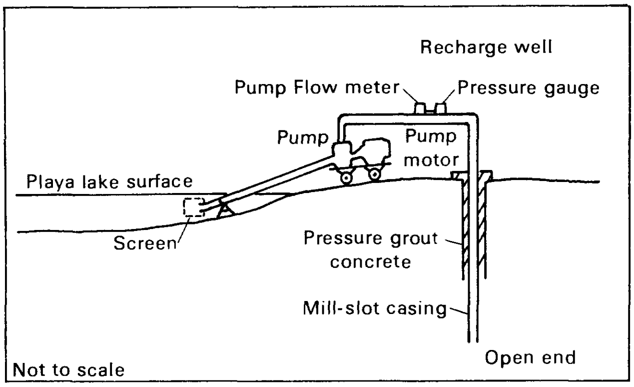


Figure 52. Recharge system, Kitten site.

lala Formation through injection under pressures ranging from about 30 to 40 lb/in^2 (see fig. 52, a repeat of fig. 15, inserted for reader convenience). The well was drilled to a depth of 263 ft, screened from 82 ft to total depth, with 10-in mill-slot casing (3/16 in by 2¾ in slots, 16 perforations per ft), and gravel packed between the screen and the wall of the 20-in drill hole. Details of construction for each of the wells and test holes at the Kitten site are shown in figure 53.

Porous cups were cemented in at two locations in order to detect moisture changes. No changes were detected during the test either because of faulty construction or nonuniform moisture distribution.

The gravel pack, which was pumped in from the surface, contained pebbles ranging from ⅜-in to ½-in diameter. Sand caved near the bottom of the well, and the driller estimated that more than 1 yd^3 of Ogallala-Formation sand was bailed from the well during construction of the gravel pack.

A pump was installed on the recharge well prior to recharge to determine aquifer constants. Severe sand upwelling through the open end of the casing during pumping required termination of the test, and data were inadequate for analysis.

Geohydrology

Core Data

The Kitten site is situated on a broad, deep, alluvial valley fill near the eastern edge of the Southern High Plains. The Ogallala Formation at the Kitten site consists of mostly fine to medium sand with some silt and clay, and thin calcareous and conglomeratic units (fig. 54). Core samples were taken to permit analysis of particle-size distribution, calcium carbonate content, moisture, and hydraulic conductivity. The graph of particle-size distribution shows a very clean sand from 150 ft to the bottom

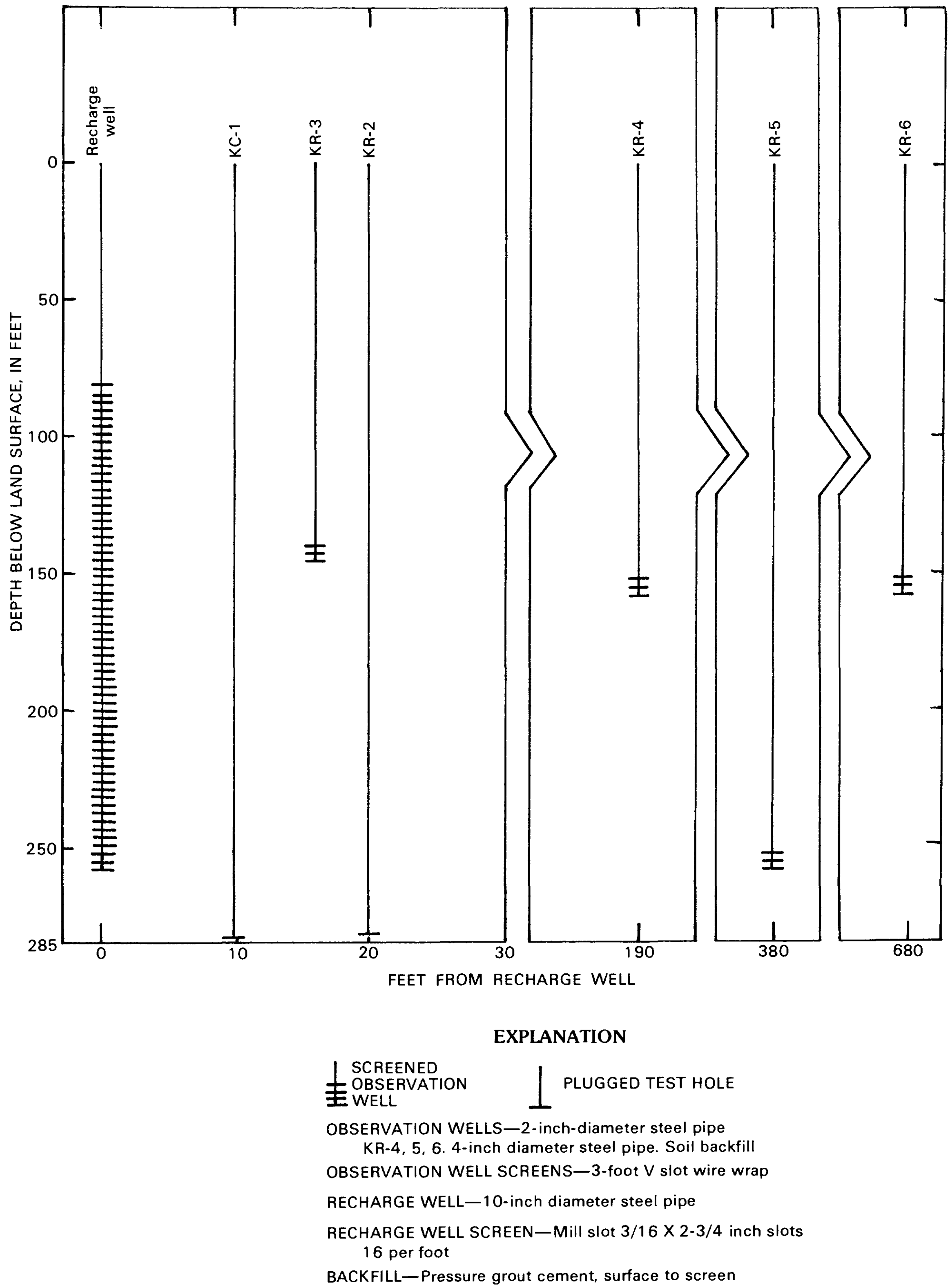


Figure 53. Construction of recharge well, observation wells, and test holes, Kitten site.

of test hole, KC–1 (fig. 55). Core was not recovered from 150 to 167 ft. The presence of several pieces of gravel in the core barrel from each core run in this interval indicates the presence of material too coarse to enter the core barrel.

