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by

James J. Butler, Jr.
Wenzhi Liu
David P. Young

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Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726

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James J. Butler, Jr., Wenzhi Liu, and David P. Young
Kansas Geological Survey
1930 Constant Avenue
Lawrence, Ks. 66047

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ABSTRACT

A series of slug tests was performed by the Kansas Geological Survey at wells in Stafford, Pratt, and Reno counties in south central Kansas in October of 1993. These tests were designed to provide more information about the hydraulic conductivity of the Permian bedrock and the overlying Great Bend Prairie alluvial aquifer. Hydraulic conductivity estimates obtained from this series of tests ranged from 0.0037 to 0.139 ft/day for wells screened in the Permian bedrock. Estimates for wells screened in the Great Bend Prairie aquifer ranged from 7.8 to 88.1 ft/day. Both of these ranges are considered quite reasonable given the geology of the tested units. The range for the Permian bedrock is also in agreement with estimates obtained from an earlier series of slug tests performed for Groundwater Management District No. 5.

INTRODUCTION

A series of slug tests was performed by the Kansas Geological Survey (KGS) at wells in Stafford, Pratt, and Reno counties in south-central Kansas in October of 1993. This work was done as part of the Mineral Intrusion Project, a research effort directed at developing an understanding of the hydrologic, water-quality, and water-resources management implications of natural saltwater intrusion into the freshwater Great Bend Prairie aquifer in the eastern portion of Groundwater Management District No. 5 (GMD5) (Buddemeier et al., 1993). This project, which is funded by the Kansas Water Office, is being carried out by the KGS in collaboration with GMD5.

KGS personnel tested wells at five sites over the three county region. Figure 1 displays a map of the KGS/GMD5 monitoring-well network in this area. The sites at which slug tests were performed are designated with stars. At each of these sites, the Great Bend Prairie aquifer directly overlies Permian-age bedrock (Cedar Hills Sandstone and/or Salt Plain Formation), which is one source of the salt water that is intruding into the aquifer (Young, 1992). These particular sites were chosen for testing because 1) intrusion of salt water into the base of the Great Bend Prairie aquifer had been detected, 2) these wells appeared to be relatively well constructed according to the driller's logs, 3) these wells were free from obstructions, 4) natural gamma and focussed induction logs had been run at all of these sites, and 5) the Permian wells were clearly screened in the bedrock (top of the screen was at least ten feet

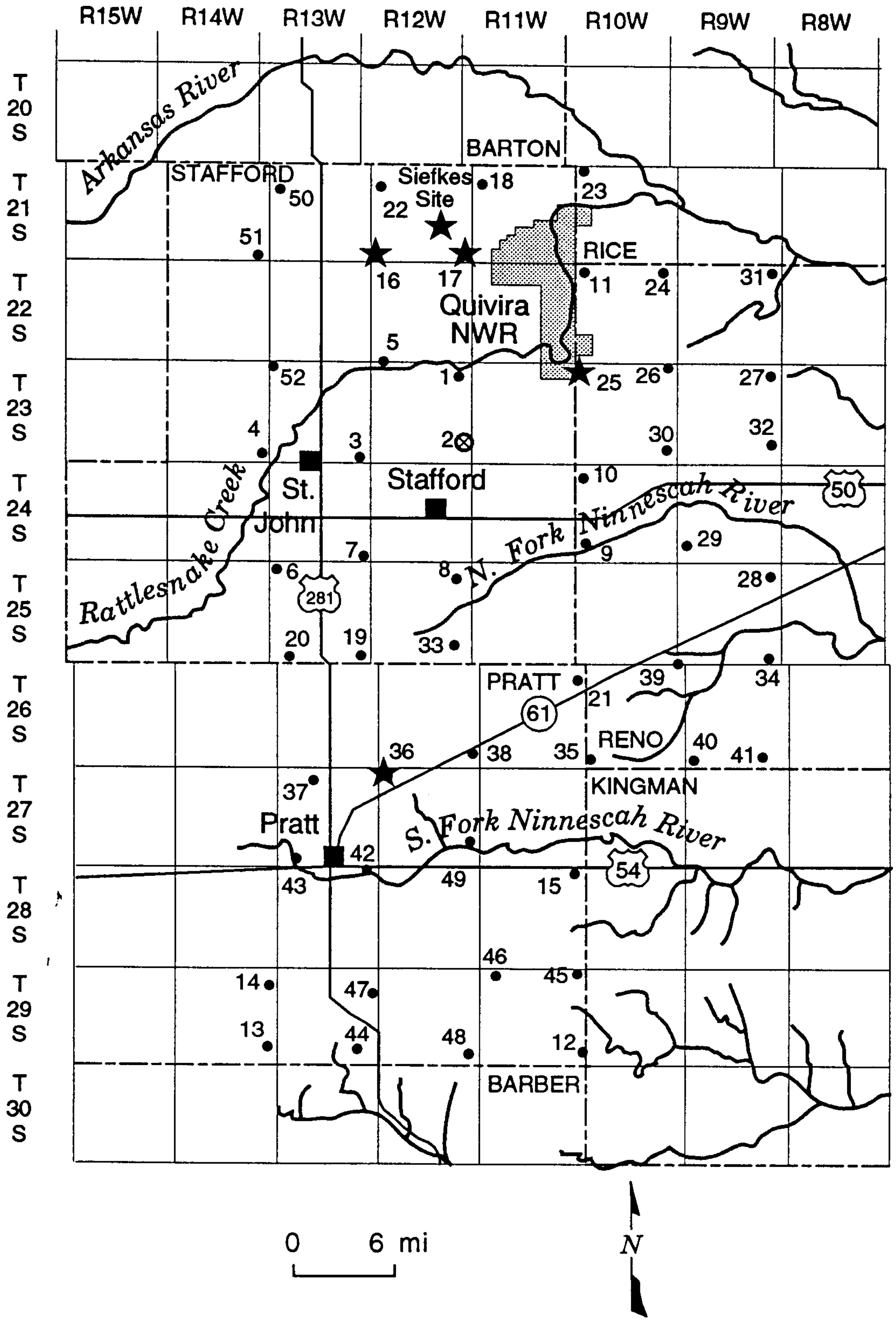


Figure 1. Slug-tested sites (★) in the KGS/GMD5 monitoring-well network.

into the bedrock according to the driller's logs).

METHODOLOGY

This series of tests was carried out following a recently defined set of guidelines for the performance and analysis of slug tests (Butler and McElwee, in preparation). These guidelines were the product of a KGS research effort directed at improving slug-test methodology. The guidelines of particular significance for this series of tests are 1) at least three slug tests should be performed at each well, 2) at least two different initial displacements (different sizes of slugs) should be used at each well during a series of tests, 3) the method used to initiate a test should allow a good estimate of the initial displacement to be obtained, and 4) data acquisition equipment that enables a large quantity of high-quality data to be collected should be employed.

The wells tested in this project included wells in the Permian bedrock and in the overlying Great Bend Prairie aquifer. Owing to the low hydraulic conductivity of the Permian bedrock, the KGS slug-test guidelines could not be strictly followed at all of the Permian wells. Specifically, only one slug test could be performed at sites 16 and 17 in Stafford County, and site 25 in Reno County because each test took on the order of days to complete. These wells will be retested in the spring of 1994 using a closed-hole slug-test approach (Bredehoeft and Papadopulos, 1980) that will greatly shorten test duration, thus allowing multiple tests to be performed at each well in a reasonable time frame.

In order to obtain a good estimate of the initial displacement in the wells screened in the permeable Great Bend Prairie aquifer, the KGS slug-test packer system was employed (Butler et al., 1990). This system involves use of an inflatable rubber packer mounted on a central pipe that can be opened or closed using a stopper attached to pump rods. The packer is placed below the static water level in the well and inflated, closing off the annular space between the outer diameter of the packer and the inner diameter of the well. The central pipe is closed and water is then added or removed from above the packer. This slug is then introduced into the screened portion of the well in a near instantaneous fashion by opening the central pipe. In all of the wells in which this system was used, water was removed and added from the well in a manner such that water from another source was not needed. In the low permeability Permian wells, the wells recovered slowly enough that the packer system was not deemed necessary. In most of these wells, the slug consisted of adding a small amount of water obtained from a nearby domestic well.

At all of the wells, changes in water level were initially measured using a pressure transducer (Instrumentation Northwest PS9000 series 0-30 psig transducer) connected to a data logger (Campbell Scientific 21X data logger). If the wells recovered very slowly, the transducer was removed from the well and an electric tape or a float recorder was used to measure further water-level changes.

The water-level data were analyzed using SUPRPUMP, an automated well-test analysis package developed at the Kansas Geological Survey (Bohling et al., 1990). SUPRPUMP obtains parameter estimates by comparing the measured data to theoretical models that are thought to closely resemble the test configuration. In this work, three theoretical models of slug tests in confined aquifers were employed. These models were 1) the model of Cooper et al. (1967) for slug tests in fully penetrating wells in confined aquifers, 2) the KGS model developed by Hyder et al. (in press) for slug tests in partially penetrating wells in confined aquifers, and 3) the model of McElwee et al. (in preparation) for slug tests in wells in confined aquifers where nonlinear phenomena (e.g., well losses and inertial effects) are of significance. In all cases, parameter estimation procedures followed the principle of parsimony, i.e. the simplest model (the model of Cooper et al. (1967) in this case) was initially used and more complex models were utilized only if the first model provided unsatisfactory results.

The primary parameter of interest in these tests was hydraulic conductivity. A considerable amount of research (e.g., Cooper et al., 1967; McElwee et al., 1989) has shown that single-well slug tests do not provide good estimates of specific storage. Thus, in most of the analyses reported here, specific storage was assumed known and given a value that appeared reasonable for the particular site. This procedure seemed appropriate since Papadopulos et al. (1973) have shown that errors of two orders of magnitude in specific storage will only produce small errors (<30%) in hydraulic conductivity.

Although the Great Bend Prairie aquifer would be classified as an unconfined aquifer, the theoretical models employed here were for slug tests in confined aquifers. The reason for use of these confined-aquifer models for the analysis of slug tests performed in an unconfined aquifer is that all the wells tested in this work were screened far below the water table. Recent work at the KGS (Hyder et al., in press; Hyder and Butler, in press) has shown that confined and unconfined models will behave exactly the same under these conditions. Thus, in order to minimize the number of theoretical models that needed to be considered, only the confined-aquifer models were employed here.

In general, the procedures outlined above produced values considered to be relatively good estimates of the in-situ hydraulic conductivity (should be within 20-30% of actual values in most cases). However, there were several sources of uncertainty that introduced error into the estimates. The most significant of these was the uncertainty concerning the appropriate well-construction parameters to use in the analyses. The well construction parameters of issue in this regard were the effective screen length and the effective screen radius. All of the tested wells were constructed by drilling a hole of larger diameter than the actual well casing and screen. The annulus between the outer diameter of the screen and the inner diameter of the drilled hole was filled with sand and gravel (henceforth designated the gravel pack). Cement or bentonite grout was then placed above the top of the gravel pack in order to prevent any fluid movement vertically along the annulus. The gravel pack extended several feet above the top of the screen in order to ensure that the grout did not move into the screened interval. In formations of moderate to low permeability (the Permian bedrock for this work), the gravel pack will be considerably more permeable than the formation itself. In this situation, the effective screen length should be the length of the gravel pack and the effective screen radius should be the radius of the gravel pack. In formations of high permeability, the contrast will be less dramatic so it is unclear exactly what values should be used for these parameters. In this work, the nominal screen length and the radius of the gravel pack were used as the effective screen length and radius, respectively, for wells screened in the Great Bend Prairie aquifer. However, further theoretical and field research is clearly required to get a better understanding of appropriate well construction parameters to use for wells sited in formations of high permeability.

A number of the tested wells were screened in intervals with waters of quite high salinity. Since the density and viscosity of these waters will be a function of the salinity, some thought was given to correcting all hydraulic conductivity estimates to a fresh-water equivalent. Laboratory data detailing viscosity and density changes as a function of sodium chloride concentration (Weast, 1976) indicate that the correction would always be less (much less in most cases) than 7% for waters at these sites. Given the other sources of error in the analysis procedure (e.g., estimation of specific storage and uncertainties concerning effective screen length and radius), this correction was not deemed necessary.

In the following sections, the test procedure and the subsequent analyses will be described in detail for each site.

STAFFORD COUNTY SITE 16

Stafford County site 16 consists of three wells, one in the Permian bedrock and two in the overlying Great Bend Prairie aquifer. Tables 1 and 2 provide well log and well construction information for this site.

Well #1

Well #1 is sited in the Permian bedrock. This well recovered so slowly from the slug-induced disturbance (in this case the addition of 3.69 ft of water to the well) that only one test could be performed during the test period. Figure 2 displays a head (relative to static, henceforth designated as relative head) versus time plot showing that the well still had not recovered after over 10,000 minutes into the test. Note that the plot displayed on Figure 2 is a combination of transducer readings, electric tape measurements, and measurements from a float recorder. The data were analyzed using the Cooper et al. model. Figure 3 displays the measured data and the best-fit Cooper et al. model in a normalized plot format (data normalized by the magnitude of the initial displacement (i.e. the size of the slug)). The parameter estimates obtained from the Cooper et al. model were .0101 ft/day and 4.25×10^{-6} ft^{-1} for hydraulic conductivity and specific storage, respectively. In this case, the specific storage was not assumed known for the analysis. Although a specific storage estimate was obtained as part of the analysis, this estimate can only be considered a rather rough approximation of the actual value

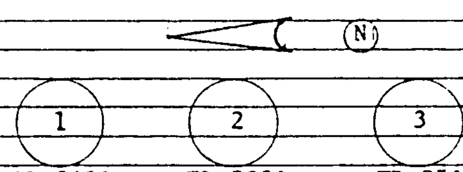
BIG BEND GMD#5-KGS
WATER QUALITY
OBSERVATION WELL
NETWORK

SITE NUMBER : 16 (KP1)
SITE LOCATION: SW SW SW

LEGAL LOCATION: 31-21-12W
COUNTY : STAFFORD

WELL LOG

FROM	TO	LITHOLOGIC LOG OWNER: FISCHER
0	5	sandy soil, yellow
5	8	sand, fine to coarse, qtz. arkosic; yellow clay
		matrix
8	9	stiff grey clay with fine sand
9	15	light grey clay with caliche nodules, silty
15	20	yellow-grey clay, silty; some fine sand and caliche
20	25	tan clay and pinkish-grey clay; some fine sand
		and trace of caliche
25	30	greenish grey clay, some pinkish-grey clay, silty
		with very fine sand, trace of caliche
30	35	light grey silty clay
35	45	med. to coarse sand, reddish tan clay matrix
45	50	fine qtz. arkosic sand with pinkish grey clay
50	70	med. to coarse sand, qtz. arkosic, with yellow-
		grey and light grey clay
70	75	fine to med. gravel; med. to coarse sand, qtz.
		arkosic; tan clay matrix
75	85	med. to fine gravel and med. to coarse sand;
		small amount of clay
85	140	coarse to med. sand, qtz. arkosic; some fine
		gravel; grey-green clay matrix
140	160	fine to coarse qtz. arkosic sand
160	165	greenish-grey silty clay
165	220	fine to med. qtz. arkosic gravel; greenish-grey
		clay stringers
220	248	red bed, sandy shale, red, fine to extra fine
		grained--PERMIAN



TD=248' TD=203' TD=85'
243'/5' 198'/5' 80'/5'

TABLE 1

Well No.	Borehole Radius[1]	Casing Radius (ESR)[2]	Total Depth	NSI (ESL)[3]	Gravel Pack Interval	Grout Interval
16-1	0.4115	0.2083 (0.4115)	248	243-248 (8)	240-248	0-10 90-240
16-2	0.4115	0.2083 (0.4115)	203	198-203 (5)	195-203	0-10 45-195
16-3	0.4115	0.2083 (0.4115)	85	80-85 (5)	77-85	0-10 30-77

1 - Units for information in this and remaining columns are ft.

