Kansas Geological Survey

Open File Report 2002-25C

Calculation of Yield for High Plains Wells: Relationship between saturated thickness and well yield

By

G.R. Hecox, P. A. Macfarlane and B. B. Wilson
With contributions from other authors in the report series

A component of the Technical Report series 2002-25: Technical Support for Ogallala Aquifer Assessment, Planning, and Management

A final report of Fiscal Year 2002 activities by the Kansas Geological Survey supported by contracts with the Kansas Water Office and the Kansas Department of Agriculture

Kansas Geological Survey Open File Report 2002-25C

GEOHYDROLOGY

The University of Kansas, Lawrence, KS 66047: (785) 864-3965; www.kgs.ukans.edu

KGS OFR 2002-25C. Calculation of yield for High Plains aquifer wells: relationship between saturated thickness and well yield

Table of Contents

KGS OFR 2002-25C. Calculation of yield for High Plains aquifer wells: relationship between saturated thickness and well yield

By G.R. Hecox, P. A. Macfarlane and B. B. Wilson

1. Introduction

Well yield is defined as the amount of water that can be pumped from a given well per unit of time. In order to support large volume pumping demands at a consistent flow rate, a substantial amount of saturated thickness is required so that when the local cone of depression is formed, the water table near the well remains above the well screen. The relationship between the saturated thickness of the aquifer and corresponding well yield is an important consideration as an area transitions to reduced water availability. Yield is also a function of aquifer hydraulic conductivity, which is related to sediment type and distribution. An aquifer composed of clean sand and gravel will produce higher and more sustained well yields than will an aquifer where the clean sands and gravels are compartmentalized by interbedding with clay and other low hydraulic conductivity units.

The saturated thickness needed for a given pumping rate depends on well construction and the local aquifer characteristics -- particularly the hydraulic conductivity (permeability), and to a lesser extent the specific yield, of the formation near the well. It can be determined experimentally by a pump test, or calculated if the aquifer and well characteristics are already known. However, pump tests are time consuming and expensive.

The objective of this report is to present calculations of the theoretical drawdown that may occur in a High Plains aquifer irrigation well using various site-specific hydraulic parameters and other assumed aquifer and well characteristics, under a range of pumping rates. These theoretical results were then used to determine the minimum saturated thickness required for the assumed rates and conditions, and these results were combined with the spatial distribution of the aquifer properties. The resulting distributions of required saturated thickness were compared to the present day estimates of saturated thickness in the aquifer. Although generalized, these results provide guidance about probable characteristics and the effective amount or remaining water in various parts of the aquifer. This report is written as part of the Kansas Geological Survey's report of ongoing technical support series (OFR 2002-25) to further understand the characteristics and properties of the High Plains Aquifer. This report was developed within the framework of contracts with the Kansas Water Office (KWO) and Kansas Department of Agriculture's Division of Water Resources (KDA-DWR). Contract documents are contained in Section 4 of KGS OFR 2002-25G.

2. Data and methods

2.1 Calculation of minimum required saturated thickness

Using either the Cooper-Jacob (1946) or a polynomial approximation (Abramowitz and Stegun (1972) of the Theis equation (1935), the minimum saturated thickness for a given well yield was calculated. This was done by setting up the equations in an Excel® spreadsheet where the hydraulic parameters could be varied. The determination of the minimum saturated thickness required for a given set of flow rates and hydraulic parameters was made by calculating the theoretical drawdown for various saturated thicknesses. For this iterative analysis, five-foot increments in saturated thickness were used from 10 up to 150 feet. Because the transmissivity is a function of saturated thickness, the parameter was varied for each saturated thickness evaluated.

These required saturated thickness results were plotted for various values of hydraulic conductivity to produce the final graph. The curves were evaluated for one well at 1 and 90 days of pumping to simulate the aquifer conditions when the aquifer is almost depleted (1 day of pumping) or when the aquifer is still capable of providing water to most of the users (90 days of pumping). To determine the effect that neighboring irrigation wells have on the required saturated thickness, one set of calculations using a 5-spot well pattern with wells on 1/2 mile centers were done. Lastly, a sensitivity analysis (Section 4) was performed to assess the relative impact of varying the individual hydraulic parameters.

The following assumptions were used in the calculations:

Table 1. Theis equation input parameters.

Parameter	**Assumed Value or Values**
Hydraulic conductivity (K, ft/d)	Variable: 50, 75, 100, 150, 200
Specific yield (S, Unitless)	0.1, 0.005 used in sensitivity analysis
Saturated thickness (b, ft)	Variable; 10–150 in 5 foot increments
Transmissivity (K*b, ft^2/d)	Variable: 500–45000 depending on K and b
Pumping rate (Q, gpm)	Variable: 50–1500
Effective well radius (ft)	1, outer radius of gravel pack, simulates 24 inch borehole
Time of pumping (d)	1 or 90
Interference from surrounding wells	Included in last set of calculations
Well efficiency (%)	50, i.e., the drawdown in the well is 1.5X the drawdown in the aquifer
Maximum screen entrance velocity (Ent. Vel., ft/sec)	0.1
Screen diameter (ft)	1.5
Screen size (in)	0.1
Screen open area (%)	30, average for high capacity screens
Distance to neighboring pumping wells (ft)	2500 (used on 5-spot well field calculations)

The following equations were used to estimate the theoretically required saturated thickness for various aquifer parameters and flow rates presented on Table 1.

For the calculations involving a single well, the Cooper–Jacob equation was used. The drawdown in the *aquifer* was calculated using:

$$s_{aquifer} = \frac{Q}{4\pi T}\left[-0.5772 - \ln\left(\frac{r^2 S}{4Tt}\right)\right]$$

For calculations involving multiple wells and the resulting interference between the pumping wells, the following polynomial approximation (Abramowitz and Stegun, 1972, eq. 5.1.53) of Theis equation was used to calculate drawdown in the *aquifer*:

$$u = \left(\frac{r^2 S}{4Tt} \right)$$

$$s_{aquifer} = \frac{Q}{4\pi T} \begin{bmatrix} -0.5772 - \ln u + 0.99999u - 0.24991055u^2 \\ +0.05519968u^3 - 0.00976004u^4 + 0.00107857u^5 \end{bmatrix}$$

In order to account for the additional drawdown required for water to migrate from the aquifer into the well screen, it is necessary to account for well losses in the theoretical calculations. This is because even for a new, properly designed, high production rate well, the well efficiency (drawdown in the aquifer/drawdown in the well) is usually only 70–80 percent (Driscoll, 1986). Therefore the drawdown in a well was calculated as:

$$s_{well} = s_{aquifer} + 0.5(s_{aquifer}).$$

The drawdown in the well was the value that was compared to the input saturated thickness value to determine whether a given set of hydraulic parameters would cause dewatering and thereby reduce the well yield.

The well screen entrance velocity was checked for each pumping rate to be certain that the water flow through the well screen did not become turbulent. This is a potential problem at high flow rates and thin saturated thickness. If the entrance velocity is greater than 0.1 ft/sec., turbulent flow may be a problem (Driscoll, 1986) and additional saturated thickness is required.

$$Ent.Vel. = \frac{Q}{7.48 \times 60 \times (screen\ open\ area)}$$

The minimum saturated thickness required for a given flow rate and hydraulic conductivity was determined either by the saturated thickness tending to zero or the entrance velocities becoming greater than 0.1 ft/sec. For all results shown in this report, the saturated thickness was the determining factor and not entrance velocity.

For the above analysis, the minimum saturated thickness results are most sensitive to the transmissivity (T), the well pumping rate (Q), and well efficiency because these three variables affect the required saturated thickness in a linear manner. The other variables affect the results in a logarithmic manner.

2.2 Use of required saturated thickness to estimate the remaining effective saturated thickness in the high plains aquifer

An extended application of the theoretical required saturated thickness is to compare the curves at various well yields to the existing aquifer resources in the High Plains aquifer in order to provide a measure of the aquifer's usability. In essence, this additional classification further refines the viability of the existing resources both for present day conditions and for future lifetime estimates by providing new minimum saturated thickness thresholds for specific well yields. Using a Public Land Survey System (PLSS) section-level database, the present estimates of saturated thickness (Figure 1) were compared to the minimum saturated thickness estimated from the curves using the 5-spot well pattern with a 90 day pumping scenario for well yields of 50, 400, and 1000 gpm. Based on the estimated hydraulic conductivity value for each PLSS section (Figure 2), the difference in feet between the required saturated thickness identified from the curves and the present day saturated thickness was calculated. This difference between the existing saturated thickness and the theoretically required minimum threshold provides a measurement of the effective saturated thickness in the aquifer and serves to illustrate how areas might relate locally-established threshold levels to possible management considerations.