In general, the Ogallala Formation at the Kitten site

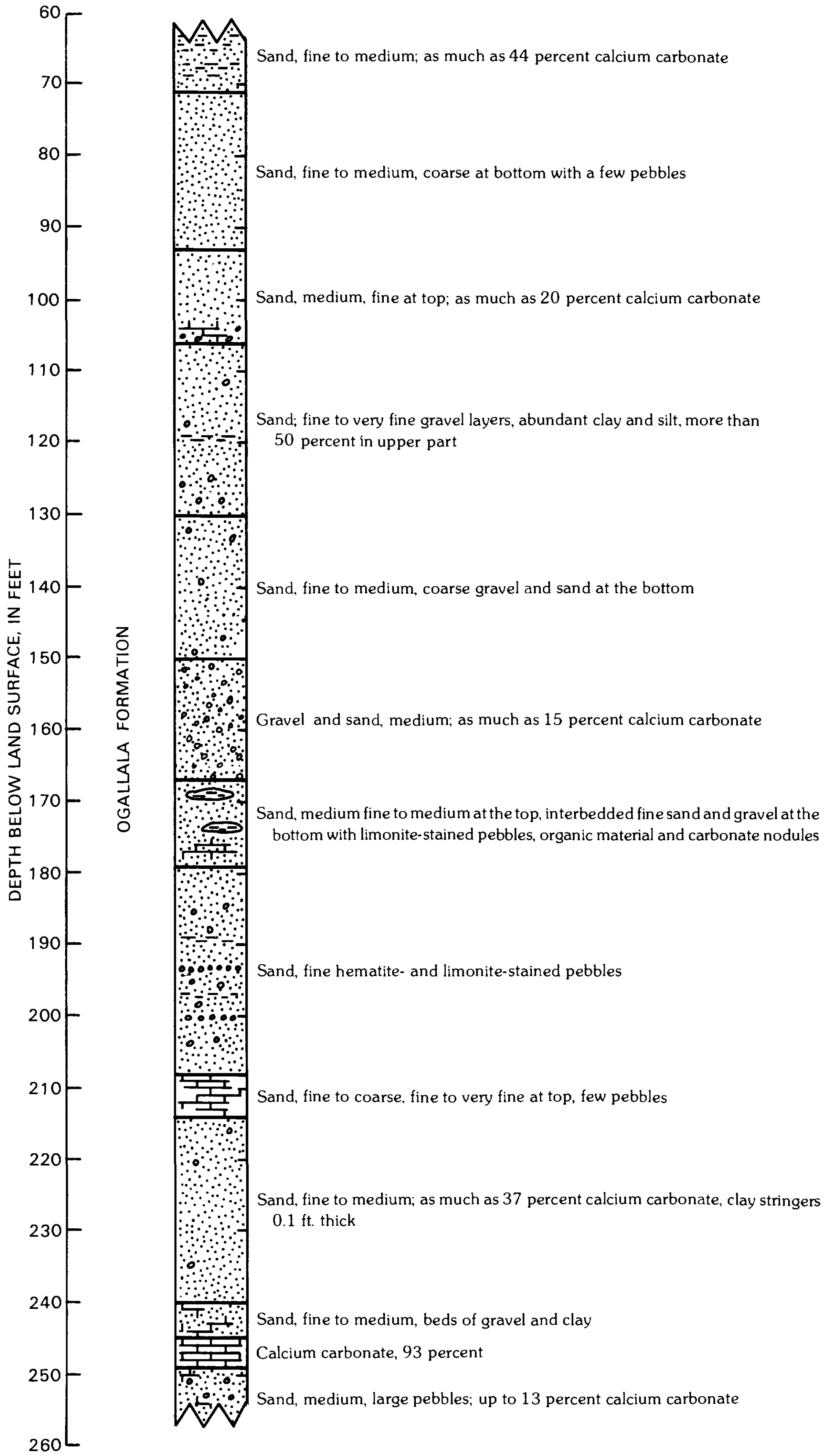


Figure 54. Lithologic log, test hole KC1, Kitten site.

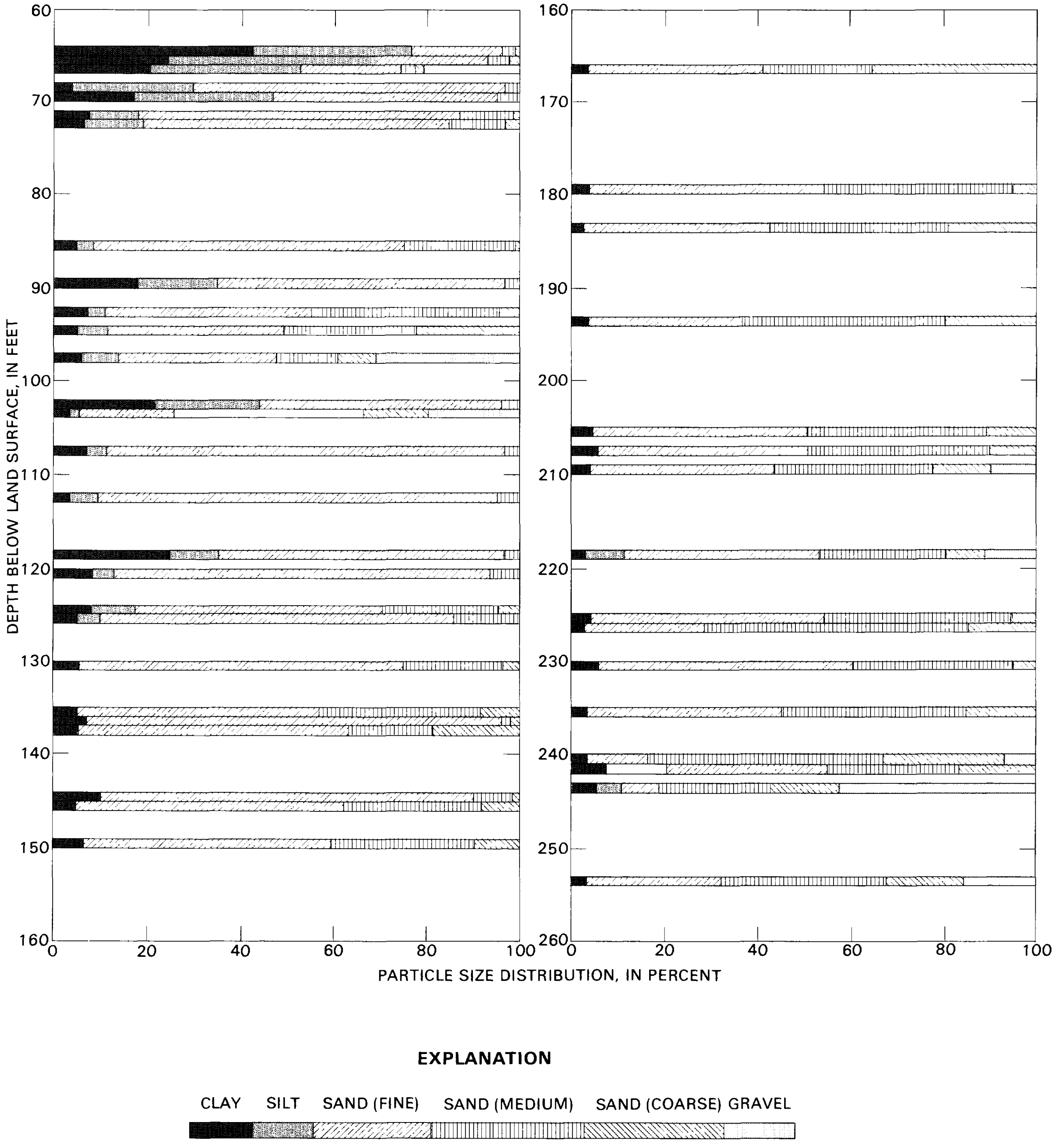


Figure 55. Particle-size distribution determined using core samples, test hole KC–1, Kitten site.

is low in calcium carbonate (fig. 56). Samples that exceeded 30 percent were found only at depths of 175 ft, 211 ft, and 249 ft. A calcium carbonate content between 10 and 20 percent was found only in the interval above 70 ft, between 95 and 105 ft, and below 240 ft.

