RESEARCH EXPERIENCES FOR
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Characterizing Hydraulic Conductivity in the Lower Arkansas Basin

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Abstract

Saline high water tables are a worldwide problem associated with agricultural irrigation. The lower Arkansas Basin in southeastern Colorado is a good example of an irrigated alluvial valley affected by saline high water tables. This study is part of a project that intends to use well-conceived data collection and modeling to develop strategies to sustain irrigated agriculture in this region. It is necessary to understand the distribution of the region's hydraulic conductivity in order to effectively model groundwater flow in the area. In this study, 96 wells were examined and 47 slug tests were performed to examine the region's shallow-aquifer hydraulic conductivity, *K*, which was found to be lognormal distributed with a mean of 6.29 m/d and standard deviation of 59.69 m/d. Values of hydraulic conductivity in the deeper portions of the aquifer are roughly two orders of magnitude greater than the shallow-aquifer *K* values measured in the slug tests. The data gathered and analyzed in this study can be used to better understand the drainage properties of the lower Arkansas River Basin and will help lead to development of accurate models which will be used to develop solutions to the problem of saline high water tables.

Introduction

Salinization and waterlogging are two of the biggest problems associated with irrigated agriculture. Intensively irrigated alluvial valleys usually experience salinity and drainage problems a few decades to a hundred years after the implementation of large-scale irrigation practices. These problems arise because water is applied to the land at a rate exceeding the natural rate of drainage, thereby causing the water table to rise. Additionally, the salts dissolved in the irrigation water are not consumed by plants and are left to accumulate in the soil. As these processes continue over the course of decades, the threat of saline high water tables increases.

Saline high water tables affect about 20-25% of the world's irrigated land, including 27% of the United States' irrigated land. Salinization of the soil is devastating to agriculture—when salinity levels exceed a crop's tolerance, the crop can no longer grow and the resulting loss of production is very costly. It has been estimated that $10 billion per year is lost to this problem worldwide (Gates et al. 2002).

The lower Arkansas Basin in southeastern Colorado has been irrigated since the 1870s. Saline high water tables began to develop in the early part of the 20th century. Subsurface drains were installed in the 1930s and these seemed to remedy the problem for a while, but conditions have worsened since the 1970s.

This project intends to use well-conceived data collection and modeling to develop strategies to sustain irrigated agriculture in this region. Additionally, this project addresses a basin-wide objective of enhancing the riverine environment, thereby addressing the problems of both the land and the river. Data on the water table, soil salinity, surface water, and many other parameters are being collected in an attempt to get a comprehensive portrait of the region. This study is unprecedented in scope and purpose and will continue for years to come.

One of the characteristics of the aquifer necessary to understand the region and to develop working models is hydraulic conductivity, a measure of water's ability to flow through soil. This study experimentally measures the distribution of hydraulic conductivity in the study area. An understanding of the hydraulic conductivity is essential for the description of regional groundwater flow. It is also necessary for the prescriptive purpose of modeling how the current conditions would change as the result of various actions. This information should bring about a better understanding of the drainage properties of the lower Arkansas River Basin, which in turn will help to determine the best method to approach the problem of saline high water tables.

Scientific Background and Theory

Hydraulic conductivity is a measure of water's ability to flow through soil, as described by Darcy's Law, the governing equation of flow through soil:

$$q = -KJ \tag{1}$$

where q is the specific discharge [m/day], K is the hydraulic conductivity [m/day], and J is the hydraulic gradient [m/m]. Hydraulic conductivity is a function of both fluid properties and the soil type. Clay soils typically have K values of $<10^{-2}$ m/d, while values for medium sand range from 0.1 – 50 m/d and coarse gravel can have K values from 860 – 8,600 m/d (Chin 2000).

Hydraulic conductivity can be measured experimentally by performing a slug test. A slug test is performed by evacuating a volume of water from a well (a "slug" of water), thereby creating a hydraulic gradient between the water level in the well and the surrounding water table. The recovery of the water level in the well is monitored and can be related to the hydraulic conductivity of the aquifer in the vicinity of the well. The field setup for a slug test is shown in Figure 1:

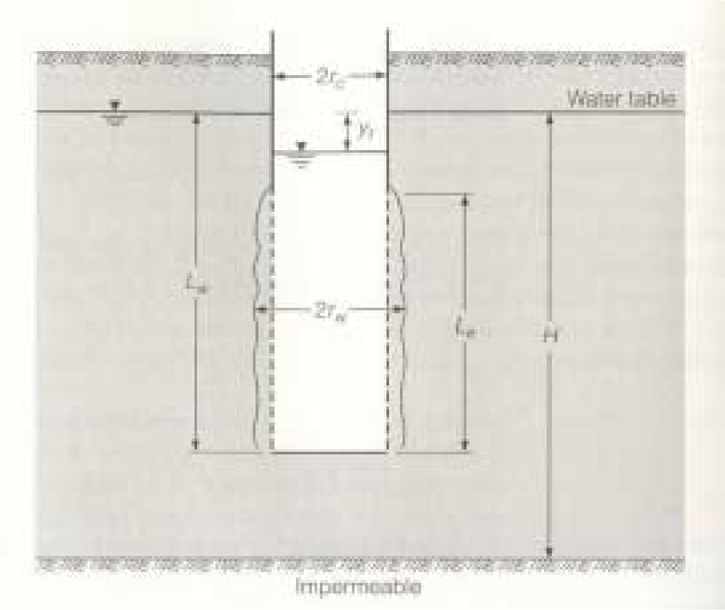

Figure 1: Field Setup for a Slug Test (Chin 2000)

The most widely-used slug-test procedure was develop by Bouwer and Rice (1976). The basis of this approach is the Thiem equation, which can be put in the form

$$y = \frac{Q_w}{2\pi K L_e} \ln\left(\frac{R_e}{r_w}\right) \tag{2}$$

where y is the drawdown at the well, Q_w is the rate at which ground water is removed from the aquifer, K is the hydraulic conductivity, and R_e is the effective radial distance over which the head y is dissipated. Because the flow rate into the well, Q_w, equals the rate at which the volume of water in the well increases,

$$\frac{dy}{dt} = -\frac{Q_w}{\pi r_c^2} \tag{3}$$

Combining these equations and solving for K yields

$$K = \frac{r_c^2 \ln\left(R_e/r_w\right)}{2L_e}\frac{1}{t}\ln\frac{y_0}{y_t} \tag{4}$$

where y_0 is the initial drawdown in the well and y_t is the drawdown at time t. The effective radial distance, R_e, for a partially penetrating well can be estimated using the following empirical relation:

$$\ln\frac{R_e}{r_w} = \left\{\frac{1.1}{\ln\left(L_w/r_w\right)} + \frac{A + B\ln\left[\left(H - L_w\right)/r_w\right]}{\left(L_e/r_w\right)}\right\}^{-1} \tag{5}$$

where A and B are dimensionless parameters related to L_e / r_w as shown in Figure 2:

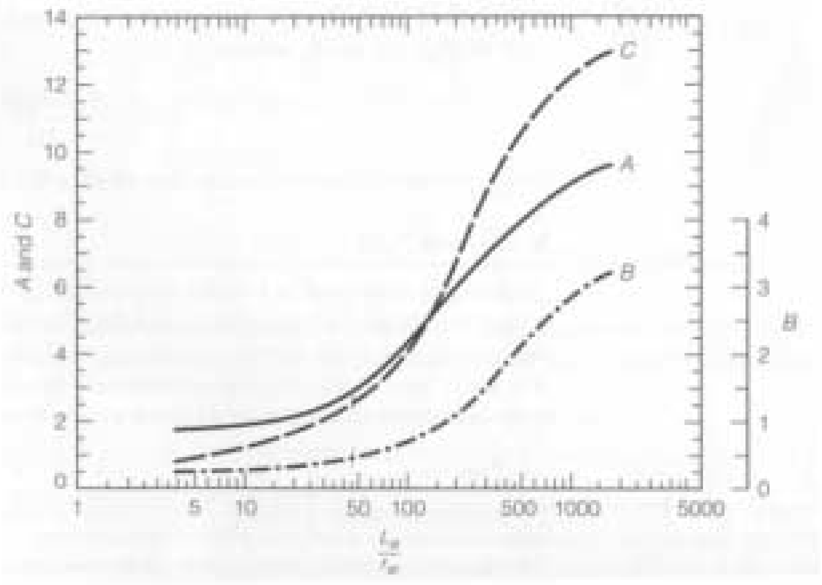

Figure 2: Parameters in Slug Test Analysis (Chin 2000)

