

Scott Valley Pumping Test Report

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Executive Summary

Three pumping tests were performed on the eastern side of the Scott River Valley between March 6th and April 30th, 2013. Pumping tests were performed at three different locations designated Hanna No. 1, Hanna No. 2, and Morris for 72 hrs, 70 hrs, and 147 hrs, respectively. Pressure transducers were placed in the pumping well and/or nearby monitoring wells to measure water table drawdown. Hydraulic conductivity values calculated from the drawdown and recession curves ranged from 70 to 110 ft/day for Hanna No. 1, 90 to 630 ft/day for Hanna No. 2, and 110 to 460 ft/day for Morris.

Scope

This report presents and discusses the pumping test data collected in the Scott River Valley between March 6th and April 30th, 2013 by Erich Yokel with the US Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) and Peter Thamer with the Siskiyou Resource Conservation District (Siskiyou-RCD).

Methods

Pumping tests were performed at three different locations on the eastern side of the Scott River Valley (Figure 1). The tests were performed between March 6th and April 30th, 2013. The timing was chosen to minimize interference with large irrigation wells, which are used after April. We are not aware of pumping from other irrigation wells in the area during the time of the tests. The pumping tests consisted of a single well pumping at a constant rate. Pressure transducers were placed in the pumping well and/or one or two monitoring wells to measure drawdown of the water table. Flow rates from the pumping wells were determined using an ultrasonic flow meter attached to the outside of the irrigation pipe.

Details of each specific test are presented below. Specific well construction information is currently not available, so typical values from the available data were used instead. The typical irrigation well diameter, start of screen depth, and screen length is 16 in, 20 ft, and 100 ft, respectively. Typical monitoring well diameter, start of screen depth, and screen length is 4 in, 13 ft, and 20 ft, respectively. Saturated thickness of the aquifer was assumed to be 150 ft at each location as sediment thickness ranges from 0 to 400 ft or more in the valley, although material sufficiently coarse enough to support groundwater pumping has not been observed

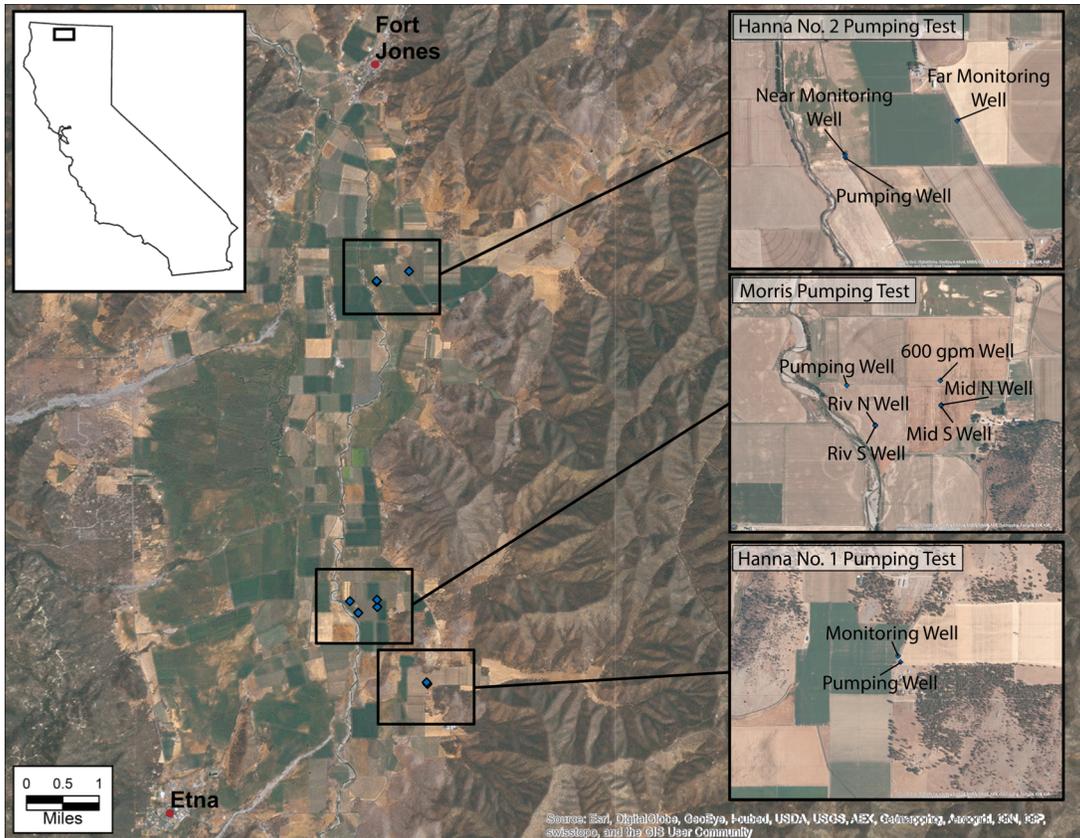


Figure 1. Location of wells used in pumping tests.

below 250 ft (Foglia et al., 2013). These values can be changed in the future as more well-specific data become available. The time vs drawdown curves were then analyzed using the commercial software AQTESOLV Pro to calculate the hydraulic conductivity for the recession and recovery periods for each well where available. Numerous solutions are available within AQTESOLV Pro, each having certain assumptions that may or may not be valid for a given set of conditions. Below is a short description of the solutions used in this report.

Theis (1935) Solution

The Theis (1935) solution was developed for unsteady flow to a fully penetrating well in a confined aquifer, given by the equations

$$s = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

s = drawdown [L]

Q = pumping rate [L^3/T]

$$\begin{aligned}
r &= \text{radial distance [L]} \\
S &= \text{storativity [dimensionless]} \\
t &= \text{time [T]} \\
T &= \text{transmissivity [L}^2\text{/t]}
\end{aligned}$$

$W(u)$ is an exponential integral and commonly referred to as the Theis well function. As it is an exponential integral its value must be approximated by the truncation of an infinite series; values of $W(u)$ are available through lookup tables. The solution can also be used on unconfined aquifers by applying the correction factor:

$$s' = s - \frac{s^2}{2b}$$

$$\begin{aligned}
s' &= \text{corrected displacement [L]} \\
s &= \text{observed displacement [L]} \\
b &= \text{aquifer saturated thickness [L]}
\end{aligned}$$

There are several assumptions used in the development of the Theis (1935) solution. First, Theis' solution assumes that the aquifer is homogeneous, isotropic, and has infinite areal extent with uniform thickness. While these conditions do not exist in nature, aquifers with lateral extent much larger than the extent to which pumping during a test affects drawdown in wells, the infinite extent assumption is justified. Also, while unconsolidated sedimentary aquifers such as in the Scott Valley are inherently highly heterogeneous, the homogeneity assumption will yield an effective, upscaled hydraulic conductivity representative of the entire aquifer thickness and the area around the pumping and observation wells.