3. Results

3.1 Saturated thickness required to sustain flow rate

The results of the theoretical calculations for required saturated thickness are presented on Figures 3-5. Dashed lines are shown on the graphs at 50, 400, and 1000 gpm representing a stock or domestic supply well, a low flow-rate irrigation well and a high flow-rate irrigation well respectively. As shown for one day of pumping for a single well (Figure 3), the minimum required saturated thickness varies from 50 feet to approximately 120 feet for a 1000 gpm well and from 30 feet to 75 feet for a 400 gpm well. For 90 days of pumping a single well (Figure 4), the results for these pumping rates are from 60 to 150 feet and 35 to 85 feet, respectively. The inclusion of neighboring pumping wells in the 90–day scenario adds from 5 to 10 feet of additional required saturated thickness for these pumping rates (Figure 5). Note that the curves presented are not linear because of the decrease in transmissivity (hydraulic conductivity x saturated thickness) as the aquifer is dewatered.

3.2 Use of required saturated thickness to estimate the remaining effective saturated thickness in the High Plains aquifer

The results for the maps of estimated saturated thickness in relation to the plots of theoretical minimum required saturated thickness for well yields at 50, 400, and 1000 gpm for the 5-spot well pattern under a 90 day pumping scenario are shown in Figures 6-8. The figures simply classify the existing saturated thickness as being below, within 25 feet above, or more than 25 feet above the theoretical required minimum levels. In terms of present day resources and at a broad regional scale, these maps indicate that much of southwest Kansas has saturated thickness values more than 25 feet above the level required to support the three selected well yields of 50, 400, and 1000 gpm, while west central Kansas is generally below or within 25 feet of the required threshold for most well yields. It should be recognized that there is great variability at the sub-regional level throughout the aquifer region, which is best illustrated in northwest Kansas.

The maps in figures 6-8 simply compare the present day saturated thickness to the theoretical minimum required saturated thickness for the selected well curves. In order to extend this comparison into possible future conditions requires additional data parameters and analysis considerations. In the Atlas of the High Plains Aquifer (Schloss et al., 2000), the usable lifetime of the aquifer is estimated by projecting recent rates of water level decline into the future until the saturated thickness reach a threshold of 30 feet. The threshold of 30 feet has been assumed by state agencies and local water users to represent an approximate value needed to support large volume water demands. Results from this report suggest that the minimum saturated thickness is actually substantially greater than this value. As such, the relationships between well yield and saturated thickness identified in this report can be used as new minimum threshold requirements in the lifetime estimates, and are further addressed in KGS OFR 2002-25D.

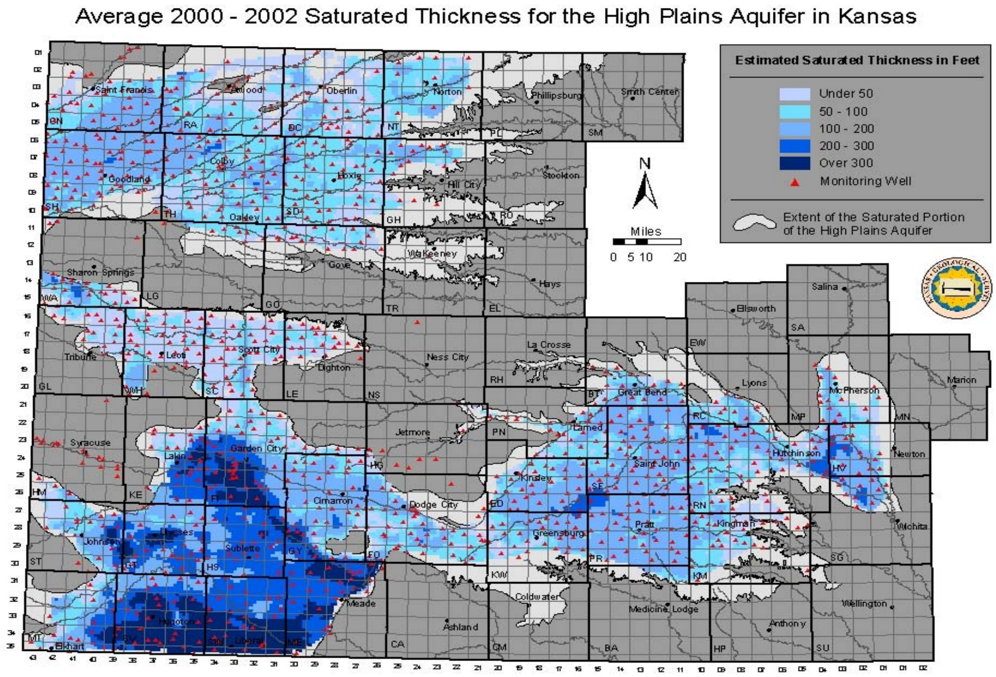


Figure 1: The average 2000-2002 saturated thickness in the High Plains aquifer is based on the difference between water table and bedrock elevations at the locations of monitoring wells identified as being screened within the aquifer. The average saturated thickness is calculated from all measurements taken in the winter months (Dec, Jan, Feb) in the years 2000, 2001, and 2002.

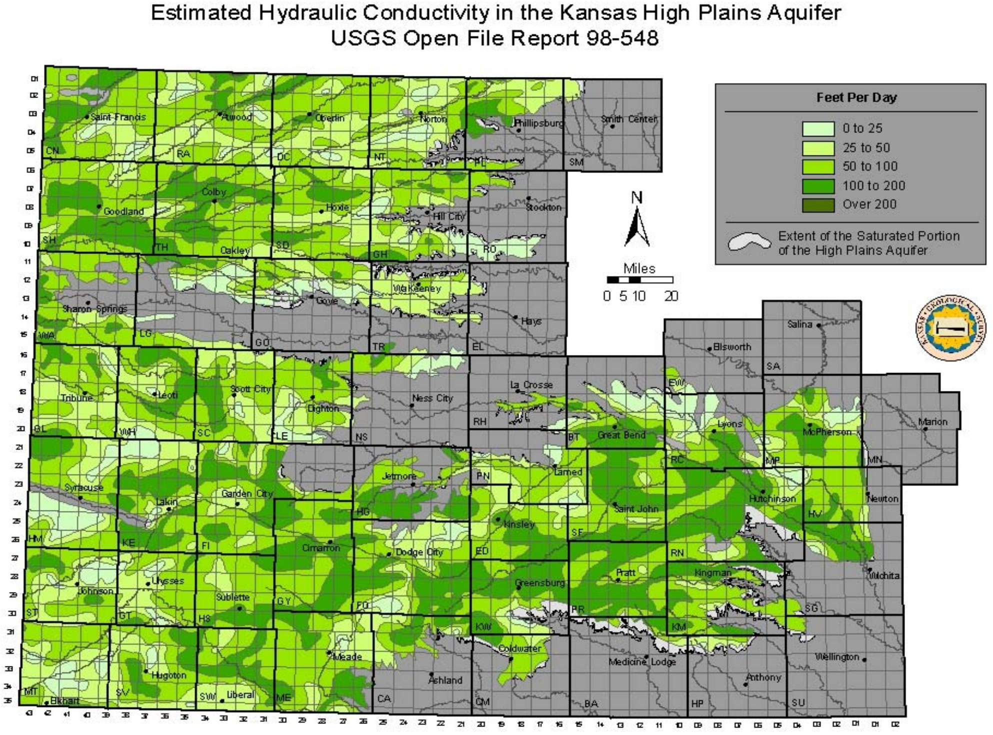
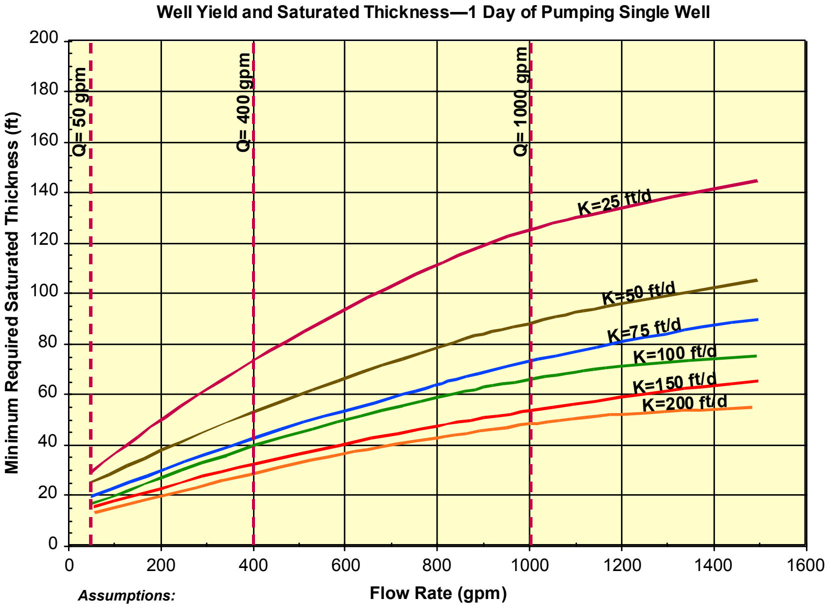


