TEXAS DEPARTMENT OF WATER RESOURCES

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EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

Results of Test Hole Drilling

By

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLES

FIGURES

EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

Results of Test Hole Drilling

RESULTS

Information was derived from 41 test holes in the High Plains aquifer, which is composed primarily of the Ogallala Formation. Four major fluvial lithofacies have been identified in the Ogallala: (1) channel; (2) distributary mouth; (3) interdistributary (interchannel); and (4) frontal fan slope deposits. Core analyses show that the fluvial channel and distributary mouth deposits have an average specific yield of 17.7 percent, whereas interdistributary and frontal fan slope sediments have an average specific yield of 13.9 percent. The average specific yield and permeability for the 41 Texas High Plains test holes is 16.06 percent and 232 gallons per day per square foot, respectively. Statistical analysis indicates that the center of gravity for transmissivity and specific yield occurs about midway in the saturated interval.

INTRODUCTION

Purpose and Scope

In 1978, the Texas Department of Water Resources initiated a regional ground-water study of the High Plains aquifer. The study, utilizing Department personnel, was partially funded by the U. S. Geological Survey, and its results are to be included in that agency's eight-state study of the Ogallala. As part of the study, the Department conducted a test hole drilling program to aid in evaluating the aquifer's specific yield and permeability. Additionally, lithofacies data and depth to the base of the aquifer were determined at each test hole site.

The High Plains aquifer in Texas consists of all formations from which fresh water can be produced on the High Plains. The aquifer consists primarily of the Ogallala Formation, but in certain areas also includes Cretaceous, Jurassic, and Triassic formations that are below the Ogallala but are hydrologically connected to it.

The scope of this investigation included the drilling and selective coring of the 41 test holes through the High Plains aquifer, the geophysical logging of each test hole, laboratory testing of cuttings and selected cores, and the interpretation of these tests to determine permeability and specific yield.

The test hole drilling program was conducted from March through November 1979, and laboratory testing was concluded in January 1980.

Location

The test holes were located in 36 counties, Figure 1, which comprise the majority of the area known as the "Texas High Plains" or the "Llano Estacado." The study area is bounded on the north and west by the Oklahoma and New Mexico

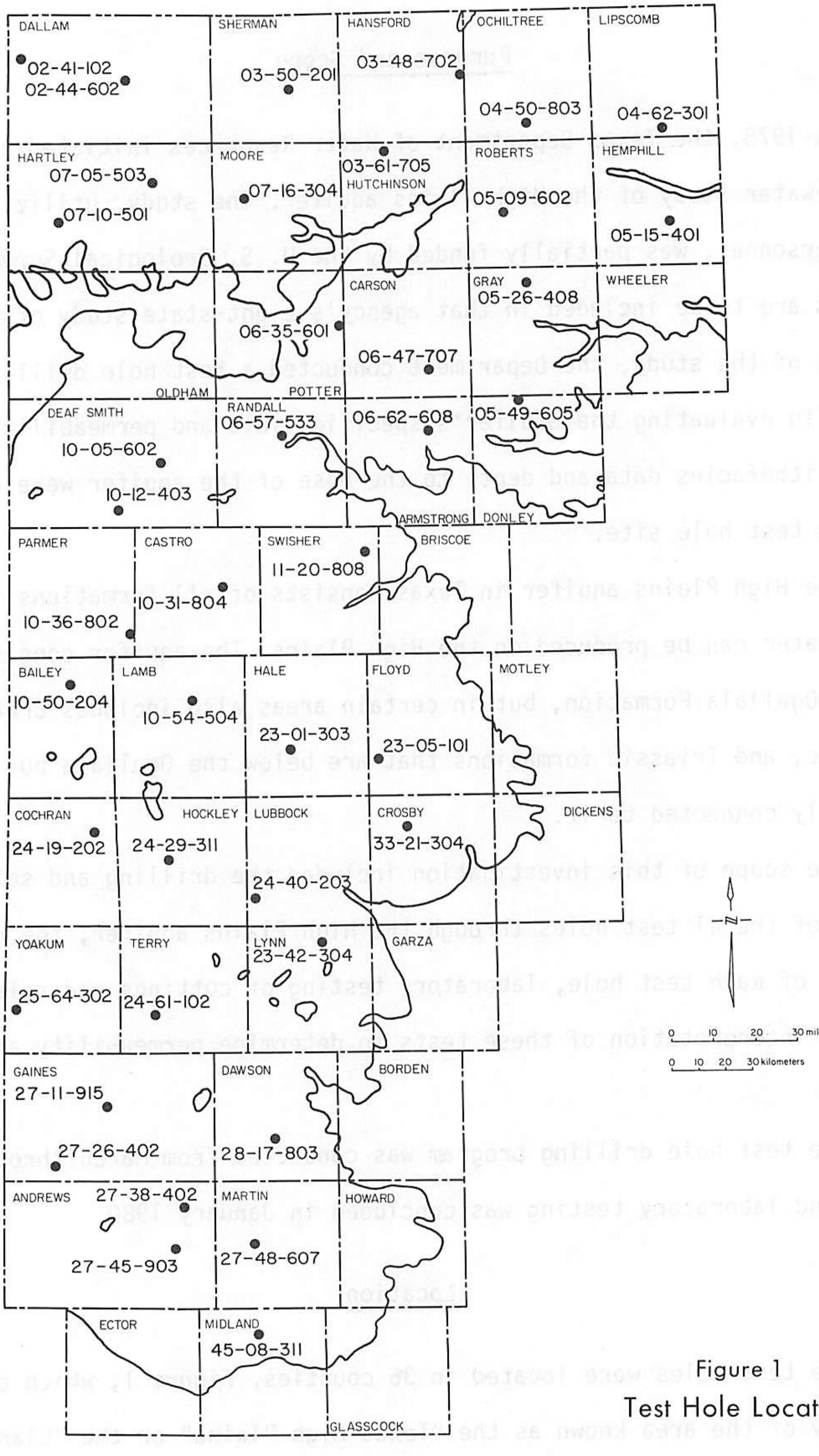

Figure 1

Test Hole Locations

borders, respectively, and on the south by a line through Ector, Midland, and Glassock Counties. The eastern boundary is defined in most places by a prominent escarpment that gives way to a roughly dissected land locally known as the "breaks". The Texas High Plains is divided into two parts by the Canadian River. These are termed the Northern and Southern High Plains.

Personnel

The test hole drilling investigation was conducted by personnel of the Data and Engineering Services Division of the Texas Department of Water Resources under the direction of C. R. Baskin, Division Director. Supervision of the project was by William B. Klemt, Head of the Ground Water Studies Unit. General supervision was provided by Dr. Tommy Knowles, Chief, Data Collection and Evaluation Section, and Jack Overton, Chief, Engineering and Technical Services Section.

The author served as rig geologist with assistance from Ann Bell, Gail Duffin, Phillip Nordstrom, and Richard Preston, all of the Data Collection and Evaluation Section. Geophysical logging was conducted by James Moore, also of the Data Collection and Evaluation Section.

Drilling and laboratory testing were conducted by the Geotechnical Services Unit under the supervision of Marion Striegler. The drilling crew was headed by Lewis Barnes.

Acknowledgements

Acknowledgment is expressed to the Texas State Department of Highways and Public Transportation for their cooperation in allowing the test holes to be drilled on state highway right-of-way, and the generous assistance of the maintenance foreman in each of the counties visited.

The author would also like to thank the many landowners and interested citizens for the valuable information they provided concerning local subsurface geologic and hydrologic conditions.