Sediments from core samples of hole KC–1 are coarser and contain less silt and clay than sediments from the other sections in the Ogallala Formation sampled in this study. Figure 57 shows the particle-size distribution in a zone of high permeability at 166 ft, and in a zone of low permeability at 242 ft. The less permeable sample has a higher percentage of clay- and silt-size particles.

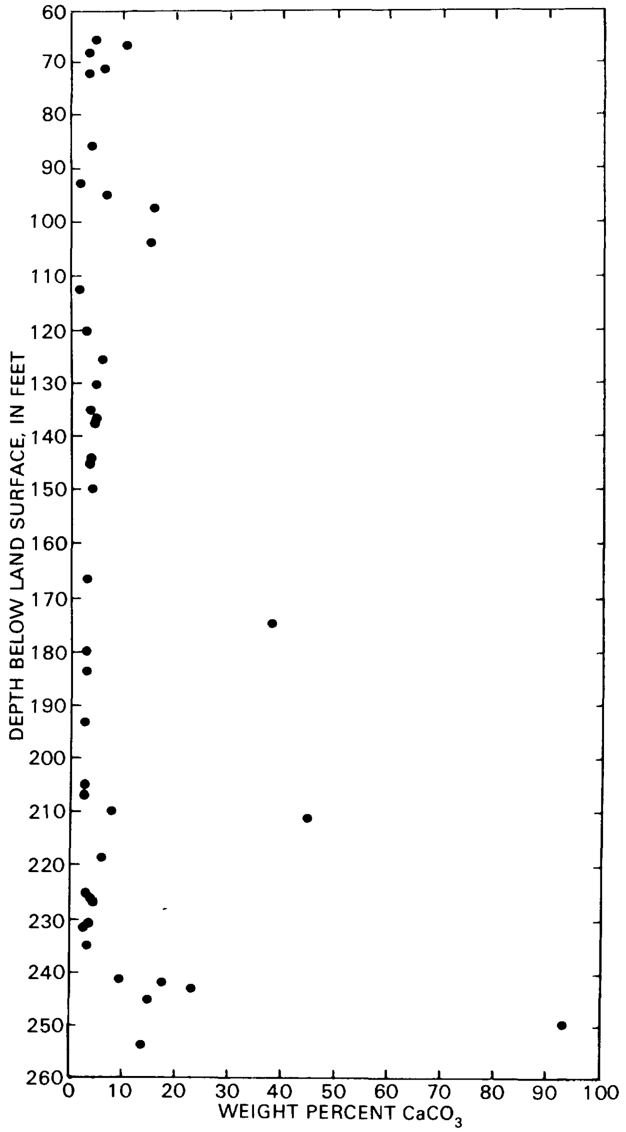


Figure 56. Calcium carbonate content determined using core samples, test hole KC–1, Kitten site.

Other analyses showed a comparable difference in particle-size distribution between units with high and low horizontal hydraulic conductivity.

The distribution of vertical and horizontal hydraulic conductivities determined using core samples are shown in figures 58 and 59. Kitten was the only site at which horizontal conductivity was measured on core samples. In earlier tests, laboratory facilities were not available to measure horizontal values. Horizontal conductivities of core samples are generally larger than vertical conductivities and are more representative of the values that control recharge-flow rates.

Geophysical Logs

As at the Dunlap site, the calcareous zones were logged as having the lowest apparent porosity on both neutron and gamma-gamma logs (fig. 60). These units also showed high resistivity on the 64-in normal-resistivity log. In figure 60, the response of the neutron and gamma-gamma logs above the water table is not the same because of variations in moisture content, and below 240 ft they show a significant decrease in apparent porosity. This is probably due to a major increase in calcium carbonate content. The same low porosity units were found in other holes at the Kitten site.

The 64-in normal-resistivity log of test hole KR–2 has a high resistivity anomaly at a depth of 50 ft, as shown in figure 60. The gamma log shows a significant increase in radioactivity at this depth, which is probably associated with an increase in calcium carbonate content.

Water Chemistry

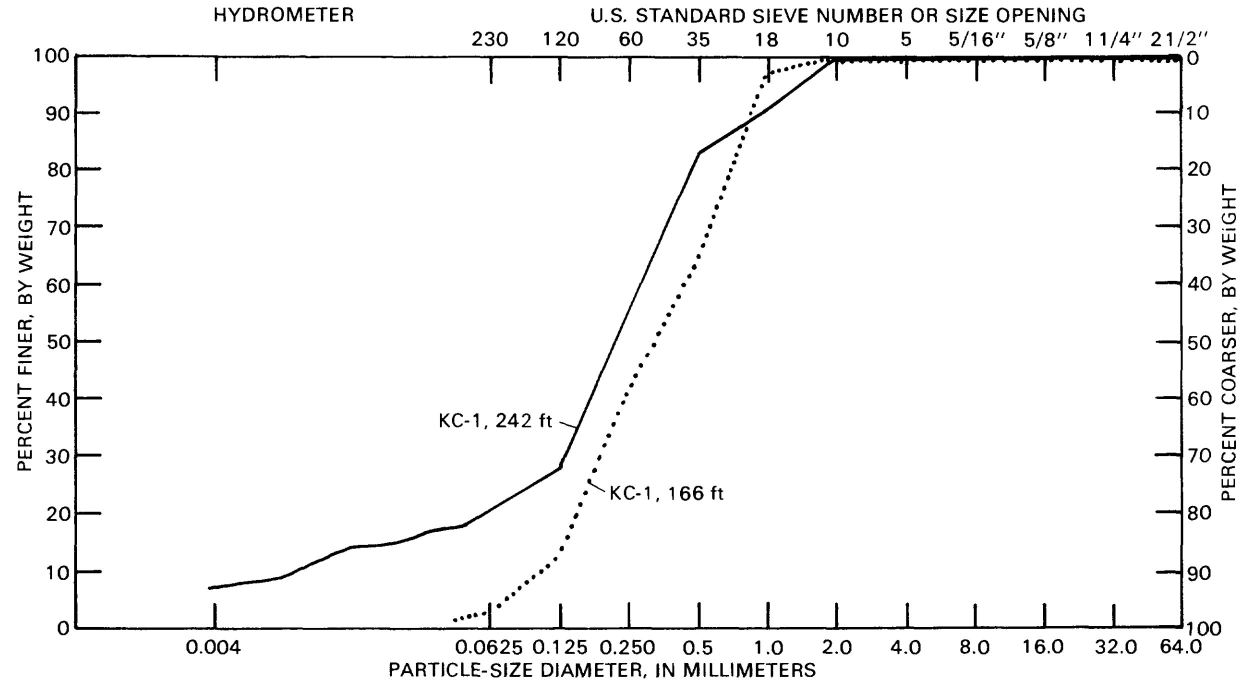
Maximum temperatures of the recharge water from the lake were higher than 27°C, compared to an average ground-water temperature of 18°C.

Water in the Kitten playa averaged about 175 mg/L suspended solids. Sediment content ranged from a low of 40 mg/L at the beginning of the test, to more than 450 mg/L at 1200 hours of the second day. The playa-lake water had a pH of 7.9 units and a specific conductance of about 370–390 μmhos. In contrast, the ground water had a pH of 7.25 units and a conductivity of 385 μmhos. Variations in lake-water quality during the test did not have a measured effect on movement of recharge water.