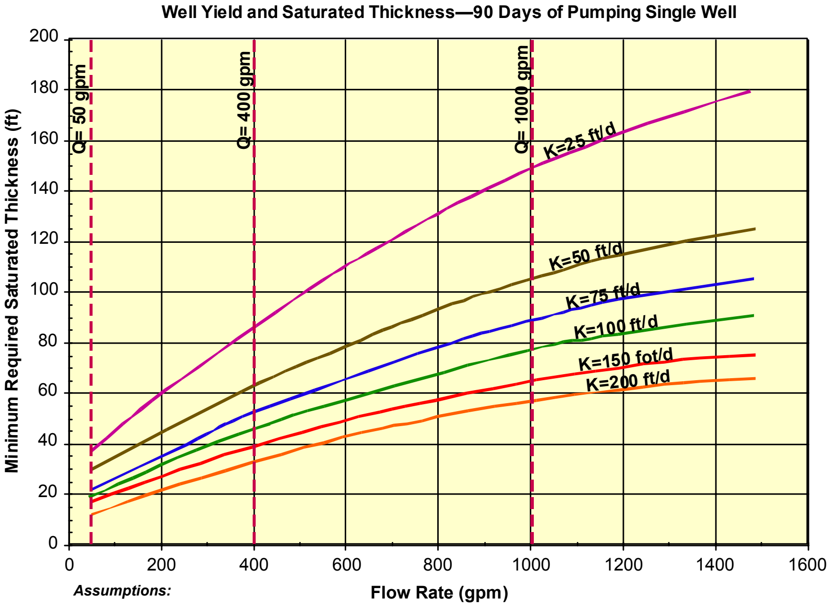
Figure 2: Estimated hydraulic conductivity in the Kansas High Plains aquifer (source: USGS Open-file report 98-548)



Assumptions:

1. Specific yield = 0.1
2. Time of pumping = 90 days
3. Well efficiency = 50%
4. Cooper-Jacob approximation of Theis equation used for calculations.

Figure 3. Relationship between Well Yield and Saturated Thickness for Various Hydraulic Conductivity Values, 1 Day of Pumping Single Well



Assumptions:

1. Specific yield = 0.1
2. Time of pumping = 90 days
3. Well efficiency = 50%
4. Cooper-Jacob approximation of Theis equation used for calculations.

Figure 4. Relationship between Well Yield and Saturated Thickness for Various Hydraulic Conductivity Values, 90 Days of Pumping Single Well

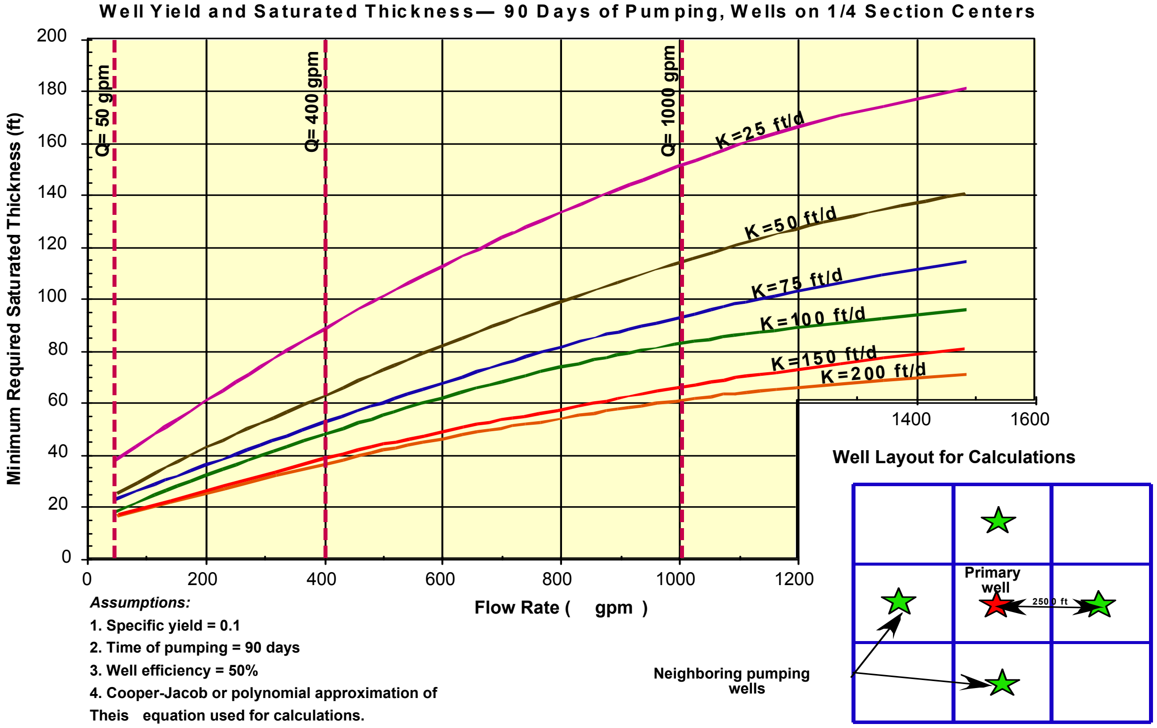


Figure 5. Relationship between Well Yield and Saturated Thickness for Various Hydraulic Conductivity Values, 90 Days of Pumping, Wells on 1/4 Section Centers

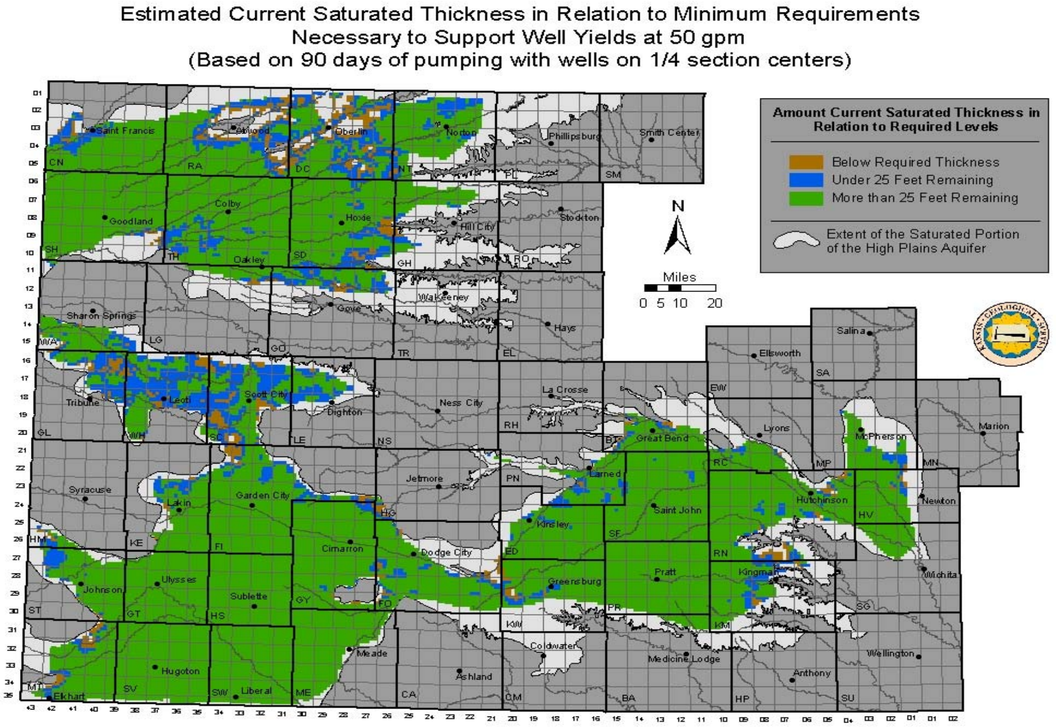


Figure 6: Estimates current saturated thickness in relation to minimum requirements necessary to support well yields at 50 gpm (based on 90 days of pumping with wells on ¼ section centers).

Estimated Current Saturated Thickness in Relation to Minimum Requirements
Necessary to Support Well Yields at 400 gpm
(Based on 90 days of pumping with wells on 1/4 section centers)

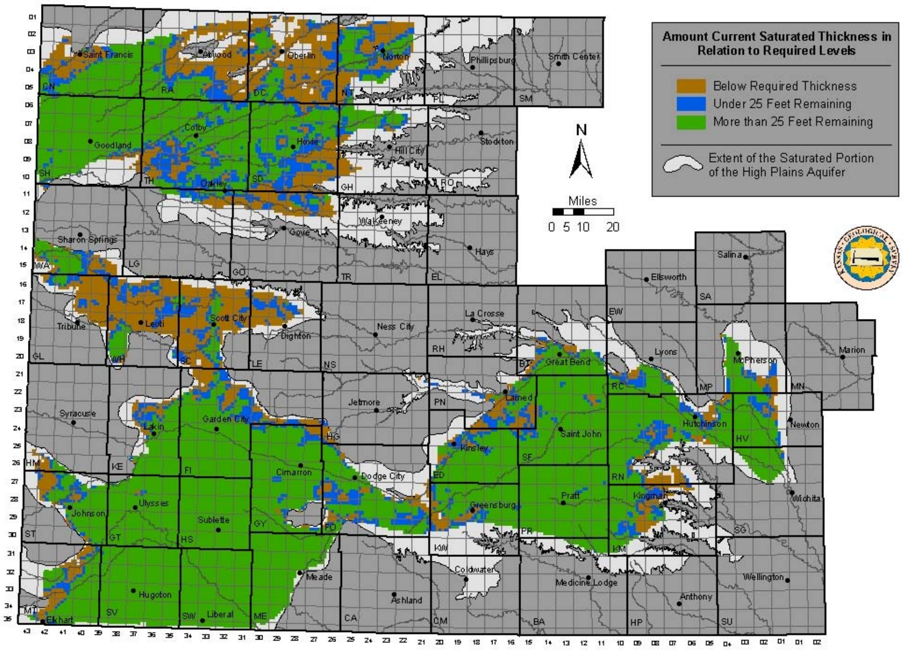


Figure 7: Estimates current saturated thickness in relation to minimum requirements necessary to support well yields at 400 gpm (based on 90 days of pumping with wells on ¼ section centers).