METHODS OF INVESTIGATION

Drilling Equipment

The test holes were drilled by the Department's modified Failing 1500 drilling rig, which is equipped with 30 feet (9 meters) of 4-inch (10.2 centimeter) drill collars, 1,450 feet (442 m) of 4-inch (10.2 cm) flush joint drill pipe, assorted 6 1/4 to 8 3/4-inch (15.9 to 22.2 cm) drill bits, and core retrieving tools including a Christensen 5 3/4-inch x 4-inch core barrel, Denison core barrel, and a Shelby push tube. The rig uses a 5-inch x 6-inch mud pump for circulation of drilling fluids. Support equipment includes a 1,000 gallon (3785 liters) water truck and a pickup truck.

Drilling and Coring Procedure

Each test hole was started with an 8 3/4-inch (22.2 cm) roller bit to a depth of 20 feet (6 m). From this depth, the hole was drilled with a 6 1/4-inch (15.9 cm) roller or wing bit to a depth predetermined to be in a zone in which the aquifer has been dewatered since 1960. A core was taken in the dewatered zone. Drilling with a 6 1/4-inch (15.9 cm) roller or wing bit was then continued into the saturated zone to the next coring point. This procedure of alternately drilling and coring was continued until a predetermined number of cores were taken. Drilling was then continued until the underlying nonwater-bearing formation was encountered. The majority of cores were taken with the Christensen core barrel. Occasionally, when the formation was too unconsolidated to be retrievable with the Christensen core barrel, a thin wall

Shelby push tube was utilized. Upon reaching total depth, the hole was logged by the Department's geophysical logging unit, backfilled, and plugged.

Well Site Procedure

A descriptive log (Appendix 1) was prepared for each test hole. The log represents a continuous lithologic description of both the core and cutting samples consisting of the principal rock name, color, particle size, roundness, condition of sorting, matrix, degree of cementation or consolidation, type of stratification, inclusions, and occasionally fossil content. Cores selected for laboratory analysis were inserted in plastic bags and placed in core boxes for transfer to the laboratory. Cutting samples, the fragmental rock broken from the rock penetrated during the course of drilling, were collected at 10-foot (3 m) intervals and placed in cloth bags.

A field test for specific yield was attempted but was not successful. Selected cores were to be allowed to gravity drain in an evaporation free environment and periodically weighed. The results were to be graphed and compared to specific retention values determined in the laboratory. The procedure was unsuccessful because of the unconsolidated condition of the large majority of the cores and difficulties in weighing the cores in the field.

Geophysical Logging

The Texas Department of Water Resources' Gearhart-Owen Widco Model 3500 logging unit was used to log each test hole. Geophysical logs run included: (a) electric, (b) gamma ray, (c) neutron, (d) gamma-gamma, and (e) caliper. The electric log included single point, spontaneous-potential, and normal (16 and 64 inch) (40.6 and 162.6 cm) resistivity curves. Spacings on the neutron and gamma-gamma tools were 19 and 5 inches (48.3 and 12.7 cm), respectively. All logs were run at a scale of 2 inches per 100 feet (5.1 cm per 30.5 m), and sensitivities were selected to give maximum definition to each curve. The test holes were uncased and filled with drilling fluid before logging, and the temperature and electrical resistivity of the drilling fluid were recorded. Correlations of geophysical logs with the descriptive logs and certain laboratory test information for six test holes are shown in Appendix 2.

Testing Procedure

The Texas Department of Water Resources' Materials Testing Laboratory conducted the following tests on the core and cutting samples collected for analysis:

Field Moisture Content

Sample cores were allowed to drain for several days and then weighed. The cores were oven dried and reweighed. The difference between the wet and dry weights represent the field moisture content which, when converted to volume and compared to the total volume of the core sample, represents an approximate value for specific retention. An undetermined amount of moisture was undoubtedly lost by evaporation even though efforts were made to prevent it. The amount of evaporation is probably relatively small and has little effect on the final results.

Mechanical Analysis

Sieve and/or hydrometer analysis were employed to establish a grain size distribution curve for the sample. The cutting samples were initially dried and then washed over a #200 sieve to determine the percentage of material smaller than .06 millimeter. Fine to coarse grained cuttings and crushed core samples (less than 10 percent of the sample was smaller than .06 millimeter) were subjected to sieves of decreasing size. A cumulative curve was drawn for each sample by plotting the percentage of grains retained on each decreasing grade size sieve. From the cumulative curve, a median grain diameter (D_{50}) and a sorting coefficient (S_o) were determined. The sorting coefficient was developed by Trask (1932) and is defined as the square root of the ratio of the grain diameter corresponding to the 75 percent level on the cumulative curve to the grain diameter corresponding to the 25 percent level ($S_o = \sqrt{D_{75}/D_{25}}$). The degree of sorting improves as the sorting coefficient approaches a value of 1.

For core samples comprised predominantely of very fine to clay sized grains, a hydrometer analysis was used. This method is based on Stokes' law, which is expressed by the following equation:

$$V = \frac{(G_s - G_w)D^2}{18n}$$

where:

V = terminal velocity
G_s = specific gravity of solids
G_w = specific gravity of the liquid in which the sphere is falling
n = viscosity of the liquid
D = diameter of the sphere

Stokes' law relates terminal velocity of a free-falling sphere in a liquid to its diameter. By measuring the density of the liquid at known depths in the suspension and at known settling times, a determination can be made of the percentage of particles remaining in suspension that are finer than the diameter of the settled particles for each time step. A cumulative curve can then be established by plotting the grain sizes and percentages as was done in the sieve analysis.

Values of D_{50} and S_o derived from cutting samples consisting of well cemented grains or crushed gravels were not used because the particle sizes were not indicative of the formation material.

Porosity

The method used to determine porosity was dependent on the degree of consolidation of the sample being tested. Well-consolidated cores were weighed when fully saturated, then oven dried and reweighed. The difference in weight was converted to volume. The ratio between this volume and the total sample volume represents the percent of the total sample occupied by void space. To accomplish full saturation, the cores were placed in a bell jar filled with de-ionized water and subjected to a vacuum of 28 inches of mercury for a minimum of 4 hours.

The porosity of the poorly consolidated to unconsolidated cores was determined by comparing the bulk density of the core sample with the bulk density of the sample at zero porosity.

Permeability

Cores and cuttings were tested for permeability using the Johnson Field Permeameter because of the generally unconsolidated nature of the samples. This test consists of uniformly repacking the unconsolidated sample into a container of known volume with a screened base and noting the time required for a given quantity of water to drain through the sample. The time value is then applied to a curve that relates test time to permeability.

Falling head and constant head permeameter tests were conducted on cores that appeared to be consolidated enough to withstand the test. Vertical permeabilities were usually negligible due to the thin layers of silt and clay that were commonly present. Attempts were made to determine horizontal permeability, but horizontal cores cut from the main cores usually crumbled because of the poorly consolidated nature of the material. Therefore, because of the above limitations, all permeability values used in this report are the results of the Johnson test procedure explained previously.

Density

Density was determined by dividing the weight of the core sample by the volume of water it displaced.

EVALUATION OF TEST DATA

Determination of Permeability and Porosity from Test Data

Values of permeability and porosity derived from laboratory analysis of samples were grouped according to their corresponding median grain size (D_{50}) and sorting coefficient (S_0). Values within the groups were then averaged. The average values of permeability within specified D_{50} and sorting ranges are shown in Table 1. Only five of the cells in the central portion of the table contain values actually based on laboratory analysis. This is because they are the only cells defined by parameters within which sufficient samples (a minimum of 5) were available to permit averaging. Samples fitting parameters of the remaining cells were either non-existent, or the few samples that did fit were not representative enough to produce a realistic average value for the D_{50} and S_0 range of each cell. Therefore, values for these remaining cells, except for those in the bottom row, were extrapolated from the laboratory determined values. Values in the cells in the bottom row of Table 1 were derived from a similar table by Beard and Weyl (1973).

