Site Background

The geologic setting, as defined by individual homeowner water supply wells, consists of hard rock with relatively few water yielding fractures. Water wells for domestic supplies required well drilling to several hundred feet into bedrock. A typical geologic cross-section (see Figure 1) indicates a thin mantle (approximately 20 ft) of overburden covering granitic (quartz monzonite) bedrock.

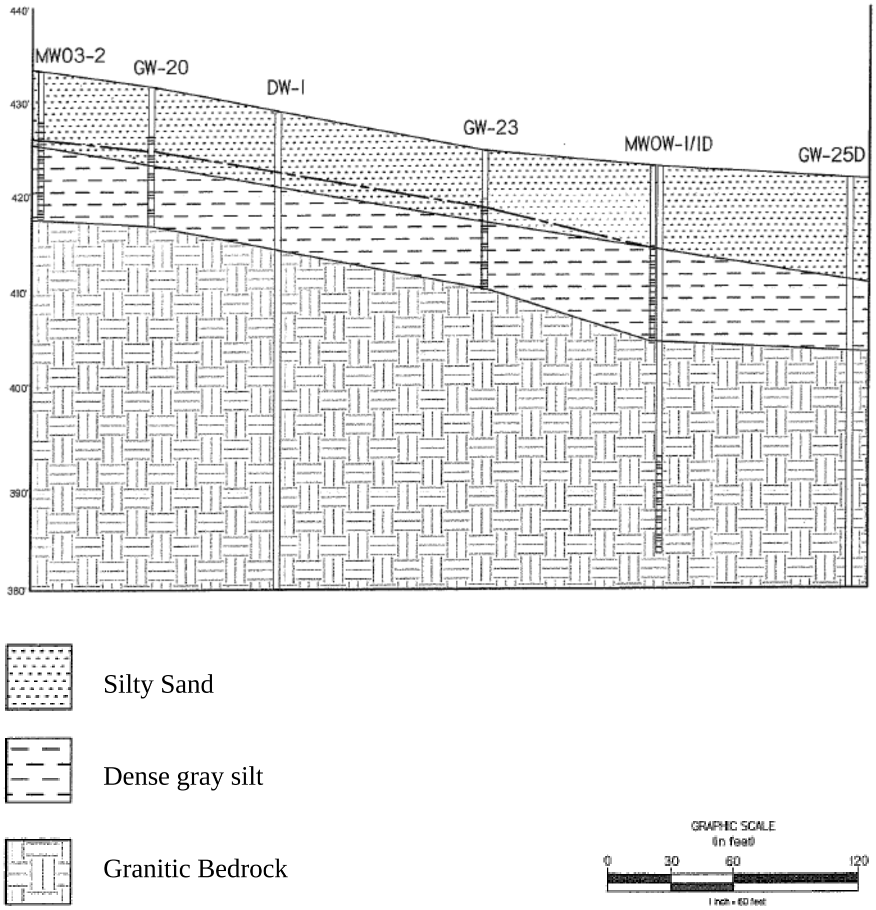


Figure 1. Geologic cross-section

Within the bedrock we might expect to find 3 major sets of fractures that align with mutually perpendicular planes (or nearly so). Each of the fracture sets would be expected to have a different average hydraulic conductivity such that we have three-dimensional anisotropy. Furthermore we therefore expect to find that a cone of depression due to pumping would exhibit an elliptical shape.

In order to get an idea of the physical nature of the fractured rock (i.e., to see what the fractures look like), borehole geophysics was used to look down-hole in two existing on-site wells (old abandoned water supply wells).

Geophysical Borehole Logging

Borehole geophysical logging was performed by Geophysical Applications, Inc. of Foxboro, MA, to help identify and characterize hydraulically-active bedrock fractures encountered by two existing abandoned water-supply wells, DW-1 (380 ft deep) and DW-2 (130 ft deep). The contracted logging suite included conventional logs (fluid temperature [FTemp], fluid resistivity [FRes]) and caliper), acoustic televiewer (ATV), and heat-pulse flowmeter testing.