2 - ESR - effective screen radius

3 - NSI - nominal screened interval

ESL - effective screen length

TABLE 2 - WELL CONSTRUCTION INFORMATION FOR STAFFORD COUNTY SITE 16

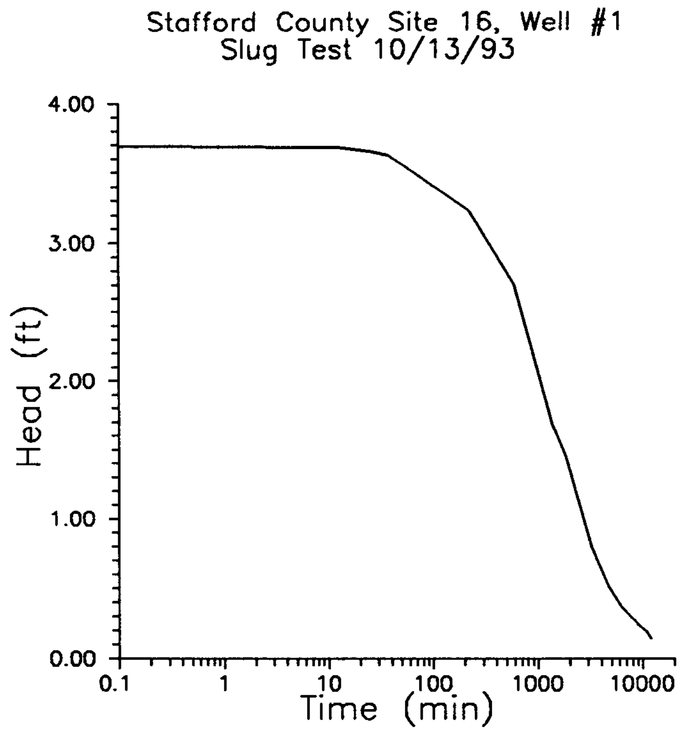


FIGURE 2

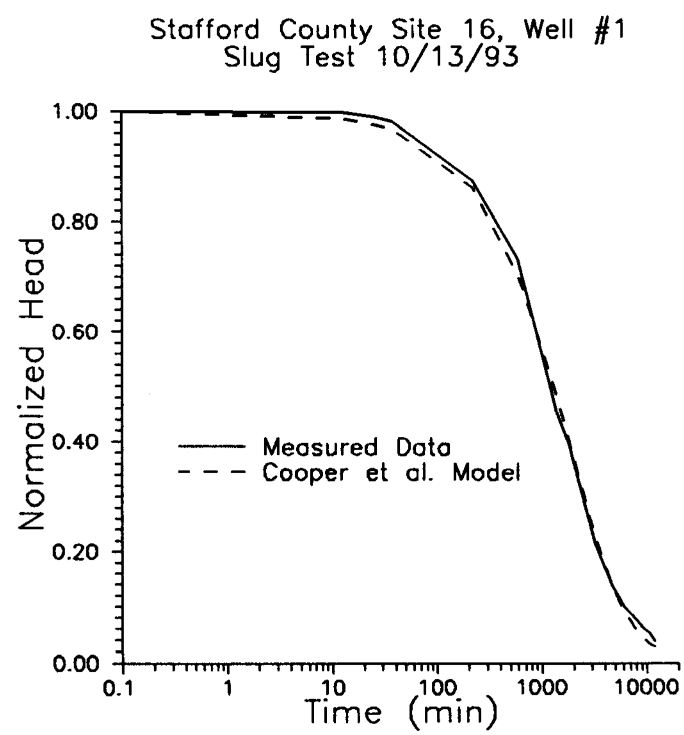


FIGURE 3

(McElwee et al., 1989). Note that the quality of the fit obtained with the Cooper et al. model suggests that there is a considerable degree of anisotropy in hydraulic conductivity in the Permian bedrock at this site.

Well #2

Well #2 is sited in the Great Bend Prairie aquifer. Since the well recovered quite rapidly from the slug-induced disturbance, three tests were performed at this site. Figure 4 is a relative head versus time plot of these three tests. Note that in this and later relative head versus time plots the time refers to the time since initiation of data collection and not the time since the start of the test. As shown in the figure, the first test was performed with an initial displacement of approximately one foot, the second test with a displacement approximately twice as large, while the third test employed the approximate displacement used in test 1. This cycling of low-high-low displacements was used in order to evaluate if the near-well portions of the formation were being altered during the series of tests and if there was any dependence of test duration on the magnitude of the initial displacement, two factors that are often overlooked during slug tests. Water was removed from the well to obtain the initial displacements used in the first two tests while a portion of that water was added back into the well for the final test. Note that water-level responses to a slug-induced disturbance in a confined aquifer should not be a function of whether the slug was induced by

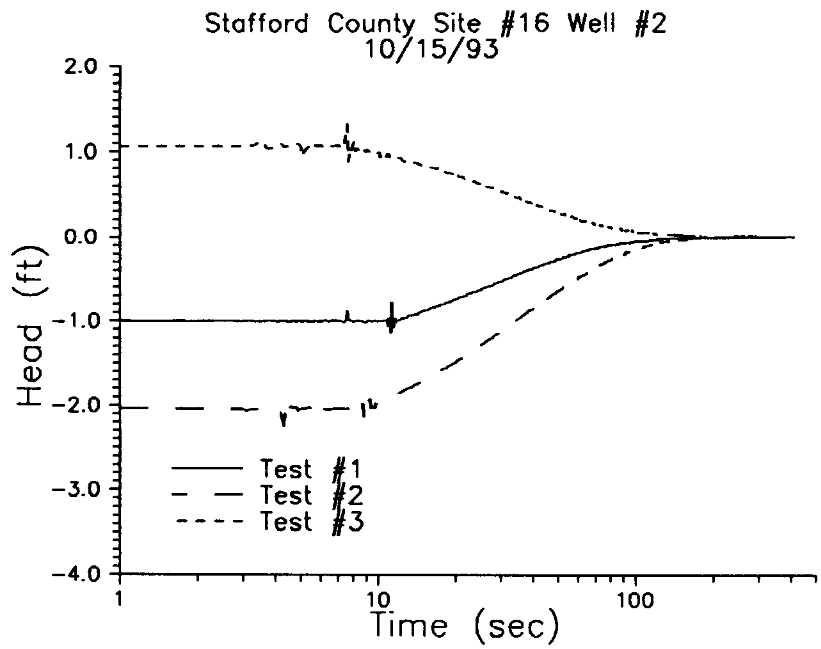


FIGURE 4

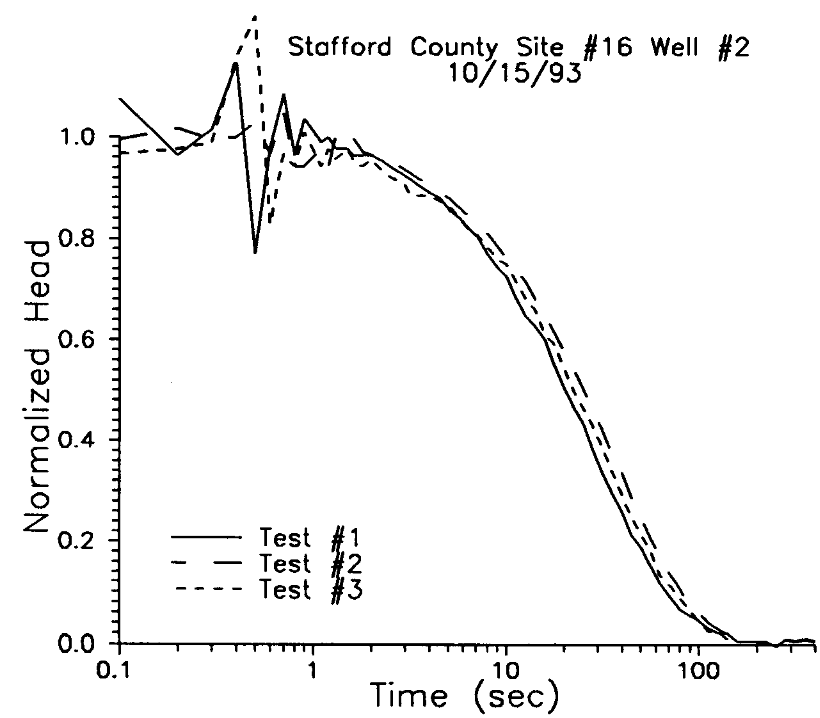


FIGURE 5

removing or adding water to the well.

A critical plot for any series of slug tests is the normalized head versus time plot, such as that shown in Figure 5. According to conventional theory, data from the three tests should fall ontop of one another when plotted in a normalized format. As shown in Figure 5, data from tests 2 and 3 are displaced to the right of the test 1 responses. This behavior indicates that the gravel pack or a portion of the formation near the screened interval is being altered during the course of testing. In this case, the responses of the later tests are slower than test 1. One possible explanation would be that some fine material is being mobilized by the introduction of the slug and is moving in a manner that produces a decrease in the permeability of the formation. The pattern seen with the slug tests at this well is an indication that further well development might be of use.

Although it was not possible to confirm with this series of tests, we assumed that test 1 was reflective of in-situ conditions and attempted to analyze data from this test using the Cooper et al. model. Figure 6 displays the measured data and the best-fit Cooper et al. model (estimated hydraulic conductivity of 74.8 ft/day assuming a specific storage of 1.00×10^{-6} ft^{-1}). The fluctuations at early times are water-hammer effects related to the introduction of the slug using the KGS packer system. Earlier work (Butler and McElwee, 1992) has shown that these effects are only significant for the first few seconds of a test and thus should be ignored for all practical purposes. Note that the best-fit Cooper

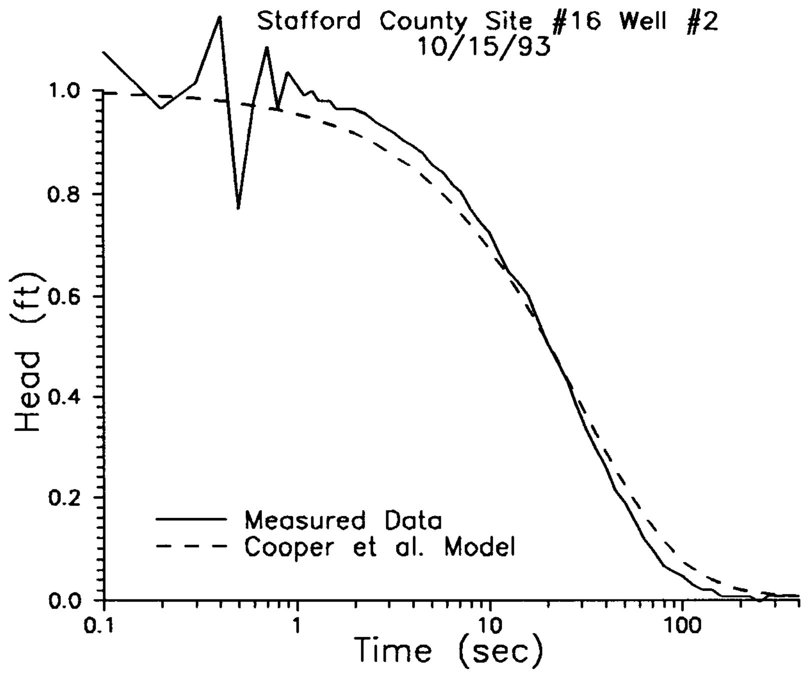


FIGURE 6

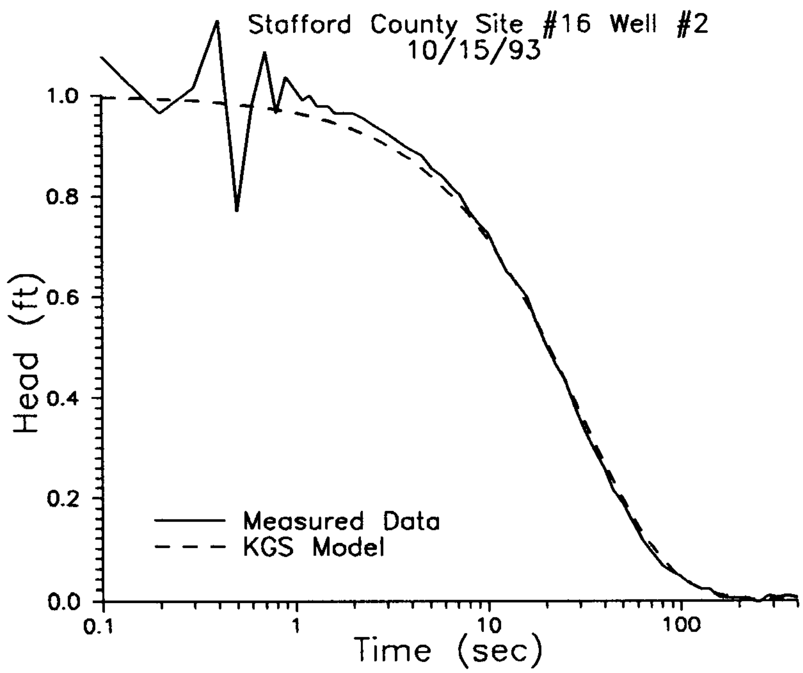


FIGURE 7

et al. model underpredicts the response at early time and overpredicts the response at late times. Since the aspect ratio (effective screen length/effective screen radius) is only 12.2, the systematic deviation between the measured data and the best-fit model is most likely produced by a significant component of vertical flow (vertical flow not considered in Cooper et al. model). The KGS model was therefore applied to the data in order to account for the vertical flow. Although the KGS model does incorporate anisotropy in hydraulic conductivity, isotropy was assumed for this analysis. Figure 7 displays the measured data and the best-fit KGS model. Note that the fit is considerably better than that obtained with the Cooper et al. model. The hydraulic conductivity estimate obtained from the KGS model was 31.6 ft/day (assuming a specific storage of 1.00×10^{-6} ft^{-1}). The deviation between the best-fit model and the measurements was most likely produced by an error in the assumed values for the effective screen length and/or radius. However, the deviation is so small that further exploration of this difference was not attempted.