Theis' solution also assumes the well is fully penetrating, and that there is no well-bore storage because the diameter of the pumping well is very small. With limited well construction information available, it is difficult to say whether the wells fully penetrate the aquifer. It is likely that the well screen at our test sites do not fully penetrate the aquifer. However, the assumption is justified if the well screen penetrates most of the aquifer and the pumping rate does not cause a large amount of upwelling or downwelling within the aquifer near the well screen. The assumption of no well-bore storage may be violated, as the pumping wells used for the tests are irrigation wells and likely have relatively large (i.e. > 10 in) diameters. Fortunately, this would only affect very early time data while the well-bore storage was being depleted, and late-time data would be unaffected.

One final assumption underlying the Theis (1935) solution is that the aquifer does not exhibit delayed gravity response. In semi-confined and unconfined aquifers, delayed gravity response may affect the drawdown curve, in which case other solution methods must be applied. Delayed gravity response can be identified from the derivative of the drawdown curve, and an appropriate solution for delayed gravity response can be applied if needed.

Cooper-Jacob (1946) Solution

The Cooper-Jacob (1946) solution was originally developed as a straight-line approximation of the Theis (1935) solution, and can be applied to unconfined aquifers by applying a correction factor. The Cooper-Jacob (1946) equation for displacement at late time is given by

$$s = \frac{2.303Q}{4\pi T} \log\left(\frac{2.25Tt}{r^2 S}\right)$$

s = drawdown [L]

Q = pumping rate [L³/T]

r = radial distance [L]

S = storativity [dimensionless]

t = time [T]

T = transmissivity [L²/t]

When a straight line is drawn through the late time data on a plot of s versus log t, T and S can be determined by the equations

$$T = \frac{2.303Q}{4\pi\Delta s}$$

$$S = \frac{2.25Tt_0}{r^2}$$

Δs = change in drawdown per log cycle time

t_0 = intercept of fitted line on time axis.

The assumptions for the Cooper-Jacob (1946) solution are the same as those for the Theis (1935) solution, with the added assumption that only late time data are used.

For the pumping tests presented in this report, drawdown is never more than about 9 ft at the pumping well and never greater than about 2 ft at the monitoring wells (see Results and Discussion section below). Applying the correction factor equation (see above) to a 150 ft thick unconfined aquifer, the actual displacement in the unconfined system is within approximately 97% and 99% of the observed displacement for the pumping and monitoring wells, respectively. As the Cooper-Jacob (1946) solution only takes late-time data into account, and therefore neglects delayed gravity response that happens during early pumping times, it is applicable to both confined and unconfined cases for the pumping tests presented in this report.

Hantush (1960) Solution

The Hantush (1960) solution was derived for unsteady flow to a pumping well in an aquifer confined by leaky aquitards. In this solution, the leaky aquitards provide water to the confined aquifer, resulting in less drawdown than would be expected if the aquifer was fully confined. The solution has similar assumptions to the Theis (1935) and Cooper-Jacob (1946) solutions.

Moench (1997) Solution

The Moench (1997) solution was derived for unsteady flow to a well with a finite diameter. Unlike the other solutions, the pumping well can be either partially or fully penetrating. Well-bore storage is also taken into account due to the finite diameter of the pumping well. Although well-specific construction data is currently not available, the estimated casing radii chosen are likely good approximations. Delayed gravity response is also accounted for with the Moench (1997) solution. Therefore, it can also be applied to unconfined aquifers.

Parameters in addition to transmissivity and storativity are required for the Moench (1997) solution. The parameters r_w (radius of the borehole) and r_c (radius of the well casing), are related to the well construction. The influence of the well skin, a zone of increased resistance around the well casing, is accounted for by S_w , the dimensionless wellbore skin factor. The solution also requires a value of β , which is given by

$$\beta = \frac{r^2 K_z}{b^2 K_r}$$

r = radial distance [L]

K_z = vertical hydraulic conductivity [L/T]

b = aquifer saturated thickness [L]

K_r = radial hydraulic conductivity [L/T]

Therefore, the value of β is constant for a given well if the radial distance, aquifer saturated thickness, and anisotropy ratio are known. The Moench (1997) solution also requires an estimation of α_1 [1/T], an empirical constant for non-instantaneous drainage at the water table.

Agarwal Method

Recovery data from the pumping tests can also be analyzed by applying a simple transformation of the time variable developed by Agarwal (1980). The transformed time variable, known as Agarwal equivalent time, is given by

$$t_{equiv} = \frac{t_p \cdot t'}{t_p + t'}$$

t_p = total time of pumping
 t' = time since pumping stopped

Recovery of drawdown is defined as

$$s_{recov} = s_p - s'$$

s_p = drawdown in the well at time t_p
 s' = residual drawdown in the well at times after pumping stopped

Plotting recovery vs Argawal equivalent time allows for application of the Cooper-Jacob (1946), Moench (1997), and Hantush (1960) solutions. The Agarwal method assumes that the pumping time is larger than the time since pumping stopped, so it is only valid for times less than twice the pumping time.

Hanna No. 1 Pumping Test

The Hanna No. 1 pumping test was performed between March 6th and March 27th, 2013 (including the recovery period), pumping for a total of 72 hours using two wells (one pumping and one monitoring) located 139 ft from each other. Two pressure transducers were placed in the monitoring well at the same depth below the water table before pumping began to establish the background water table elevation. Drawdown and recovery data for the pumping well was not recorded.

Pumping began March 6th at 2:21 pm and ended March 9th at 2:19:pm. The flow rate from the pumping well averaged approximately 655 gal/min (Figure 2) during the pumping test.

Hanna No. 2 Pumping Test

The Hanna No. 2 pumping test was performed between April 1st and April 9th, 2013 (including the recovery period), pumping for a total of 70 hours using a pumping well and two monitoring wells located 70 ft and 757 ft from the pumping well. A total of five pressure transducers were used, with two placed in the pumping well, two in the near monitoring well, and one in the far monitoring well. When two loggers were used in the same well, one was set to collect data every second and the other every minute. The pressure transducers were deployed before the start of pumping to establish background water table elevations at each well.