Experimental data from slug tests consists primarily of measurements of the well properties (r_c, r_w, and L_e) and the drawdown, y_t, as a function of time, t. These data are used with Equation 4 to estimate hydraulic conductivity. First, the measured data of ln y_t vs. t are plotted. A straight line is fitted through the linear portion of the plot and the slope, m, of that line is determined. Values for A and B are determined from Figure 2, and the value of $\ln(R_e/r_w)$ is calculated using Equation 5. The hydraulic conductivity, K, is then calculated as

$$K = -\frac{r_c^2 \ln\left(R_e/r_w\right)}{2L_e} m \qquad (6)$$

Method

The study area for this portion of the project is the alluvial aquifer of the Arkansas River valley extending from Lamar, Colorado to the Kansas border. In this region, 96 monitoring wells with depths ranging from about 3 to 8 meters below the ground surface were examined. Roughly half of the wells were dry and could not be tested. Figure 3 is a satellite image of the study area. It is a “false-color image,” wherein irrigated areas appear to be red. The gridded area is the study section; the Arkansas River flows through this area. Lamar is located at the southwest corner of the study area and the Kansas border is the vertical edge on the eastern side of the study area. The small yellow crosses are wells that were tested; the green markings represent locations for which the depth to bedrock is known. The blue markings represent locations where the hydraulic conductivity of the deeper portions of the aquifer is known.

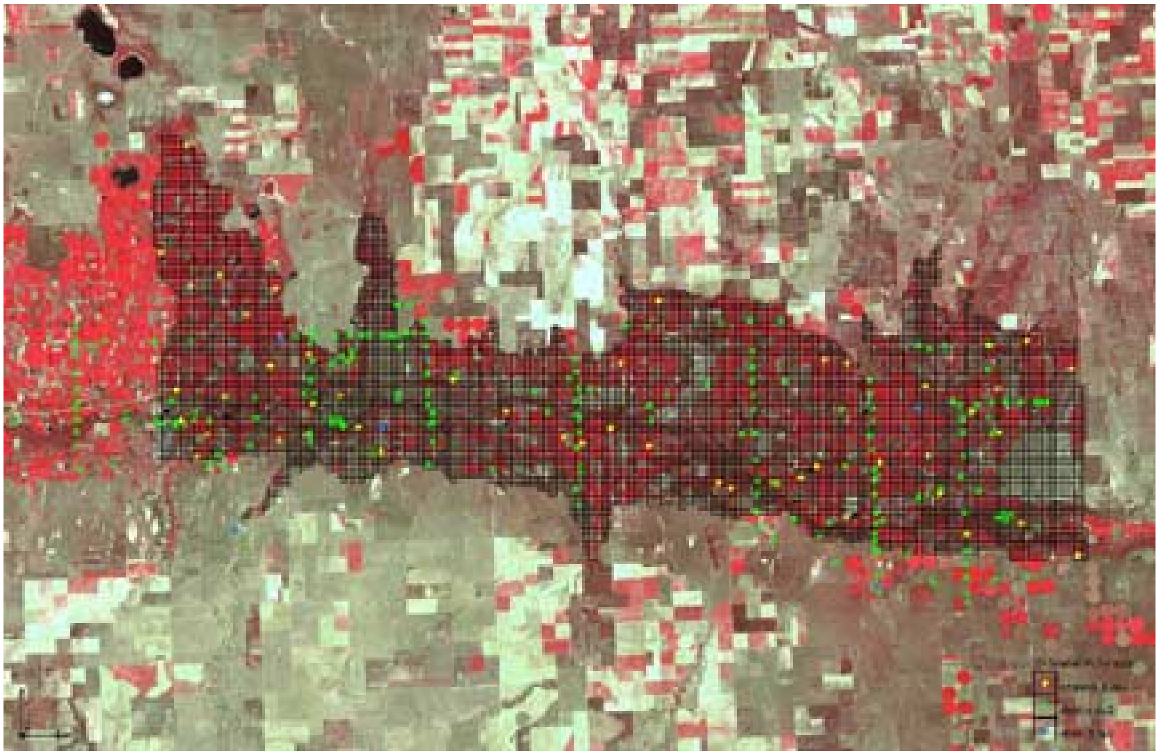

Figure 3: Arial view of the downstream study section

The wells that were not dry were initially bailed once with a bailer, a plastic tube that collected some water and excess sediment from the bottom of the well. The purpose of this bailing was to remove excess sediment from the bottom of the well to help minimize the negative effects it would otherwise have on the pumping and monitoring equipment. After bailing, each well was allowed at least 1-2 hours for the water level in the well to recover to its original level.

After recovery of the well, the depth of the casing was measured using an engineer's measuring tape with a weight (in this case, a padlock) attached to the end of the tape. Additionally, the depth to water was measured using another measuring tape with a carefully calibrated float attached to its end. The height of the casing above ground level and the inner diameter of the casing were also measured.

Once these measurements were taken, a Druck PDCR 1830-8388 pressure transducer was lowered into the well until it reached the bottom of the casing or could not otherwise go any deeper. This pressure transducer measured gauge pressure and was connected to a Campbell Scientific 21X Micrologger that took a measurement every half-second. A program that converted the output from the pressure transducer into the depth of water in feet above the transducer probe was loaded into the datalogger. This setup is shown in the photograph in Figure 4.

Figure 4: Slug Test Equipment

With the pressure transducer already at the bottom of the well, a small, battery-operated pump was lowered into the well. This pump was used to evacuate as much water as possible from the well. The water in some wells had too much sediment to be pumped, clogging the pump and making the well not testable. For wells that could be tested, the pump was immediately removed after the water was evacuated.

The pressure transducer measured and recorded the recovery of the water level in the pumped wells for up to thirty minutes after the pumping was completed. The thirty-minute time limit became necessary because the datalogger would begin to run out of free memory after taking measurements every half-second for that amount of time. However, if the well had completely recharged in a shorter amount of time, as was often the case, the pressure transducer was removed sooner. Once all measurements at a well had been taken, the data was uploaded to a laptop computer brought to the site. Finally, after the test was completed, the casing depth and depth to water level were measured again to ensure that the pressure transducer readings remained accurate throughout the duration of the test.

Results

For the purposes of an example, the method of analyzing the data acquired in each slug test is shown below for well 345. A summary of all calculations can be found in Appendix A.

The drawdown, y_t, at each half-second measurement interval is calculated by subtracting the depth of water measured by the pressure transducer from the initial depth of water in the well before pumping. Then, a plot of ln y_t vs. elapsed time t is created, as shown in Figure 5:

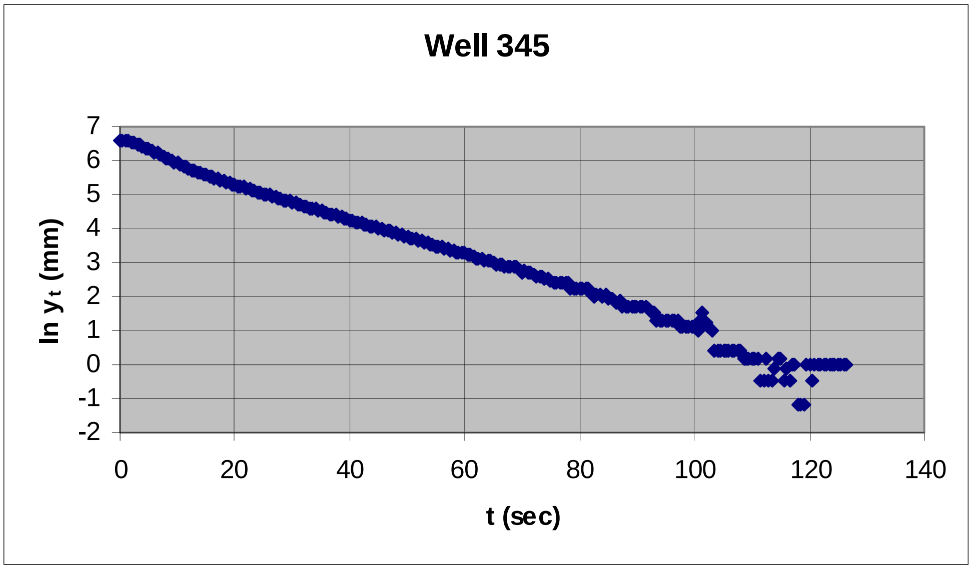

Figure 5: Initial plot of ln y_t vs. t (Well 345)