Estimated Current Saturated Thickness in Relation to Minimum Requirements
Necessary to Support Well Yields at 1000 gpm
(Based on 90 days of pumping with wells on 1/4 section centers)

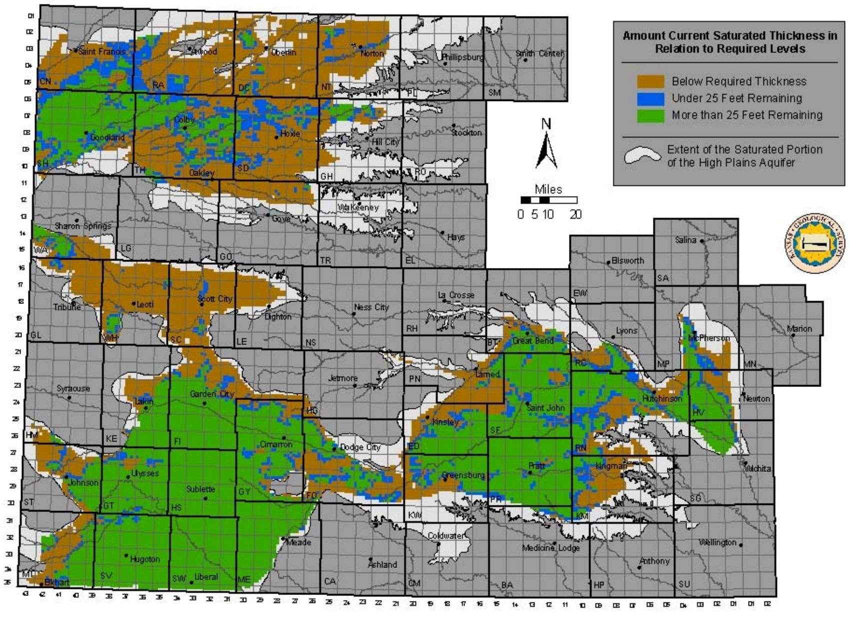


Figure 8: Estimates current saturated thickness in relation to minimum requirements necessary to support well yields at 1000 gpm (based on 90 days of pumping with wells on ¼ section centers).

4. Impact of Geologic Framework on Estimation of Ogallala Aquifer Hydraulic Conductivity Values

Efforts are underway to assess the influence of sediment heterogeneity on the variation in Ogallala aquifer hydraulic conductivity, the occurrence of semi-confined areas, and the pattern of water-level declines. Information resulting from this study will have implications for fine-scale definition of aquifer subunits and the tailored management plans to be developed once the subunits have been identified.

The study relies on using well-log information in the publications and files of the Kansas Geological Survey and the WWC-5 well-record database. Most of the raw data used in this study comes from the WWC-5 database, which requires careful screening before it is used. The only logs used are those where it is evident that the bedrock surface was encountered during the borehole drilling. Another criterion used to screen the logs is the amount of detail presented in the log. Logs are not used where the descriptions of the drill cuttings or the behavior of the rig during drilling is sketchy or vague. Where there is information from nearby test holes drilled by the KGS, comparisons are made with the WWC-5 logs to assess consistency in description and to assist in log interpretation. The locations entered on the WWC-5 forms are checked for consistency with the directions provided to the nearest town or the street address provided. None of the wells with WWC-5 records used to date have been field-checked for location or to determine land-surface elevation of the well site.

Initial work has been completed only in and a 9-township study area centered on the eastern Sherman County area. Logs from 6 KGS boreholes and over 500 WWC-5 well records were available from this 9-township area. Out of the 500 WWC-5 records only 188 logs were found to be minimally suitable for subsurface characterization of the Ogallala aquifer. This smaller number of logs is probably not sufficient to characterize the geologic framework at the scale of the radius of influence of a pumping well. However, if the logs of wells not penetrating bedrock are included, the usable information would double and it is likely that the additional data would allow a finer-scale characterization.

4.1 Preliminary Results

The 188 WWC-5 and the 7 KGS test-hole logs were examined to estimate the depth to bedrock from land surface, the sand and sand & gravel fractions, the total number and the occurrence of caliche and cemented sand and sand & gravel zones within the Ogallala. Because of the variability in lithologic descriptions and the tendency toward lumping lithologies for a given depth interval on the WWC-5 log, a system was devised to assist in the consistent interpretation of the driller's descriptions and apportionment of interval thickness according to lithology (Table 2). In most cases, the level of detail presented in the WWC-5 logs is generally indicated by the total number of entries made by the driller. In Figure 9, the total number of entries does not seem to noticeably increase with depth for logs where the total borehole depth is less than about 225 ft. Interestingly, there seems to be a general trend toward increasing information for borehole depths greater than 225 ft.

Table 2. Interpretation of WWC-5 driller's log entries and translation into standard lithology descriptions.

Sandy Clay	70% clay and 30% sand
Rock layer Sand rock, hard Sand rock strips Sandstone Cemented sand & gravel	Caliche/Cemented sand & gravel
Clay rock Oker and shale Ochre and shale	Pierre Shale bedrock
Soapstone	Silt or weathered shale
Sand & gravel with layers of clay	70% sand & gravel and 30% clay
Clay & layers of sand rock	Clay (90%) interbedded with caliche/cemented sand (10%)
Sand and clay strips	Interbedded sand (60%) and clay (40%)
Sandy clay and sand strips	Interbedded sand (58%) and clay (42%)
Good sand	Medium- to coarse-grained sand and granule- to pea-size gravel
Joint clay	Compacted clay
Fine to medium sand and gravel with clay lens	80% sand & gravel and 20% clay
A, B (as a list)	60% A and 40% B
A,B,C (as a list)	50% A, 30% B, and 20% C

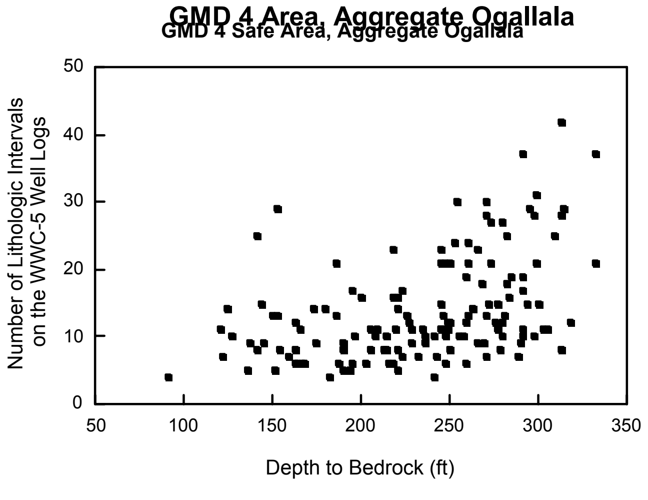
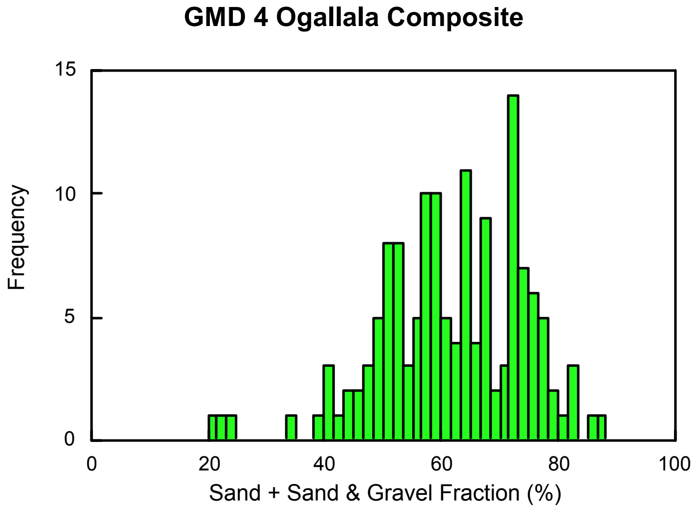


Figure 9: Lithologic intervals recorded on WWC5 well logs as a function of depth to bedrock in the Sherman County study area of GMD4.