Results from logging are shown in Figures 2 through 5. Figure 2 shows some of the acoustic televiewer results indicating both closed and open fractures. Figures 3 and 4 are field sketches made as the results of the borehole logging were revealed. Figure 5 shows the results of caliper, temperature, resistivity and flowmeter logging in DW-2.

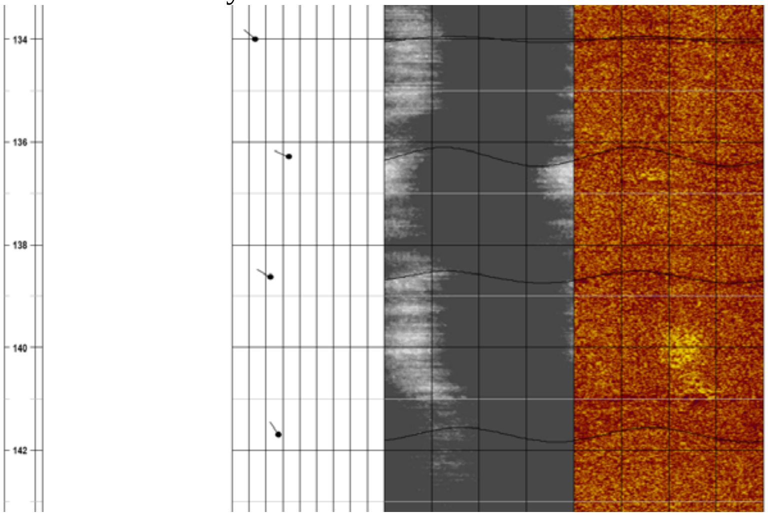
The DW-2 caliper log shows one distinct enlargement near 43 feet deep, and numerous other minor enlargements at various depths. Several distinct step-wise changes in the FRes log may represent hydraulically active zones, including near 26, 43, and 81 feet deep. Downward flow was observed entering the borehole between 28 and 45 feet deep (probably at the 43-foot caliper enlargement & FRes anomaly) and exiting between 55 and 68 feet deep (probably at the smaller 66-foot deep caliper anomaly). The remaining ambient flow tests showed zero flow (or flow less than the probe’s minimum detection limit).

Inflow while pumping originated between 68 and 80 feet deep, and increased step-wise at the following intervals: a) between 55 and 68 feet deep (probably at the 66-foot deep caliper enlargement), b) between 28 and 45 feet deep (probably at the 43-foot caliper enlargement), and c) between the casing bottom and 28 feet deep (probably at the 26-foot caliper enlargement and ATV-inferred open features, or from leakage around the casing). Most inflow while pumping occurred between 28 and 45 feet deep.

Most interpreted less-open features dip down towards the northwest in this borehole. Relatively few open features were observed. Two open features dip down towards the northwest, and two dip down towards due north. The stereoplot for DW-2 (not shown) indicates most interpreted planar-feature poles on the lower right side of the diagram, primarily with dip angles less than 45 degrees from horizontal.

The stereoplot for DW-1 (see Figure 2), which is a much deeper borehole (380 ft), shows most interpreted features centered on the southeast portion of the diagram, representing planar features that dip down towards the northwest. A distinct cluster of black poles near the diagram’s lower right side represents a group of less-open planar features dipping approximately 80 degrees from horizontal, down towards the northwest or west-northwest.

Note: only 4 fractures in 10 ft and all “closed”