Table 2, which illustrates the variability of porosity, was compiled in a manner similar to the procedure used to construct Table 1. For this table, a laboratory tested value was assigned to a cell if the grain size and sorting coefficient for two samples were within the ranges of the cell. Laboratory-determined average values fit more cells in this table because porosity varies less than does permeability.

TABLE 1

*Permeability of the High Plains Aquifer From Drilling Samples

MEDIAN GRAIN SIZE (D_{50}), mm

**SORTING COEFFICIENT $So=\sqrt{D_{75}/D_{25}}$	1.00 – .710	.710 – .500	.500 – .350	.350 – .250	.250 – .177	.177 – .125	.125 – .062	.062 – .033
1.2-1.4 Well Sorted	*2985*	*1755*	*1032*	*530*	*361*	*208*	*122*	*72*
1.4-2.0 Moderately Sorted	*1148*	*675*	397	204	139	80	*47*	*28*
2.0-2.7 Poorly Sorted	*434*	*255*	150	*78*	*53*	*31*	*18*	*11*
2.7-5.7 Very Poorly Sorted	*136*	*77*	*44*	*22*	*13*	*7*	*4*	*2*
	Medium	Medium Fine		Fine		Very Fine		Silt

* Permeability in gallons per day per square foot.

** Sorting coefficient from Trask (1932).

$\boxed{397}$ Average permeability determined from laboratory tested samples.

$\boxed{\mathit{760}}$ Average permeabilities extrapolated from the laboratory determined values and from values given by Beard and Weyl (1973).

TABLE 2

Porosity and Specific Yield of the High Plains Aquifer From Drilling Samples

MEDIAN GRAIN SIZE (D_{50}), mm

* SORTING COEFFICIENT $So = \sqrt{D_{75} / D_{25}}$	1.00–.710	.710–.500	.500–.350	.350–.250	.250–.177	.177–.125	.125–.062	.062–.033	Avg. Porosity 1/ & Sp. Yield
1.2-1.4 Well Sorted	*37* *20*	*37* *20*	35 19	38 20	41 20	41 20	*38* *20*	*37* *20*	38.0 19.9
1.4-2.0 Moderately Sorted	*32* *18*	*33* *19*	34 19	33 19	36 20	37 20	34 19	*33* *19*	34.0 19.1
2.0-2.7 Poorly Sorted	*29* *17*	*32* *18*	*33* *19*	32 18	*32* *18*	*33* *19*	31 18	*31* *18*	31.6 18.1
2.7-5.7 Very Poorly Sorted	*30* *17*	*26* *15*	*27* *16*	*25* *15*	*31* *18*	*31* *18*	30 17	30 17	28.8 16.6
	Medium	Medium Fine		Fine		Very Fine		Silt	

* Sorting coefficient from Trask (1932).

$\boxed{\begin{matrix}35\\17\end{matrix}}$ Average porosity (top) and specific yield (bottom) determined from laboratory tested samples.

$\boxed{\begin{matrix}\mathit{33}\\\mathit{16}\end{matrix}}$ Average porosity (top) and specific yield (bottom) extrapolated from laboratory determined values and from values given by Beard and Weyl (1973).

1/ Average of values shown for all cells in each sorting range.

A neutron log was run in each test hole with the intention of correlating counts per second with porosity. However, the definition of the curve did not adaquately reflect the change in porosity due to the dampening effects of high values of porosity on the log response.

Gravel zones were not adequately tested because of the inability to retrieve representative cores. Evaluation of cutting samples taken from gravel zones generally indicate a D_{50} value above the 1.0 millimeter range but, because the sorting coefficient was usually extremely high, (greater than 5.7), the permeability was often greatly reduced.

The tables demonstrate that change in permeability is a function of both sorting and grain size, whereas change in porosity is primarily a function of sorting rather than grain size. Although a few test samples had values of D_{50} and sorting coefficients that were beyond the boundaries of Tables 1 and 2, the great majority of samples, and particularly samples taken from the best production zones, tended to fit the central portion of the tables.

Determination of Specific Yield from Test Data

Specific yield values were determined by subtracting the field moisture content (apparent specific retention) from total porosity. Specific yield versus porosity was then plotted, Figure 2, and an envelope curve was drawn to fit the array of points. An envelope curve was used because the test values for field moisture content did not uniformly reflect a true value for specific retention due to the lack of time necessary to reproduce in the laboratory the same gravity drainage that would occur in situ. Increased drainage time would result in the migration of the data points in Figure 2 upward toward the curve. Also, the loss of some porosity in the cores is possible during the coring process which results in decreased porosity values. The curve indicates a ratio of 1.2:2 between specific yield and porosity for values of porosity

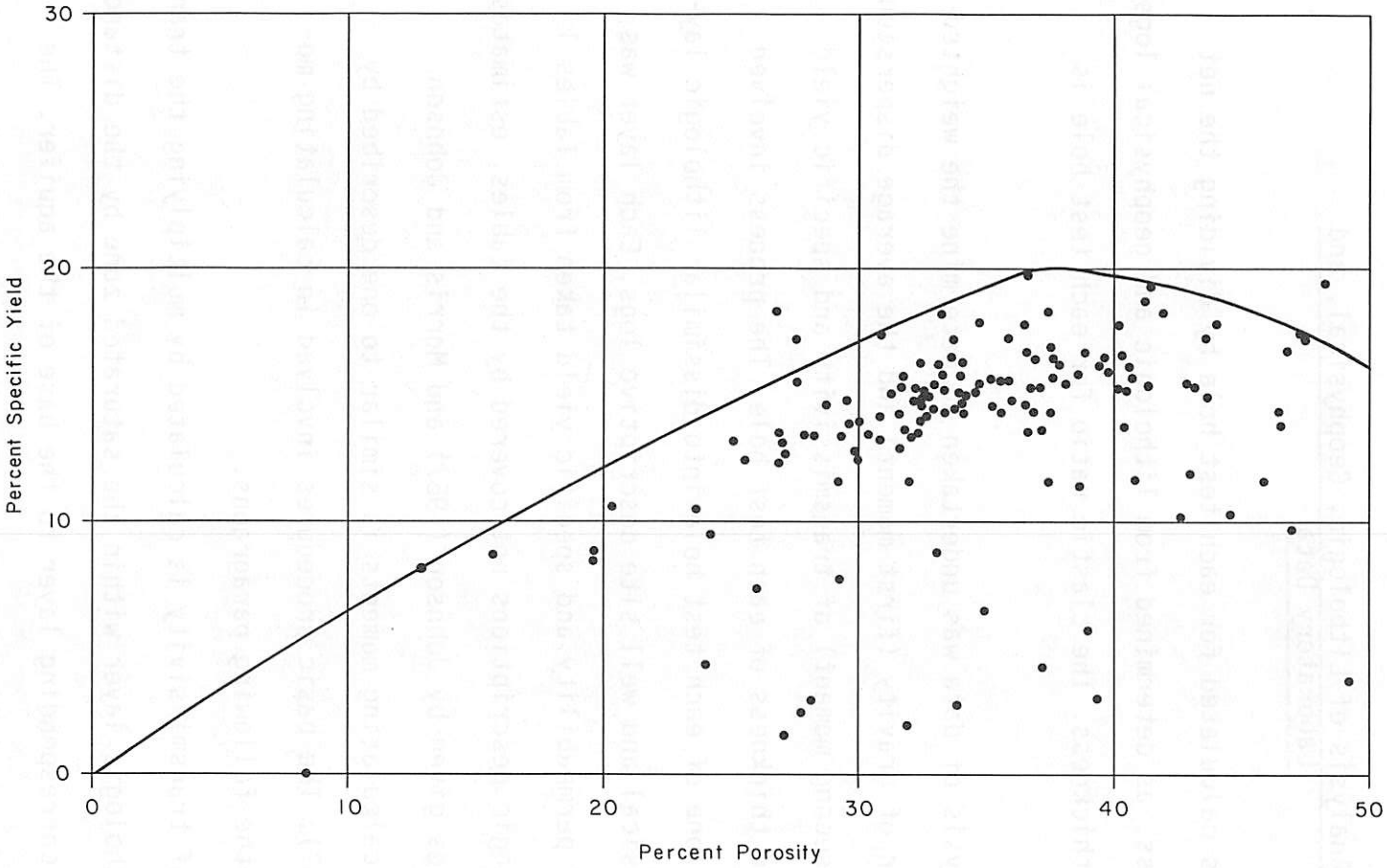

Figure 2

Specific Yield and Porosity From High Plains Aquifer Cores ranging up to approximately 36 percent. Values of specific yield were assigned from the curve in Figure 2 to Table 2 according to the predetermined porosities.