Although it is extremely difficult to obtain good estimates of formation anisotropy from a single slug test, the results of the analyses of test 1 indicate that anisotropy is rather small for the portion of the formation near the screened interval. Thus, the clay stringers noted on the well log (see Table 1) for this interval are apparently not numerous enough to impart significant anisotropy to the formation on the scale of a slug test. Note that the hydraulic conductivity estimate of the Cooper et al. model is

2.37 times larger than the KGS model estimate. This is a dramatic illustration of how a failure to recognize the inappropriateness of a particular model can introduce a large amount of error into the estimated parameters. It is important to realize that the isotropic version of the KGS model has only two parameters (hydraulic conductivity and specific storage). Thus, the dramatic improvement in model fit obtained through use of the KGS model was not accompanied by an increase in the number of estimated parameters.

Well #3

Well #3 is also sited in the Great Bend Prairie aquifer. As with well #2, three tests were performed at this well. Figure 8 is a relative head versus time plot of these three tests. A normalized relative head versus time plot for this series of tests is given in Figure 9. Note that, as predicted by conventional theory, the data from the three tests essentially fall ontop of one another when plotted in a normalized format. This indicates that the formation is not being altered during the course of testing, that the test duration is independent of the magnitude of the initial displacement, and that the water-level responses are independent of whether the slug was induced by removing or adding water from/to the well.

Test 2 was selected as the test to use for analysis because of the smaller water-hammer effects recorded in this test. Figure 10 displays the measured data and the best-fit Cooper et al. model

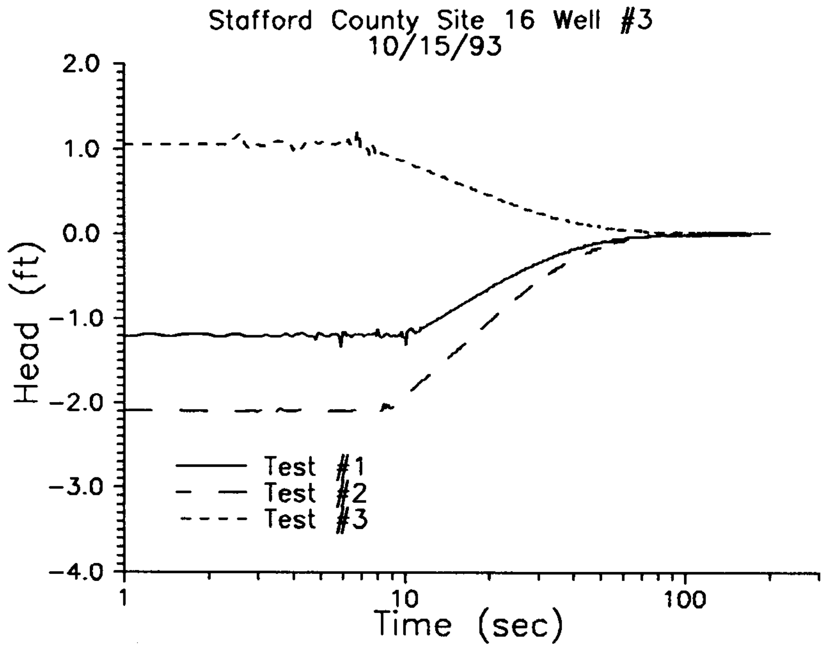


FIGURE 8

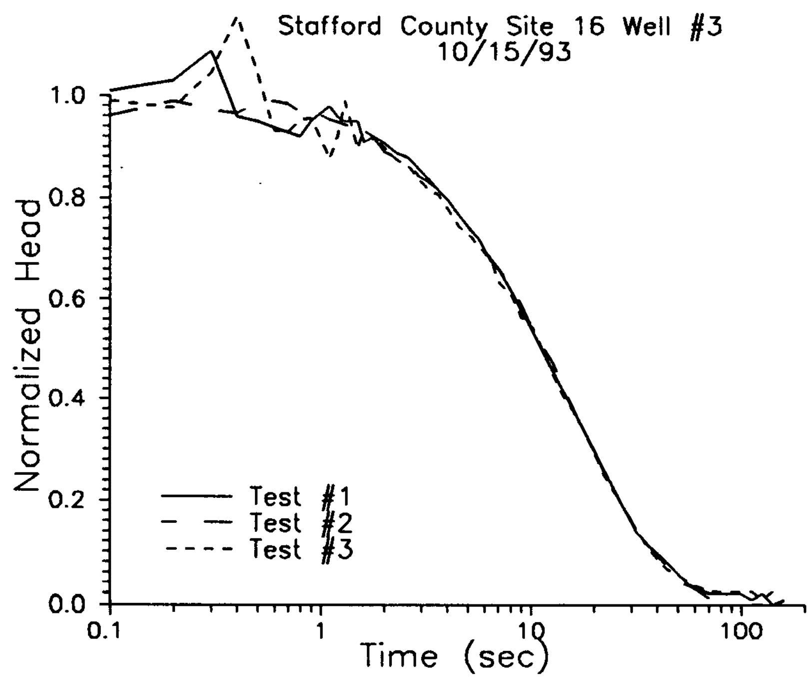


FIGURE 9

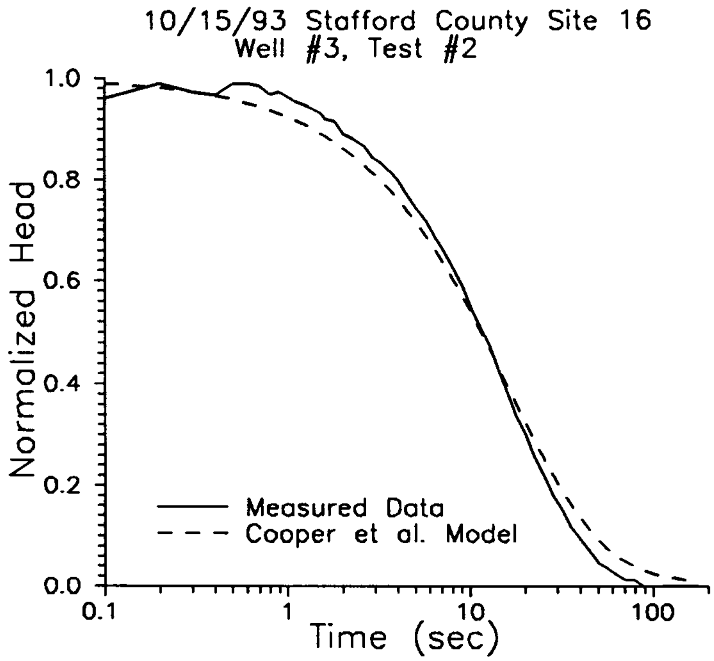


FIGURE 10

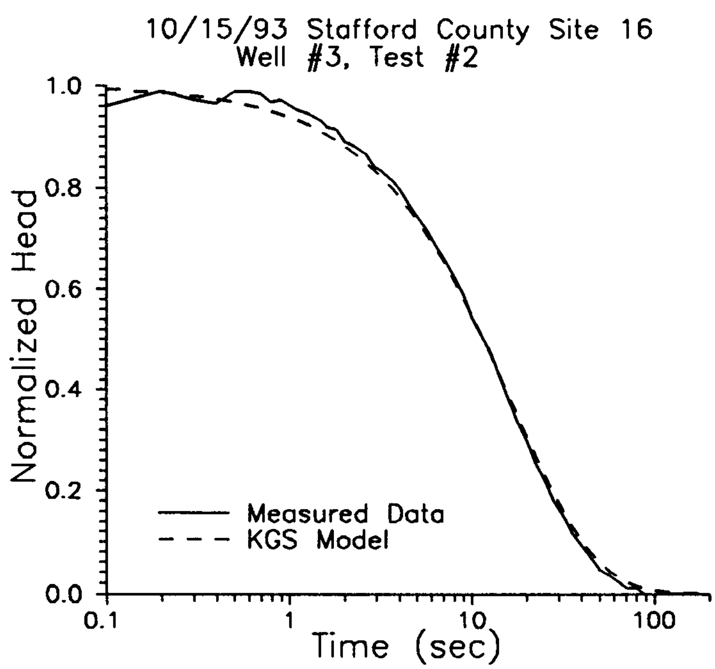


FIGURE 11

(estimated hydraulic conductivity of 135.3 ft/day assuming a specific storage of 1.00×10^{-6} ft^{-1}). Again, note the systematic deviation between the measured data and the best-fit model. Since the aspect ratio of well #3 was also 12.2, the KGS model was selected for further analysis. Figure 11 displays the measured data and the best-fit KGS model for this test. Note that the fit is considerably better than that found with the Cooper et al. model. The hydraulic conductivity estimate obtained from the KGS model was 56.8 ft/day (assuming a specific storage of 1.00×10^{-6} ft^{-1}). The deviation between the best-fit model and the measurements again is so small that further exploration of this difference was not attempted. As with well #2, the results of the analyses of the tests at well #3 indicate that anisotropy is rather small for the portion of the formation near the screened interval. The hydraulic conductivity estimate provided by the Cooper et al. model was 2.38 times larger than the KGS model estimate, a ratio very close to that seen with well #2. Thus, the formation in the vicinity of both wells appears to exhibit approximately the same degree of anisotropy.

STAFFORD COUNTY SITE 17

Stafford County site 17 consists of three wells, one in the Permian bedrock and two in the overlying Great Bend Prairie aquifer. Tables 3 and 4 provide well log and well construction information for this site. Only well #1, screened in the Permian bedrock, was tested as part of this work.

Well #1

Well #1 is sited in the Permian bedrock. This well recovered so slowly from the slug-induced disturbance (in this case the addition of 3.69 ft of water to the well) that only one test could be performed during the test period. Figure 12 displays a relative head versus time plot of the test data. Note that the plot displayed on Figure 12 is a combination of transducer readings, electric tape measurements, and measurements from a float recorder. Unfortunately, a problem with the float recorder resulted in the loss of data from the late portions of the test. The available data were first analyzed using the Cooper et al. model. Figure 13 displays the measured data and the best-fit Cooper et al. model (estimated hydraulic conductivity of 0.0072 ft/day assuming a specific storage of 1.00×10^{-6} ft^{-1}). Although data from the late portion of the test are not available, it is clear that there is the same systematic deviation between measured data and the Cooper et al. model as seen in the analyses described earlier. Figure 14 displays the measured data and the best-fit KGS model. As with the earlier analyses, the application of the KGS model significantly improves the quality of the fit. The hydraulic conductivity estimate obtained from the KGS model was .0037 ft/day (assuming a specific storage of 1.00×10^{-6} ft^{-1}). Note that the hydraulic conductivity estimate from the Cooper et al. model (.0072 ft/day) was 1.94 times greater than the KGS estimate.

BIG BEND GMD#5-KGS
WATER QUALITY
OBSERVATION WELL
NETWORK

SITE NUMBER : 17(KP2)
SITE LOCATION: ~~SE~~ SE SE
SW

LEGAL LOCATION: 36-21-12W
COUNTY : STAFFORD

WELL LOG

FROM	TO	LITHOLOGIC LOG OWNER: SAYLER/SITTNER
0	2	topsoil
2	40	clay; some caliche
40	95	gravel, qtz. arkose; clay matrix, tan
95	97	clay
97	105	gravel, qtz. arkose
105	114	clay, tan with fine sand
114	134	siltstone, red PERMIAN

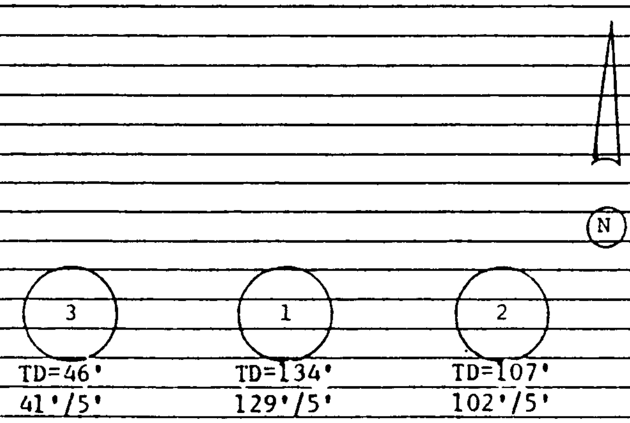


TABLE 3

Well No.	Borehole Radius[1]	Casing Radius (ESR)[2]	Total Depth	NSI (ESL)[3]	Gravel Pack Interval	Grout Interval
17-1	0.4115	0.2083 (0.4115)	134	129-134 (8)	126-134	0-10 40-126

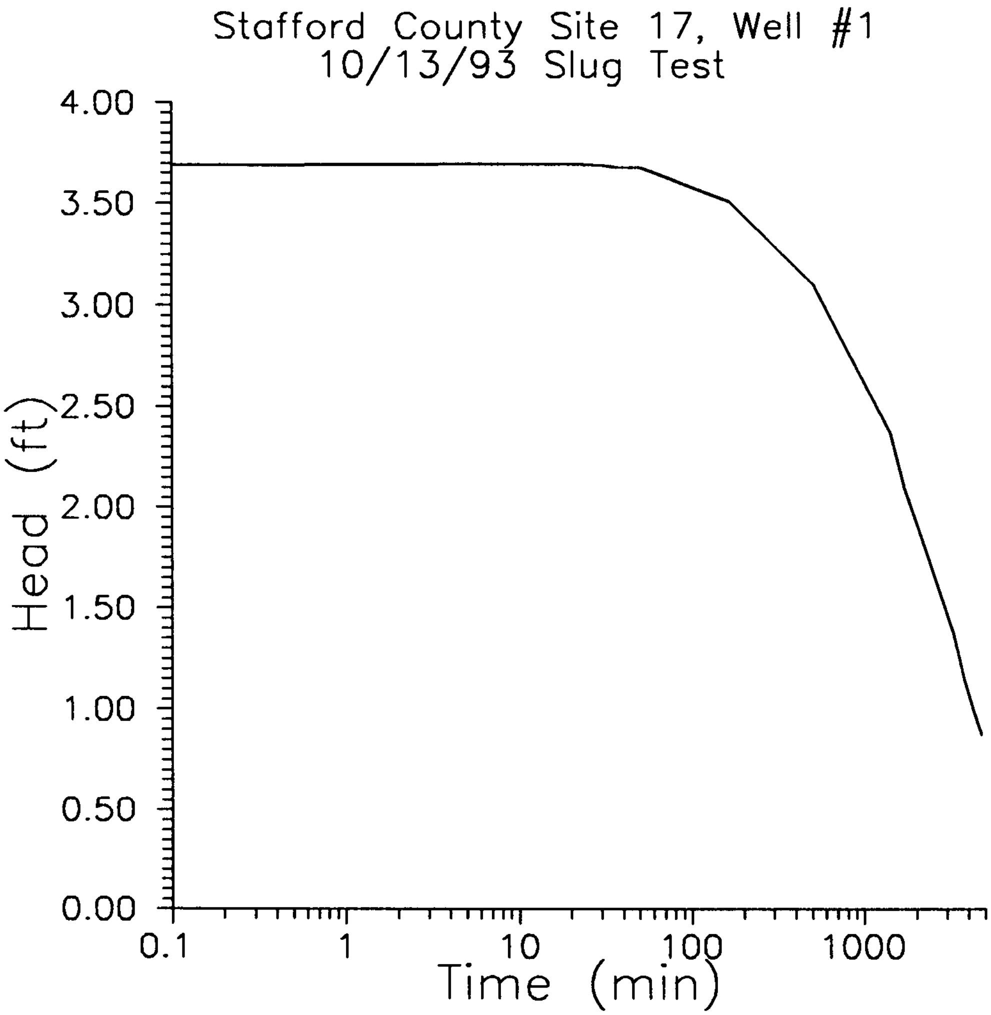
1 - Units for information in this and remaining columns are ft.