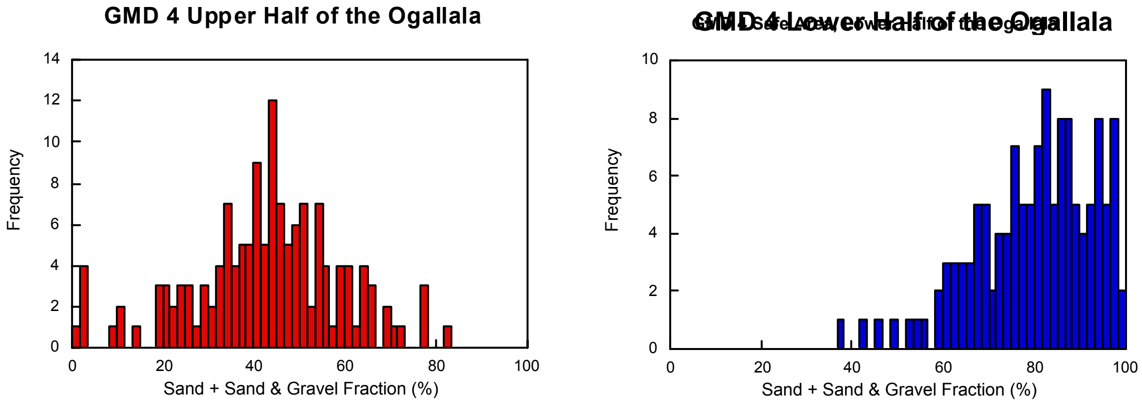
Within the study area, the sand + sand & gravel fraction of the Ogallala aquifer ranges from about 20% up to slightly less than 90%, with an average of about 60% (Figure 10). Together, Figures 10 and 11 show that most of the sand + sand and gravel is in the lower half of the aquifer over most of the study area. Figure 12 shows that there appears to be no difference between the level of detail provided on the log and the sand + sand & gravel fraction. Also, there does not seem to be any relationship between Ogallala thickness (depth to bedrock) and the sand + sand & gravel fraction (Figure 13).

An analysis of the logs also shows that the number of cemented sand and caliche layers reported on the logs is directly related to the level of detail presented on the logs, as might be expected (Figure 14). The analysis also shows that the frequency of occurrence of caliche varies widely, but is greater for the lower half than for the upper half (Figures 15 and 16).



GMD 4 Ogallala Composite

Figure 10: Frequency of occurrence of sand and sand + gravel layers as a percentage of the total Ogallala section in WWC5 well logs from the GMD4 Sherman County area.



GMD 4 Upper Half of the Ogallala

GMD 4 Lower Half of the Ogallala

Figure 11: Frequency (as percentage of the total Ogallala section) of sand and sand + gravel layers in the upper (left) and lower (right) halves of the Ogallala deposits in the GMD4 Sherman County area.

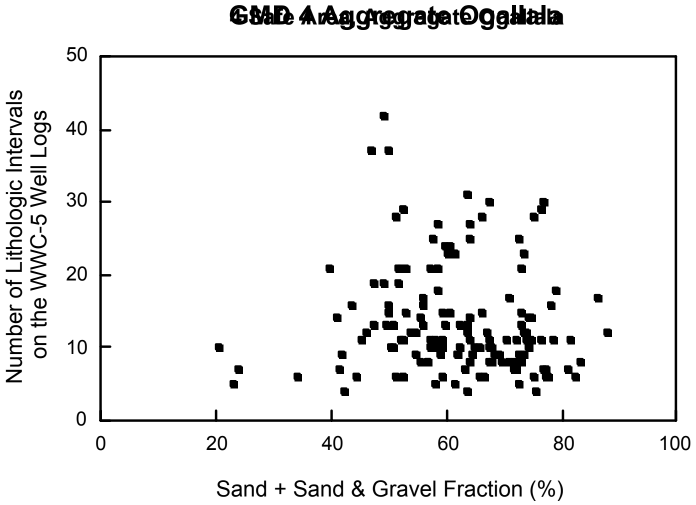


Figure 12: Percentage of sand and sand and gravel reported in WWC5 well logs for the GMD4 Sherman County area as a function of the number of lithologic intervals logged.

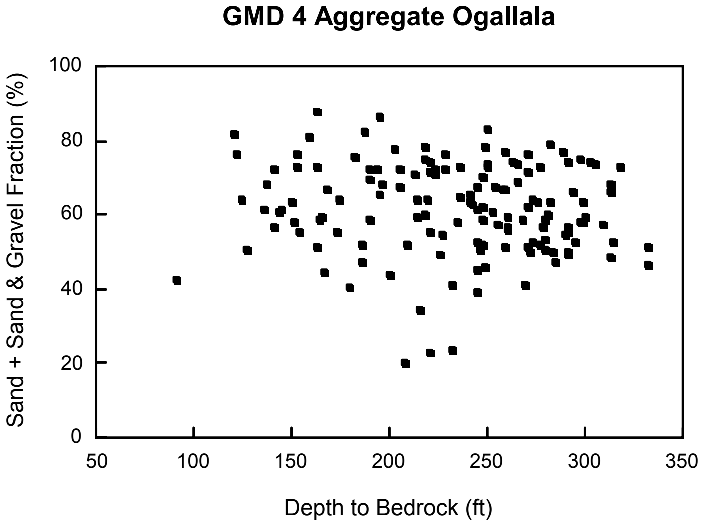


Figure 13: Percentage of sand and sand and gravel reported in WWC5 well logs for the GMD4 Sherman County area as a function of the depth to bedrock.

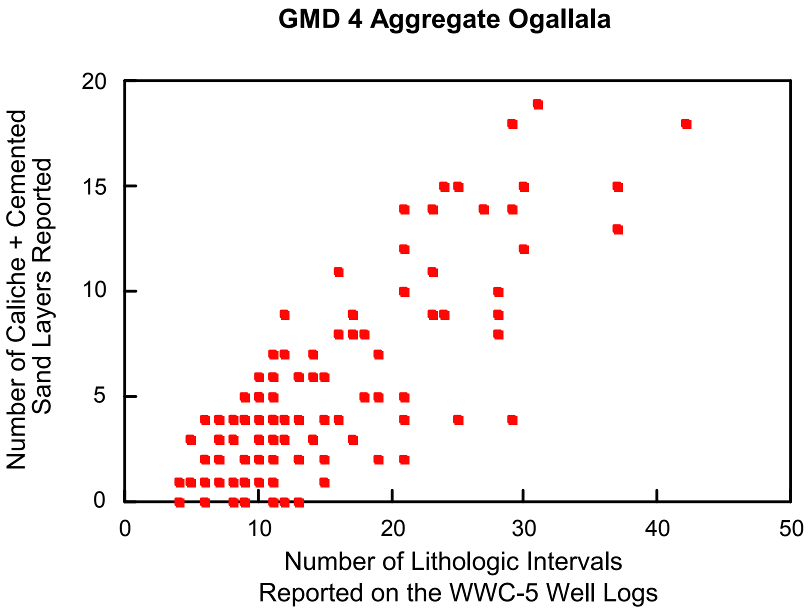


Figure 14: Percentage of sand and sand and gravel reported in WWC5 well logs for the GMD4 Sherman County area as a function of the number of lithologic intervals reported in WWC5 well logs for the GMD 4 area.

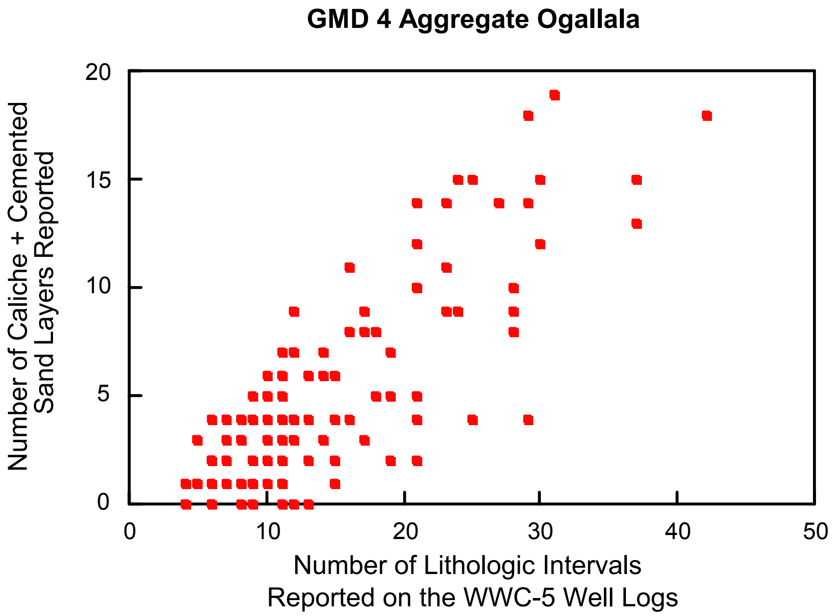


Figure 15: Incidence of caliche and cemented sand layers (x-axis = number of layers) plotted as a function of the number of lithologic intervals reported in WWC5 well logs for the GMD 4 Sherman County area.