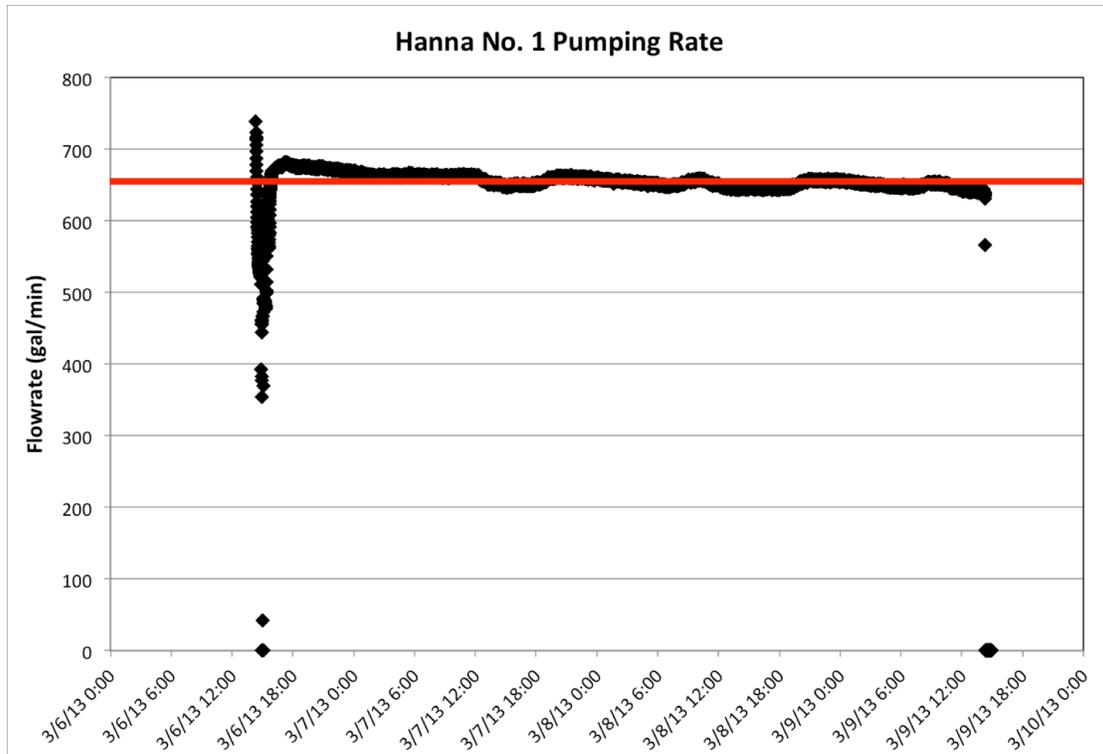


Figure 2. Pumping rate for Hanna No. 1 recorded by Greyline ultrasonic flow meter attached to the outside of the pipe. The red line indicates the average flow rate of 655 gal/min.

Pumping began April 2nd at 3:57 pm after two failed attempts initially due to technical difficulties with the flow meter. The initial pumping attempts were of short duration with enough time passing after the second failed attempt that water levels appeared to have fully recovered by the time the successful pumping test began.

Pumping ended on April 5th at 2:48 pm, with an average pumping rate of 840 gal/min (Figure 3).

Morris Pumping Test

The Morris pumping test was performed between April 9th and April 30th, 2013 (including the recovery period), pumping for a total of 147 hours using a pumping well and five monitoring wells. The monitoring wells, designated Riv N, Riv S, Mid N, Mid S, and 600gpm were located approximately 1029 ft, 1041 ft, 2034 ft, 2036 ft, and 1974 ft from the pumping well. Note that the well labeled 600 gpm is an irrigation well that was not pumping during the test and was used as a monitoring well. Pressure transducers were placed in the monitoring wells and the pumping well to measure drawdown during the pumping test. An additional transducer was placed in the stream near the pumping well to measure water height in the stream during the pumping test.

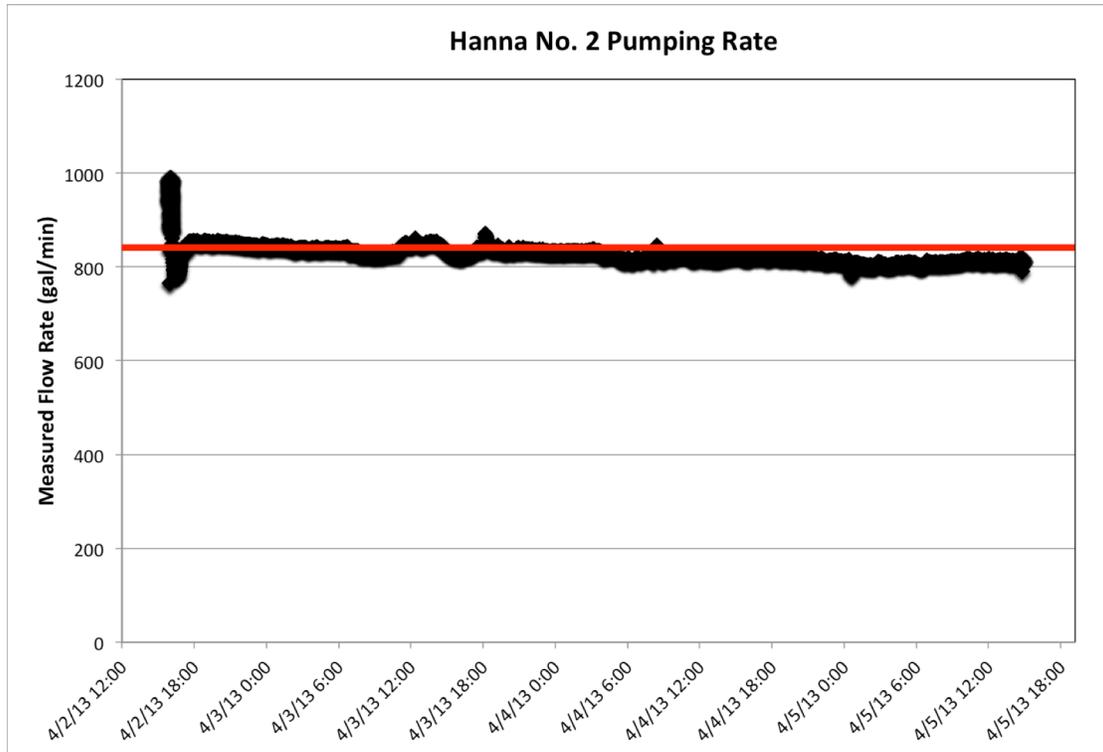


Figure 3. Pumping rate for Hanna No. 2 recorded by Greyline ultrasonic flow meter attached to the outside of the pipe. The red line indicates the average flow rate of 840 gal/min.

Pumping began April 12th at 1:20 pm after a failed attempt the previous day due to technical difficulties with the flow meter. The initial pumping attempt was of short duration with enough time passing after the second failed attempt that water levels appeared to have fully recovered by the time the successful pumping test began. Pumping ended on April 18th at 4:15 pm. Average pumping rates were difficult to obtain. The placement of the flow meter was not ideal but better placement was impossible due to the construction of the well. However, the flow meter did record a steady flow averaging approximately 1100 gal/min (Figure 4). Flow rate calculations using discharge from the irrigation wheel line were estimated at 580 gal/min. These two flow rates will be used to obtain an upper and lower estimate of the hydraulic conductivity for this pumping test.