Samples of sediment taken from the lake were analyzed by X-ray diffraction. Mineralogic constituents are listed in table 7.

Recharge Operation

The well at the Kitten site was recharged for approximately 30 hours on June 18 and 19, 1972. The recharge rates ranged from 1,700 gal/min at the start of the test to approximately 750 gal/min at the end of the test. Well-head pressure increased from 5 to 36 lb/in^2 during the test (fig. 61). It was necessary to shut the injection pump down several times due to mechanical failures. The test was terminated when water began to flow from animal burrows at several sites that were remote from the observation well and test holes (fig. 62). The total volume of water recharged was 5.76 acre-ft. An estimated 2,800 lb of sediment was injected into the aquifer.



PERCENT OF SIZE

		Depth below land surface 166 feet	Depth below land surface 242 feet
CLAY		3.2	7.
SILT		0	13.4
SAND	Very fine	9.5	7.2
	Fine	28.9	27.4
	Medium	22.7	28.4
	Coarse	33.0	7.6
	Very coarse	2.6	9.0

Figure 57. Particle-size distribution determined using core samples at depths of 166 and 242 ft, test hole KC–1, Kitten site.

Analysis Of Recharge Test

Movement Of Recharge Water

Nine of the temperature logs made in hole KR–2 during recharge are shown in figure 63. The highest indicated velocity, and thus hydraulic conductivity, was in the depth interval from 157 to 170 ft. Subsequent arrivals of recharge water on June 18 indicated intervals of lower hydraulic conductivity at depths of 100 to 110 ft, 140 to 150 ft, and 222 to 227 ft. The logs made on June 19 suggested 10 identifiable depth intervals where hydraulic conductivity was conspicuously higher than in adjacent sediments. The temperature anomalies logged at depths of 140 to 150 ft and 222 to 227 ft on June 18 were logged at greater depths in the hole about 27 hours after start of the test, whereas others remained at the depth where they were first measured. Such changes in depth at which water moves may indicate plugging of the upper part of a permeable zone, or development of the lower part, or both.

Core data indicated that two of the most permeable zones are in a coarse gravel and a friable sand. The latter is lithologically similar to the sand at the Stewart site.

Figure 64 is a plot of temperature changes during recharge at eight depths in test hole KR–2. Because of the short duration of the test, only part of one diurnal cycle was measured. Based on initial arrivals, thermal-pulse velocities ranged from 1.4 to 16 ft/h. The lowest velocities were measured above the original water table. Periodic temperature logs and neutron logs showed that a cone of recharge water was rising rapidly toward the surface. The test was terminated when water flowed at the surface at several locations. These surface springs, at considerable distance from the recharge well and test holes, were further evidence of the nonuniform movement of water, and they suggest that secondary porosity and permeability may be important, at least near surface.

Measurements of vertical flow were recorded with a borehole flowmeter in the injection well during a pumping test prior to recharge. Measurement of flow was recorded every 5 ft from the bottom of the pump at 210

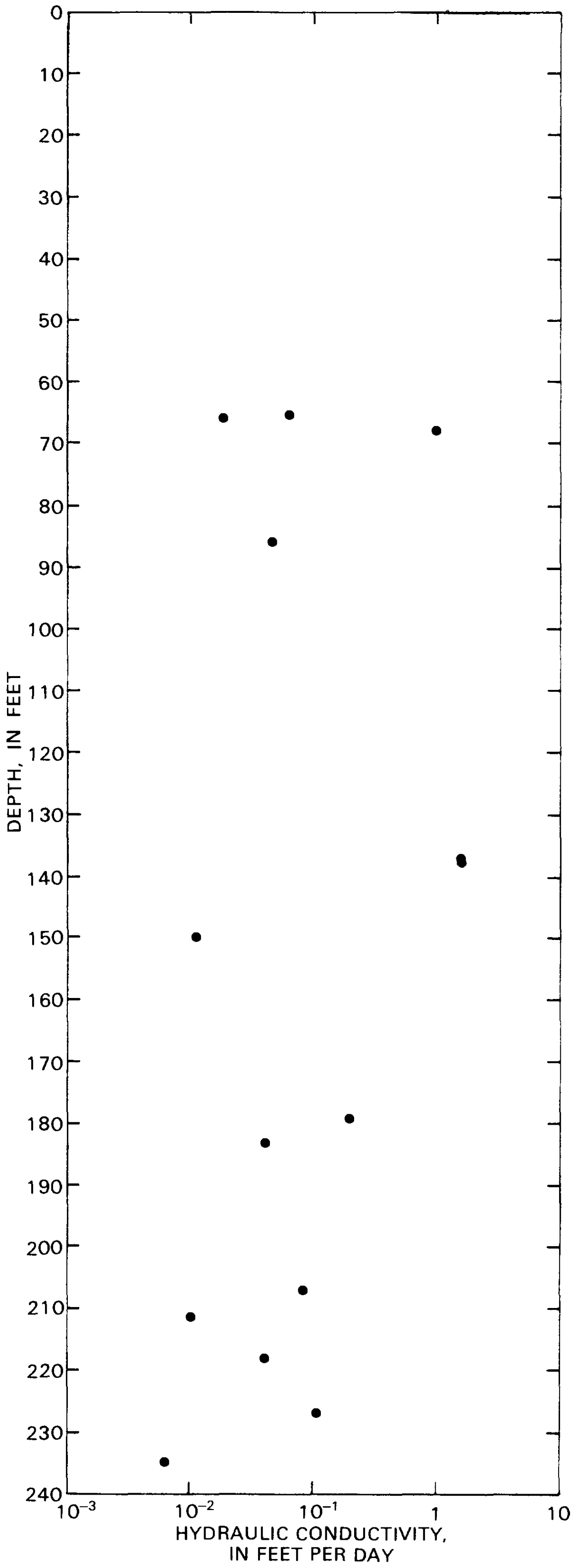


Figure 58. Horizontal hydraulic conductivity determined using core samples, test hole KC–1, Kitten site.