As expected, the graph is linear. A line is then fitted to the plot as shown in Figure 6:

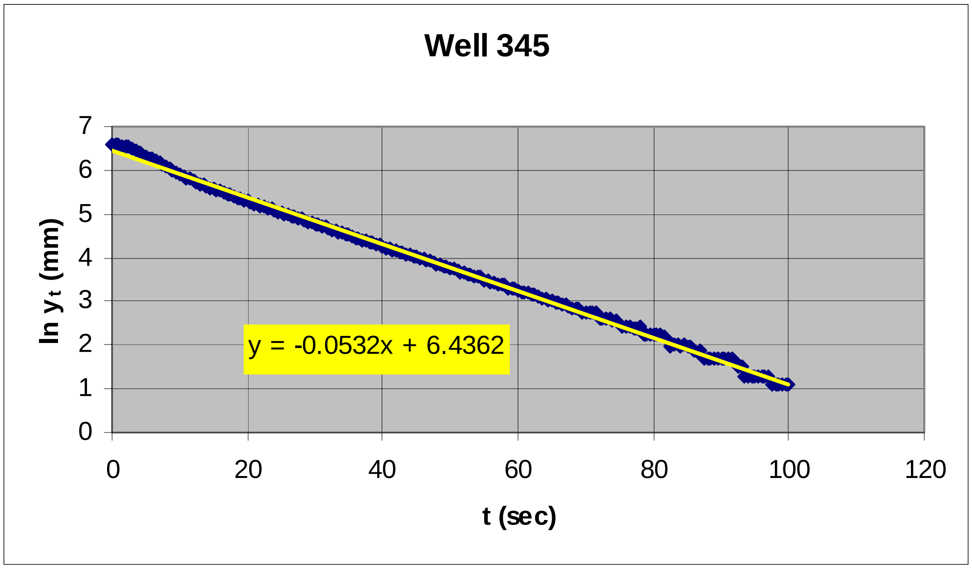

Figure 6: Best fit line to the linear portion of the plot (Well 345)

The slope of this line, *m*, is necessary to calculate *K*, the hydraulic conductivity. In this case, the regression equation is

$$\ln y_t = -0.0532t + 6.4362$$

which has a slope, *m*, of –0.0532. The R^2 error for this regression is 0.9976.

Other variables necessary to calculate *K* include r_c, r_w, L_w, L_e, *A*, and *B* (see Scientific Background and Theory section). For all of the wells in this study, the casing radius r_c is assumed to be equal to the effective radius r_w, because none of the wells have an engineered high permeability region (such as a gravel pack) surrounding them. Additionally, the casing depth below the water table L_w = the intake (screen) length L_e for all of these wells because in each case, the perforated section of well runs from the bottom of the casing to within a few inches of ground level; therefore, the entire section of well below the water table serves as an intake. The coefficients *A* and *B* are taken from the chart in Figure 2.

The only remaining variable necessary to determine the hydraulic conductivity at each location is the aquifer thickness, *H*. Direct measurement of this variable would require extensive drilling operations at each location. Fortunately, this was not necessary because such a study has already been performed. The United States Geological Survey (USGS) began an investigation of the water resources in the Arkansas River Valley in 1963; this study included a fairly extensive analysis of the lithology and geology of the valley from Pueblo to the Kansas border (Major et al. 1970). The study's information includes the depth from ground level to bedrock at 204 locations in Prowers County (represented by the green markings on Figure 3). For the purpose of calculating the hydraulic conductivity, the depth measured at the USGS study location that appeared to be closest to the well in question was applied to the well being examined. The estimated value of *H* used in the calculation was the difference between this USGS-measured depth to bedrock and the depth from the ground level to the water table, measured during the slug test. For the example of well 345, the USGS study location was approximately 0.05 miles from the well. The uncertainty associated with this method of estimating *H* is examined in the Discussion section of this report.

The combination of the measured radii and depths, the calculated slope, and estimated thickness *H* and parameters *A* and *B* are used to calculate *K* at each well. An EXCEL spreadsheet was used to calculate this information at each well, and these tables of calculation are included in Appendix A.

Contour maps can give a good image of the spatial variation of the depth to bedrock and hydraulic conductivity. A groundwater-modeling program named Groundwater Modeling Software (GMS) using GIS technology was used to create these contour maps. Another researcher used Ashtech surveying equipment to determine the precise location of the wells in Universal Transverse Mercator (UTM) coordinates. Time limitations only allowed about half of the wells to be surveyed, however, so the locations of rest of the tested wells were estimated from working maps of the area. The locations of the USGS aquifer-depth measurements also had to be estimated visually, as the original data were given in a township-range-section format incompatible with the GMS software. Contour maps of the depth to bedrock and shallow-aquifer hydraulic conductivity (as measured in the slug tests) are shown in Figures 7 and 8 on the following pages. In each of the contour maps, as can be seen in the legend on the upper-left corner of the map, low values are represented by purple and blue while the highest values are displayed red.