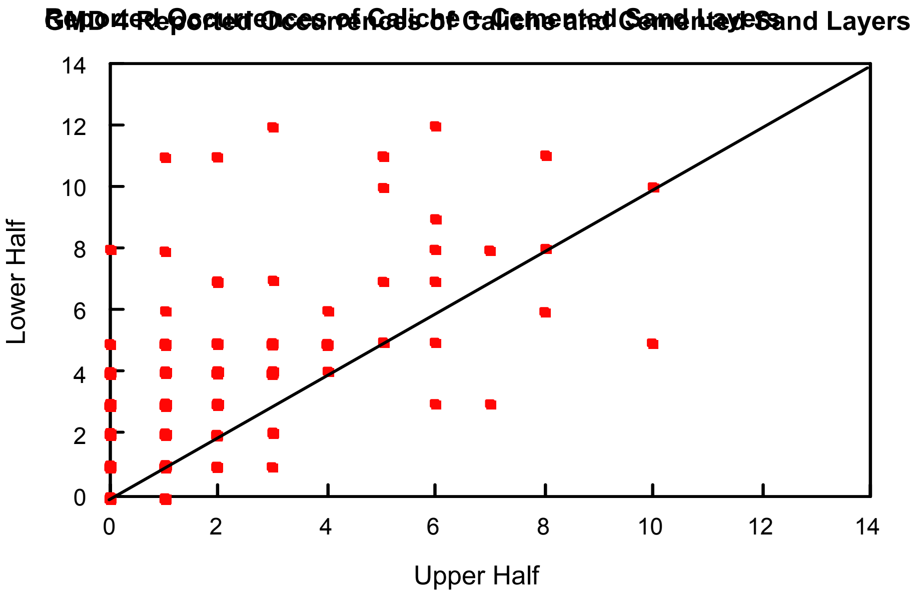


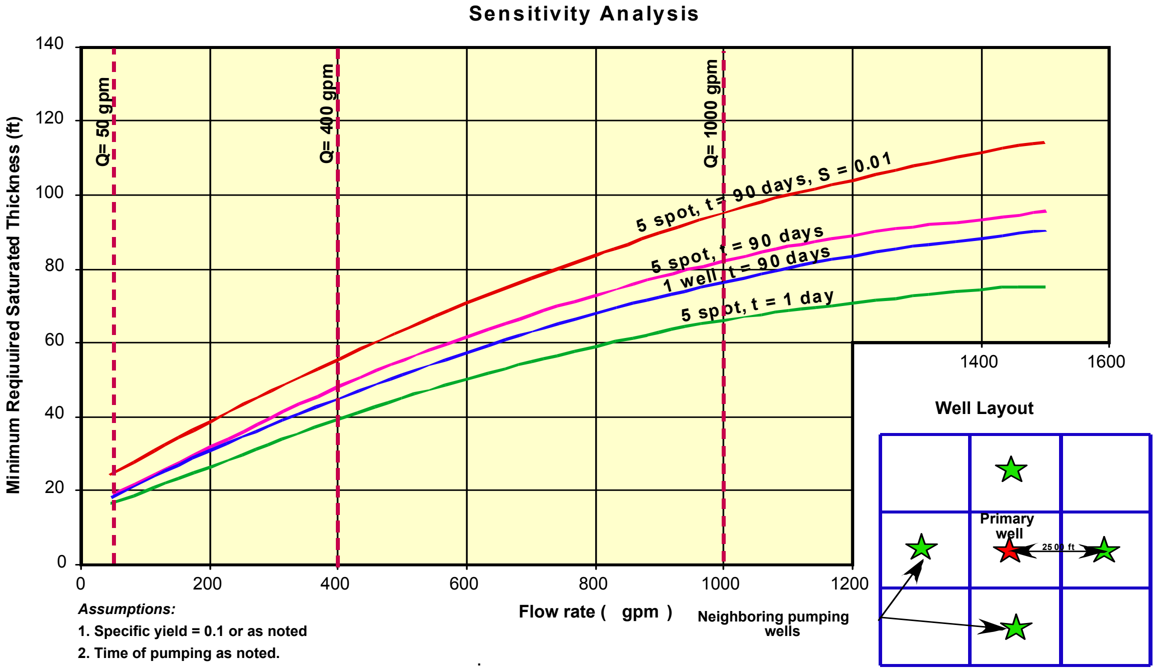
Figure 16: Incidence of caliche and cemented sand layers (x-axis = number of layers) plotted with respect to their occurrence of in the upper or lower half of the logged section. From WWC5 well logs for the Sherman County area in GMD 4.

5. Data limitations and applications

In order to assess the applicability of the preceding theoretical calculations, a sensitivity analysis of a few of the variables was performed. The time of pumping, number of surrounding wells, and specific yield (storage coefficient) were changed for this analysis. The results are presented in Figure 17.

For the sensitivity analysis, the hydraulic conductivity was kept at a constant value of 100 ft/d. Figure 18 and Table 3 (located at end of paper) present the data and histogram of hydraulic conductivity values compiled from GMD4. Figure 18 is a cumulative plot of hydraulic conductivity values on a linear scale; and figure 19 is a simular plot of specific yield values. Figure 20 presents the hydraulic conductivity data on a logarithmic scale, and shows that the reported hydraulic conductivity values from the pumping tests are log-normally distributed. The value of hydraulic conductivity chosen for the sensitivity analysis is slightly higher than the estimated geometric mean value of 86 ft/day from the pumping tests. The wide range in reported values (19 ft/day to 735 ft/day) is, at least in part, a reflection of the lithologic heterogeneity of the Ogallala aquifer in GMD4. This heterogeneity is demonstrated by the variability in the sand + sand and gravel fraction (Figs. 10 and 11) in the 9 townships investigated around the Sherman County area.

As shown on the figure, at 400 gpm there is about a 15-foot difference between the thinnest and thickest saturated thickness required. At 1000 gpm, there is a difference of about 30 feet. A lower specific yield may be more applicable because most of the pumping tests in GMD-4 where observation wells were available had apparent short-term specific yield values between 0.01 and 0.1 (Table 3, Figure 19).



Assumptions:

1. Specific yield = 0.1 or as noted
2. Time of pumping as noted.
3. Well efficiency = 50%
4. Hydraulic conductivity = 100 ft/d
5. Cooper-Jacob or polynomial approximation of Theis equation used for calculations

Figure 17. Sensitivity analysis for single well and section-centered cases.

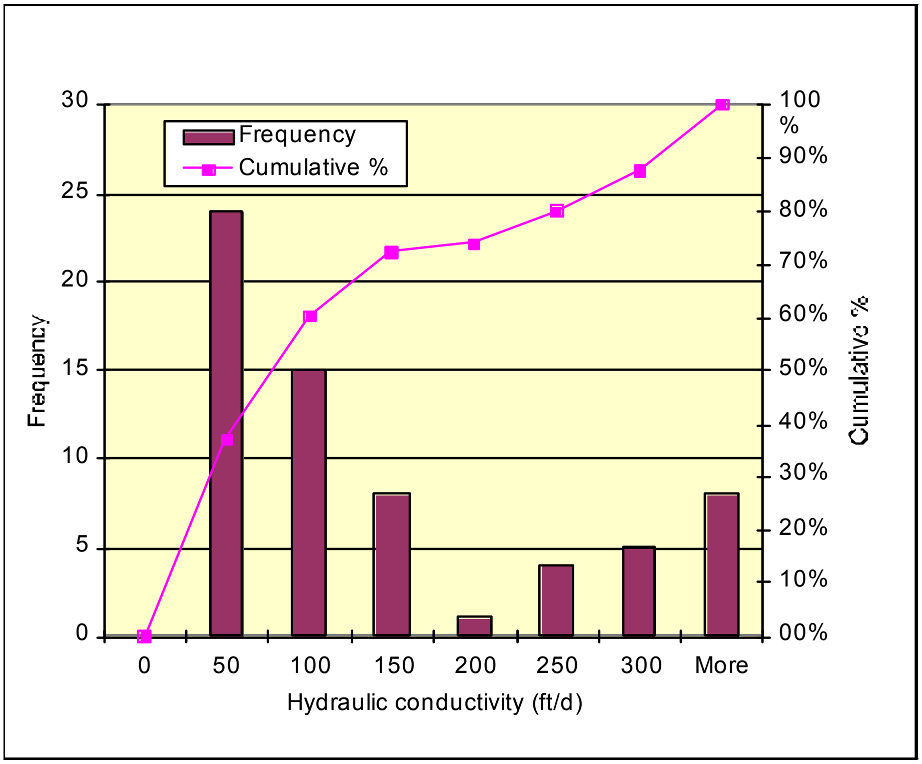


Figure 18. Hydraulic conductivity histogram for GMD4 (based on pump test data; see table 3 at end of report), with a linear plot of cumulative conductivity values.