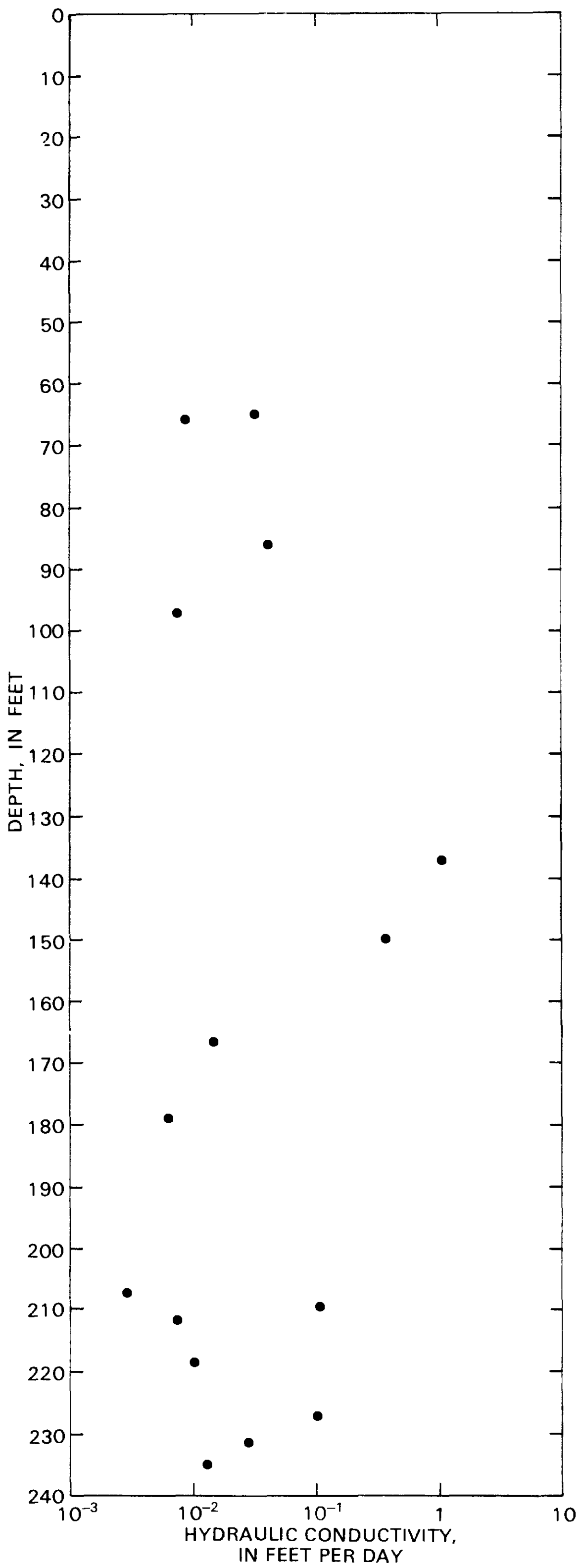


Figure 59. Vertical hydraulic conductivity determined using core samples, test hole KC–1, Kitten site.

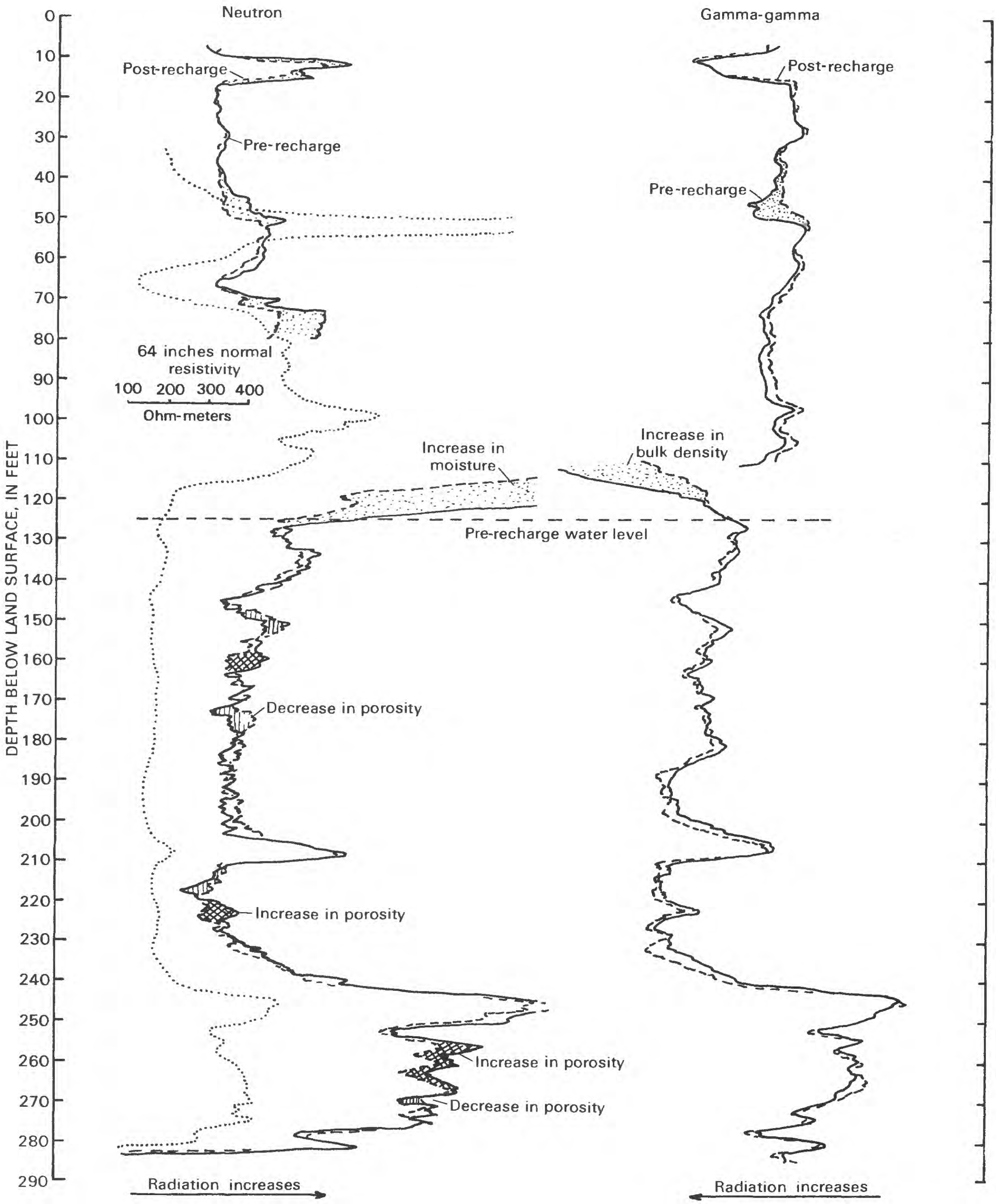


Figure 60. Prerecharge resistivity log and prerecharge and postrecharge neutron and gamma-gamma logs, test hole KR–2, Kitten site.

ft to the bottom of the well at 263 ft to determine whether differences in permeability at various depths, or changes of permeability with time, could be detected. The casing was slotted and gravel packed throughout this interval. Flowmeter logs were made on June 16 and 17, while the well was being pumped at 500 gal/min and 485 gal/min,

Table 7. Mineralogic composition of playa-lake water, Kitten site

Constituents	Composition (weight percent)		
Sample no.---	23	28	44
Quartz	5	25	1
Calcite	58	40	81
Potassium feldspar	0	3	0
Plagioclase feldspar	0	4	0
Total clay minerals[1/]	10	15	0

[1/]Clay minerals were dominantly montmorillonite and mixed layer.

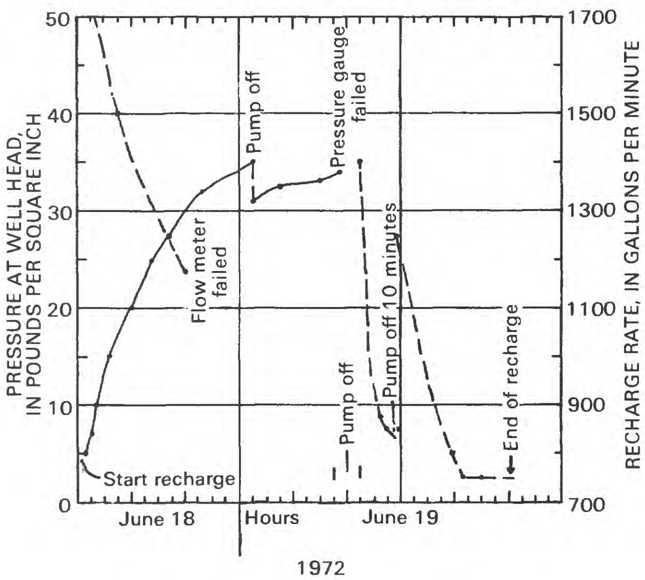


Figure 61. Recharge sequence, Kitten site.

respectively. On both days, the maximum velocity was measured just below the pump, and consistent but decreasing velocity was measured to 230 ft. Below this depth, the flowmeter recorded lower velocities on June 17 than on June 16, evidence of some caving of the lower part of the hole. Flow at the bottom of the hole was not detectable at a pumping rate of 485 gal/min. Apparently, more than half of the water was coming from above 235 ft, which is the approximate bottom of the deepest permeable zone. The temperature logs indicate that no water was recharged at depths greater than 250 ft.