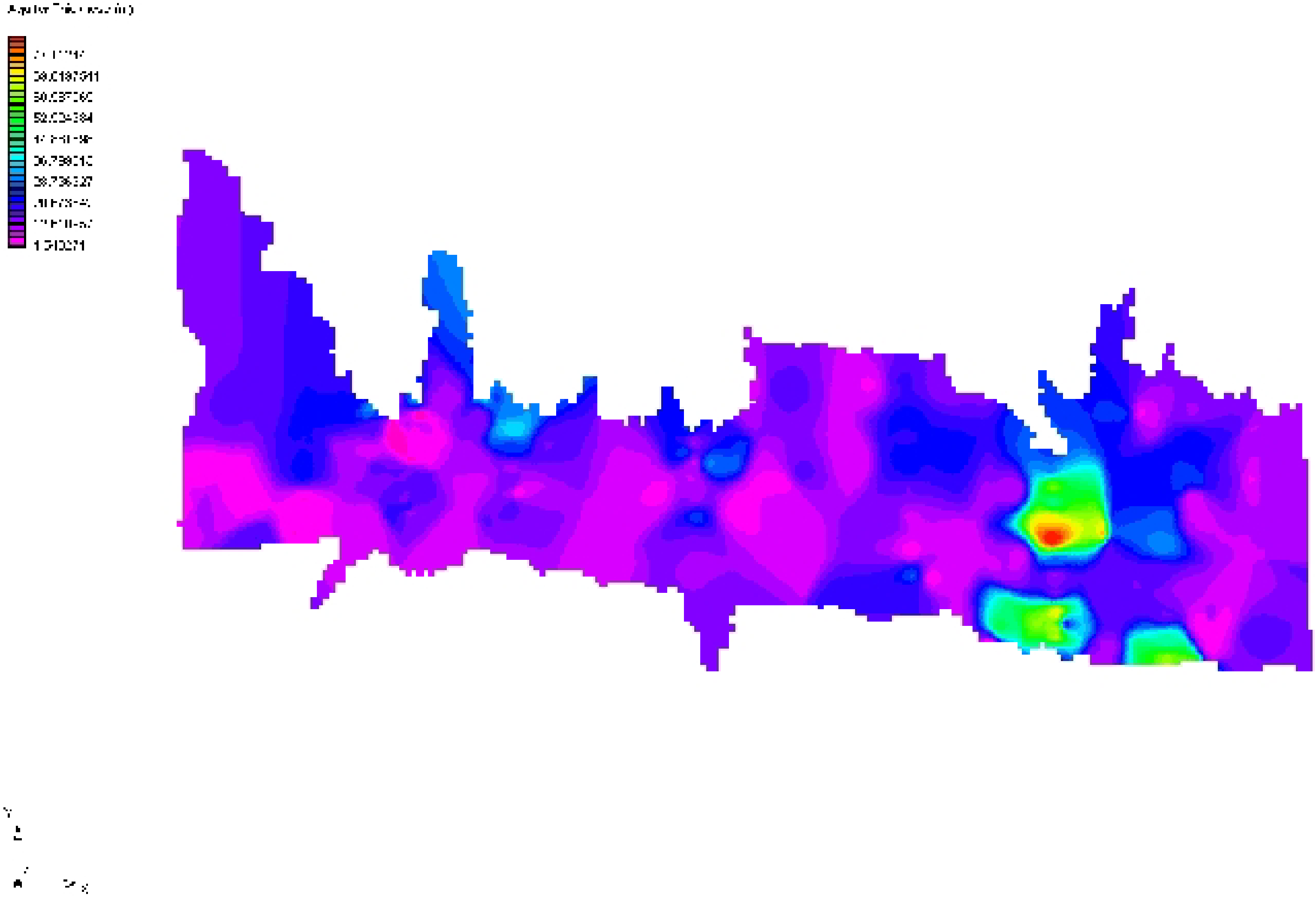

Figure 7: Contour map of depth to bedrock

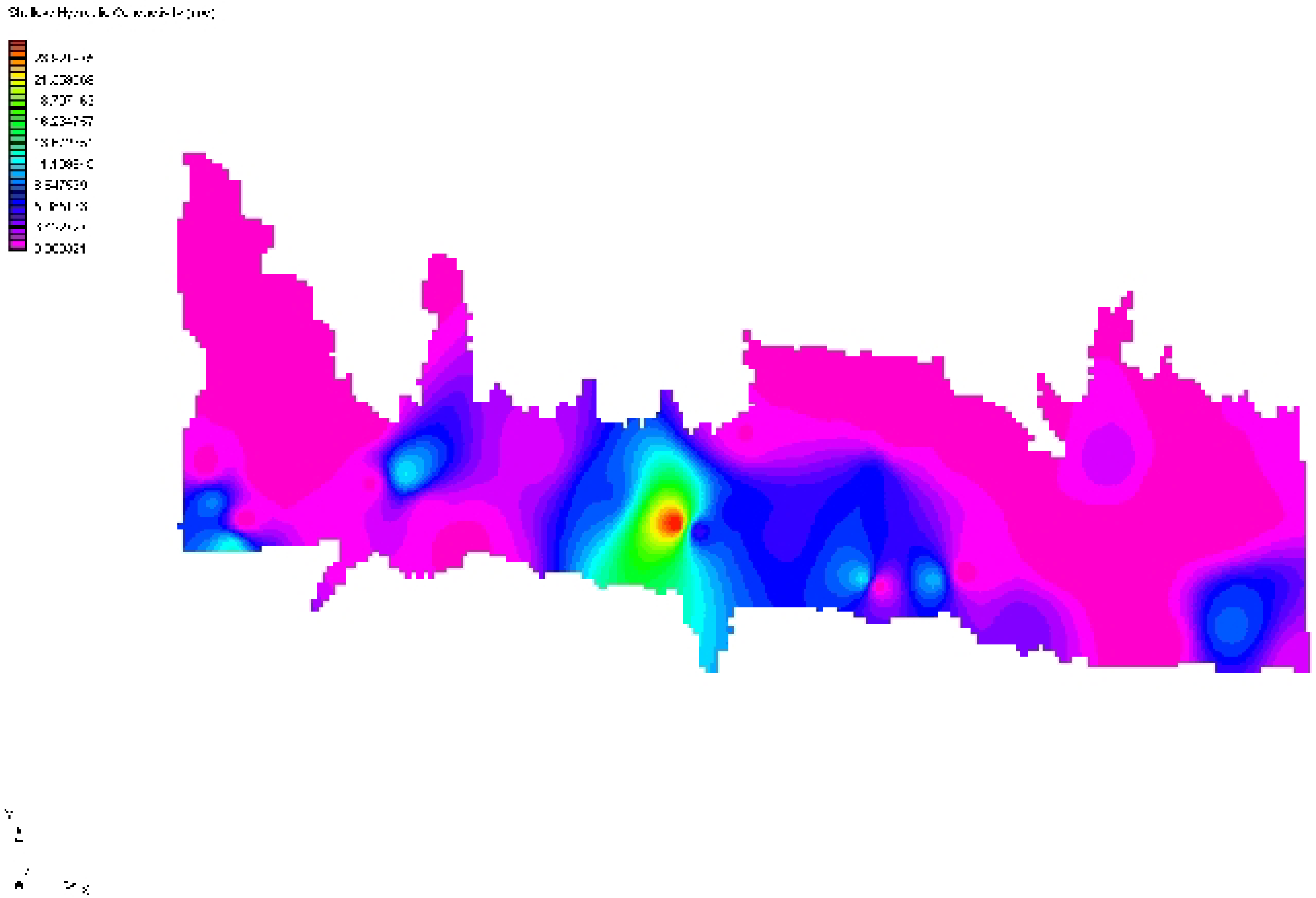

Figure 8: Contour map of shallow-aquifer hydraulic conductivity

In the 1950s, the USGS performed a series of pumping tests in Colorado, including 11 tests in Prowers County (Wilson 1965). These sites are shown as blue markings in Figure 3. These pumping tests were extensive operations that measured the hydraulic conductivity of the deep portions of the aquifer. These results complement those of the slug tests, which give the hydraulic conductivity of the shallow portions of the aquifer. Table 1, below, shows the data from these tests. Figure 9, on the following page, shows a contour map of the hydraulic conductivity of the deeper portions of the aquifer. As with the aquifer thickness data, these data locations were presented in a township-range-section format incompatible with the GMS program, and the locations had to be visually estimated.

Loc. No.	m (ft)	T1 (gpd/ft)	P1 (gpd/sq.ft)	P1 (ft/d)	P1 (m/d)
C22-42-33abb	77	145000	1900	253.99	77.42
C22-42-33abb2	77	150000	1900	253.99	77.42
C22-45-15-dda	56	190000	3400	454.51	138.54
C22-45-33bab	47	430000	9100	1216.49	370.79
C22-45-33bab2	47	430000	9100	1216.49	370.79
C22-46-14aaa	98	280000	2900	387.67	118.16
C22-46-14aaa2	98	350000	3600	481.25	146.69
C22-47-31cbc2	29		6200	828.82	252.62
C23-42-30ddd	57	200000	3500	467.88	142.61
C23-46-15bca	13	135000	10400	1390.28	423.76
C23-46-15bca2	13	140000	10800	1443.75	440.06

average	232.62
stdev	142.74
CV	0.61

LEGEND

m	aquifer thickness
T1	Transmissivity
P1	Hydraulic conductivity

Table 1: Deep aquifer hydraulic conductivity data (USGS, 1965)