Statistical Analysis of Lithologic, Geophysical, and Laboratory Data

A clastic ratio was calculated for each test hole by dividing the net sand and gravel thickness, as determined from lithologic and geophysical logs, by the total saturated thickness. The clastic ratio for each test hole is shown in Table 3.

A statistical analysis of data was undertaken to determine the weighted mean position or center of gravity (first moment) and the average dispersion or standard deviation (second moment) of transmissivity and specific yield throughout the saturated thickness of each test hole. The process involved dividing the saturated zone of each test hole into dissimilar lithologic layers based on the geophysical and well site descriptive logs. Each layer was then assigned values of permeability and specific yield taken from Tables 1 and 2. For those lithologic descriptions not covered by the tables, estimates were made based on values given by Johnson (1967) and Morris and Johnson (1967). This method of calculating moments is similar to one described by Krumbein and Libby (1957). The basic procedures involved in calculating moments are described in the following paragraphs.

The first moment of transmissivity is calculated by multiplying the transmissivities of each lithologic layer within the saturated zone by the distance from the center of the corresponding layer to the base of the aquifer. The products are then summed and divided by the sum of the transmissivities:

$$\begin{array}{l}\text{center of gravity of T}\\ \text{above base of aquifer}\end{array} = \frac{\Sigma TD}{\Sigma T} \qquad (1)$$

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TABLE 3

Results of Lithologic, Geophysical, and Laboratory Data Analysis

State well number	County	North latitude ° ' "	West longtitude ° ' "	Surface elevation (ft)	Depth (ft)	Depth to base of aquifer (ft)	Elevation of base of aquifer (ft)	Depth to static water level (ft)	Elev. of static water level (ft)	Saturated thickness (ft)	Transmissivity T [1] [2] gpd/ft	Average specific yield Sy [1] [2] (%)	1st Moment T [1] [2] (%)	2nd Moment T [1] [2] (%)	1st Moment Sy [1] [2] (%)	2nd Moment Sy [1] [2] (%)	Average [1] permeability (gpd/ft^2)	Clastic ratio [1] gravel + sand / gravel + sand + clay	Lithofacies type [1] [3]	Remarks
27-38-402	ANDREWS #1	32 26 07	102 20 37	3,026	125	119	2,907	73	2,953	46	44,353	18.02	53	19.43	50	26.68	964	.80	A	
27-45-903	ANDREWS #2	32 17 24	102 23 19	3,039	121	115	2,924	53	2,986	62	7,894	7.23	10	17.23	35	33.26	127	.93	--	40' to 115' Cretaceous
06-62-608	ARMSTRONG	35 04 28	101 15 55	3,344	316	310	3,034	250	3,094	60	2,295	13.98	56	25.74	58	26.05	38	.74	D	
10-50-204	BAILEY	34 14 36	102 49 02	3,831	200	180	3,651	85	3,746	95	7,610	18.37	51	25.92	49	27.78	80	.95	C	
06-47-707	CARSON	35 16 50	101 14 21	3,362	518	490	2,872	320	3,042	170	50,173	18.43	29	16.65	49	24.99	295	.86	A	
10-31-804	CASTRO	34 32 21	102 10 11	3,785	350	342	3,443	240	3,545	102	9,486	18.55	44	23.39	52	26.95	93	.89	A	
24-19-202	COCHRAN	33 43 10	102 41 01	3,711	280	265	3,446	149	3,562	116	36,268	16.97	38	18.07	50	24.64	313	.87	A	
33-21-304	CROSBY	33 44 24	101 24 36	3,120	360	340	2,780	208	2,912	132	17,274	17.55	54	16.58	54	26.26	131	.87	C	
02-44-602	DALLAM #1	36 17 42	102 32 12	4,130	452	445	3,685	265	3,865	180	5,069	11.63	52	33.89	56	30.80	28	.67	--	280' to 445' Triassic
02-41-102	DALLAM #2	36 21 03	102 59 29	4,560	310	302	4,258	120	4,440	182	12,747	19.12	50	24.02	51	26.49	70	.87	--	133' to 302' Cretaceous 302' to 310' Jurassic
28-17-803	DAWSON	32 39 29	101 56 05	2,940	188	183	2,757	80	2,860	103	29,966	16.83	79	29.63	48	29.09	291	.79	A	178' to 183' Cretaceous
10-05-602	DEAF SMITH #1	34 57 28	102 24 06	3,888	420	411	3,477	152	3,736	259	24,633	19.54	57	22.46	50	23.59	95	.94	C	
10-12-403	DEAF SMITH #2	34 49 30	102 36 10	3,952	240	230	3,722	195	3,757	35	2,100	15.00	50	25.61	50	25.61	60	.69	B	
05-49-605	DONLEY	35 10 57	100 54 25	3,195	640	620	2,575	310	2,885	310	68,534	15.00	56	20.07	49	29.54	221	.83	A	
23-05-101	FLOYD	33 57 45	101 28 45	3,223	426	425	2,798	187	3,036	238	17,278	14.17	51	29.97	46	26.80	73	.88	D	
27-26-402	GAINES #1	32 33 17	102 51 07	3,400	231	224	3,176	157	3,243	67	7,919	14.96	61	36.79	46	29.38	118	.92	B	
27-11-915	GAINES #2	32 46 35	102 38 22	3,324	121	98	3,226	--	--	0	--	--	--	--	--	--	--	--	--	No water encountered
05-26-408	GRAY	35 32 54	100 50 34	3,182	540	525	2,657	360	2,822	165	8,036	19.26	60	18.10	51	26.50	49	.92	C	
23-01-303	HALE	33 59 34	101 52 45	3,410	342	328	3,082	175	3,235	153	38,176	18.67	55	22.28	51	25.46	250	.94	A	
03-48-702	HANSFORD	36 15 37	101 05 35	3,076	680	662	2,414	345	2,731	317	200,987	18.85	47	7.61	50	13.18	634	.95	A	
07-10-501	HARTLEY #1	35 48 55	102 49 33	4,085	400	385	3,700	175	3,910	210	15,470	17.62	65	23.13	53	28.77	74	.81	B	
07-05-503	HARTLEY #2	35 55 29	102 25 10	3,928	500	462	3,466	375	3,553	87	52,179	18.60	40	16.68	50	27.05	600	.95	A	
05-15-401	HEMPHILL	35 47 37	100 14 11	2,560	380	330	2,230	143	2,417	187	50,878	18.40	59	19.64	50	28.51	272	.87	A	
24-29-311	HOCKLEY	33 35 44	102 24 35	3,540	204	178	3,362	146	3,394	32	704	15.00	50	0	50	0	22	.92	A	
03-61-705	HUTCHINSON	36 00 30	101 27 43	3,180	362	344	2,836	75	3,105	269	12,369	8.22	41	18.21	40	23.51	46	--	B	
10-54-504	LAMB	34 11 01	102 18 21	3,657	326	314	3,343	100	3,557	214	31,957	14.50	28	33.03	45	27.84	149	.95	B	
04-62-301	LIPSCOMB	36 05 53	101 16 35	2,682	535	440	2,242	118	2,564	322	47,877	15.08	53	25.11	52	30.80	149	.82	D	
24-40-203	LUBBOCK	33 28 35	102 03 10	3,320	210	206	3,114	141	3,179	65	47,970	17.00	50	0	50	0	738	.94	A	
23-42-304	LYNN	33 20 07	101 45 30	3,138	115	112	3,026	103	3,035	9	1,224	17.00	50	0	50	0	136	.95	A	
27-48-607	MARTIN	32 18 10	102 02 14	2,822	191	185	2,637	138	2,684	47	90,900	18.00	49	23.88	50	23.69	1,934	.93	A	
45-08-311	MIDLAND	31 59 41	102 02 10	2,748	91	70	2,678	63	2,685	7	315	10.00	50	0	50	0	45	.96	D	
07-16-304	MOORE	35 51 57	102 01 13	3,689	660	645	3,044	307	3,382	338	32,350	13.92	56	33.20	56	30.30	96	.87	--	430' to 650' Triassic
04-50-803	OCHILTREE	36 08 23	100 49 13	2,982	640	590	2,392	310	2,672	280	21,301	15.90	36	29.07	46	27.23	76	.83	A	
10-36-802	PARMER	34 23 00	102 33 06	3,886	372	366	3,520	218	3,668	148	19,515	16.78	37	28.27	47	27.85	132	.93	C	
06-35-601	POTTER	35 25 05	101 38 05	3,477	680	665	2,812	320	3,157	345	56,823	18.47	41	28.24	50	28.46	165	.83	A	
06-57-533	RANDALL	35 03 28	101 55 05	3,647	270	270	3,377	177	3,470	93	2,427	10.91	53	25.58	51	26.92	26	.92	B	
05-09-602	ROBERTS	35 49 28	100 54 40	2,942	480	468	2,474	120	2,822	348	25,156	14.03	39	28.05	55	29.67	72	.92	B	
03-50-201	SHERMAN	36 14 18	101 49 28	3,497	561	497	3,000	187	3,310	310	72,065	19.17	41	20.65	49	27.36	233	.88	A	
11-20-808	SWISHER	34 39 21	101 32 45	3,369	203	176	3,193	78	3,291	98	3,354	17.95	57	35.60	52	28.68	34	.94	B	
24-61-102	TERRY	33 05 38	102 27 47	3,371	115	97	3,274	--	--	0	--	--	--	--	--	--	--	--	--	No water encountered
25-64-302	YOAKUM	33 06 41	103 01 01	3,745	181	167	3,578	83	3,662	84	9,840	17.77	57	11.26	55	15.16	117	.88	C	