Changes In The Aquifer

The lithology at the Kitten site is similar to that of fill in numerous Pliocene channels that cross the Southern High Plains. Sediments are coarse and well sorted in comparison to the great bulk of the Ogallala Formation.

Figure 62. Spring outlet, Kitten site.

Analysis of data collected during the test showed that recharge water moved most rapidly through zones of coarse gravel. A constant increase in pressure and correlative decrease in recharge rate with time is shown in figure 61. This is interpreted to indicate gradual plugging of pore space by the injected sediment. Most of this sediment was deposited in intergranular pore space in the permeable zones in the aquifer and thus diminished the permeability of these zones.

A comparison of prerecharge and postrecharge neutron and gamma-gamma logs at the Kitten site showed only minor changes in porosity below the water table. Changes in these logs above the water table were apparently due to changes in moisture content. Several of the intervals of minor change below the water table are adjacent to highly permeable zones which were detected by temperature logging. In test hole KR–2, these are at depths of 157–170 ft and 222–227 ft. The fact that both apparent increases and decreases in porosity were logged suggests redistribution of material immediately adjacent to the hole, probably in the annulus.

Effect Of Well Construction On Recharge

The recharge well at the Kitten site was gravel packed and mill-slot perforated. The Kitten well was designed exclusively for recharge. Following removal of the pump which was installed to determine pretest conditions, a horizontal section of well casing was welded to the vertical well casing to conduct recharge water from the lake

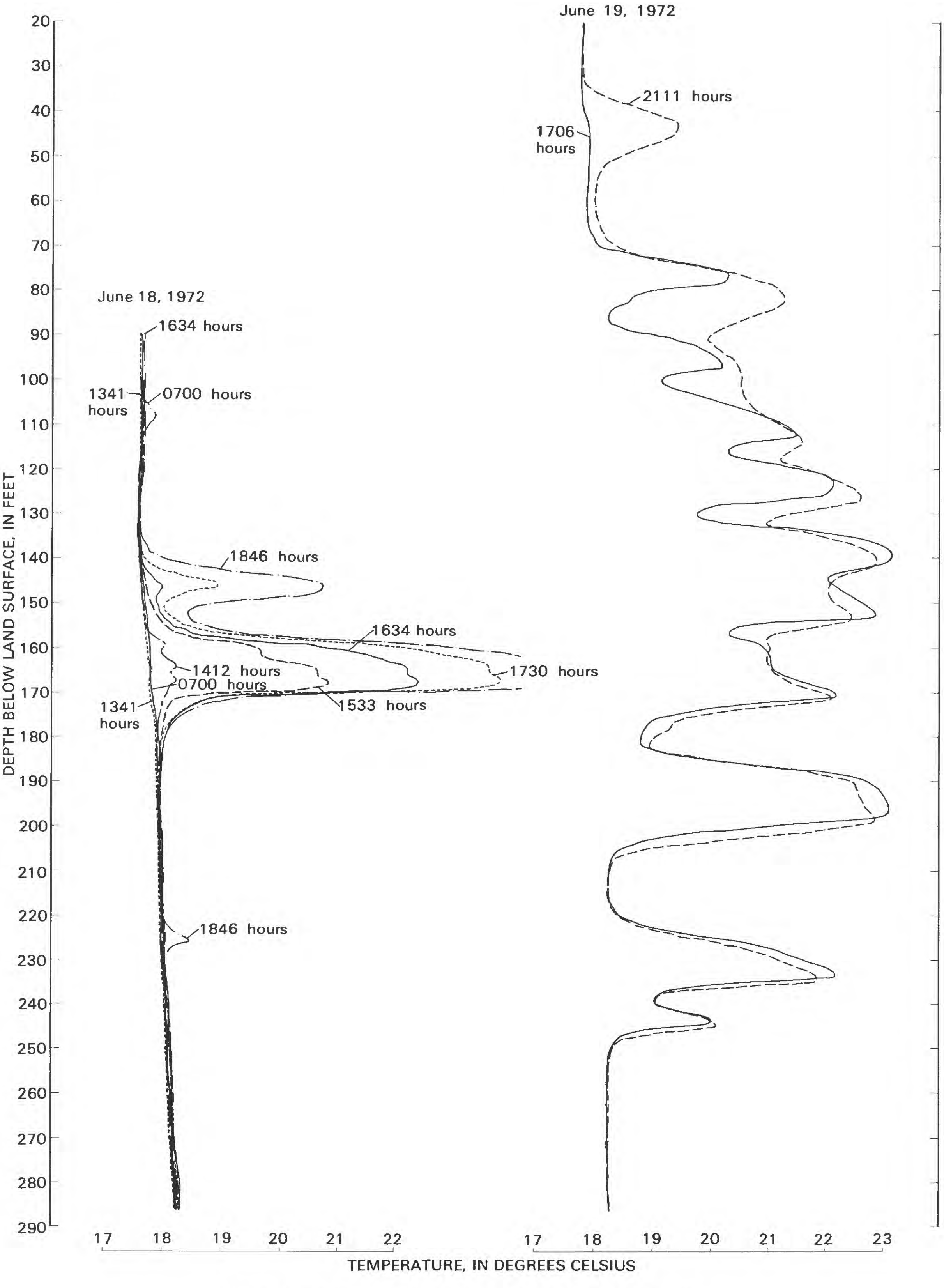


Figure 63. Temperature logs, test hole KR–2, Kitten site.