2 - ESR - effective screen radius

3 - NSI - nominal screened interval

ESL - effective screen length

TABLE 4 - WELL CONSTRUCTION INFORMATION FOR STAFFORD COUNTY SITE 17



Stafford County Site 17, Well #1
10/13/93 Slug Test
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Head (ft)
0.1
1
10
100
1000
Time (min)

FIGURE 12

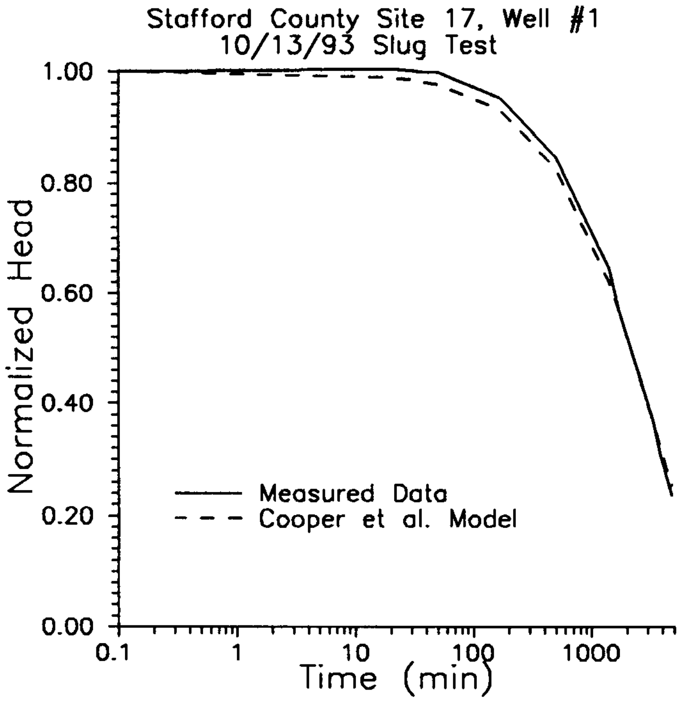


FIGURE 13

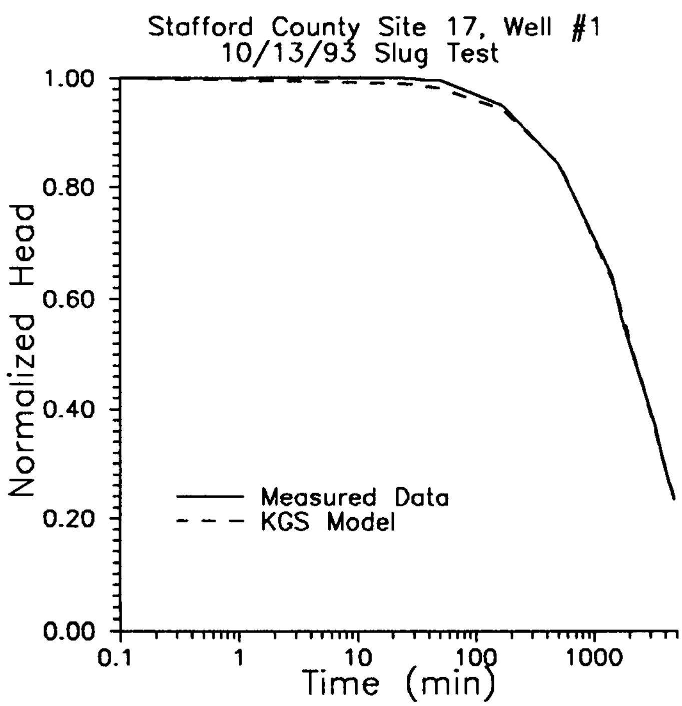


FIGURE 14

SIEFKES SITE

The Siefkes site consists of two wells, one screened in the Permian bedrock and one screened in the Great Bend Prairie aquifer. Tables 5 and 6 provide well log and well construction information for this site. Only the well screened in the Permian bedrock was tested as part of this work. The well sited in the Great Bend Prairie aquifer was not tested because of the nonstandard well diameter (wells were 3 inches in diameter) used at the Siefkes site. The use of this nonstandard well diameter presented problems because the KGS currently does not have a packer system for testing 3" ID wells screened in material of high permeability. Since the aquifer well recovered very rapidly, other easily implemented methods of slug-test initiation (e.g., pouring water down the well) would not allow a good estimate of the initial displacement to be obtained. Thus, testing of the Great Bend Prairie aquifer well at this site was postponed until the spring of 1994 when appropriate equipment could be constructed.

Permian Well

Unlike the Permian wells at Stafford sites 16 and 17, the recovery of the Siefkes well was rapid enough to allow three tests to be performed over a two day period. Figure 15 displays a relative head versus time plot for this series of tests (rising limb on plot indicates water being poured into the well to initiate test). The maximum initial displacement for these three tests was 10.05 feet. Figure 16 displays a normalized relative head versus time plot. Although there are some unexplained deviations in the late portions of the tests, the data from the three tests essentially fall ontop of one another.

Figure 17 displays the measured data and the best-fit Cooper et al. model for test #1 (estimated hydraulic conductivity of 0.158 ft/day assuming a specific storage of $1.00x10^{-6}$ ft^{-1}). Note that a systematic deviation between the measured data and the best-fit Cooper et al. model is again observed, although the degree of deviation is less dramatic than seen earlier. The less dramatic deviation is primarily a function of the aspect ratio. In this case, the aspect ratio is 248, a considerably larger ratio than that seen in the earlier wells. Figure 18 displays the measured data and the best-fit KGS model. The difference between the measured data and the best-fit model is quite small. The hydraulic conductivity estimate obtained from the KGS model was .139 ft/day (assuming a specific storage of $1.00x10^{-6}$ ft^{-1}). Note that the hydraulic conductivity estimate from the Cooper et al. model (.158 ft/day) was only 1.14 times greater than the KGS estimate. As shown in Hyder et al. (in press), the small difference between the hydraulic conductivity estimates obtained from the two models is a direct result of the larger aspect ratio (i.e. vertical flow effects are less important at this ratio).

KGS MONITORING WELL
SIEFKES SITE
PERMIAN WELL

LOCATION: SW SW NE SE Sec. 27 21-12 COUNTY: STAFFORD

WELL LOG

FROM	TO	LITHOLOGIC LOG
0	7	brown sandy loam
7	17.5	red sandy clay
17.5	24	light gray sandy clay
24	35	interbedded red medium sand and clay
35	37	caliche
37	51	light brown sandy clay
51	52.5	caliche
52.5	86	interbedded red coarse sand and light gray clay
86	121	coarse red sand with minor limestone fragments
121	124	dark gray clay
124	130	coarse red sand
130	137	dark gray clay
137	166	coarse red sand and gravel; minor dark gray clay
166	186	light brown silty clay
186	200	PERMIAN-red silty clay and siltstone
200	203	core loss-probably siltstone or very fine sandstone
203	203.5	moderate reddish-brown muddy siltstone
203.5	204	light gray siltstone
204	207.5	moderate reddish-brown muddy siltstone
207.5	213	core loss-probably siltstone or very fine sandstone
213	223.5	moderate reddish-brown muddy siltstone
223.5	225.5	moderate reddish-brown very fine sandstone
225.5	226.5	moderate reddish-brown muddy siltstone

TABLE 5

Well No.	Borehole Radius[1]	Casing Radius (ESR)[2]	Total Depth	NSI (ESL)[3]	Gravel Pack Interval	Grout Interval
SIEF	0.1208	0.1250 (0.1208)	227	197-227 (30)	none	0-197

1 - Units for information in this and remaining columns are ft.

2 - ESR - effective screen radius

3 - NSI - nominal screened interval

ESL - effective screen length

TABLE 6 - WELL CONSTRUCTION INFORMATION FOR SIEFKES SITE

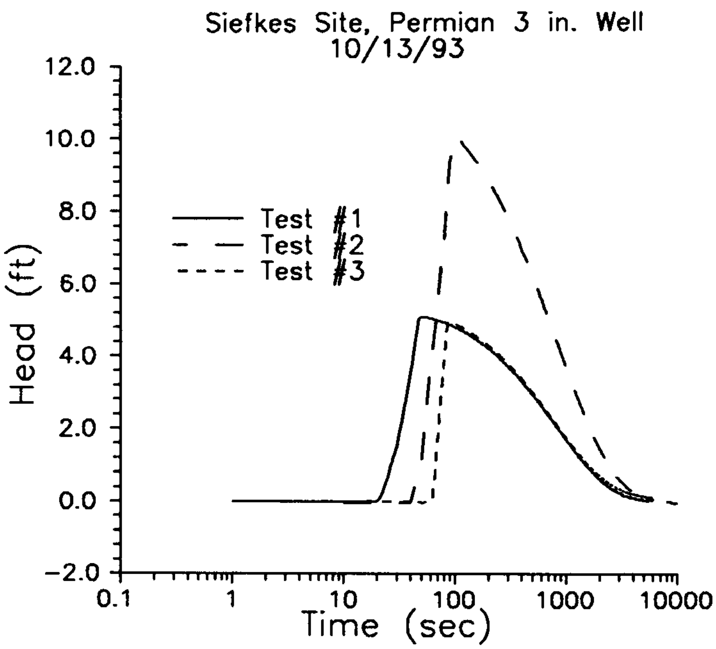


FIGURE 15

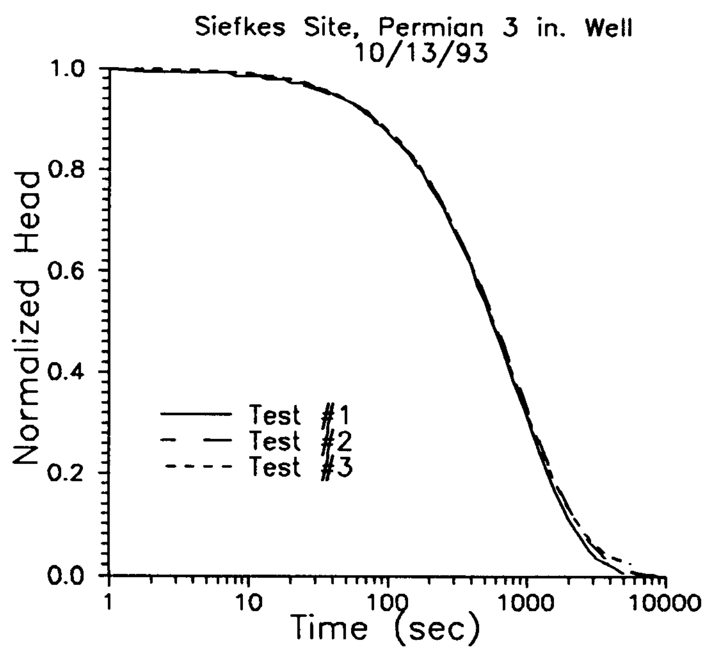


FIGURE 16

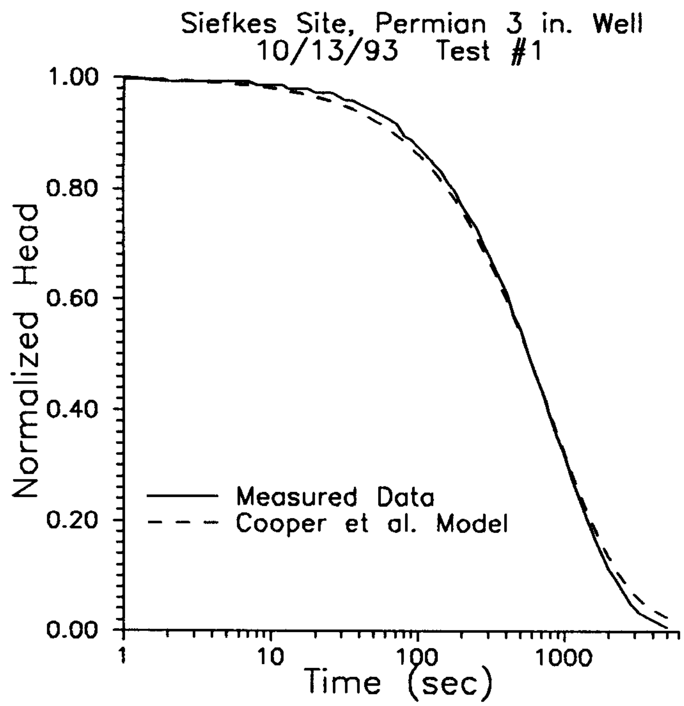


FIGURE 17

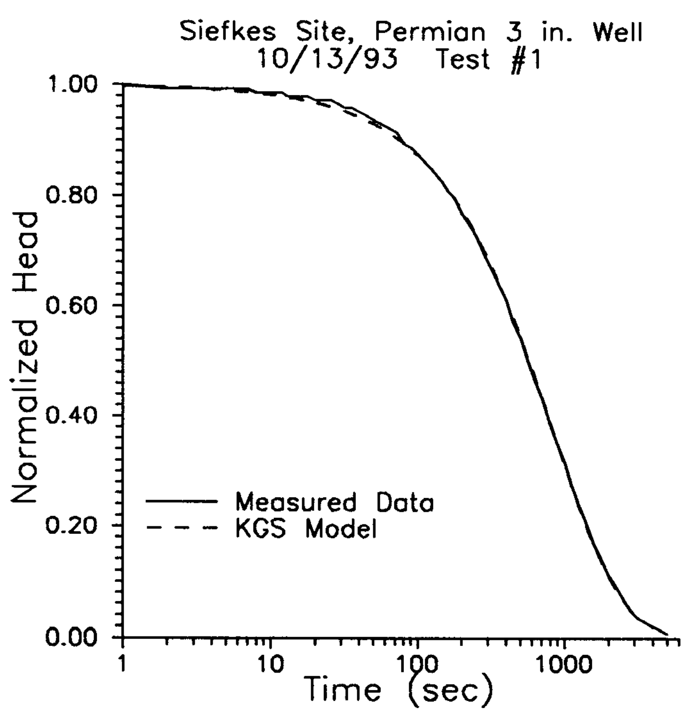


FIGURE 18

PRATT COUNTY SITE 36

Pratt County site 36 consists of four wells, one in the Permian bedrock and three in the overlying Great Bend Prairie aquifer. Tables 7 and 8 provide well log and well construction information for this site.