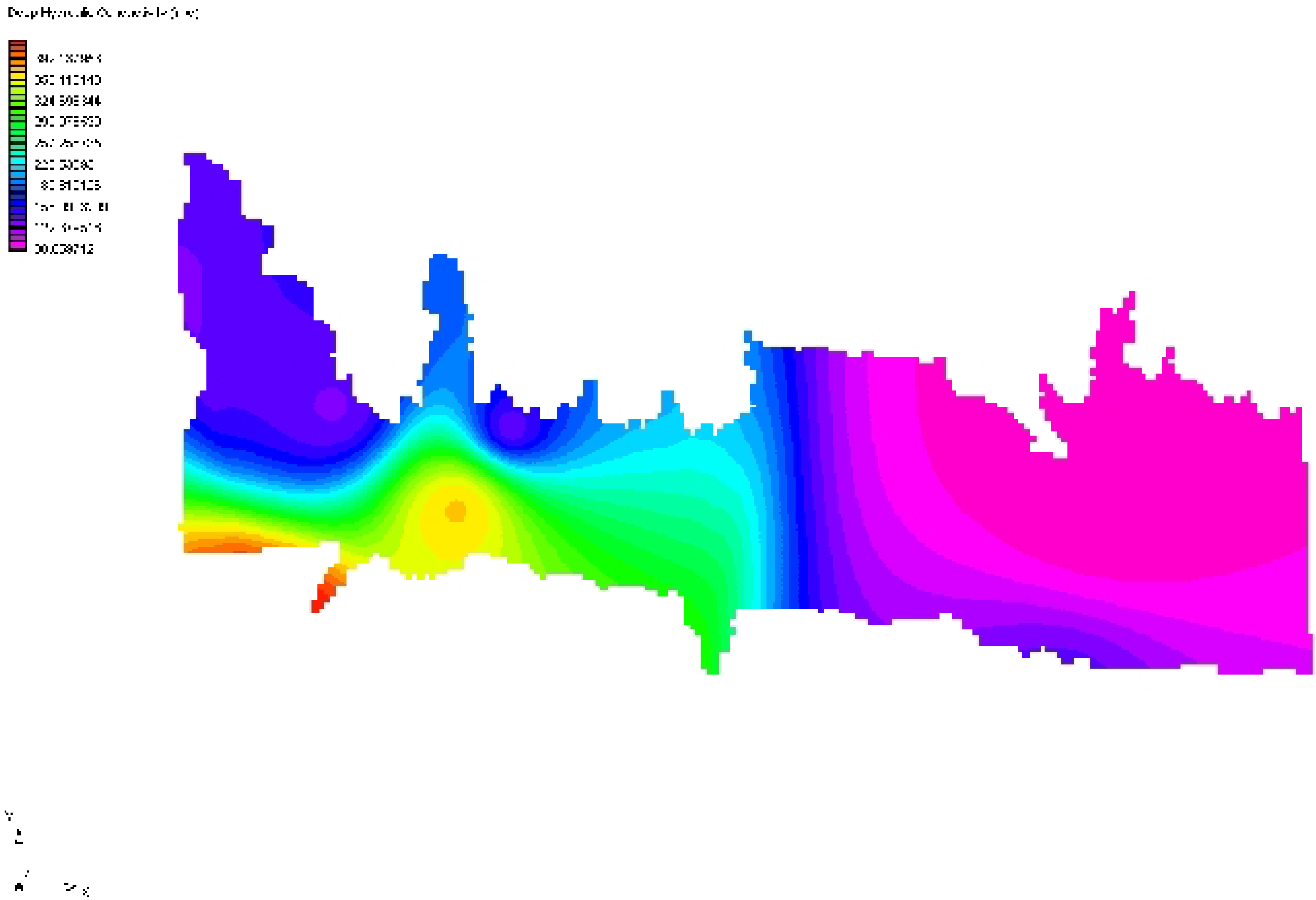

Figure 9: Contour map of deep-aquifer hydraulic conductivity

Discussion

The calculated hydraulic conductivity values for this downstream study section were loaded into a computer program named BestFit for statistical analysis. The BestFit program reads in data and automatically fits the data to 26 distribution types. It uses built-in algorithms to perform statistical tests that compare the quality of fit for each distribution, and these distributions are then ranked in order of goodness of fit.

Statistical analyses found the data for the downstream study section to be best approximated by a lognormal distribution. The Chi-Square test was rejected in most cases for this data, but the lognormal distribution ranked second in the Kolmogorov-Smirnov test (with a test value of 0.109401) and first in the Anderson-Darling test (with a test value of 0.520076). The fit of the lognormal distribution to the data is shown below in Figure 10:

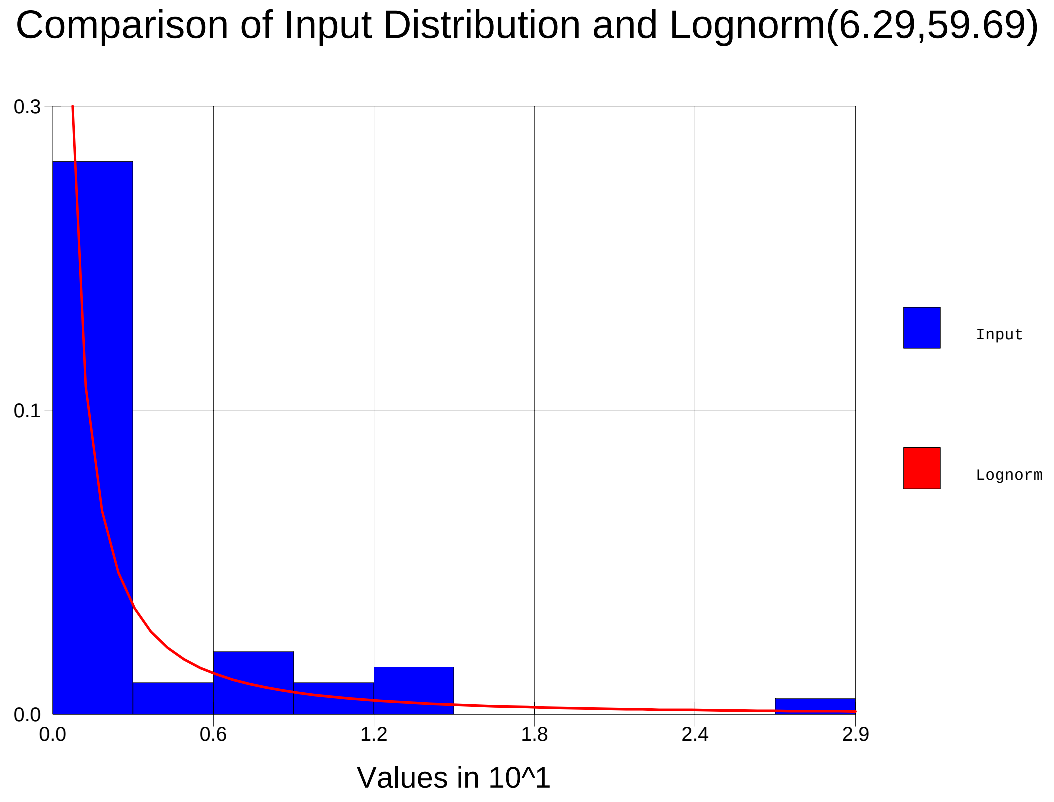

Figure 10: Lognormal distribution fitted to entire downstream study section dataset

To examine how the hydraulic conductivity of the aquifer changes throughout the region, the downstream study section was divided into three areas, labeled Lamar, Granada, and Holly (the primary communities in each section). These divisions are shown in Figure 11 on the following page. On this figure, red crosses indicate wells where slug tests were performed.