Results and Discussion

Hanna No. 1 Pumping Test

Time vs drawdown and the derivative of the pumping curve for the Hanna No. 1 pumping test are shown in Figure 5. At late time, the derivative appears to have reached a constant value, indicating conditions of radial flow in an infinite-acting aquifer. Delayed gravity response was not observed in the drawdown data. All of the

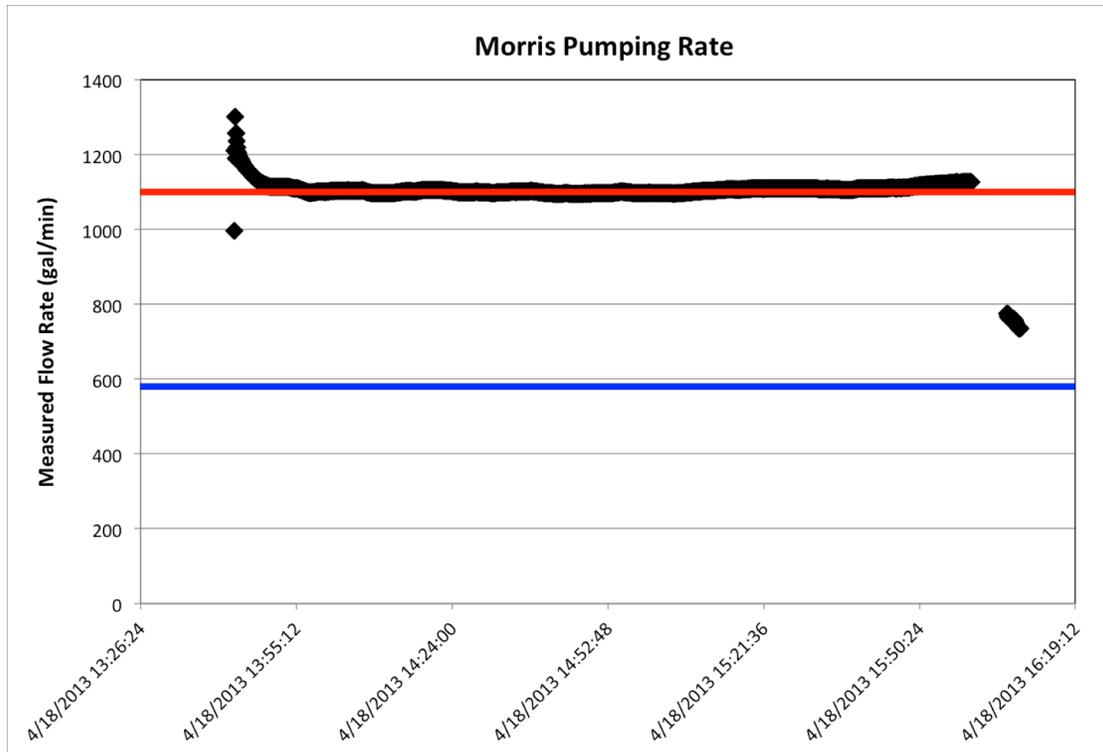


Figure 4. Pumping rate for Morris recorded by Greyline ultrasonic flow meter attached to the outside of the pipe. The red line indicates the average flow rate of 1100 gal/min recorded by the flow meter. The blue line indicates the flow rate of 580 gal/min measured from the sprinkler lines.

solutions for unconfined aquifers were tested, with the two providing the best fit presented below. Curve matching using the Cooper-Jacob solution for late time pumping data yields an aquifer transmissivity (T) estimate of $1.2 \times 10^4 \text{ ft}^2/\text{day}$ (Figure 6a). Storativity (S) of the aquifer was estimated to be 0.003. This is unusually low for a phreatic aquifer, where values typically range from 0.01 to 0.3 depending on the material. This may be due to invalid assumptions about the construction of the wells, although using typical storativity values produce solution curves that are much steeper than the drawdown data collected. Another explanation for the low value of S is that the well is in fact semi-confined with nearly negligible contribution from specific yield (S_y).

The Moench (Figure 6b) and Hantush (Figure 6c) solutions to the drawdown data provide similar estimates of transmissivity and storativity compared with those obtained from the Cooper-Jacob solution. All solutions fit the late-time data well, indicating the estimated values obtained from the solutions apply to the aquifer at a scale larger than the area immediately surrounding the pumping well.

Recovery data collected from the near monitoring well was analyzed using the Agarwal method. The same three methods used to analyze the drawdown data were also applied to the drawdown data. Transmissivity and storativity using the Cooper-

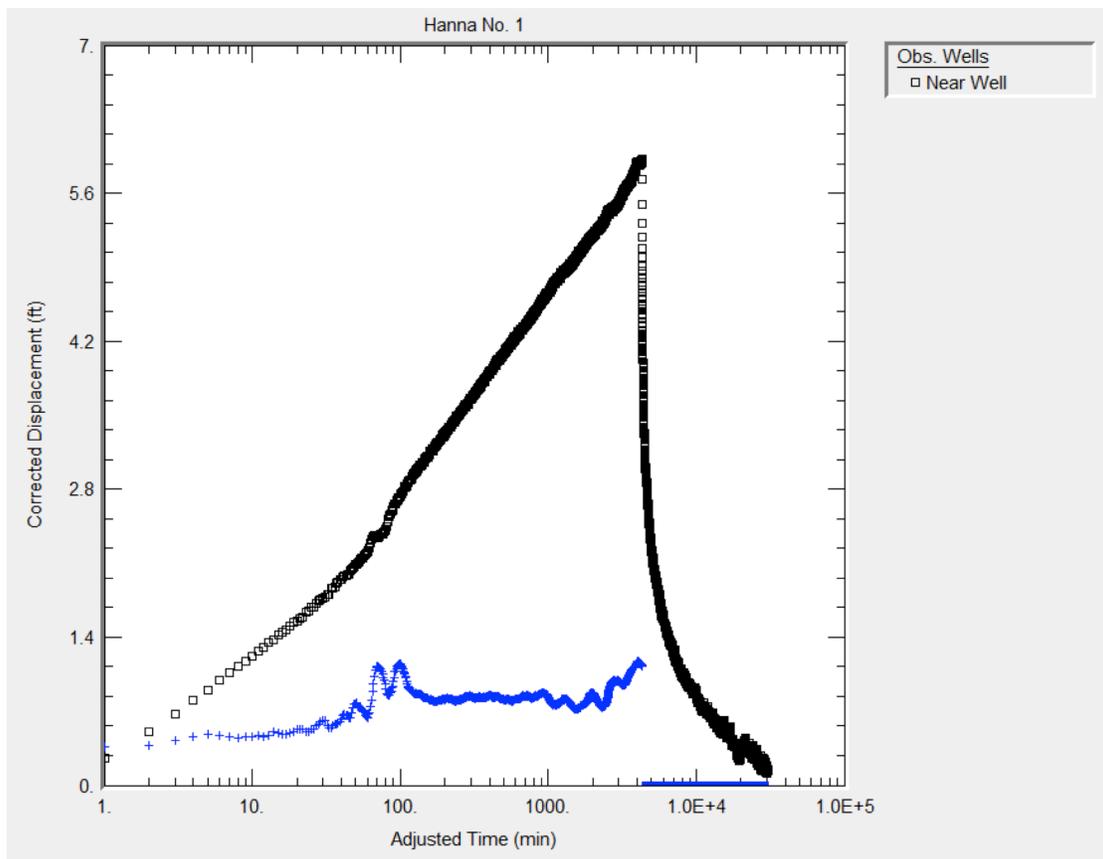


Figure 5. Drawdown and recovery data for the near monitoring well of the Hanna No. 1 pumping test. The black squares are the measured data and the blue crosses are the derivatives of the data.