Well #1

Well #1 is sited in the Permian bedrock. This well recovered the fastest of all the Permian wells, so three tests were performed. Figure 19 displays a relative head versus time plot for this series of tests. The normalized relative head versus time plot for these tests is shown in Figure 20. Note that the responses from the three tests do not fall ontop of one another when plotted in a normalized format. The nature of the deviations between the various tests seen on the normalized plot cannot be readily explained. Based on conversations with KGS personnel responsible for well development at this site, we strongly suspect that there is a problem with the integrity of the well casing.

Although we do not have confidence that the measured responses are reflective of conditions in the Permian bedrock at this site, we did attempt to analyze the data from test #1. Figure 21 displays a plot of the measured data and the best-fit Cooper et al. model. Note that there is a large difference between the best-fit model and measurements in the late portions of the test. This deviation cannot be readily explained. It is possible that a portion of the deviation could be a result of fracturing in the

BIG BEND GMD#5-KGS
WATER QUALITY
OBSERVATION WELL
NETWORK

SITE NUMBER : 36 (KP11)
SITE LOCATION: NE NE NW

LEGAL LOCATION: 6-27-12W
COUNTY : PRATT

WELL LOG

FROM	TO	LITHOLOGIC LOG OWNER: BRIGGEMANN/McFADDEN
0	7	light brown sandy loam, little clay
7	18	light brown sandy clay with minor streaks of fine to medium sand
18	22	fine to medium sand with some clay streaks
22	28	light reddish-brown clay, little sand, some silt some lime layers
28	31	light reddish-brown sandy clay, sticky drilling
31	37	sand interbedded with sandy clay
37	41	small gravel layers at 37'; continuation of sand interbedded with sandy clay
41	45	lime layers interbedded with clay, light grey-brown color, slightly sandy
45	51	light grey-brown sandy clay, small sand layers, increase in sand with depth
51	72	sand and gravel, fine to coarse grained
72	74	light red-brown sandy clay
74	89	sand with some clay streaks and gravel, sand is fine to medium grained
89	92	light grey-brown sandy clay
92	112	light grey-brown clay interbedded with lime; clay is sandy but very gummy--slow drilling
112	113	sand, fine grained
113	116	light grey-brown sandy clay and limestone
116	129	sand interbedded with limestone at top, grading into sand and gravel
129	130	brown clay, very sticky, no sand, little silt
130	135	sand and gravel
135	138	sticky clay
138	149	sand and gravel
149	152	silty, slightly sandy clay, light brown color
152	187	sand and gravel
187	188	reddish clay
188	190	red shale
190	195	sand and gravel
195	215	red shale--PERMIAN

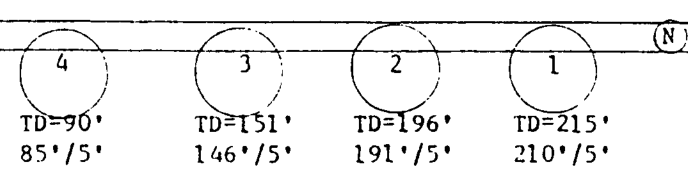


TABLE 7

Well No.	Borehole Radius[1]	Casing Radius (ESR)[2]	Total Depth	NSI (ESL)[3]	Gravel Pack Interval	Grout Interval
36-1	0.4115	0.2083 (0.4115)	215	210-215 (12)	203-215	143-203
36-2	0.4115	0.2083 (0.4115)	196	191-196 (5)	176-196	137-176
36-2	0.4115	0.2083 (0.4115)	151	146-151 (5)	127-151	91-127
36-4	0.4115	0.2083 (0.4115)	90	85-90 (5-12)	78-90	68-78

1 - Units for information in this and remaining columns are ft.

2 - ESR - effective screen radius

3 - NSI - nominal screened interval

ESL - effective screen length

TABLE 8 - WELL CONSTRUCTION INFORMATION FOR PRATT COUNTY SITE 36

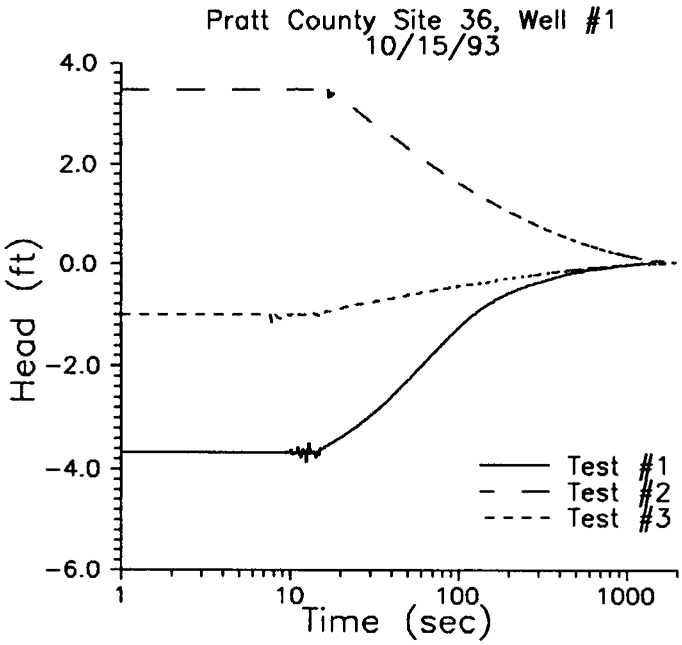


FIGURE 19

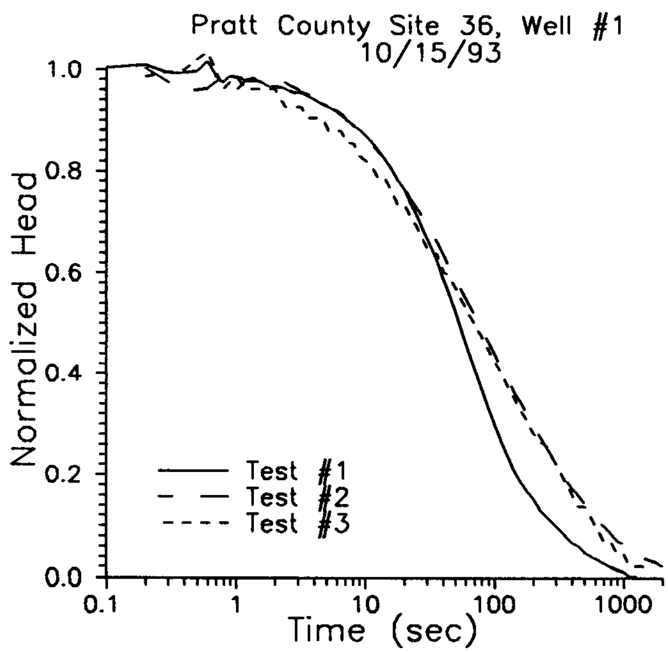


FIGURE 20

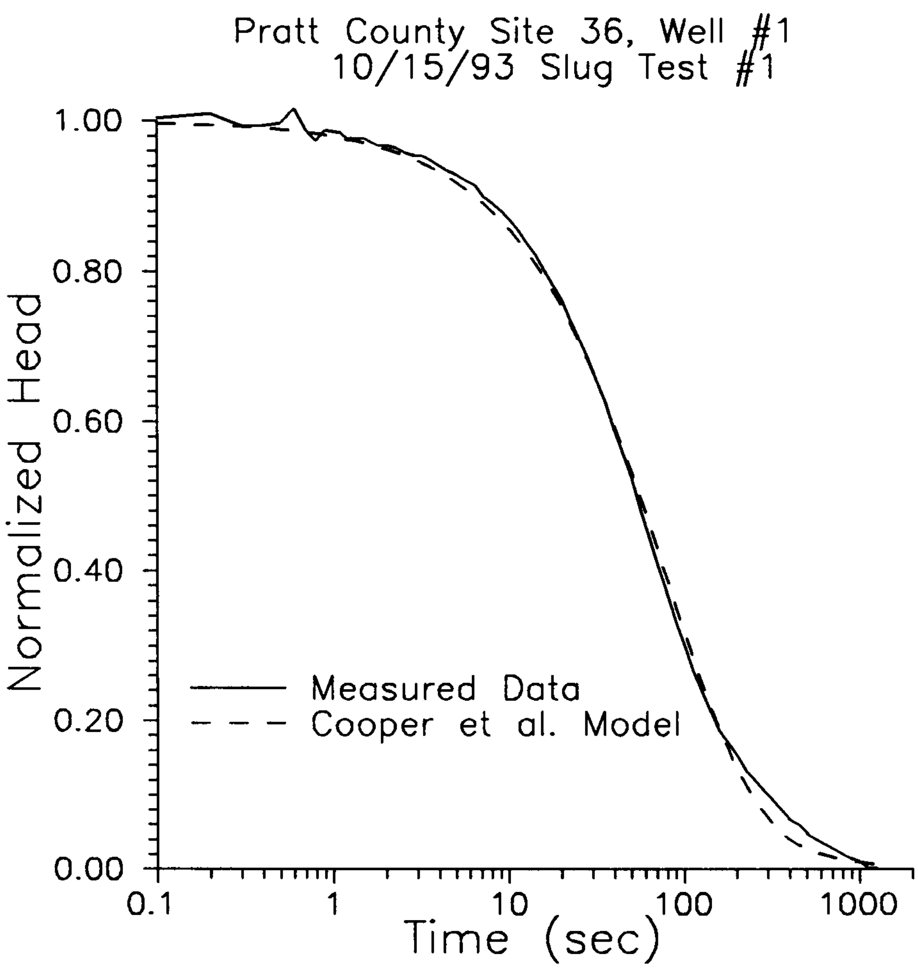

Pratt County Site 36, Well #1
10/15/93 Slug Test #1
Normalized Head
1.00
0.80
0.60
0.40
0.20
0.00
Measured Data
Cooper et al. Model
0.1
1
10
100
1000
Time (sec)

FIGURE 21

Permian bedrock. A double-porosity model (e.g., Barker and Black, 1983; Dougherty and Babu, 1984), which incorporates flow both in fractures and matrix, might be a better model of conditions at this well. However, the lack of agreement between test responses seen on the normalized head plot is so dramatic that use of a double-porosity model was not warranted. The hydraulic conductivity estimate obtained from the Cooper et al. model was 10.6 ft/day (assuming a specific storage of 1.00×10^{-6} ft^{-1}). This value seems quite large relative to the estimates obtained from the other Permian wells. Given the large amount of uncertainty concerning conditions at this well, little credence should be attached to this estimate.

Well #2

Well #2 is screened in the Great Bend Prairie aquifer. Five tests were performed at this well. Figure 22 is a relative head versus time plot of the five tests. A normalized relative head versus time plot for these tests is given in Figure 23. Note that the normalized responses for tests three and four (the large initial displacement tests) are shifted to the right of the normalized responses for tests one, two, and five (the small initial displacement tests). Since the normalized responses for tests one and five essentially fall ontop of one another, the observed shift is clearly not a result of the formation being altered during testing. Instead, the duration of a test appears to be dependent on the magnitude of the initial displacement. Such a

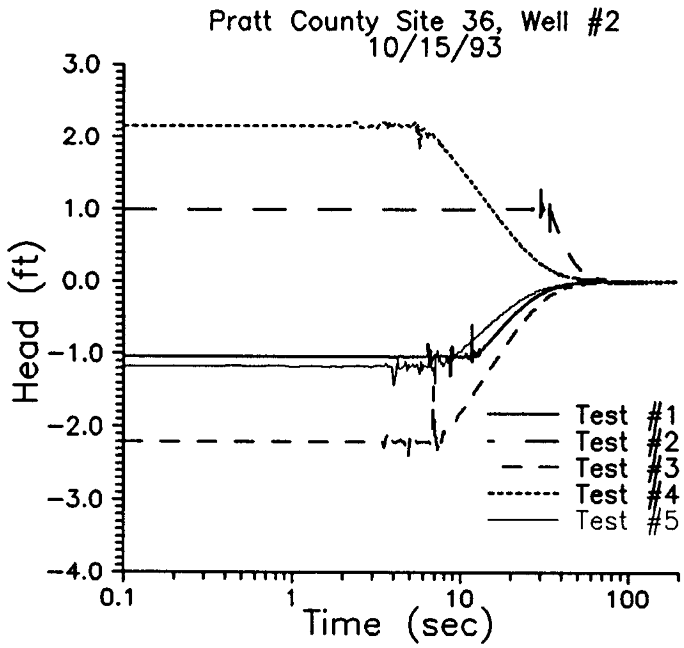


FIGURE 22

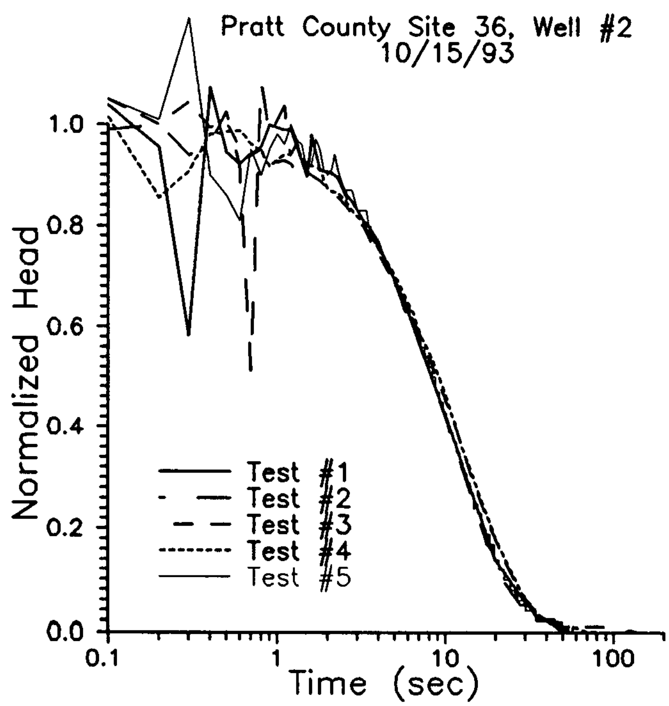


FIGURE 23

dependence has also been observed at a KGS research site in the Kansas River alluvium (Butler and McElwee, 1992).