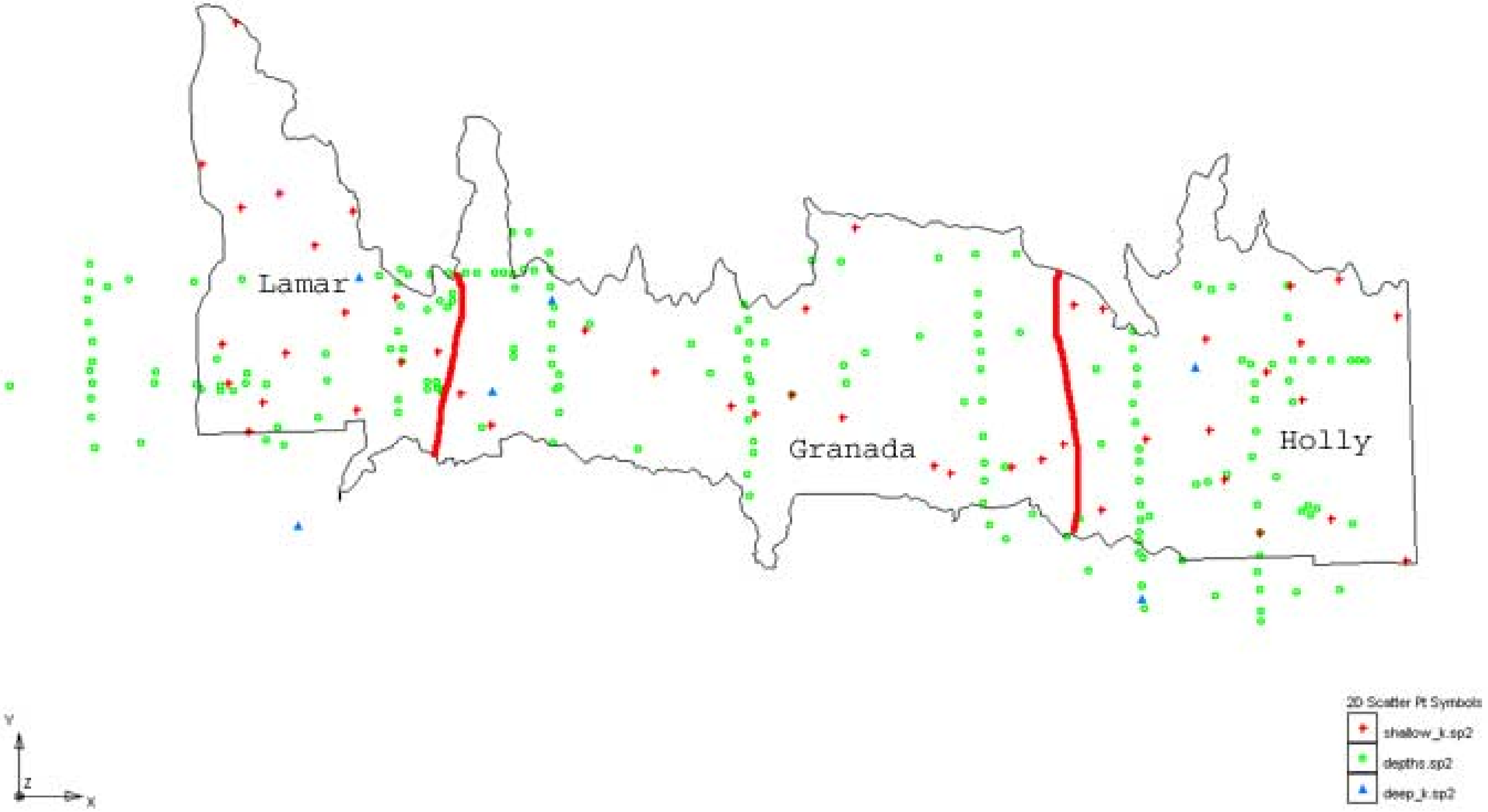

Figure 11: Statistical division of downstream study site

Fitting a distribution to the data in each section is more difficult because there are only 15-16 data points in each section. However, because the data for the entire downstream study section is lognormal, it can be assumed that the distribution in each subsection is also lognormal. The fit of lognormal distributions to the data for each subsection is shown in Figures 12, 13, and 14:

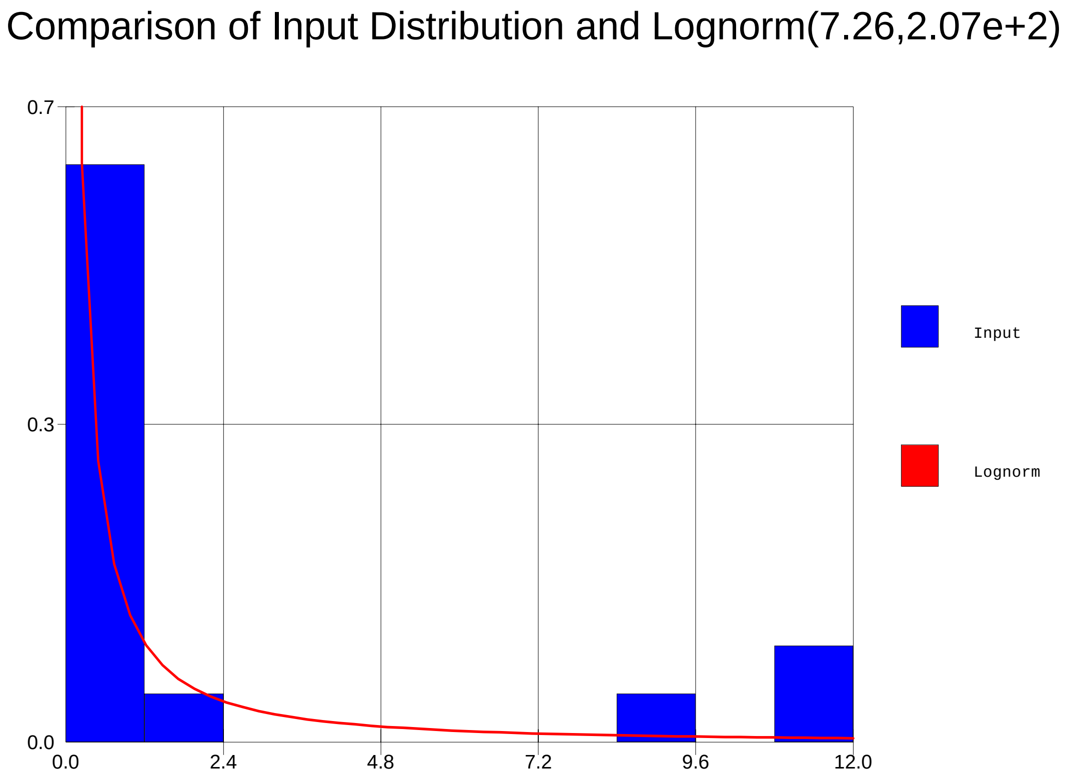

Figure 12: Lognormal distribution fitted to data from the Lamar subsection of the downstream study section.

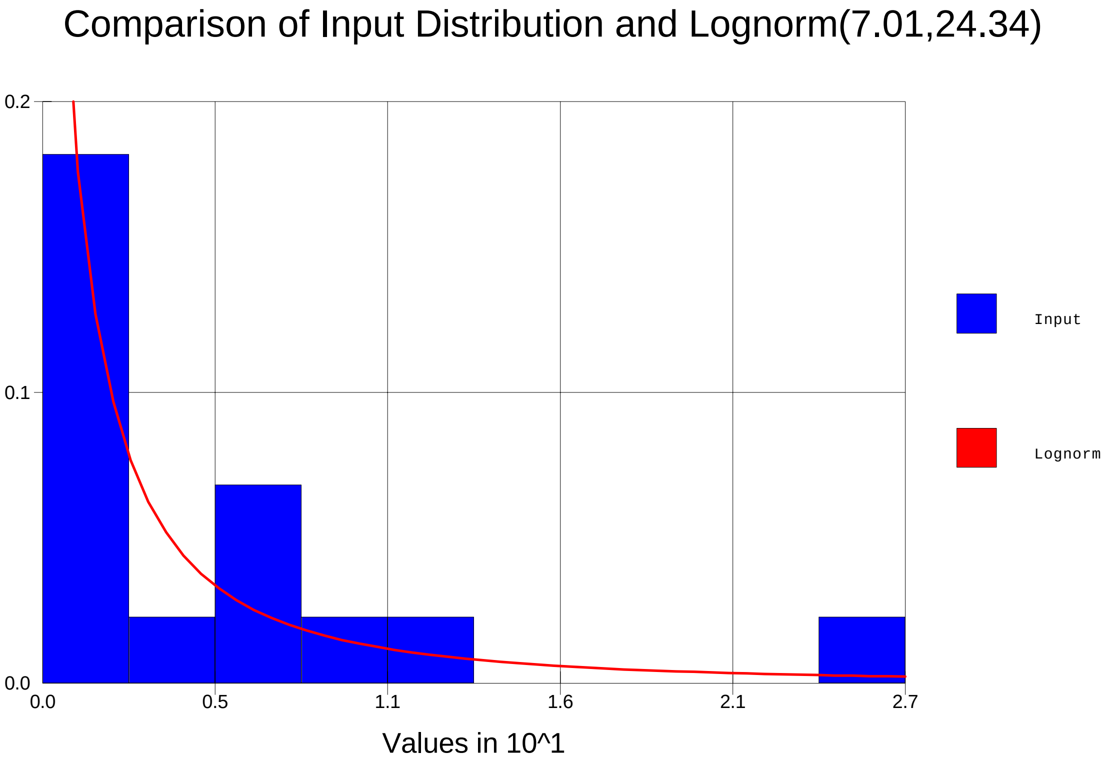

Figure 13: Lognormal distribution fitted to data from the Granada subsection of the downstream study section.