Jacob solution (Figure 6d) were about 1.7×10^4 ft²/day and 0.002, respectively, although the straight-line solution does not fit late-time data well. The Moench solution (Figure 6e) appears to fit the data best, with transmissivity and storativity estimated at 1.1×10^4 ft²/day and 0.0006, respectively. The Hantush solution (Figure 6f) fit early time data well, but was unable to match late-time data. Transmissivity and storativity were estimated at 1.7×10^4 ft²/day and 0.002, respectively, using the Hantush solution.

Hanna No. 2 Pumping Test

The drawdown data collected from the pumping well and near monitoring well are shown in Figure 7. Recorded drawdown in the far monitoring well (757 ft away) was not significant for the duration of pumping and therefore excluded from further analysis. Derivative analysis of the pumping well and near monitoring well observations show that the aquifer is approximately infinitely-acting at late times.

Estimated transmissivity and storativity using the Cooper-Jacob approximation for the pumping well observations (Figure 8a) are 2.8×10^4 ft²/day and 0.003, respectively. The Hantush solution for a semi-confined aquifer also provides a

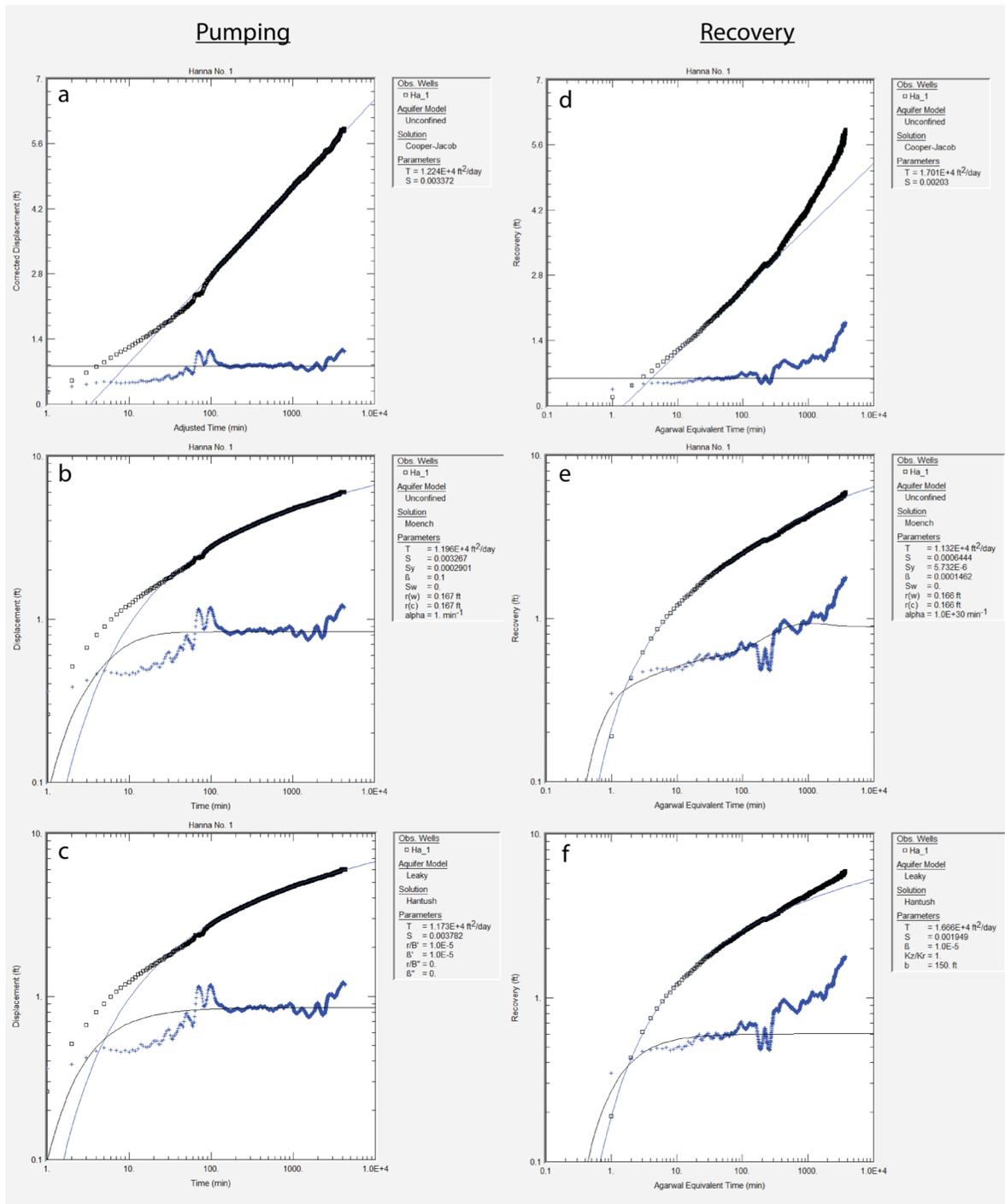


Figure 6. The left column shows the estimated transmissivity and storativity during pumping using the a) Cooper-Jacob straight-line approximation, b) Moench solution, and c) Hantush solution for the Hanna No. 1 pumping test data collected in the monitoring well. The right column shows the recovery data with the d) Cooper-Jacob straight-line approximation, e) Moench solution, and f) Hantush solution applied. Black squares are measured data points, blue crosses are calculated derivatives of the measured drawdown.