Tests three and five were chosen for further analysis because of the relatively small water-hammer effects measured in those tests. Tests using small and large initial displacements were selected for analysis in order to assess the dependence of the estimated hydraulic conductivity on the magnitude of the initial displacement. The data were initially analyzed using the model of Cooper et al. Figure 24 displays the measured data and the best-fit Cooper et al. model for tests three and five (estimated hydraulic conductivity of 181.2 ft/day and 182.6 ft/day for tests #3 and #5, respectively, assuming a specific storage of 1.00×10^{-6} ft^{-1}). Note the very large systematic deviation between the measured data and the best-fit model. Since well #2 had a small aspect ratio (12.2), the KGS model was selected for further analysis. Figure 25 displays the measured data and the best-fit KGS model for these two tests (estimated hydraulic conductivity of 75.9 ft/day and 77.5 ft/day for tests #3 and #5, respectively, assuming a specific storage of 1.00×10^{-6} ft^{-1}). The systematic deviation between the measured data and the best-fit KGS model is still rather large, especially when considering the nature of the fits obtained at the other wells with the KGS model. Clearly, the Cooper et al. and the KGS models are not accounting for all of the relevant physical mechanisms controlling water-level changes during these tests.

McElwee et al. (in preparation) have recently proposed a model

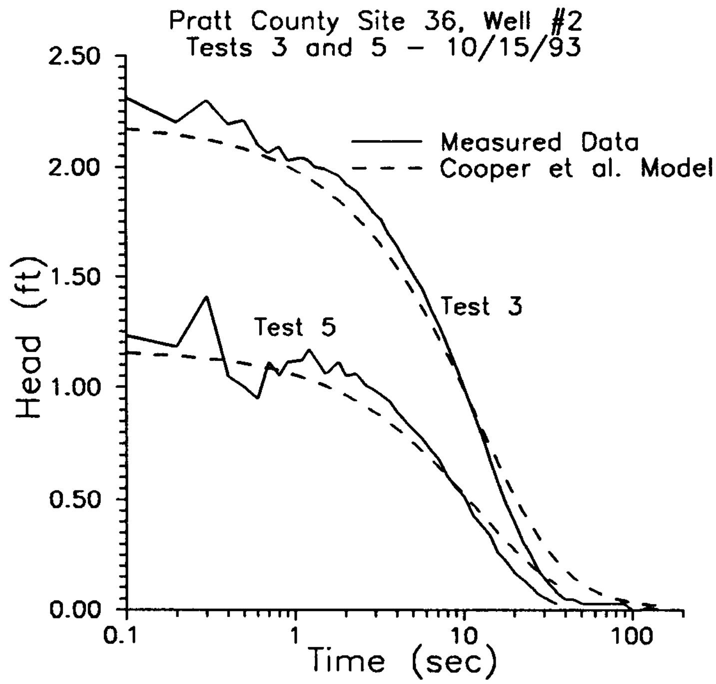


FIGURE 24

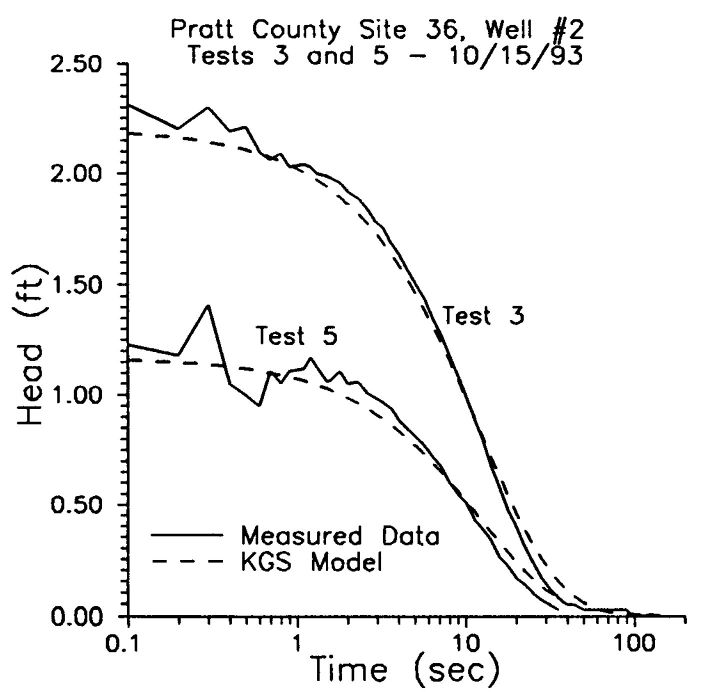


FIGURE 25

for the analysis of response data from slug tests that exhibit a dependence on the magnitude of the initial displacement. Figure 26 displays the measured data and the best-fit McElwee et al. model for tests three and five. Note that these fits were obtained using the same parameters for both tests. The fits obtained using the McElwee et al. model must be considered quite good relative to those of the other two models. The hydraulic conductivity estimate obtained from the McElwee et al. model is 88.1 ft/day. Although the McElwee et al. model incorporates nonlinear flow losses in the well bore, the representation of flow mechanisms in the aquifer itself does involve an approximation that is not employed by either of the other two models. In this case, the model of Hvorslev (1951) is used to represent slug-induced flow in the aquifer. Recently, Hyder et al. (in press) have shown that the Hvorslev model will provide parameter estimates within 25% of the actual value in homogeneous, isotropic formations. Thus, the estimate of 88.1 ft/day is considered acceptable for the purposes of this report.

Well #3

Well #3 is also sited in the Great Bend Prairie aquifer. As with well #2, five tests were performed at this well. Figure 27 is a relative head versus time plot of the five tests. A normalized relative head versus time plot for this series of tests is given in Figure 28. Note that, as predicted by conventional theory, the data from the five tests essentially fall ontop of one another when

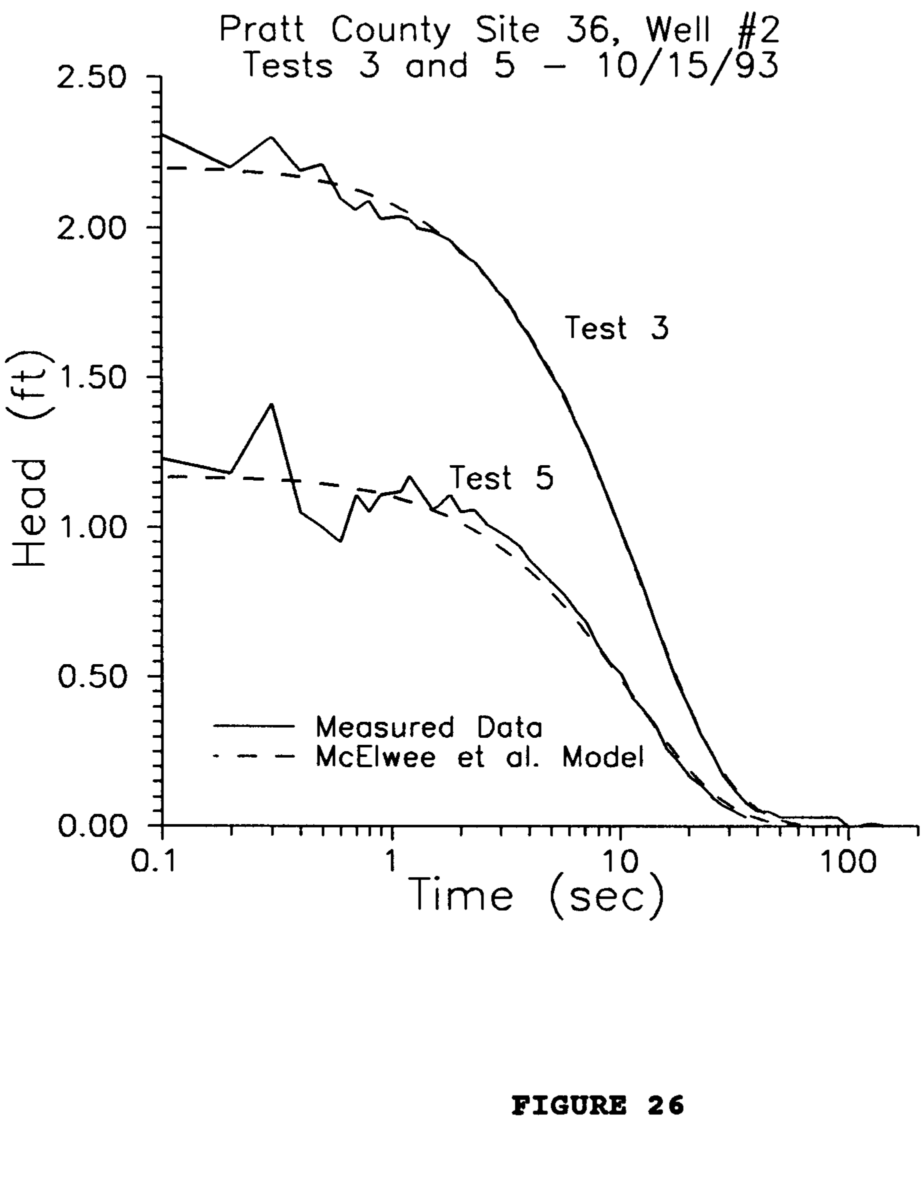

Pratt County Site 36, Well #2
Tests 3 and 5 - 10/15/93
2.50
2.00
1.50
1.00
0.50
0.00
Head (ft)
Test 3
Test 5
Measured Data
McElwee et al. Model
0.1
1
10
100
Time (sec)

FIGURE 26

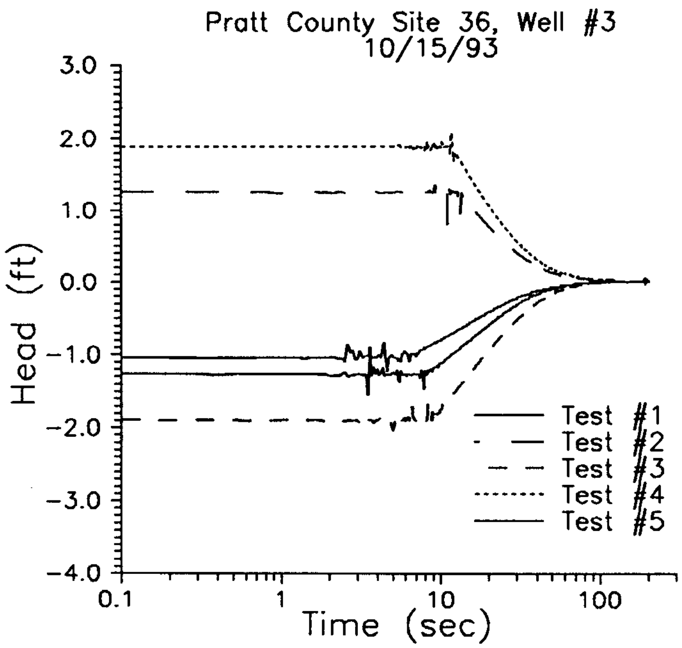


FIGURE 27

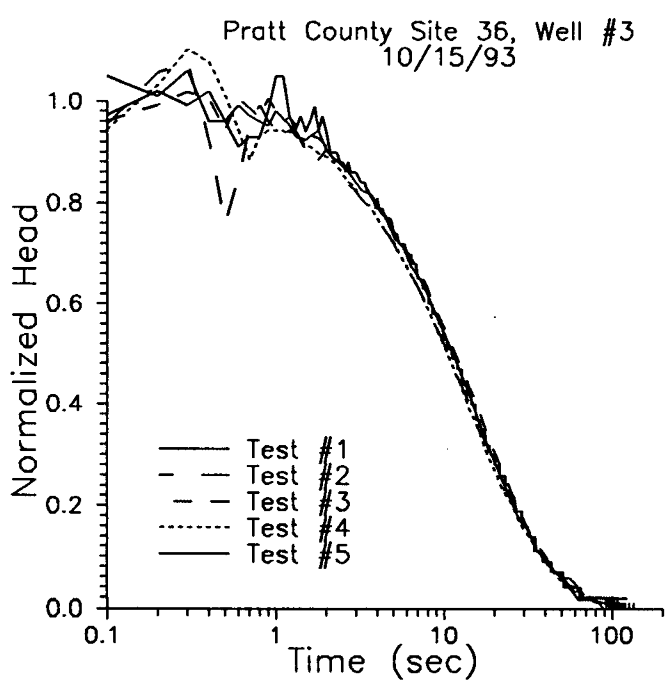


FIGURE 28

plotted in a normalized format. This indicates that the formation is not being altered during the course of testing, that the test duration is independent of the magnitude of the initial displacement, and that the responses are independent of whether the slug was induced by removing or adding water from/to the well.

Test #1 was selected as the test to use in the analysis because of the relatively small water-hammer effects recorded in this test. Figure 29 displays the measured data and the best-fit Cooper et al. model (estimated hydraulic conductivity of 137.9 ft/day assuming a specific storage of 1.00×10^{-6} ft^{-1}). Again, note the systematic deviation between the measured data and the best-fit model. Since well #3 had a small aspect ratio (12.2), the KGS model was selected for further analysis. Figure 30 displays the measured data and the best-fit KGS model for this test. Note that the fit is considerably better than that found with the Cooper et al. model. The hydraulic conductivity estimate obtained from the KGS model was 57.9 ft/day (assuming a specific storage of 1.00×10^{-6} ft^{-1}). The deviation between the best-fit model and the measurements again is so small that further exploration of this difference was not attempted. As with the Great Bend Prairie aquifer wells at Stafford site 16, the results of the analyses of test #1 indicate that anisotropy is rather small for the portion of the formation near the screened interval. Note that the hydraulic conductivity estimate provided by the Cooper et al. model was 2.38 times larger than the KGS model estimate, a ratio very close to that seen at the Stafford Great Bend Prairie aquifer wells.