[1] Determined in saturated zone only.
[2] T = Transmissivity, Sy = Specific yield.
[3] Lithofacies type designations:
A-Fluvial channel
B-Interdistributary
C-Distributary mouth fan
D-Frontal fan slope

where

T = transmissivity of lithologic layer
D = distance from center of lithologic layer
to base of aquifer

The above value is then expressed as a percentage of the saturated thickness above the base of the aquifer by dividing it by the total saturated thickness and multiplying by 100:

$$\text{relative center of gravity in percent above base} = \frac{\text{center of gravity}}{\text{saturated thickness}} \text{ X } 100 \qquad (2)$$

The center of gravity or first moment of specific yield is calculated by substituting specific yield multiplied by bed thickness for transmissivity (T) in formula (1).

The second moment or standard deviation of transmissivity is determined by the following formula:

$$\text{standard deviation} = \left(\frac{\Sigma(TD)^2 - \left[\frac{(\Sigma TD)^2}{\Sigma T} \right]}{\Sigma T} \right)^{\frac{1}{2}} \qquad (3)$$

and

$$\text{relative standard deviation in percent of total section} = \frac{\text{standard deviation}}{\text{saturated thickness}} \text{ X } 100 \qquad (4)$$

The standard deviation or second moment of specific yield, likewise, is determined by substituting specific yield multiplied by bed thickness for transmissivity (T) in formula (3). Approximately 2/3 of the distribution will be within one standard deviation of the center of gravity.

A computer program which utilizes input values of permeability and storage coefficient (specific yield for water table aquifers) for each lithologic layer within the saturated zone was used to calculate the moments of transmissivity and specific yield. The program also calculates transmissivity, average permeability, and average specific yield for each hole.

To test the validity of the average specific yield and permeability values determined in this investigation, a comparison was made with values derived from independent studies made by Johnson (1967) for specific yield and by Morris and Johnson (1967) for permeability.

Specific yield and permeability values previously assigned to each lithologic layer in the moment computation procedure were replaced by values listed for various lithologies from the above references. A linearly decreasing correction factor based on the percent of clay in each lithologic layer was applied to the assigned values. The correction factor was determined from the natural gamma ray log that was used to measure the percentage of clay within each lithologic layer. Thus, if a layer consisted of 90 percent fine sand and 10 percent clay, a value that represents 90 percent of the maximum value for a fine grained sand would be assigned to that layer.

The average specific yield and permeability of each test hole using the corrected estimated values were then calculated. These average values were then summed and divided by the number of test holes to get an overall average value of specific yield and permeability. The comparison is as follows:

Specific Yield	High Plains test hole investigation	Modified From Johnson (1967)
Average of all test holes	16.06 %	17.38 %
Highest test hole average: Deaf Smith Co. #1 (10-05-602)	19.54 %	23.39 %
Lowest test hole average: Andrews Co. #2 (27-45-903)	7.23 %	7.68 %

	High Plains test hole investigation	Modified From Morris and Johnson (1967)
Average Permeability	232 gallons per day per square foot	398 (gal/d)/ft^2
	9,452 liters per day per square meter	16,215 (l/d)/m^2

Permeability versus depth for each test hole was plotted in an attempt to determine if permeability would increase with depth at a predictable rate as does median grain size over most of the study area. Graphs corresponding to selected test holes are shown in Appendix 2. Evaluations of the graphs indicate that there is no overall predictable slope to the plots. The explanation for this lack of trend probably lies in the mode of deposition of the Ogallala Formation. The initial deposits, composed of gravels and coarse sands and often intermixed with silts and clays, represent a high energy environment in which poor sorting, and thus retarded permeability, prevails. Sorting conditions generally improve upward in the formation along with decreasing grain size as a result of less energy involvement in deposition. It is the author's opinion that there is not an overall clear relationship between permeability and depth within the Ogallala Formation.

Vertical distribution of specific yield was also examined. The fact that the value of specific yield was found to have little variance throughout the saturated zone is reflected in the first moment and high second moment values shown in Table 3.

Results of lithologic, geophysical, and laboratory data analysis for each test hole are shown in Table 3.

Description of Ogallala Lithofacies

The primary environment of deposition was determined for the saturated zone (aquifer) of each test hole based on lithologic descriptions, characteristic geophysical log curves, and results of laboratory testing of samples. Average specific yield and permeability for each test hole were assigned to the corresponding environment of deposition of lithofacies determined for that test hole. These correlations were plotted as shown in Figure 3. Table 3 lists the type lithofacies assigned to each test hole.

Major and minor fluvial channel deposits were the most prevalent lithofacies encountered. They consist of fine to coarse sand and gravel with silt and clay matrix material often in abundance. A large D_{50} grain size and very poor sorting are characteristic of this lithofacies. The average specific yield ranges from approximately 15 to 19 percent with 80 percent of the characteristic test holes being in the 17 to 19 percent range. The fluvial channel lithofacies has a wide variance in average permeability as compared to the other lithofacies types (Figure 3). This wide variance is primarily influenced by the varying degree of sorting and amount of interstitial clay content.