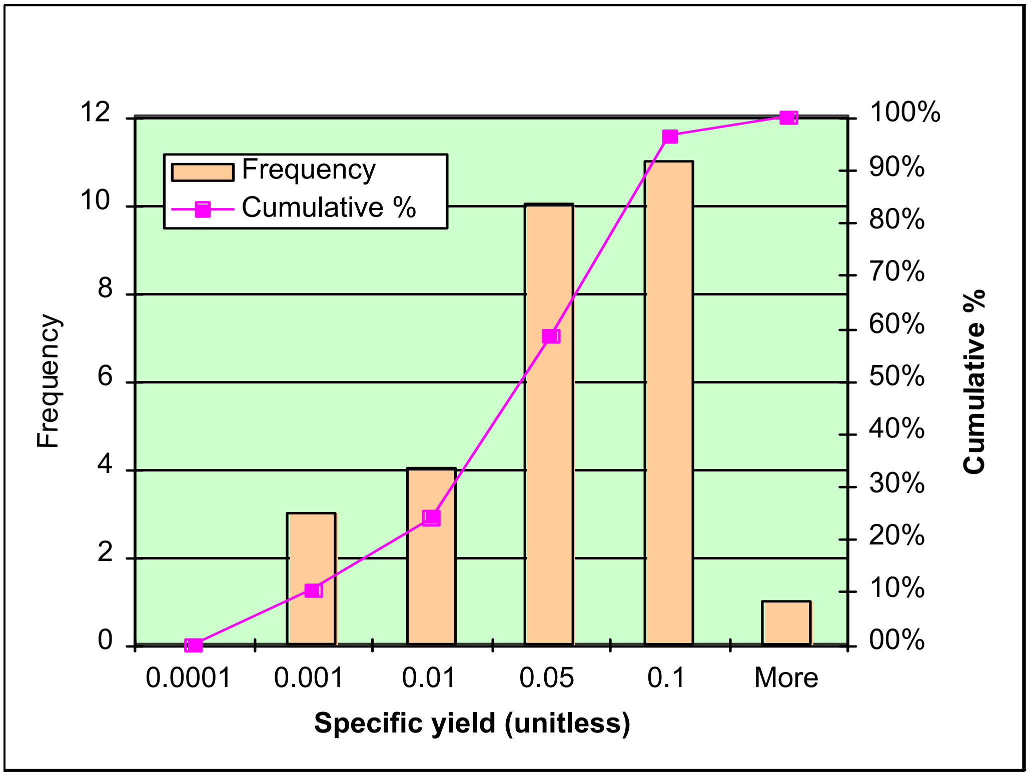


Figure 19. Specific yield histogram for GMD4 (based on pump test data; see table 3 at end of report), with a linear plot of cumulative conductivity values.

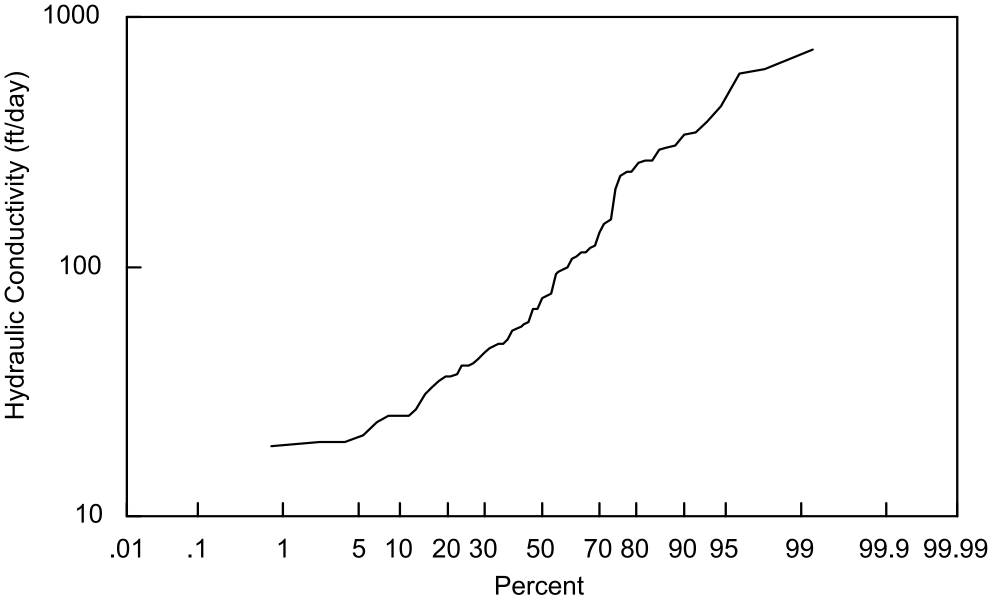


Figure 20: Logarithmic plot of pump-test hydraulic conductivity (K) in GMD4, showing that K is log-normally distributed (data from table 3).

It should be noted that the results presented probably represent a somewhat optimistic case, in that actual observed field results may indicate that the saturated thickness required to sustain a given well yield are actually greater than those shown. There are several reasons for this:

- The above calculation ignored drawdown resulting from repeated pumping; i.e. the calculation assumed that the aquifer completely recovered before the well was pumped again. Including this would increase the required saturated thickness for all three conditions.
- The calculation assumed that there was only drawdown interference from four neighboring wells. Including additional wells or wells distributed over a larger area would increase the required saturated thickness.
- The specific yield in an area may be less than that used, compounding the interference between wells.
- The well efficiency was assumed to be 50%. This is a reasonable assumption for a 10-year old well. Generally, as wells age the efficiency declines and the required saturated thickness would increase.

The present understanding of the distribution of aquifer characteristics such as hydraulic conductivity and specific yield, which are needed for refined estimation the relationship between well yield and saturated thickness, is suitable only for initial identification of aquifer subunits and management approaches. Detailed application to the management of priority subunits will require local refinement of aquifer characterization.

6. Policy and management implications

Results from these theoretical calculations between well yields and saturated thickness are important for management considerations in terms of the potential future use of the aquifer. As the physical amount of water stored within the aquifer area is reduced and large volume water demands cannot be fully satisfied, both the estimated rate of water decline and potential water uses can be better evaluated if well yields are considered.

A second implication of these results is that the earlier estimates of the usable lifetime of the aquifer (Schloss et al., 2000; see also OFR 2002-25D) for large volume pumping demands are unrealistically long. The primary assumption used in those estimates was that thirty feet of saturated thickness is an approximate value at which large volume pumping is likely to become impractical. Results from this report suggest large volume water demands will be impaired if not curtailed when the saturated thickness of the aquifer approaches forty to fifty feet.

7. Potential for improved data or applications.

In order to improve on the preceding theoretical estimates, the following are recommended:

- Field observations of actual irrigation well drawdown and yield should be obtained for critical areas of the High Plains aquifer. This could be done using a subset of the existing Wizard water level wells that are monitored in January of each year. By monitoring these same wells in July or early August when they are pumping, the well drawdown can be measured. For wells with meters the flow rate would be measured at the same time. These data would allow for determination of the actual well drawdown while pumping, calculation of specific capacity (Q/s), and an estimation of transmissivity and hydraulic conductivity at each well location.

- Analysis of the distribution of lithologies within the Ogallala-High Plains at a more local scale than is currently available from the USGS will be needed in order to improve estimation of aquifer hydraulic conductivities at scales appropriate to aquifer subunits (radius of influence of a pumping well up to township scale).

- A database of aquifer tests such as has been compiled for GMD-4 (Table 3) should be assembled for the other GMDs. This would improve the estimates of the hydraulic parameters used in this calculation and allow for better sub-regional estimates of the hydraulic parameters used.

- A well-field simulator should be constructed for each GMD that allows consideration of the effects of all of the actual pumping wells in critical areas of interest. Such a well-field simulator could be developed using analytical element methods and are implemented in the free software VisualBlueBird (http://www.groundwater.buffalo.edu/software/software.html, June 24, 2002) and other software packages. This would allow individual GMDs to evaluate their own areas and assess the potential impacts of management modifications.

References

Abramowitz, M. and Stegun, I.A., 1972, Handbook of Mathematical Functions, Dover Publications, Inc. New York, 1046 p.

Cederstrand, J.R. and Becker, M.F., 1998, Digital Map of hydraulic conductivity for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, U.S. Geological Open File Report 98-548.

Cooper, H.H. and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history, Transactions of the American Geophysical Union, v. 27, pp. 526–534

Driscoll, F.G., 1986, Groundwater and Wells, Johnson Division, St. Paul, MN, 1089 p.

Schloss, J. A., Buddemeier, R. W., and Wilson, B. B. (eds.), 2000. An Atlas of the Kansas High Plains Aquifer, http://www.kgs.ukans.edu/HighPlains/atlas/, and also published as Educational Series 14, Kansas Geological Survey, Lawrence, KS, 90 pp.

Theis, C.V., 1935, The relations between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Transactions of the American Geophysical Union, v. 2, pp. 519–524

Table 3. Pump test results compiled forGMD-4. Original source Wayne Bossert, GMD-4 manager.