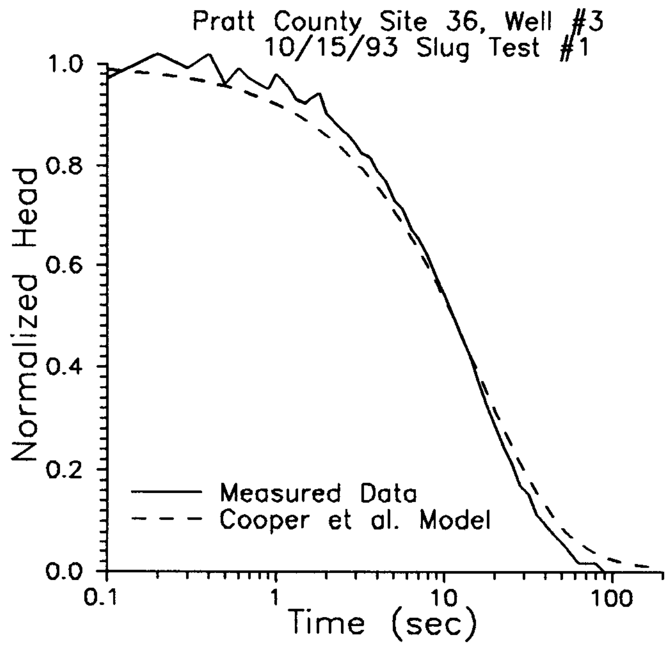


FIGURE 29

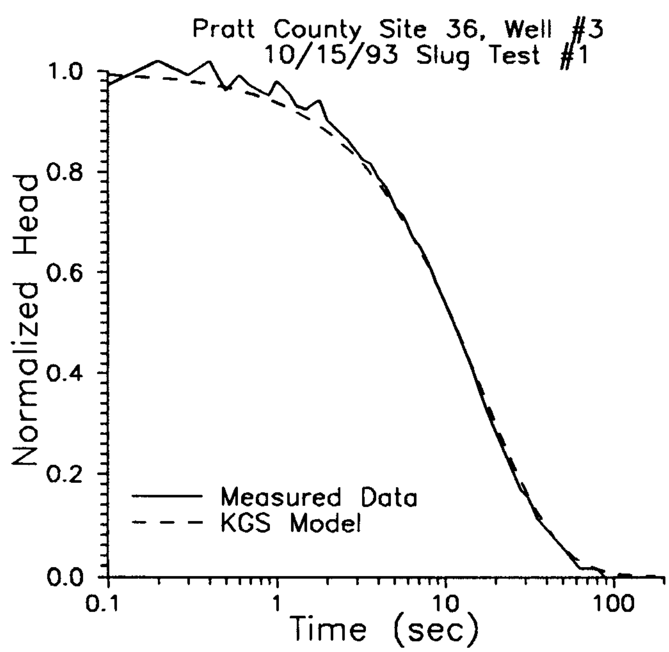


FIGURE 30

Well #4

Well #4 is also sited in the Great Bend Prairie aquifer. Only three tests were performed at this well because of time limitations. Figure 31 is a relative head versus time plot of the three tests. A normalized relative head versus time plot for these tests is given in Figure 32. The data from the three tests essentially fall ontop of one another when plotted in a normalized format, providing strong evidence that conventional theory should be applicable at this well.

Test #2 was selected for analysis because of the relatively small water-hammer effects recorded in this test. Figure 33 displays the measured data and the best-fit Cooper et al. model (estimated hydraulic conductivity of 38.2 ft/day assuming a specific storage of 1.00×10^{-6} ft^{-1}). Note that the systematic deviation between the measured data and the Cooper et al. model fit is not as large as that seen at other wells. Since well #4 had a small aspect ratio (12.2 to 29.2 depending on what value is used for the effective screen length), the KGS model was selected for further analysis. Figure 34 displays the measured data and the best-fit KGS model for an aspect ratio of 12.2. The hydraulic conductivity estimate obtained from the KGS model was 16.0 ft/day (assuming a specific storage of 1.00×10^{-6} ft^{-1}). Note that the fit is inferior to that found with the Cooper et al. model, as the model significantly overpredicts the measured data at early times and slightly underpredicts the measured data at late times. This deviation is most likely a result of a specific storage estimate

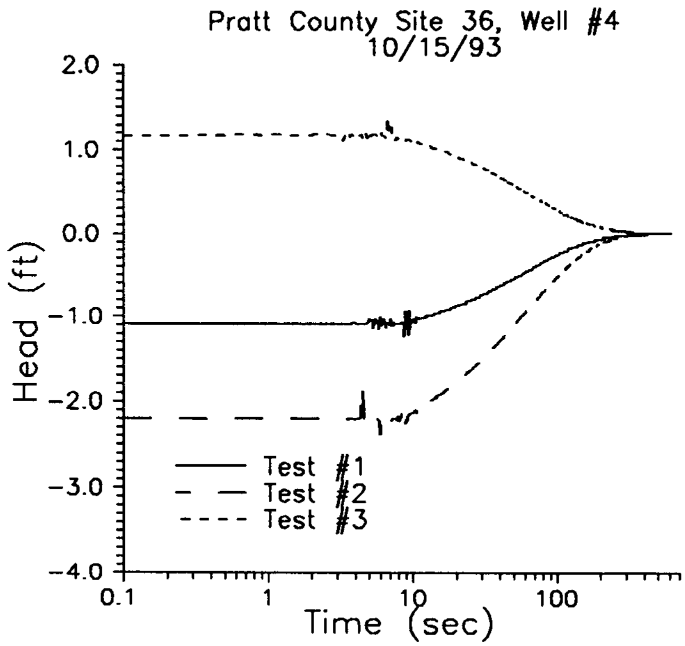


FIGURE 31

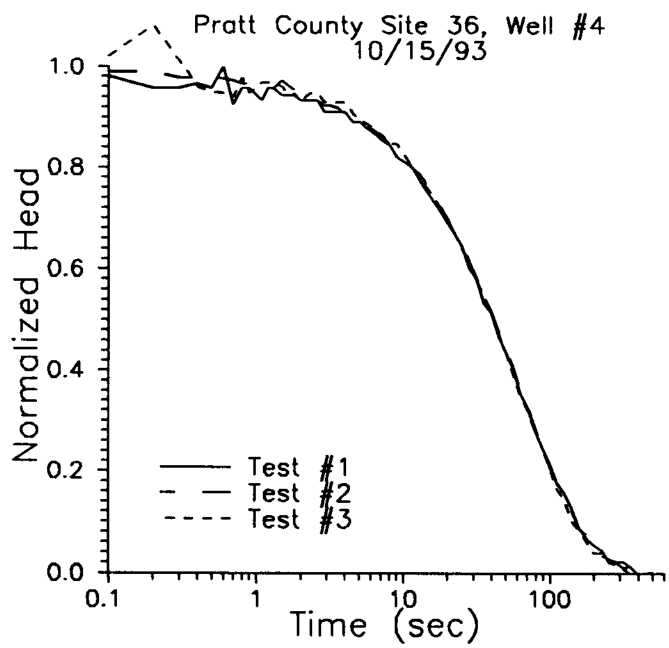


FIGURE 32

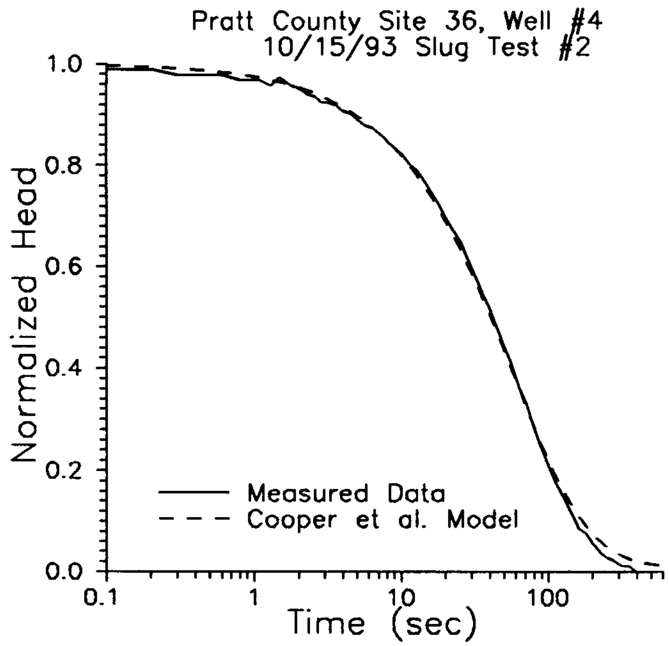


FIGURE 33

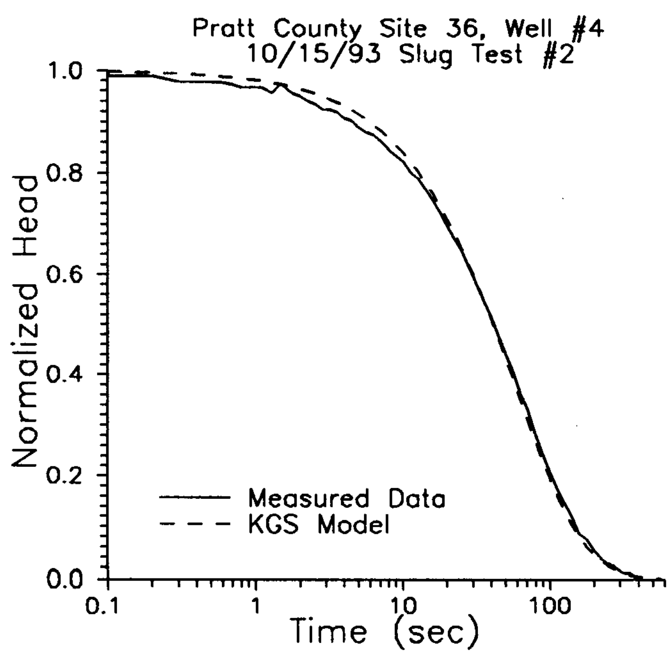
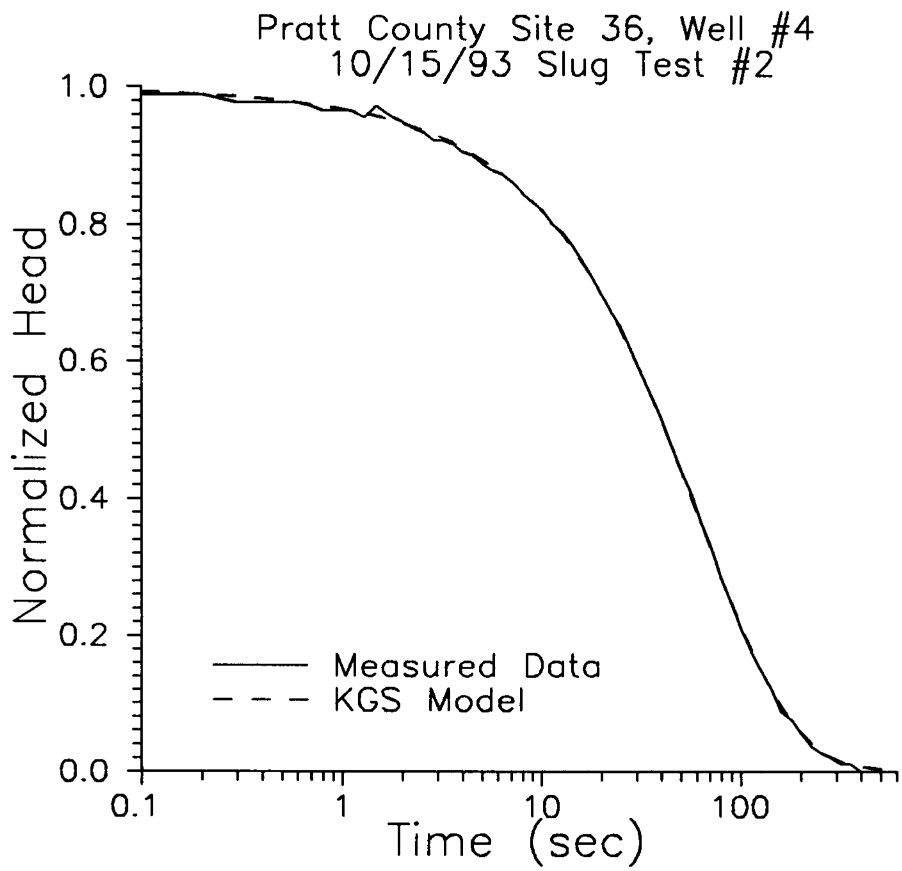


FIGURE 34

that is too low or some degree of anisotropy. In an attempt to improve the model fit, the KGS model was applied again to the data, this time estimating both hydraulic conductivity and specific storage. Figure 35 displays the measured data and the best-fit KGS model for the analysis. The fit between the model and the measurements is extremely good. The hydraulic conductivity estimate obtained from the second application of the KGS model was 13.8 ft/day, while the specific storage estimate was 1.61×10^{-4} ft^{-1}. Although the specific storage estimate changed by a factor of 161 between the two analyses using the KGS model, the hydraulic conductivity estimate only changed 14%. This result is a clear field demonstration of the theoretical finding that hydraulic conductivity estimates from slug tests are relatively insensitive to the value assumed for specific storage.

There was considerable uncertainty about what value to use for the effective screen length at this well. As shown in Table 8, the gravel pack is thought to be 12 feet in length (note that there is some uncertainty about the length of the gravel pack). Since the slug tests at this well took a few hundred seconds to complete, it is almost a certainty that the effective screen length is longer than the nominal screen length of 5 ft. If we take 12 feet as the maximum possible effective screen length, an analysis using the KGS model produces estimates of 7.80 ft/day and 2.72×10^{-5} ft^{-1} for hydraulic conductivity and specific storage, respectively (fit very similar to that shown in Figure 35). The 7.80 ft/day estimate should be considered the minimum possible value for hydraulic



Pratt County Site 36, Well #4
10/15/93 Slug Test #2
Normalized Head
1.0
0.8
0.6
0.4
0.2
0.0
Measured Data
KGS Model
0.1
1
10
100
Time (sec)

FIGURE 35

conductivity at this site. Clearly, the maximum value for hydraulic conductivity cannot be any greater than the 38.2 ft/day value determined using the Cooper et al. model assuming an effective screen length of 5 ft. We hesitate to put more restrictive bounds on the maximum hydraulic conductivity because it is possible that there is some degree of anisotropy at this site. However, the actual hydraulic conductivity value for the screened interval most probably lies between 7.8 and 13.8 ft/day, the two estimates obtained using the KGS model assuming an isotropic formation.