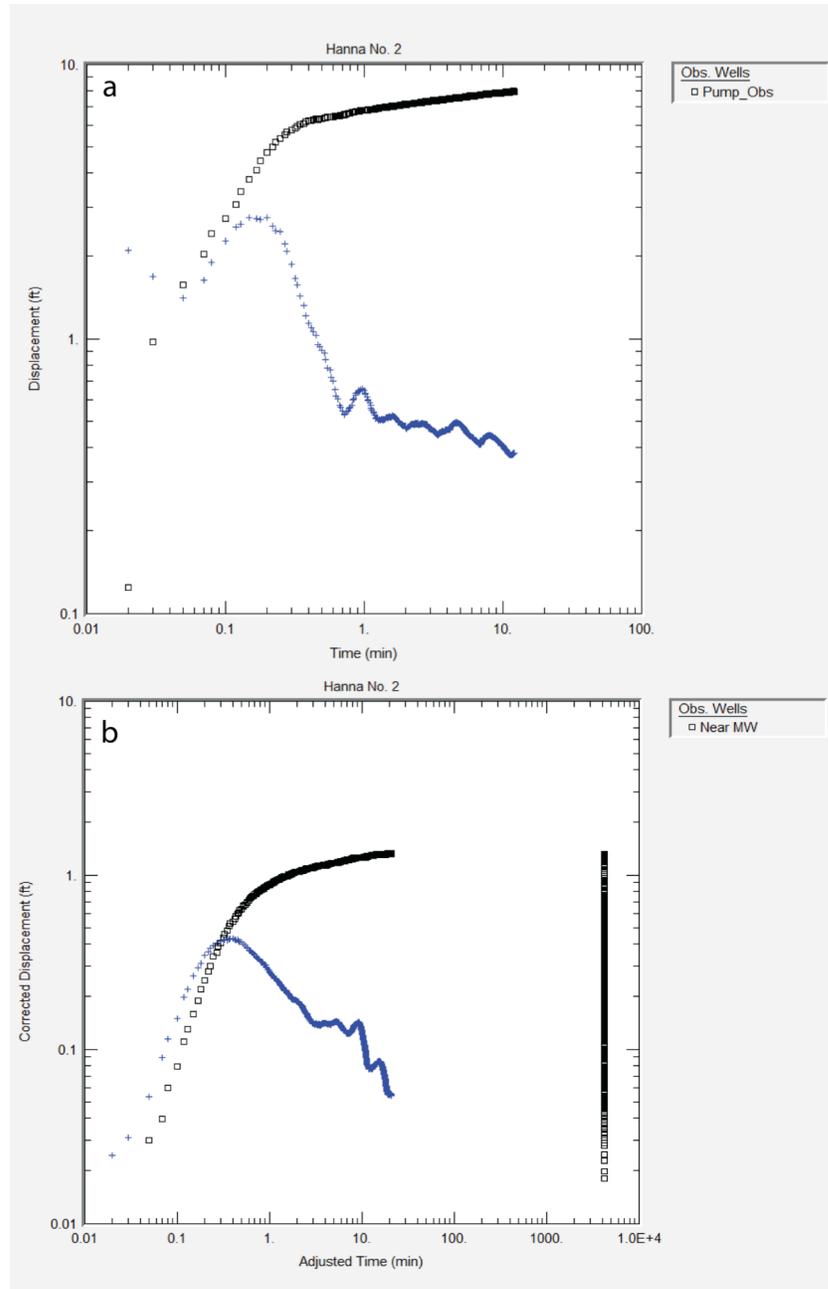


Figure 7. Drawdown data collected from a) the pumping well and b) near monitoring well during the Hanna No. 2 pumping test. Black squares are measured data points, blue crosses are calculated derivatives of the measured drawdown.

reasonable type curve match to the late-time data (Figure 8b), but does not match early time data. Estimated transmissivity and storativity are 1.4×10^4 ft²/day and 2.8×10^{-6} , respectively. The transmissivity estimated from the Hantush solution is similar to that estimated using the Cooper-Jacob straight-line approximation, but the Hantush solution provides a much smaller estimate of storativity than what would be expected for an unconfined aquifer. The peak in the drawdown derivative

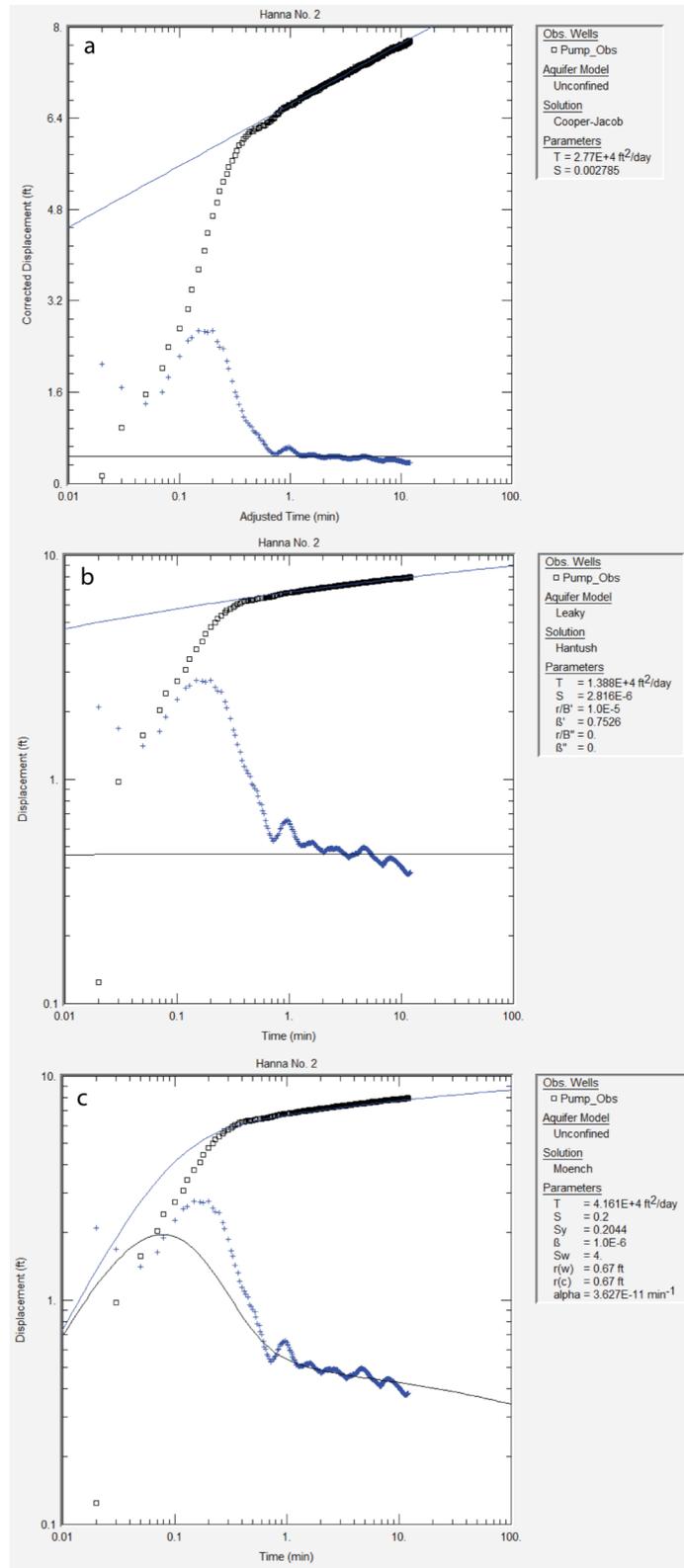


Figure 8. Estimated transmissivities from the pumping well drawdown data for the Hanna No. 2 pumping test using the A) Cooper-Jacob (1946) straight-line approximation, B) the Hantush (1960) solution, and C) the Moench (1997) solution. Black squares are measured data points, blue crosses are calculated derivatives of the measured drawdown.