Well Number	CTY *3/*	Principal Aquifer *1/*	Depth of Well (ft) *2/*	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) *4/*	Hydraulic conductivity (ft/d) *4/*	Storage Coefficient (Specific Yield) *4/*	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
1-26-17caa	DC	Qal	50	19	31	105	7	15.0	68	2,273	119				5/10/66
1-29-30bdd	DC	Qal	75	46	29	1450			24	13,369	303	0.02		1700	1962
1-38-2cdc	CN	Qal	41	18	23	485	9	53.9	73	14,706	735	0.07		1050	4/7/67
2-27-7dca	DC	Qal	75	36	39	960	11	87.3	3	10,027	294	0.06		1250	4/13/67
2-31-9bda	RA	Qal	40	29	11	440	24	18.3	48	8,690	348	0.01		2800	7/25/67
2-36-18ccb	RA	To	300	76	222	445	37	12.0	123	6,016	78	0.05			7/8/66
3-28-32bca	DC	To	205	70	134	435	53	8.2	44	1,337					7/27/67
3-29-21bad	DC	Qal	62	39	22	1500			24	16,043	382	0.02			8/1/62
3-33-3dcc	RA	Qal	68	37	25	625	27	23.1	190	7,353	230	0.015	.01-.02	450	4/16/68
3-36-27cbb	RA	To	299	129	167	1000	56	17.9	1150	5,682	43			1700	3/29/67
3-40-28abc	CN	Qal, To	24	17	7	165	15	11.0	Many Days	5,080	299				1965
4-26-8ddd	DC	Qal	70	38	32	460	18	25.6	168	5,882	155	0.004		1450	6/26/68
4-37-17aac	CN	To	342	138	187	850	53	16.0	90	3,476	25	0.08			5/31/66
4-38-4bac	CN	To	330	115	212	810	54	15.0	815	3,877	33	0.02			7/22/67
4-39-21dbd	CN	To	268	122	145	640	56	11.4	288	2,807	24	0.09		700	7/12/67
4-41-16daa	CN	Qal	38	20	18	235	33.8	7.0	141	6,818	341	0.006		1300	7/3/68
4-42-26bda	CN	Qal, To	50	28	22	560	27	20.7	6	7,353	267				9/15/50
4-42-26dbc	CN	Qal, To	36	29	7	630	12	52.5	5	17,112	590				8/5/65
4-42-26dbc	CN	Qal, To	36	29	7	630	12	52.5	5	18,048	623				
4-42-27add	CN	Qal, To	54	27	27	235	10	23.5	18	4,011	148				1965
4-42-27add	CN	Qal, To	54	33	21	235	10	23.5	18	4,011	122				
5-28-5dcd	SD	Qal	58	29	22	800			24	9,358	267	0.03			1962
5-33-29bda	TH	To	115	96	19	600	25	24.0	360	5,348	56	0.03		940	3/14/68

Well Number	CTY *3/*	Principal Aquifer *1/*	Depth of Well (ft) *2/*	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) *4/*	Hydraulic conductiv-ity (ft/d) *4/*	Storage Coefficient (Specific Yield) *4/*	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
5-40-27aba	SH	To	333	158	174	925	35	26.4	610	3,075	20	0.06			7/1/66
5-40-27bba	SH	To	327	148	176	900	31	29.0	65	7,353	49				6/29/66
5-41-12adc	SH	To	315	115	198	680	62	11.0	112	5,573	48				4/18/67
6-27-3dbd	SD	Qal	92	63	27	195	20	9.8	23	2,005	31				5/13/66
6-29-5dcb	SD	To	212	89	121	725			240	8,690	95	0.02			7/5/66
6-30-14ccd	SD	To	205	100	103	470	76	6.2	47	2,941	27	0.07			6/2/66
6-32-29cdb	TH	To	204	92	112	820	69	11.9	17	10,027	110				4/4/66
6-33-33cab	TH	Qal	38	25	13	637	15.4	41.4	3	6,016	241				10/20/43
6-35-26acd	TH	To	260	113	147	485	?		1390	7,353	67	0.12			7/9/66
6-37-3bcc	SH	To	280	121	157	780			210	8,021	67				3/11/68
6-39-33bdd	SH	To	314	176	133	840	84	10.0							6/??/64
6-42-26baa	SH	To	303	108	195	870	41	21.2	120	4,947	45	0.08			6/24/66
7-26-28cab	SD	To	247	93	150	880	25	35.2	98	8,690	94				8/1/66
7-28-21aba	SD	To	254	122	130	1040	32.5	32.0	242	9,358	76	0.08		1950	7/3/68
7-31-26ccc	TH	To	177	72	105	588	42.1	14.0	3	7,086	99				10/19/43
7-32-7aca	TH	To	135	62	72	1021	18.1	56.6	3						10/16/43
7-33-10cbd	TH	To	195	67	127	295	26.3	11.2	4	4,011	60				10/18/43
7-33-35add	TH	To	265	133	132	970	28	34.6							7/21/67
7-34-25dbb	TH	To	197	99	98	600	22	27.3	340	11,364	115				8/27/66
7-36-17dad	TH	To	275	135	139	1080	80	13.5	725	5,348	40				3/28/67
7-39-20bad	SH	Qal, To	139	118	21	1170	16	73.1	4	52,941	441			220	7/29/49
7-40-6adb	SH	To	345	193	150	1080	70	15.4	625	8,690	49	0.08	.03-.13	4900	3/27/68
7-42-27aab	SH	To	321	180	141	770	33	23.3	950	4,144	25	0.03			3/9/67
8-26-16cdd	SD	Qal	72	35	35	270	6	45.0	44	8,690	241				5/16/66
8-26-21bab	SD	Qal	72	37	35	225	7	32.1	24	7,353	205				5/16/66

Well Number	CTY *3/*	Principal Aquifer *1/*	Depth of Well (ft) *2/*	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) *4/*	Hydraulic conductivity (ft/d) *4/*	Storage Coefficient (Specific Yield) *4/*	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
8-28-9abc	SD	To	206	114	119	403	63	6.4	8	6,684	59				10/8/52
8-30-13bba	SD	To	268	144	120	1100	41	26.8	2	6,684	47				4/21/66
8-33-2cda	TH	To	265	137	126	1800	51	35.3	1414	14,706	108	0.08		4600	2/14/67
8-33-34bcc	TH	To	227	110	117	1090	58	18.8	71	5,348	55				4/11/66
8-34-1bcb	TH	To	270	142	128	950									9/15/71
8-34-13cbd	TH	To	245	88	157	1000	18	55.6	170	12,032	136				4/25/66
8-37-28abc	SH	To	243	122	116	820	60.5	13.6	390	6,417	51	0.09		1100	6/29/68
8-39-15ccc	SH	To	254	127	127	640	32	20.0	10	4,545	36				8/4/49
8-39-15ccc	SH	To	254	127	127	640	32	20.0	4						
8-40-12dba	SH	To	247	117	122	315	9	35.0	4	4,813	41				7/27/49
8-40-12dbb	SH	To	306	162	140	710	68	10.4	175	12,032	75	0.005			7/7/66
8-40-29bbb	SH	To	280	193	85	290	44	6.6	28	6,684	35	0.001			7/16/66
8-40-35cbb	SH	To	274	140	132	600	27	22.2	140	3,610	25				6/25/66
8-42-19abb	SH	To	317	184	126	970	33	29.4	25	6,684	36				8/24/55
9-32-29adc	TH	To	220	105	110	720	63	11.4	190	5,348	58				8/18/66
9-35-32daa	TH	To	238	48	187	390			620						4/1/67
9-41-31aba	SH	To	265	148	112	830	49	16.9	290	17,380	114	0.0003		740	6/27/68
9-42-16cdd	SH	To	296	174	117	655	58	11.3	670	7,019	40	0.00055	.0003-.0008		7/14/65
10-27-20bcd	GO	Qal	68	23	45	380	18	21.1	168	3,342	98	0.02		?	1/25/68
10-31-28bcc	GO	To	185	109	74	1080	45	24.0	10	2,273	21				8/18/66
10-32-11baa	LG	To	185	79	106	290	49	5.9	69	1,471	19				8/3/66
10-39-25cca	SH	Qal	40	21	19	220	8	27.5	217	5,214	261				5/11/66
10-42-13acc	SH	To	203	95	82	1010	85	11.9	90	3,610	37				6/28/66

Well Number	CTY *3/*	Principal Aquifer *1/*	Depth of Well (ft) *2/*	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) *4/*	Hydraulic conductiv-ity (ft/d) *4/*	Storage Coefficient (Specific Yield) *4/*	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
10-42-24bba	SH	To	205	119	83	1030	75	13.7	20	2,406	20				6/28/66
11-26-4cdc	GO	To	167	130	60	700									7/2/70
Average Values:								24.1		7737	140	0.043			

FOOTNOTES:

1/ = Geologic Source: Qal = Alluvium; To = Ogallala Formation

2/ All depths are feet below ground surface

3/ CTY= Counties, CH= Cheyenne, DC=Decatur, GO=Gove, LO=Logan, RA=Rawlins, SD=Sheridan, SH=Sherman, TH=Thomas

4/ =Average value for test results