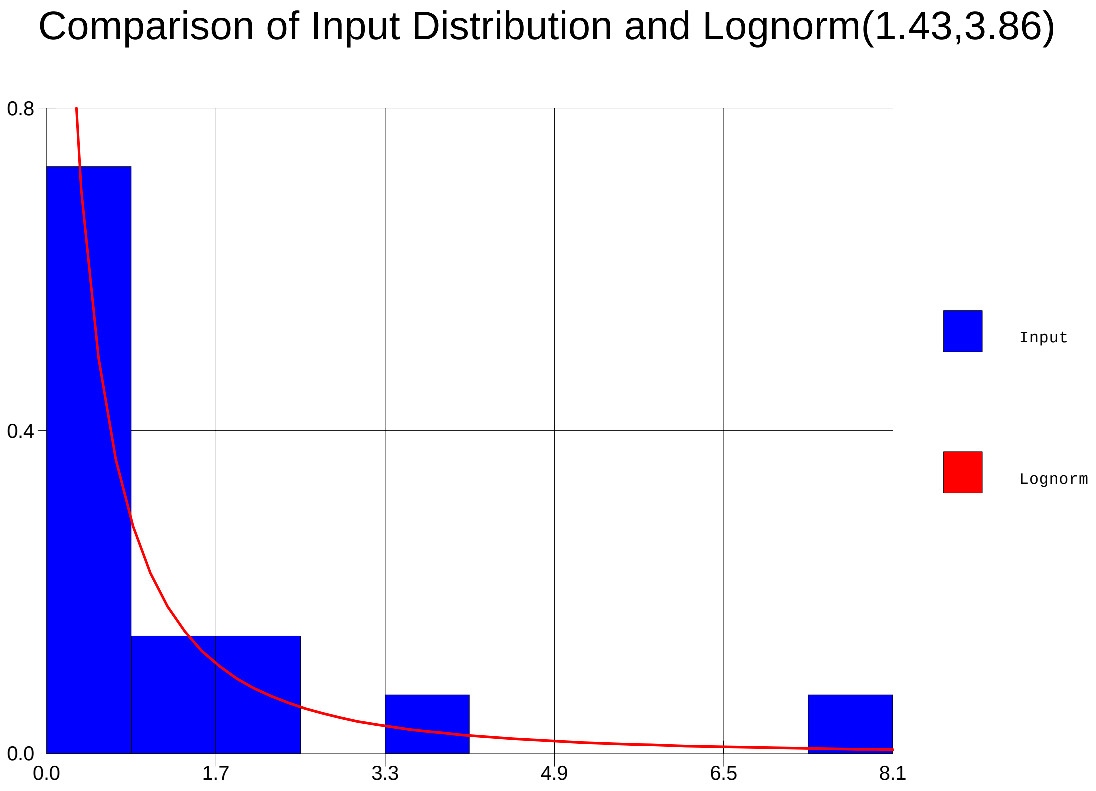

Figure 14: Lognormal distribution fitted to data from the Holly subsection of the downstream study section

In a prior study, slug tests were performed on a section of the Arkansas River Valley just upstream of this study area. The lognormal distribution fitted to that data is shown in Figure 15:

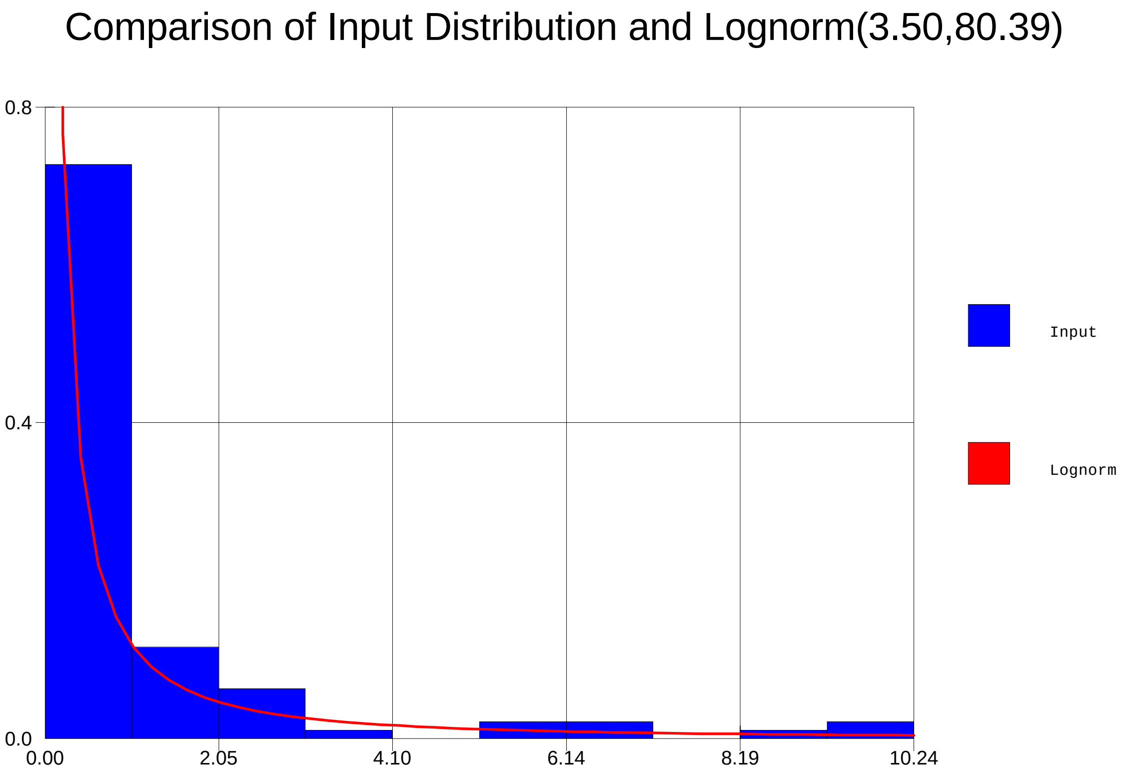

Figure 15: Lognormal distribution fitted to the dataset from the upstream study section

A summary of the sample mean, sample standard deviation, and the lognormal distribution's mean and standard deviation of the for the entire downstream study section, Lamar, Granada, and Holly subsections, and the upstream study section is presented in Table 2 below:

	K (m/d)				
	Downstream	Lamar	Granada	Holly	Upstream
Sample mean	2.89	2.27	5.25	1.29	1.10
Sample standard deviation	4.99	4.19	7.02	2.06	2.08
Lognormal distribution mean	6.29	7.26	7.01	1.43	3.50
Lognormal distribution standard deviation	59.69	206.52	24.34	3.86	80.39

Table 2: Summary of sample and distribution statistics

Table 3 shows, for each study section or subsection, calculated percentiles based on the lognormal distributions.

Percentile	Downstream study section	Lamar subsection	Granada subsection	Holly subsection	Upstream study section
10%	0.0433	0.0093	0.2484	0.0775	0.0062
20%	0.1102	0.0289	0.5029	0.1469	0.0186
30%	0.2162	0.0657	0.8363	0.2329	0.0410
40%	0.3846	0.1325	1.2914	0.3452	0.0809
50%	0.6587	0.2553	1.9385	0.4988	0.1526
60%	1.1283	0.4917	2.9098	0.7207	0.2877
70%	2.0066	0.9917	4.4934	1.0684	0.5671
80%	3.9365	2.2536	7.4721	1.6938	1.2548
90%	10.0215	7.0347	15.1259	3.2090	3.7745
95%	21.6828	18.0123	27.0824	5.4398	9.3736

Table 3: Percentiles based on the lognormal distributions

This table indicates the percent likelihood of finding a *K* value (in m/d) below the stated value in the selected section or subsection. For example, there is a 95% chance of finding a *K* value of 5.4398 m/d or lower in the Holly subsection, while the 95th percentile in the Lamar subsection corresponds to a *K* value of 18.0123 m/d. This information is shown graphically in Figure 16:

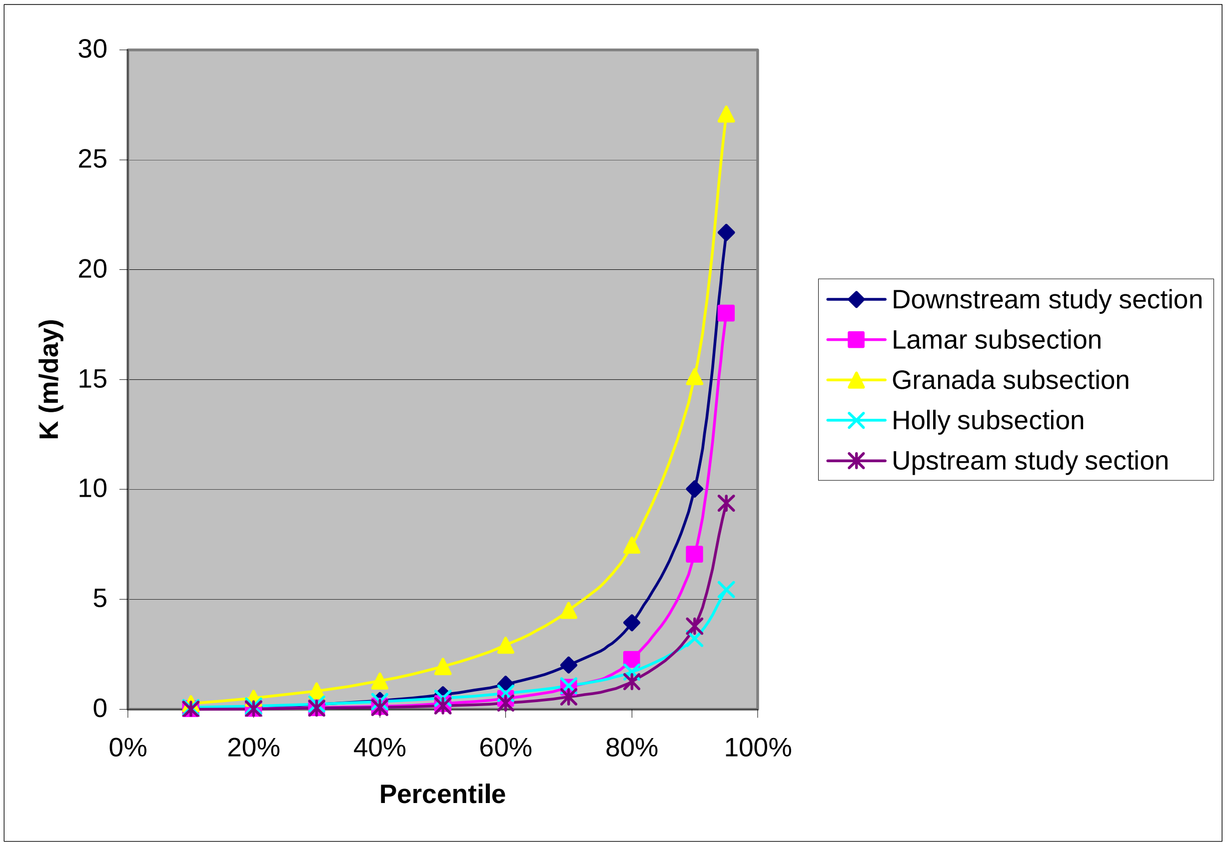

Figure 16: Graph of percentiles

All of the statistical data discussed in this section are presented in tabular format in Appendix B.

As is readily apparent on the map in Figure 8, the hydraulic conductivity in the Granada subsection is much higher than in Holly. The statistical analysis verifies this observation. It is interesting to note, however, that the mean of the distribution in the Lamar area is on the same order as Granada, although the standard deviation of the Lamar distribution is an order of magnitude greater than the Lamar area. Both the mean and the variance of the distribution of hydraulic conductivity decrease moving eastward from Lamar.

Additionally, the average hydraulic conductivity of the downstream study section is greater than that of the upstream study section. These results coincide with observations of the geology of the two regions: the soil in the downstream section of the aquifer seems to be sandier than that of the upstream section.

The values of the deep-aquifer hydraulic conductivity as measured in the USGS pumping tests (see Table 1) are roughly two orders of magnitude higher than the shallow-aquifer measurements. This indicates that the soil becomes very sandy and gravelly at greater depths. These data are consistent with observations made when drilling wells and digging augur holes—the soil becomes very course and sandy as depth increases.

Uncertainties

The most uncertain of the all the variables that enter into the calculation of K is the aquifer thickness, H. Not only was this information measured by the USGS about 40 years ago, but for some wells the nearest USGS data point is up to seven miles away. To examine the effect of this variable on the calculated K values, a sensitivity analysis was performed. To perform such an analysis, K was calculated again for each well using all of the same variables except for H. To estimate the smallest value that K could reasonably be, the calculation was performed substituting for H the largest value of depth to bedrock as measured in Prowers County by the USGS (a depth of 85.6 m below the surface). Similarly, to estimate the maximum possible value of K, the smallest measured value for depth to bedrock was substituted for H into the equations (1.83 m below the surface). Two wells had depths below the water table (L_w) greater than 1.83 m; for these wells, the smallest measured depth to bedrock resulting in a positive value for ($H - L_w$) was substituted for H. The results of this sensitivity analysis are shown in Appendix C. With these extreme values for H used in the calculations, the resultant K values differed from the original results on average between 5-8%. This analysis shows that the computed value for the hydraulic conductivity is quite insensitive to H. Therefore, the uncertainty in this variable is relatively insignificant.

Additional uncertainties may be associated with the readings of the pressure transducer. Druck, the manufacturer of the pressure transducer, claims accuracy to within ±0.1% for the device. In reality, the uncertainty was probably on the order of 5-10%, because silts and clays in the water tended to get into the sensor and thereby could affect its readings. The readings were still quite accurate, however, as was verified before and after each test with the measuring tapes. The linear relationship observed when plotting $\ln(y_t)$ vs. t also validates the results.

There is an inherent uncertainty associated with slug tests. The calculated hydraulic conductivities are assumed to be K_H, the hydraulic conductivity in the horizontal direction. This assumes that the groundwater is flowing only in the horizontal direction. In reality, the water is flowing back into the well with a slight vertical velocity component, so K_V, the vertical hydraulic conductivity is also a factor in what is being observed. However, layering in soils tends to make horizontal flow much easier than vertical flow, so K_V is usually much smaller than K_H, and in slug tests it is considered negligible. Bouwer and Rice (1976) claim that values of $\ln(R_e/r_w)$ are within 10% of experimental values when $L_e/L_w > 0.4$. Because $L_e/L_w = 1$ in all of these slug tests (the wells are perforated throughout), it can be assumed that the computed values of K_H are within 10% of the actual ones.

Conclusion

The following has been learned in this study:

- The hydraulic conductivity of the downstream study section fits a lognormal distribution with a mean of 6.29 m/d and standard deviation of 59.69 m/d. This is higher than the mean of the distribution of the upstream study section, which has a mean of 3.50 m/d and standard deviation of 80.39 m/d. These results coincide with an observed increase in sandiness of the soil in the downstream section when compared to the upstream section.
- Within the downstream study section, the mean and variance of the hydraulic conductivity decreases moving eastward from Lamar toward the Kansas border.
- Values of hydraulic conductivity in the deeper portions of the aquifer measured by the USGS in the 1950s are roughly two orders of magnitude greater than the shallow K values measured in the slug tests. This is consistent with an observed increase in the sandiness of the soil as depth increases.

Future uses of this work may include:

- Once all of the study points have been surveyed, contour maps of the ground surface elevation can be created. These can be used in conjunction with the USGS depth to bedrock data to generate a profile of the bedrock elevation. This will be useful in modeling the groundwater flow of the region.
- A relationship between the shallow and deep hydraulic conductivities may be determined. Such a relationship would enable the deep-aquifer hydraulic conductivity at a point to be estimated by performing a slug test to determine the shallow hydraulic conductivity. Costly and difficult pumping tests can therefore be avoided.
- The shallow-aquifer hydraulic conductivity is especially useful when examining the possibility of installing subsurface drains. These drains would be installed 2-3 meters below the ground surface, which is precisely the section of the aquifer for which the slug tests measured K_H.

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