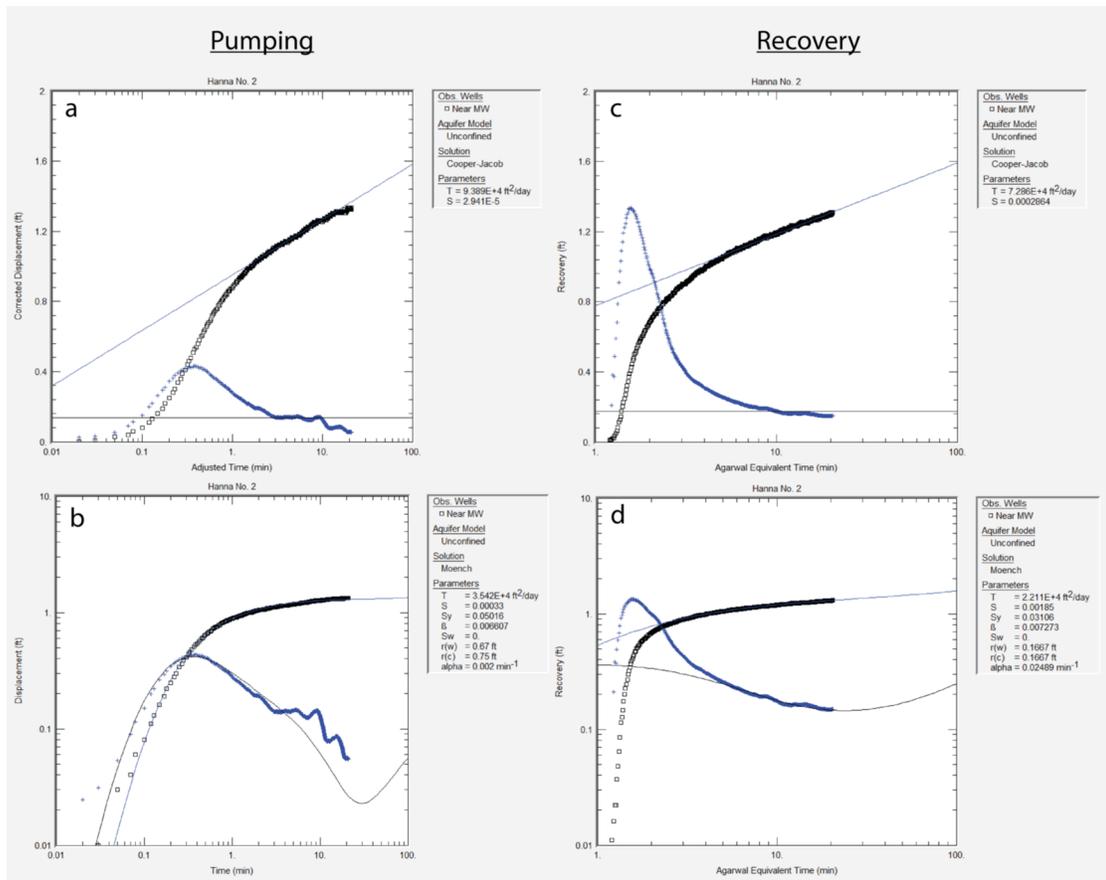


Figure 9. The left column shows the a) Cooper-Jacob and b) Moench solutions with estimated aquifer properties applied to the drawdown data collected from the near monitoring well during the Hanna No. 2 pumping test. The right column shows the c) Cooper-Jacob and b) Moench solutions applied to the recovery data from the same well. Black squares are measured data points, blue crosses are calculated derivatives of the measured drawdown.

during the intermediate portion of the pumping test indicates a delayed gravity response of the aquifer, suggesting unconfined conditions.

The Moench (1997) solution for the pumping well accounts for delayed gravity response, and using this solution transmissivity and storativity are estimated at $4.2 \times 10^4 \text{ ft}^2/\text{day}$ and 0.2, respectively (Figure 8c). This estimate of storativity is much closer to the specific yield that would be expected for an unconfined aquifer. While the solution appears to fit late time data well, early time drawdown data are not well represented by this solution. The solution is also highly sensitive to parameters related to well construction that we have estimated, such as borehole radius and well casing radius. The combination of poor fit for early time data and solution sensitivity to estimated parameters results in greater uncertainty for transmissivity and storativity values obtained using this solution.

Estimated transmissivity and storativity for the near monitoring well observations during pumping are $9.4 \times 10^4 \text{ ft}^2/\text{day}$ and 2.9×10^{-5} , respectively, using the Cooper-

Jacob straight-line approximation (Figure 9a). The Moench solution curve also provided a good fit (Figure 9b), estimating transmissivity and specific yield at 3.5×10^4 ft²/day and 0.05, respectively (Figure 9b). This solution also captures the delayed gravity response present in the data, indicating unconfined aquifer conditions at this location. The calculated values for transmissivity are of the same magnitude for the two solutions, but the Moench solution provides an estimate of specific yield that is closer to what would be expected for an unconfined aquifer. Since the Moench solution requires the input of well construction data the estimate could likely be improved if well-specific construction data become available in the future.

Recovery data collected from the near monitoring well were also analyzed using the Cooper-Jacob straight-line approximation (Figure 9c) and the Moench solution (Figure 9d). Estimated transmissivity and storativity from the Cooper-Jacob were 7.3×10^4 ft²/day and 2.9×10^{-4} , respectively, with the model fitting the late time data well. The Moench solution estimated transmissivity at 2.2×10^4 ft²/day and specific yield at 0.03. While the model does not fit the early-time recovery data, it does match the late-time data well. The Moench solution appears to provide a better fit for both the drawdown and recovery data as compared with the Cooper-Jacob solution.

Morris Pumping Test

Time vs drawdown for the pumping, Riv N, Mid S, and 600gpm wells are shown in Figure 10. Data from the other monitoring wells involved in the test either did not show significant drawdown (i.e., low signal to noise ratios) or did not behave in an expected way (e.g., drawdown in Riv S continued well after pumping had ceased). Using the upper flow rate of 1100 gal/min, transmissivity ranges from 4.0×10^4 to 6.9×10^4 ft²/day and storativity ranges from 0.04 to 0.35 (Figure 11) when Cooper-Jacob straight-line approximation is applied. If the lower pumping rate of 580 gal/min is used transmissivities range from 2.1×10^4 to 3.6×10^4 ft²/day, approximately half those estimated from the upper flow rate.

The derivative curve for the pumping well data reaches a constant value at late time, indicating the aquifer is infinite-acting. Unfortunately, the limited drawdown data in the monitoring wells and their respective derivative curves only appear to reach a quasi-constant value, suggesting the assumptions necessary to apply the Theis (1935) or Cooper-Jacob (1946) solutions have not been met. This reduces the confidence in transmissivity and specific yield estimates for the monitoring wells. Therefore, the most reliable estimate of aquifer transmissivity and specific yield is from data collected from the pumping well.