The interdistributary lithofacies is characterized by fine sand, silt, and clay with small D_{50} grain size and poor sorting. Average specific yield ranges from approximately 8 to 18 percent. Average permeability is low, less than 150 (gal/d)/ft^2 (6,111 (l/d)/m^2), as a result of small grain size and poor sorting.

The frontal fan slope lithofacies contains sediments having characteristics similar to the interdistributary lithofacies. Average specific yield ranges from 10 to 15 percent, and average permeability is less than 150 (gal/d)/ft^2 (6,111 (l/d)/m^2).

The distributary mouth section of the alluvial fan consists of fine to coarse sand and silt with generally small D_{50} grain size and moderate to good sorting. This lithofacies has average specific yields ranging from 15 to 19.5 percent and an average permeability of less than 150 (gal/d)/ft^2 (6,111 (l/d)/m^2).

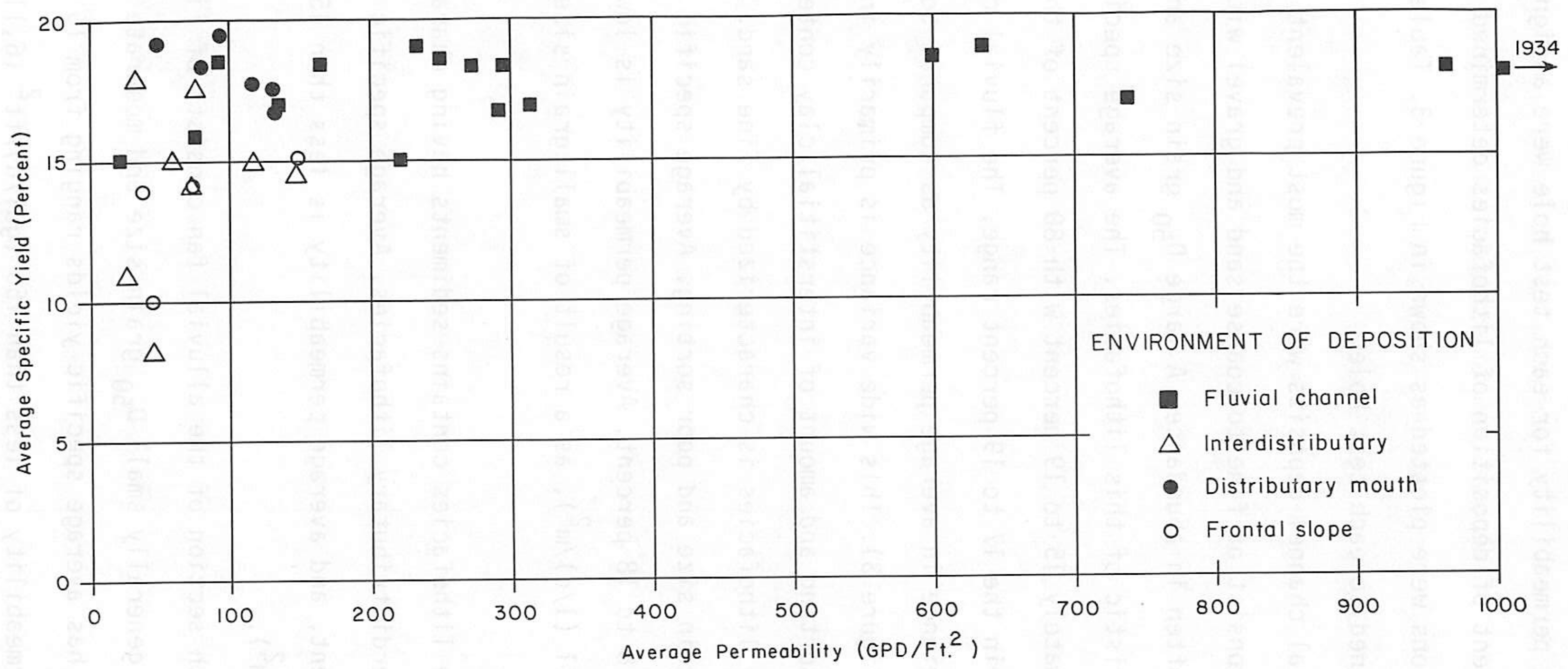

Figure 3

Distribution of Average Specific Yield and Permeability of the Four Lithofacies

Four of the test holes encountered primarily Cretaceous or Triassic water-bearing sands and therefore could not be included in the previously described lithofacies. These sand layers were generally thin and clayey and thus less productive.

SUMMARY

Forty-one test holes were drilled with the Department's modified Failing 1500 drilling rig (14,336 feet) in 36 counties of the Texas High Plains. Cores were analyzed to determine the following concerning the High Plains aquifer: (a) porosity and specific yield values; (b) permeability; (c) lithofacies; and (d) center of gravity and standard deviation of transmissivity and specific yield.

The core analysis, geophysical logging, and hydrogeological tests indicate that: transmissivities range from 315 to 200,987 gallons per day per foot (3,912 to 2,495,857 liters per day per meter); average permeabilities range from 22 to 1,934 gallons per day per square foot (896 to 78,791 liters per day per square meter) with an overall average of 232(gal/d)/ft^2(9,452 (l/d)/m^2); and the specific yield ranges from 7.23 to 19.54 percent with an overall average of 16.06 percent.

Center of gravity calculations concerning the transmissivity and specific yield parameters for the aquifer show that the center of gravity occurs about midway in the saturated interval, and the standard deviation indicates a lack of concentration about the center of gravity. Therefore, there does not appear to be any correlation between permeability and specific yield with depth. The results of these calculations for each test hole are shown on Table 3.

Four distinct lithofacies have been identified, and they consist of the following deposits: (a) fluvial channel; (b) interdistributary; (c) frontal fan slope; and (d) distributary mouth sediments. The fluvial channel and distributary mouth lithofacies have characteristically higher specific yields than the other lithofacies. Additionally, it has been noted that, due to a wide range of median grain size (D_{50}) and sorting values, the fluvial channel deposits have a much greater range of permeability (Figure 3) than the other lithofacies types.

LIMITATIONS AND RECOMMENDATIONS

Core analysis results obtained during this investigation were affected by the condition of the "undisturbed" core samples. The term "undisturbed" is relative and somewhat of a misnomer, since no sample is completely undisturbed. In an investigation of this type, it means a sample that has been recovered in such a manner that its physical structure and properties are unchanged from what they were in the ground.

Except for a few "undisturbed" sandstone cores, the large majority of cores were either unconsolidated or poorly consolidated, which resulted in their reaching the laboratory in a "disturbed" condition. An additional limited amount of disturbance of the samples occurred in the transporting of the specimens from the Texas High Plains to the Department's laboratory in Austin. This distortion and possible contamination of the samples may have affected the core analysis results.

Important to the moment calculations previously described is the knowledge of the change of the median grain size (D_{50}) and sorting with depth. Because only a limited number of core samples were obtained, drilling or cutting samples were taken at regular depth intervals and later subjected to mechanical analysis in order to predict the grain size and sorting changes with depth. The information gained from cuttings or drilling samples resulted in a somewhat dampened depth trend due to contamination of the sample from other horizons, drilling mud, and crushed gravels.

Future test holes in the High Plains aquifer should be cored from the historical water level depth to the base of the aquifer, and laboratory testing should be conducted on cores obtained at 5-foot intervals. This method would avoid the limitations imposed by the cutting samples and thus improve the overall reliability and coverage of test results.