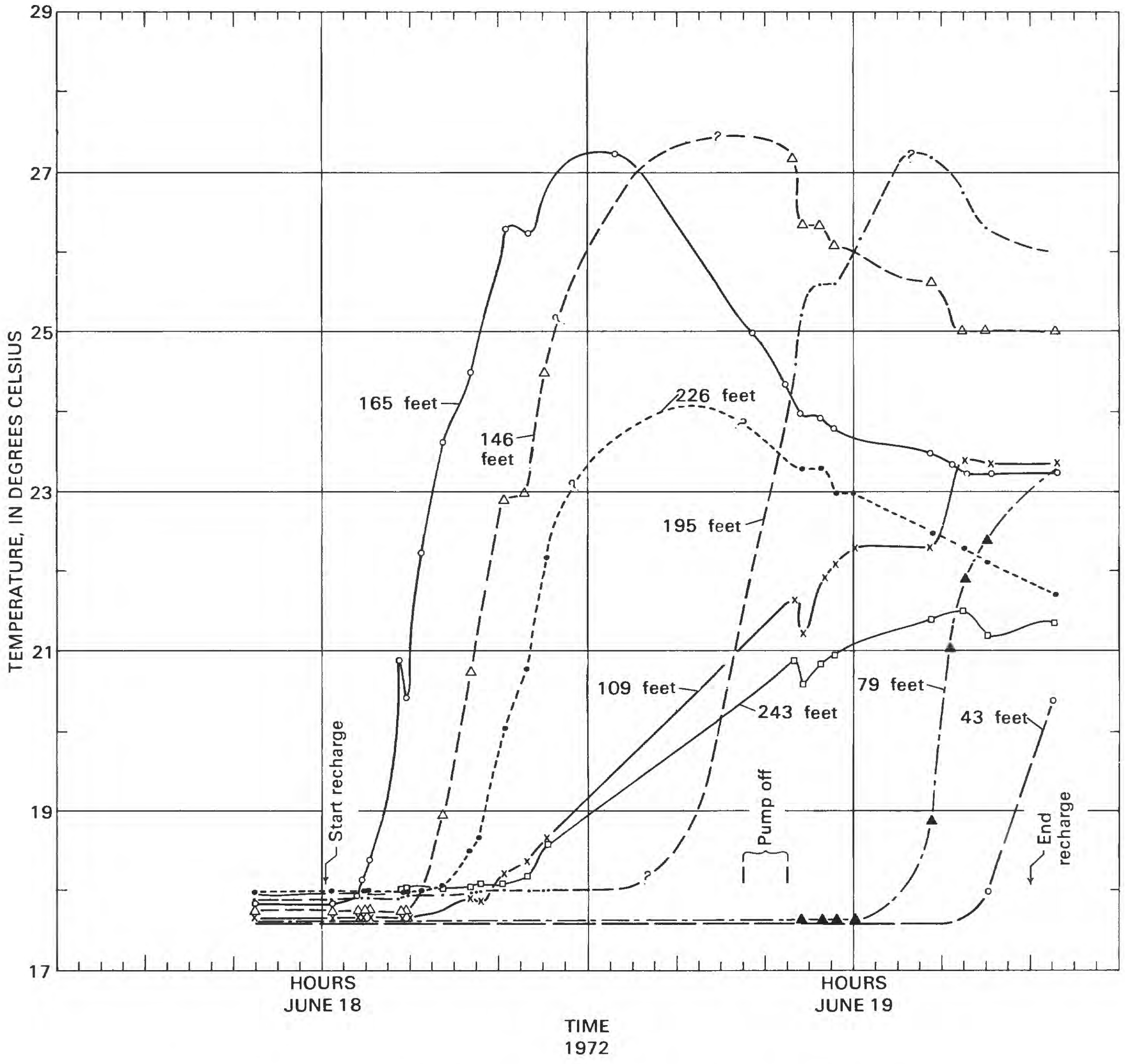


Figure 64. Temperature changes at eight depths, test hole KR–2, Kitten site.

pump into the well. Thus, subsequent to recharge, there was no means of pumping the well.

All test holes were pressure grouted to minimize the upflow of water around casing during periods of high-pressure injection. Such grouting probably is desirable for pressure recharge. However, in most sections of the Ogallala Formation, permeable strata above the water table do not restrict the rising mound of water created by sustained periods of pressure recharge, and surface springs result, regardless of the effectiveness of the seal between the casing and the formation.

FULLINGIM SITE

At the Fullingim site, test holes were drilled and cored, and geophysical logs were recorded, but the project was terminated before a recharge well could be drilled (fig. 65). It is possible that the site will be recharged in the future. Two types of acoustic logs not previously run in the Ogallala Formation were recorded at this site and are potentially useful for investigating recharge sites in the future.

Acoustic-velocity and acoustic-televiewer logs re-

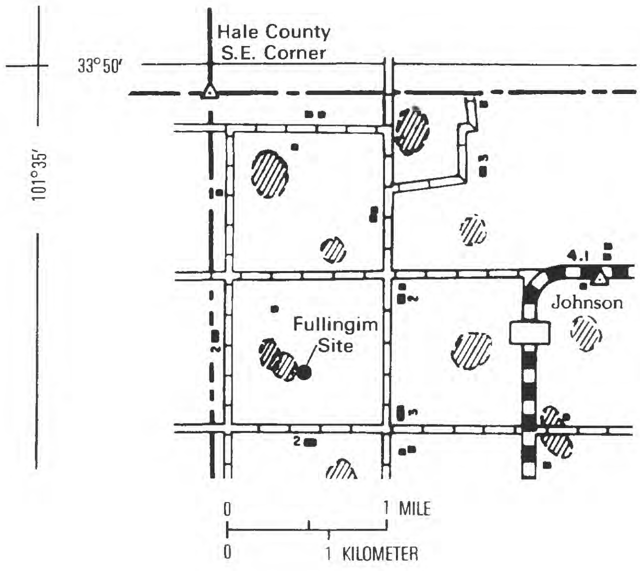


Figure 65. Location of Fullingim site.

quire liquid in the borehole and that the logged section consist of relatively consolidated rocks. The acoustic-velocity log was of restricted value at depths less than than 180 ft because of cycle skips caused by the high attenuation of acoustic energy in unconsolidated sediments. Where transit time was measured, the values ranged from 140 to 160 μs/ft which indicates very little cementation. However, a few values less than 60 μs/ft were recorded, which probably represent concentrations of calcium carbonate.

The acoustic-televiewer log recorded considerable detail for such poorly reflective rocks. Figure 66 shows acoustic-televiewer and caliper logs for an interval of the core hole from 20 to 30 ft. Both logs show several irregular openings that are probably due to solution of calcium carbonate. Several other major openings on the televiewer log may be due to solution of calcium carbonate and are immediately adjacent to gamma-log maxima. The televiewer thus provides a potential means for logging solution openings which are important to the successful recharge of sediment-laden water to the Ogallala Formation.

The televiewer log also shows channel-type cut and fill deposits. Figure 67 shows what is apparently a channel scour at 151 ft and a similar contact at 157 ft. The core is mostly gravel immediately above the upper contact. The core samples indicated this gravel had a high permeability.

Short and long normal-resistivity logs were also made in the core hole at the Fullingim site, and they show the highest average resistivities in the intervals with high calcium carbonate content. Resistivity logs may therefore