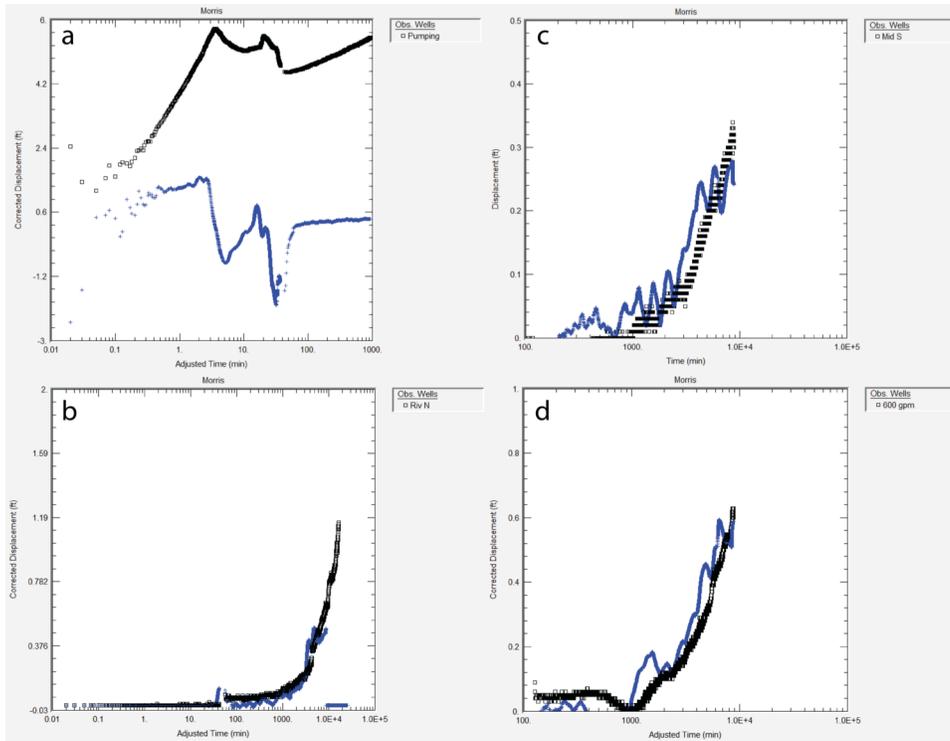


Figure 10. Morris pumping test time vs drawdown data for a) pumping well, b) Riv N well, c) Mid S well, and d) 600 gpm well. Black squares are measured data points, blue crosses are calculated derivatives of the measured drawdown.

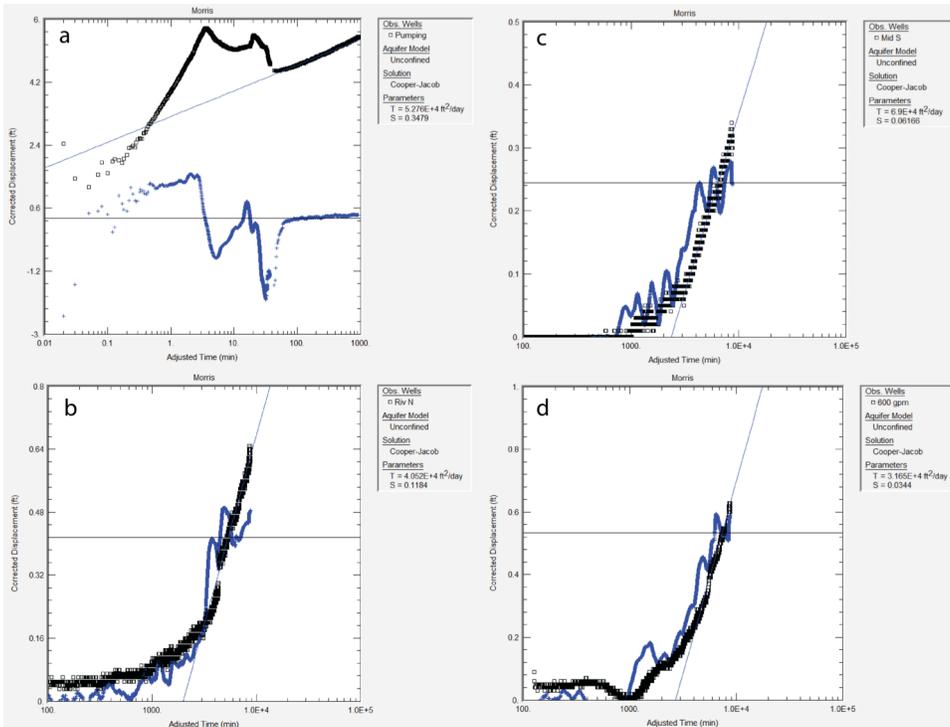


Figure 11. Estimated transmissivity and specific yield using the Cooper-Jacob (1946) straight-line approximation for the a) pumping well, b) Riv N well, c) Mid S well, and d) 600 gpm well. Black squares are measured data points, blue crosses are calculated derivatives of the measured drawdown.

Table 1. Summary of estimated hydraulic conductivity values from pumping tests. Assumed aquifer thickness is 150 ft for all tests.

<u>Pumping Test</u>	<u>Estimated Transmissivity</u> <u>(x10⁴ ft²/day)</u>	<u>Estimated Hydraulic Conductivity</u> <u>(ft/day)</u>	<u>Estimated Storativity</u> <u>(Specific Yield)</u>
Hanna No. 1	1.1 - 1.7	70 - 110	6x10 ⁻⁴ - 0.004
Hanna No. 2	1.4 - 9.4	90 - 630	2.9x10 ⁻⁵ - 0.05
Morris (1100 gpm)	3.2 - 6.9	210 - 460	0.03 - 0.35
Morris (580 gpm)	1.7 - 3.6	110 - 240	0.03 - 0.35

Conclusions

A summary of the estimated hydraulic conductivities from the pumping tests is shown in Table 1. Hanna No. 2 and Morris show similar hydraulic conductivities, with Hanna No. 1 being approximately an order of magnitude lower. This may be due to the locations where the pumping tests were performed. The pumping wells for Hanna No. 2 and Morris were located relatively near the Scott River, where coarser material is expected to be found. Hanna No. 1 is located farther from the Scott River and away from coarse-grained alluvial material near the mouth of a tributary valley. The increased distance from the Scott River may have resulted in more fine-grained material being deposited at that location, resulting in a lower hydraulic conductivity. Another plausible explanation is coarse-grained sediments where Hanna No. 1 is located are thinner than at the Hanna No. 2 and Morris pumping test locations, as overestimation of aquifer thickness results in an underestimation of hydraulic conductivity.

The estimated hydraulic conductivities from the pumping tests are similar to those reported in the literature for sand and gravel. Foglia et al. (2013) reported that nearly half of the sediments in the Scott Valley are made up of sand and gravel, and provides support for our estimates. However, the limited well construction information currently available results in greater uncertainty for the estimates. Well-specific construction details and sediment thickness at each location would improve transmissivity and hydraulic conductivity estimates.

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