Additional studies are needed to determine the extent of available ground water in the Cretaceous, Jurassic, and Triassic Formations below the Ogallala Formation. As ground water in the Ogallala is depleted, emphasis will be placed on alternate sources, and there is presently a lack of information concerning the water-bearing characteristics of these lower formations.

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APPENDIX 1

DESCRIPTIVE LOGS FOR SIX SELECTED TEST HOLES

CROSBY
23-21-304

	Depth (feet)		
Topsoil, dark sandy loam.	0	to	3
Clay, bluish grey.	3	to	10
Silt, white to greyish green, calcareous to silicious.	10	to	25
Caliche, white, hard, with minor amounts of pink, hard, fine to medium fine grained sandstone.	25	to	36
Caliche, white, silty, soft.	36	to	40
Silt and clay, pink.	40	to	46
Silt, pink to occasionally white.	46	to	58
Clay, red, silty.	58	to	72
Silt, red and white, clayey.	72	to	80
Silt, brown, and red, silty clay with occasional stringers of fine grained sand.	80	to	106
Clay, pink to red, sandy to shaley.	106	to	142
Clay, white, fine grained sandy.	142	to	146
Clay, brown, silty.	146	to	155
Sand, tan, fine grained to clayey, with a poorly sorted thin zone of brown clay at 193 feet.	155	to	220
Sand, brown, fine grained to clayey, poorly sorted, poorly consolidated, calcareous matrix, abundant white, limy nodules, with occasional thin stringers of red shale.	220	to	248
Sand, brown, medium to fine grained clear quartz grains, well rounded, moderately sorted, poorly consolidated, calcareous matrix, occasional scattered pebbles, with a fine grained, moderately cemented gravel and sand at 277 feet.	248	to	280

CROSBY 23-21-304
(Continued)

	Depth (feet)
Sand, brown, fine grained, well rounded, moderate to poorly sorted, silty matrix, poorly consolidated, calcareous matrix.	280 to 308
Clay, brown, silty, with minor amount of coarse grained sand and numerous white calcareous nodules.	308 to 310
Clay, brown, sandy.	310 to 322
Clay, reddish brown, sandy.	322 to 330
Sand, yellow and brown, fine grained to silty, poorly sorted, poorly consolidated.	330 to 338
Sand, yellow to brown, coarse to fine grained and medium gravel, very poorly sorted.	338 to 339
Sand, red, coarse to fine grained, rounded, poorly sorted, and medium to large gravel in a clayey matrix.	339 to 340
Clay, red, with grey, silty clay stringers.	340 to 360

GAINES
27-26-402

	Depth (feet)
Windblown sand.	0 to 2
Caliche, white, hard, with thin stringers of fine red sand.	2 to 10
Caliche, white, hard, and fine, red sand.	10 to 30
Sandstone, red and white, fine grained to silty.	30 to 120
Sandstone, maroon and white, fine grained, rounded, well to moderately sorted, silty matrix, firm calcareous cement.	120 to 130
Sandstone, white to brown, fine grained, very hard.	130 to 145
Sand, reddish brown, fine grained to silty.	145 to 160
Sand, reddish brown, fine grained clear quartz grains, well rounded, moderate to well sorted, calcareous matrix.	160 to 168
Sandstone, reddish brown, medium grained, well rounded, moderately sorted, numerous 1/8 inch multicolored, oblong, horizontally oriented grains, calcareous matrix, and red clay inclusions.	168 to 170
Silt, red, moderately sorted, clayey to sandy.	170 to 185
Sand, red, fine grained.	185 to 200
Sand, red, fine grained to silty, moderately sorted, calcareous matrix, with thin layer of fine gravel at 210.	200 to 210
Sand, red, fine grained, with white limestone, poorly sorted.	210 to 224
Limestone, white.	224 to 231

HANSFORD

03-48-702

	Depth (feet)
Topsoil, black.	0 to 2
Caliche, white to pink, hard.	2 to 4
Silt, reddish brown.	4 to 11
Caliche, tan.	11 to 20
Silt and fine sand, tan to white.	20 to 38
Caliche, white with red streaks, hard, with zones of silt and fine sand.	38 to 48
Sandstone, dark reddish brown, fine grained, moderately cemented and white, fine grained, well cemented; with streaks of tan, silty clay.	48 to 65
Sandstone, tan, fine grained, moderately cemented, with layers of tan, sandy clay and hard white caliche.	65 to 90
Sand, light reddish brown, fine grained to silty.	90 to 95
Sandstone, reddish brown to white, fine grained, moderately cemented.	95 to 112
Silt, tan to white, with layers of reddish brown and tan, fine grained sandstone.	112 to 130
Sandstone, reddish brown to tan, fine grained, moderately cemented, with occasional tan, silt layers.	130 to 140
Sand, tan with multicolored grains, medium to fine grained, unconsolidated, rounded to subangular.	140 to 160
Sand, tan, with clear, medium grained, well rounded grains and multicolored, coarse grained, subrounded to subangular grains; and a minor amount of tan, fine grained sandstone and small gravel.	160 to 200

HANSFORD 03-48-702
(Continued)

	Depth (feet)		
Sand, tan with multicolored grains, medium to coarse grained; and tan, fine grained, poorly cemented sandstone.	200	to	220
Sand, tan to white, fine grained to silty, with a minor amount of medium grains.	220	to	250
Sand, tan with clear and multicolored grains, medium to coarse grained and small gravel.	250	to	270
Sand, tan with multicolored grains, fine to coarse grained, with hard, white calcareous nodules; and tan, fine grained, poorly cemented sandstone.	270	to	300
Sand, tan with clear to multicolored grains, fine grained, well rounded, well sorted, unconsolidated.	300	to	305
Sand, tan with multicolored grains, fine to medium grained with minor amount of coarse grained, rounded to well rounded, moderate to poorly sorted, unconsolidated.	305	to	315
Sand, tan with multicolored grains, fine to medium coarse grained, with white limy nodules.	315	to	320
Sand, tan with multicolored grains, fine to coarse grained; and red silt to clay.	320	to	340
Sand, tan with multicolored grains, fine to coarse grained, poorly sorted.	340	to	360
Sand, brown, fine grained, poorly sorted, with minor amount of medium and coarse grained; and brown, sandy clay.	360	to	373
Sand, brown with multicolored grains, fine to coarse grained, poorly sorted.	373	to	380
Clay, yellow to brown.	380	to	381
Sand, brown, fine to coarse grained, well rounded, moderate to poorly sorted, unconsolidated; with a minor amount of small, rounded, flat gravel; two inch fine grained sandstone layer at 382 feet.	381	to	386

HANSFORD 03-48-702
(Continued)

	Depth (feet)
Sand, brown, fine grained with occasional thin medium to coarse grained layers, moderately sorted, poorly consolidated.	386 to 390
Sand, brown, fine to coarse grained, moderate to poorly sorted, occasional hard white limy streaks.	390 to 420
Sand, brown, medium to coarse grained, well rounded, very poorly sorted.	420 to 430
Sand, brown, fine to medium grained, moderately sorted, with occasional white limy streaks.	430 to 450
Sand, brown, fine to coarse grained, moderately sorted.	450 to 480
Sand, brown, very fine grained, well sorted, poorly consolidated.	480 to 482
Sand, brown, fine to medium fine grained, well rounded, moderately sorted, with occasional slightly cemented layers.	482 to 485
Sand, brown, fine to coarse grained with a minor amount of small gravel, rounded to subrounded, poorly sorted, unconsolidated, with occasional clay layers.	485 to 490
Sand, brown, medium to coarse grained, well to very poorly sorted, with a trace of red clay.	490 to 510
Sand, brown, fine grained with a minor amount of medium to coarse grained, moderately sorted.	510 to 520
Sand, brown, fine to coarse grained, moderate to poorly sorted, with zones of soft white lime.	520 to 540
Sand, brown, fine to medium grained; and pink silt.	540 to 550
Sand, brown, fine to medium grained, moderate to poorly sorted.	550 to 570
Sand, brown, fine to coarse grained, rounded, poorly sorted, unconsolidated.	570 to 572