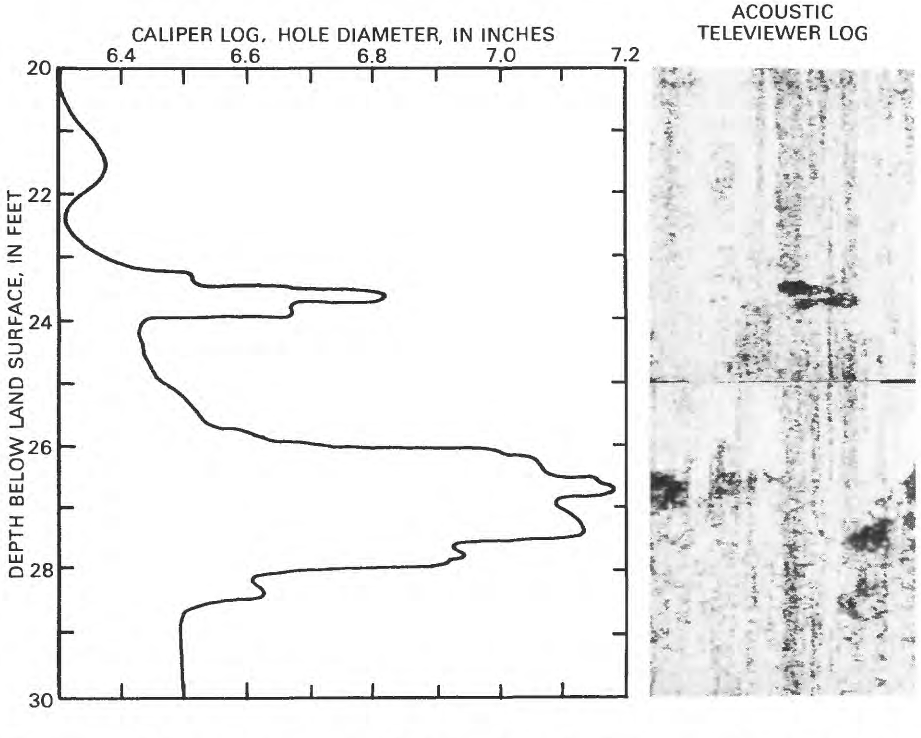


Figure 66. Caliper and acoustic televiewer logs of solution openings, core hole, Fullingim site.

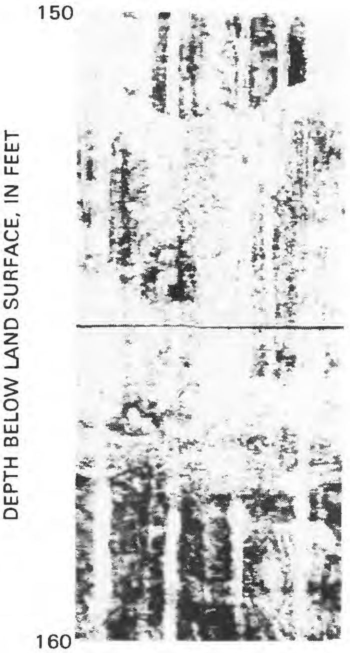


Figure 67. Acoustic televiewer log of the interal 150 to 160 ft showing possible channel scours at 151 and 157 ft, core hole, Fullingim site.

provide a relatively simple technique for identifying zones which have a potential for accepting recharge water.

SUMMARY

Water from playa lakes was injected into four wells in the Ogallala Formation, under different geohydrologic conditions. Table 8 is a summary of the conditions and results of these tests.

The four tests demonstrate the effects of the wide range in lithologies present in the Ogallala Formation on well recharge, and the diverse methods that are applicable for injecting playa-lake water. The analytical techniques developed during the tests for site selection and recharge operation are the principle product of the study, although the importance of extensive secondary porosity in the Ogallala Formation may be of equal significance to the success of artificial recharge on the Southern High Plains.

A deterrent to the use of artificial recharge has been the inability to determine: (1) The capacity of aquifers to accept recharge, (2) the distribution of recharge water, and (3) the placement of injected sediment. The lack of data on the effect of repumping recharge water and of redevelopment of formations clogged with injected suspended sediment is equally limiting. The extensive use of borehole-geophysical logs during these tests has resulted in the development of log-analysis techniques that give much additional field information relative to these problems.

Borehole-geophysical techniques permit acquisition of field data that can be related directly to laboratory sand-column experiments and to mathematical models. Additional research extending the findings in this report and relating field, laboratory, and theoretical studies will further the economic feasibility of artificial recharge operations.

The most successful recharge was into secondary porosity developed by ground-water solution in zones of high calcium carbonate content. Additional solution of the calcium carbonate that occurred during recharge may have increased available storage. Intervals of high calcium carbonate content can be identified by gamma-spectral data, and zones of high porosity in these intervals may be located by neutron or gamma-gamma logs. The areal and stratigraphic distribution of porous calcareous intervals and their origin have not been determined.

Channel deposits in the Ogallala Formation, similar to those at the Kitten site, have a potential for accepting large volumes of recharge water, particularly if the concentration of suspended sediment in the recharge water is low. Where the Ogallala Formation is composed of sand and silt without secondary porosity, as at the Hufstedler site, rapid reduction in permeability takes place when untreated playa-lake water with a high content of suspended solids is injected.

Intervals having high permeability that are above the zone of saturation may accept recharge water readily. Some of these intervals may be perched on units having lower permeability and, even after a year, much of the water may be retained in these perched zones. Locally most of the available porosity may be in these unsaturated intervals.

Pressure recharge, as at the Dunlap and Kitten sites, prevents air entrainment and recharges water rapidly. Laboratory tests show that montmorillonite clays can be moved through medium sand under greater than gravity head, and thus force more water into a system than could be recharged by gravity injection. Use of moderate pressure, adjusted according to the rate of rise of the potentiometric surface, would permit injection of more water into a system before it became clogged, than injection at lower pressure.

Geophysical logs suggest that suspended sediment was deposited more than 6 ft from the injection well at the Hufstedler site. The small volume of clay removed by pumping did not significantly improve yield. This result is supported by laboratory studies on sand columns recharged with water containing suspended montmorillonite clay, which show that backwashing removes very little clay.

It is apparent from the tests described that effective recharge of the Ogallala Formation is possible where

Table 8. Summary of recharge tests

	Hufstedler	Dunlap	Stewart	Kitten
Lithology of permeable intervals	Coarse sand	Coarse sand and fine gravel; some solution openings	Friable fine sand with solution openings	Coarse gravel and sand
Construction of well	Gravel packed 13-in. casing in 24-in. hole	Gravel packed 10-in. casing in 20-in. hole	Naturally developed; 10-in. casing in 14-in. hole	Gravel packed; 10-in. casing in 20-in. hole
Injection rate & time	150 gal/min for 21 h	Average 1,500 gal/min for 50.5 h	600 gal/min for 13.5 days	750-1700 gal/min for 30 h
Total volume injected	0.58 acre-ft	14 acre-ft	34 acre-ft	5.76 acre-ft
Water & sediment injected	950 lb	5,100 lb	approx. 11,500 lb	2,800 lb
Injection technique	Gravity flow	Pumped in at 50-85 lb/in^2	Gravity flow	Pumped in at 5-36 lb/in^2
Solids in water	Average 600 mg/L	Average 137 mg/L	30-170 mg/L	Average 175 mg/L
Prerecharge specific capacity	4.5 to 5.7 gal/min/ft	No pump in the well	150 gal/min/ft No drawdown data	Questionable data
Postrecharge specific capacity	3.8 to 4.8 gal/min/ft	No pump in the well	380 gal/min/ft No drawdown data	No pump in the well
Zones of recharge	Most permeable zone below the water table plugged, then cone built rapidly	Significant quantity of water moved out above the water table	Most of recharged water moved out at one depth below the water table	Water moved in at least 10 different permeable zones over a wide depth range
Results	Significant decrease in permeability	Injected water discharged at the surface. Much recharged water perched and not available for immediate pumping	No significant decrease in permeability and a significant increase in productivity of the well	Due to plugging, cone of recharge built rapidly until water discharged at the surface

geohydrologic conditions are favorable and the recharge system is constructed to optimize recharge. Core samples and borehole-geophysical logs can be utilized to select sites for recharge wells and to define the operation of hydrologic-recharge systems. Construction of the recharge well and injection system seem generally less critical to success than the character of the aquifer system into which recharge takes place. Treatment of water to reduce suspended-sediment load would certainly increase effectiveness of recharge.

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