RENO COUNTY SITE 25

Reno County site 25 consists of three wells, one in the Permian bedrock and two in the overlying Great Bend Prairie aquifer. Tables 9 and 10 provide well log and well construction information for this site. Only well #1, screened in the Permian bedrock, was tested as part of this work.

Well #1

Well #1 is sited in the Permian bedrock. This well recovered so slowly from the slug-induced disturbance (in this case the addition of 3.76 ft of water to the well) that only one test could be performed during the test period. Figure 36 displays a relative head versus time plot for the test. Note that the plot displayed on Figure 36 is a combination of transducer and electric tape measurements. The data were first analyzed with the Cooper et al. model. Figure 37 shows the measured data and the best-fit Cooper et al. model. Note that, other than the underprediction of heads at early times, the model fit is reasonably good. The hydraulic conductivity estimate obtained from the Cooper et al. model was .044 ft/day (assuming a specific storage of 1.00×10^{-6} ft^{-1}). The deviations between the best-fit model and the measured data were not considered to be large enough to warrant further exploration. Note that when the KGS model (assuming isotropy) was applied to this data set, the fit was inferior to that shown in Figure 37. Thus, it appears that there is a considerable degree of anisotropy in hydraulic conductivity in the Permian bedrock at this site.

BIG BEND GMD#5-KGS
WATER QUALITY
OBSERVATION WELL
NETWORK

SITE NUMBER : 25
SITE LOCATION: NE NW NW

LEGAL LOCATION: 6-23-10W
COUNTY : RENO

WELL LOG

FROM	TO	LITHOLOGIC LOG OWNER: MILLER
0	14	red silt, fine to v.f. sand, some clay
14	16	clay and silt increases, some gravel
16	19	yellow and red silty clay with fine sand
19	21	gravel (QA), with tan silty clay
21	26	very fine to medium sand
26	42	same QA (quartz/arkose)
42	45	QA sand and fine gravel
45	47	yellow silty clay and fine QA sand
47	52	light red clay and some medium fines as above
52	57	tan clay with fine QA sand
57	58	yellow stringer
58	60	caliche zone
60	71	tan & yellow clay; f. sand & traces of white clay
		light red clay at bottom
71	80	mostly light red clay, trace of f. sand & caliche
80	85	same with some gravel
85	90	hard zone- caliche, red clay
90	95	red to tan clay, some medium to coarse sand
95	99	sand and gravel lense
99	100	reddish clay
100	100.5	caliche zone
100.5	101	medium/coarse sand; medium/fine QA gravel
101	110	gravel, fine siltstone, weathered red bed
110	125	unweathered red bed PERMIAN

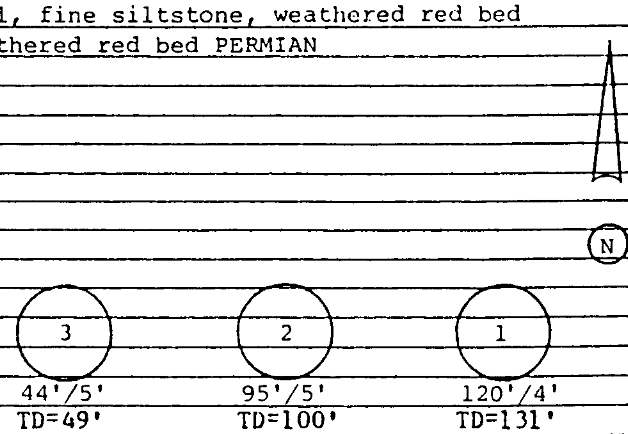


TABLE 9

Well No.	Borehole Radius[1]	Casing Radius (ESR)[2]	Total Depth	NSI (ESL)[3]	Gravel Pack Interval	Grout Interval
25-1	0.4115	0.2083 (0.4115)	125	120-124 (9)	115-124	0-10 40-115

1 - Units for information in this and remaining columns are ft.

2 - ESR - effective screen radius

3 - NSI - nominal screened interval

ESL - effective screen length

TABLE 10 - WELL CONSTRUCTION INFORMATION FOR RENO COUNTY SITE 25

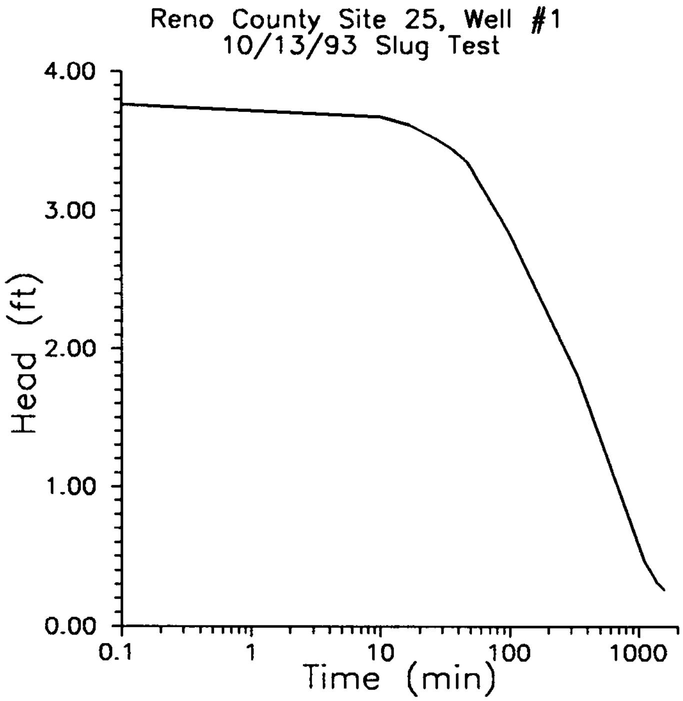


FIGURE 36

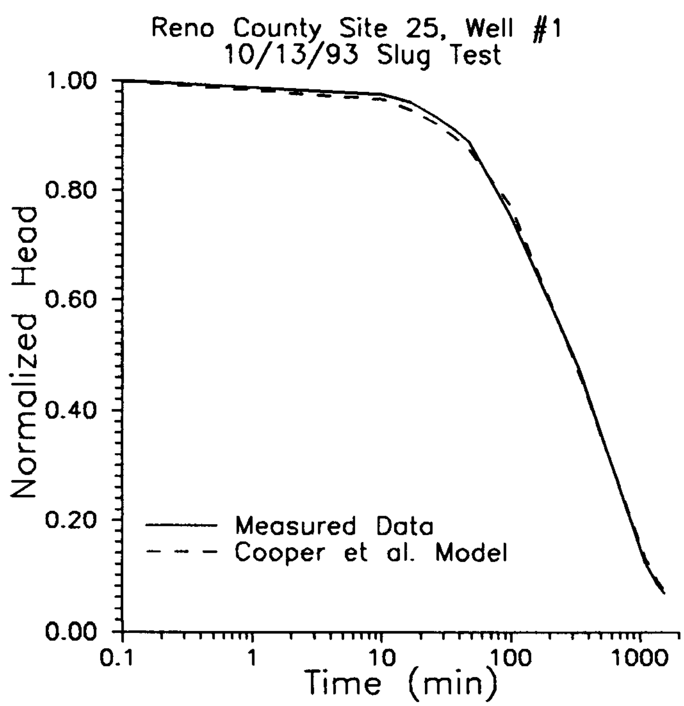


FIGURE 37

SUMMARY OF TESTING PROGRAM

Table 11 provides a summary of the hydraulic conductivity estimates obtained from this program of slug tests. In the wells screened in the Great Bend Prairie aquifer, hydraulic conductivity estimates ranged from 7.8 to 88.1 ft/day. Hydraulic conductivity estimates obtained from wells screened in the Permian bedrock ranged from 0.0037 to 0.139 ft/day (value from well #1 at Pratt County site 36 is not considered in this range because we have very little confidence in the estimates obtained from tests at that well). Both of these ranges are considered quite reasonable given the geology of the tested units.

In an earlier series of slug tests performed in this region for GMD5 (Olsen, unpublished data), hydraulic conductivity estimates obtained from wells screened in the Permian bedrock ranged from 0.00581 to 0.198 ft/day, a range very similar to that obtained here. The only well common to both series of tests was well #1 at Stafford County site 17. The earlier testing program obtained an estimate of 0.00879 ft/day, while an estimate of 0.0037 ft/day was obtained here. The primary reason for the difference between the estimates was the use of the nominal screen length for effective screen length in the GMD5 testing program and the use of the length of the gravel pack for the effective screen length in the analyses reported here. The GMD5 estimates were also obtained using the approximate Hvorslev model, while the analyses reported here were performed with the more appropriate KGS model. Only two hydraulic conductivity estimates (14.7 and 4.93 ft/day) were obtained for the Great Bend Prairie aquifer from the earlier testing program because a number of the wells recovered too rapidly for the approach used to initiate the slug test (same problem as we faced at the Siefkes Great Bend Prairie aquifer well).

Although the series of tests reported here was relatively successful, the program of testing has not been completed. Additional tests need to be performed at the Permian wells at Stafford sites 16 and 17, and Reno site 25, in order to ensure that the hydraulic conductivity estimates obtained from the single tests performed at each of these sites are valid representations of the hydraulic conductivity of the formation at these sites. These repeat tests will be carried out in the spring of 1994 using a closed-hole slug-test system currently under development at the KGS. In addition, the Great Bend Prairie aquifer well at the Siefkes site, which could not be tested during this series of tests because of the nonstandard casing diameter, will be tested in the spring of 1994 using a pressurized slug-test system also currently under development at the KGS. Prior to the next round of field tests in the spring of 1994, a theoretical evaluation of the effects of well construction on slug test responses will be performed. This evaluation will focus on an assessment of the effect of well-construction uncertainties (effective screen length and effective well radius) on parameter estimates. The results of this study will aid in the definition of appropriate well-construction parameters to be used in future analyses.

WELL LOCATION	TESTED UNIT*	K** (FT/DAY)
STAFFORD COUNTY SITE 16		
Well 1	P	0.0101
Well 2	GBPA	31.6
Well 3	GBPA	56.8
STAFFORD COUNTY SITE 17		
Well 1	P	0.0037
SIEFKES SITE		
Permian Well	P	0.139
PRATT COUNTY SITE 36		
Well 1	P	NV***
Well 2	GBPA	88.1
Well 3	GBPA	57.9
Well 4	GBPA	7.8 - 13.8
RENO COUNTY SITE 25		
Well 1	P	0.044

* - P - Permian Bedrock
GBPA - Great Bend Prairie aquifer

** - K - hydraulic conductivity

*** - Estimate obtained at this well (K=10.6 ft/day) was considered a nonviable estimate.

TABLE 11 - SUMMARY OF HYDRAULIC CONDUCTIVITY ESTIMATES OBTAINED FROM OCTOBER, 1993 SERIES OF SLUG TESTS IN STAFFORD, PRATT, AND RENO COUNTIES

DATA AVAILABILITY

The data collected in the series of slug tests described in this report are available from the Kansas Geological Survey in an electronic form. Please request KGS Open-File Rept. #93-52a for a floppy disk copy of the test data. The disk has the following files:

READ.ME - explanatory file that describes contents of the disk

STAFFORD COUNTY SITE 16 files

well 1 - times are in minutes

cusf1611.dat

well 2 - times are in seconds

cusf1621.dat

cusf1622.dat

cusf1623.dat

well 3 - times are in seconds

cusf1631.dat

cusf1632.dat

cusf1633.dat

STAFFORD COUNTY SITE 17 files

Well 1 - times are in minutes

cusf1711.dat

SIEFKES SITE files

Permian Well - times are in seconds

cusil1.dat

cusil2.dat

cusil3.dat

PRATT COUNTY SITE 36 files

Well 1 - times are in seconds

cupr3611.dat

cupr3612.dat

cupr3613.dat

Well 2 - times are in seconds

cupr3621.dat

cupr3622.dat

cupr3623.dat

cupr3624.dat

cupr3625.dat

Well 3 - times are in seconds

cupr3631.dat

cupr3632.dat

cupr3633.dat

cupr3634.dat

cupr3635.dat

Well 4 - times are in seconds

cupr3641.dat

cupr3642.dat

cupr3643.dat

RENO COUNTY SITE 25 files

Well 1 - times are in minutes

curn2511.dat

File naming scheme - cu??!!#*.dat - c designates converted data (voltage readings from data logger have been converted into physical units), u designates data that have not been normalized, ?? designates site abbreviation (Stafford - sf, Siefkes - si, Pratt - pr, and reno - rn), !! designates site no. (note that Siefkes site does not have a site no.), # indicates well no. (Permian well is considered well 1 at Siefkes site), and * indicates test no.

Each file consists of two columns, the first column is the time (in seconds or minutes) since the start of the test and the second column is the deviation from static (in feet). Note that the magnitude of the initial displacement (i.e. size of slug) may be somewhat difficult to determine from these data. The initial displacements determined for these tests from pre-test data are as follows:

STAFFORD COUNTY SITE 16

well 1

test 1 - 3.69 ft.

well 2

test 1 - -1.00 ft.

test 2 - -2.04 ft.

test 3 - 1.06 ft.

well 3

test 1 - -1.21 ft.

test 2 - -2.09 ft.

test 3 - 1.06 ft.

STAFFORD COUNTY SITE 17

Well 1

test 1 - 3.69 ft.

SIEFKES SITE

Permian Well

test 1 - 5.08 ft.

test 2 - 10.05 ft.

test 3 - 4.93 ft.

PRATT COUNTY SITE 36

Well 1

test 1 - -3.67 ft.

test 2 - 3.47 ft.

test 3 - -1.00 ft.

Well 2

test 1 - -1.04 ft.

test 2 - 0.99 ft.

test 3 - -2.20 ft.

test 4 - 2.15 ft.

test 5 - -1.17 ft.

Well 3

test 1 - -1.26 ft.

test 2 - 1.26 ft.

test 3 - -1.90 ft.

test 4 - 1.89 ft.

test 5 - -1.04 ft.

Well 4

test 1 - -1.09 ft.

test 2 - -2.20 ft.

test 3 - 1.17 ft.

RENO COUNTY SITE 25

Well 1

test 1 - 3.76 ft.

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