HANSFORD 03-48-702
(Continued)

	Depth (feet)		
Sand, brown, fine to medium grained, rounded, moderately sorted, poorly to unconsolidated, with occasional thin, red, clay layers.	572	to	598
Sand, brown, fine to medium grained, moderate to poorly sorted, with red and white clay layers, and a trace of blue shale.	598	to	662
Shale, red; and very fine sand.	662	to	680

HARTLEY
07-05-503

	Depth (feet)		
Topsoil, dark brown, fine grained to silty sand.	0	to	4
Sand, light brown to yellowish brown, very fine grained to silty, with white clay streaks.	4	to	26
Sand, brown, medium to fine grained, with minor amount of small gravel.	26	to	34
Sand, brown to yellow, medium to fine grained, with streaks of grey silty clay.	34	to	54
Sandstone, white, fine to medium grained, with minor amount of white clay.	54	to	60
Sand, grey, fine grained, with sandstone and clay layers.	60	to	72
Sand, brown to yellow, fine grained with clay layers.	72	to	94
Gravel, multicolored, and sand, grey, medium to fine grained.	94	to	102
Sand, yellow to brown, fine grained to silty, with yellow clay layers.	102	to	138
Clay, yellow to brown, silty.	138	to	156
Sand, brown to yellow, fine grained.	156	to	165
Gravel, multicolored, and sand, medium to fine grained.	165	to	172
Sand, light brown, medium to fine grained, and multicolored gravel.	172	to	184
Gravel, multicolored, and medium to fine grained grey sand.	184	to	212
Sand, light red to yellow, fine grained to silty, with some yellow to grey clay and a few hard streaks.	212	to	260
Sand, pink to yellow, very fine grained to silty with some clay.	260	to	280

HARTELY 07-05-503
(Continued)

	Depth (feet)
Sand, red to yellow, fine grained to silty, and grey clay layers.	280 to 295
Sand, red to yellow, fine grained, and multicolored gravel.	295 to 305
Sand, yellowish brown, fine grained to silty, and grey clay, with some scattered gravel.	305 to 320
Sand, reddish brown, fine to medium grained, rounded, sorted, with some gravel.	320 to 324
Sand, reddish brown, fine grained, rounded, well sorted, minor amount of gravel.	324 to 350
Sand, yellow to reddish brown, medium to fine grained, rounded, sorted, poorly consolidated, with some gravel and lenses of brown to white clay and friable white sandstone.	350 to 360
Sand, tan to yellowish brown, fine grained with few gravel and clay lenses.	360 to 380
Sand, yellowish brown, medium to coarse grained, subrounded, moderate to very poorly sorted, and small to medium gravel.	380 to 410
Gravel, small to large, and medium to coarse, poorly sorted, yellow unconsolidated sand.	410 to 443
Sand, multicolored, medium coarse to medium grained, well rounded, moderately sorted, poorly to unconsolidated, with thin clay and silt lenses and some small gravel.	443 to 446
Sand, light brown, medium to fine grained, well rounded, moderately sorted, poorly to unconsolidated with few thin brown clay layers.	446 to 462
Clay, brown, sandy, with few dark brown shale layers.	462 to 482
Shale, red, brown, and bluish grey.	482 to 499

HEMPHILL
05-15-401

	Depth (feet)
Topsoil, brown, fine grained to silty.	0 to 6
Sand, pink, fine grained, with thin layers of hard, pink to grey sandstone.	6 to 30
Sand, pinkish tan, fine grained, with thin layers of fine, grained, white sand.	30 to 56
Clay, pinkish tan.	56 to 70
Silt, pinkish tan, with thin layers of white lime.	70 to 85
Clay, pinkish tan, silty.	85 to 95
Sand, multicolored grains, very coarse, rounded to subangular.	95 to 108
Sand, pinkish tan to grey, fine grained.	108 to 120
Sand, multicolored grains, very coarse grained.	120 to 145
Clay, pinkish tan, with layers of fine grained, grey sand.	145 to 160
Clay, reddish brown, sandy, with thin layers of reddish brown shale and light grey calcareous silt.	160 to 176
Sand, pinkish tan, fine grained, very poorly sorted, silty matrix.	176 to 189
Gravel and coarse grained sand, tan, poorly sorted, with thin layers of sandy silt.	189 to 200
Sand, tan, very fine grained.	200 to 210
Sand, tan with multicolored grains, medium to coarse grained, subrounded, well sorted, with zones of fine to medium grained sand.	210 to 220
Sand, tan, fine to medium grained, poorly sorted.	220 to 230

HEMPHILL 05-15-401
(Continued)

	Depth (feet)		
Sand, tan, medium to coarse grained, subrounded.	230	to	250
Gravel and multicolored, coarse grained sand, with thin layers of reddish brown clay.	250	to	260
Sand, tan, fine to medium grained, with thin layers of gravel.	260	to	270
Sand, tan, medium to coarse grained, subrounded, with thin layers of gravel and reddish brown clay.	270	to	287
Clay, reddish brown, with a minor amount of fine grained sand and white calcareous nodules.	287	to	294
Sand, reddish brown, fine to medium grained, rounded, moderately sorted.	294	to	300
Clay, reddish brown, sandy.	300	to	303
Sand, tan, fine to coarse grained, with thin gravel layers.	303	to	330
Clay, red; and fine grained sand, with greyish green and yellow sandy clay zones.	330	to	350
Sand, tan, fine grained, with layers of red clay.	350	to	360
Silt and fine grained sand, tan, with thin layers of red clay.	360	to	370
Clay, red, with a minor amount of fine grained sand.	370	to	380

PARMER
10-36-802

	Depth (feet)
Topsoil, dark brown, sandy loam.	0 to 3
Clay, tan to red, silty.	3 to 20
Silt, red, clayey.	20 to 34
Caliche, white; and red to brown silt.	34 to 38
Sand, red to tan, very fine grained, silty matrix, with cccasional caliche streaks.	38 to 67
Sandstone, white, fine grained, hard.	67 to 85
Sand, grey to pink, fine grained, silty to clayey matrix.	85 to 95
Sandstone, pinkish brown, fine grained.	95 to 125
Lime, white, sandy, with layers of brown, very fine grained sand.	125 to 140
Sand, brown, fine to very fine grained, moderately sorted, unconsolidated, with hard sandy lime nodules.	140 to 230
Sand, brown, fine grained, moderately sorted, limy matrix.	230 to 270
Sand, multicolored grains, medium to medium fine grained, moderately sorted.	270 to 300
Sand, brown, alternating layers of medium fine grained, well rounded, well sorted, unconsolidated; and fine to very fine grained, well rounded, moderately sorted, poorly consolidated, with mica flakes.	300 to 309
Sand, pinkish brown, fine grained, poorly sorted, clayey matrix.	309 to 330
Sand, multicolored grains, fine to medium grained, very poorly sorted.	330 to 340
Sand, multicolored grains, fine to coarse grained and small gravel, poorly to very poorly sorted.	340 to 362

PARMER 10-36-802
(Continued)

	Depth (feet)		
Sand, tan, fine to medium fine grained, well rounded, well sorted, unconsolidated.	362	to	366
Shale, red and light blue.	366	to	372

APPENDIX 2

GEOPHYSICAL LOGS AND LABORATORY DATA FOR SIX SELECTED TEST HOLES