Note: a swarm of fractures – open and closed

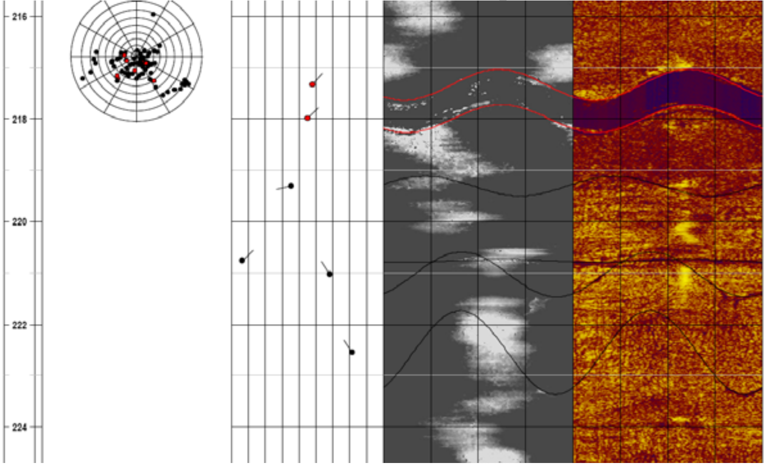


Figure 2.   Borehole Geophysics – Acoustic Televiewer

Drilling and Step Drawdown Testing

Drilling

Drilling was conducted using an air hammer drill rig (Northeast Water Wells, Inc. of Hudson, NH). Driller’s logs (on-site observation and querying the driller) as well as sequential falling head tests as drilling proceeds were used to get an idea of the relative magnitude of pumping that might be sustained.

After completion of drilling all four wells to depths of 300 ft to 400 ft, step drawdown tests were conducted on each well.

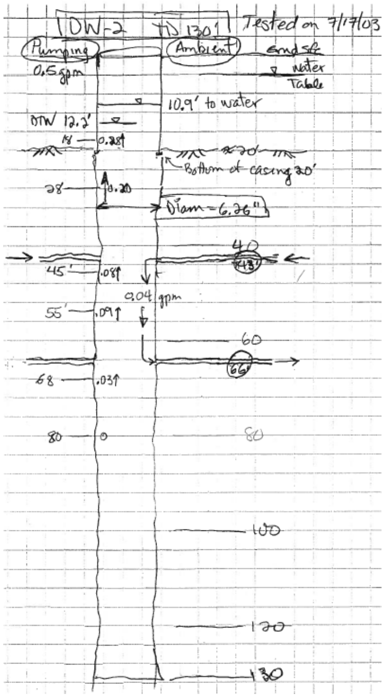
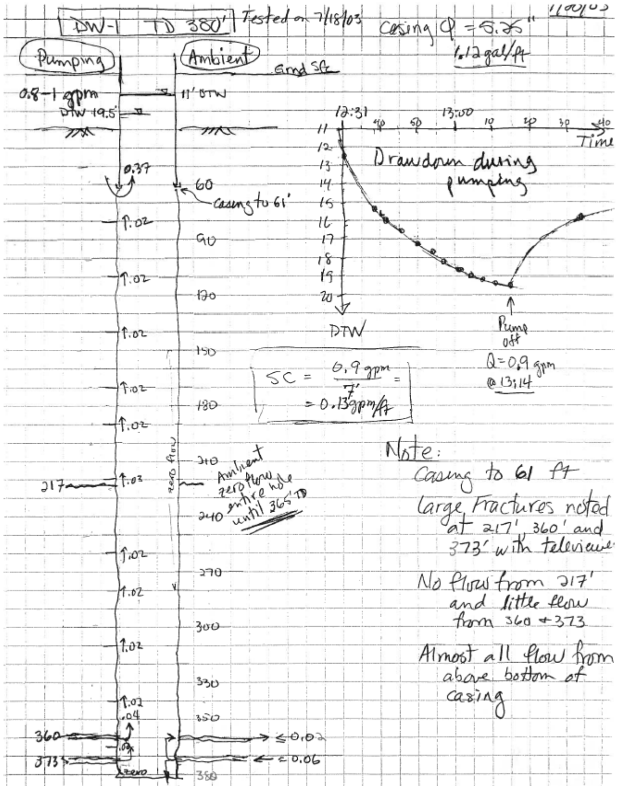


Figure 3. Field Sketch of Borehole Tests in DW-2



$$SC = \frac{0.9\ \text{gpm}}{7'} = 0.13\ \text{gpm/ft}$$

Note:
Casing to 61 ft
Large Fractures noted at 217', 360' and 373' with televiewer
No flow from 217' and little flow from 360 + 373
Almost all flow from above bottom of casing

Figure 4. Field Sketch of Borehole Tests in DW-1

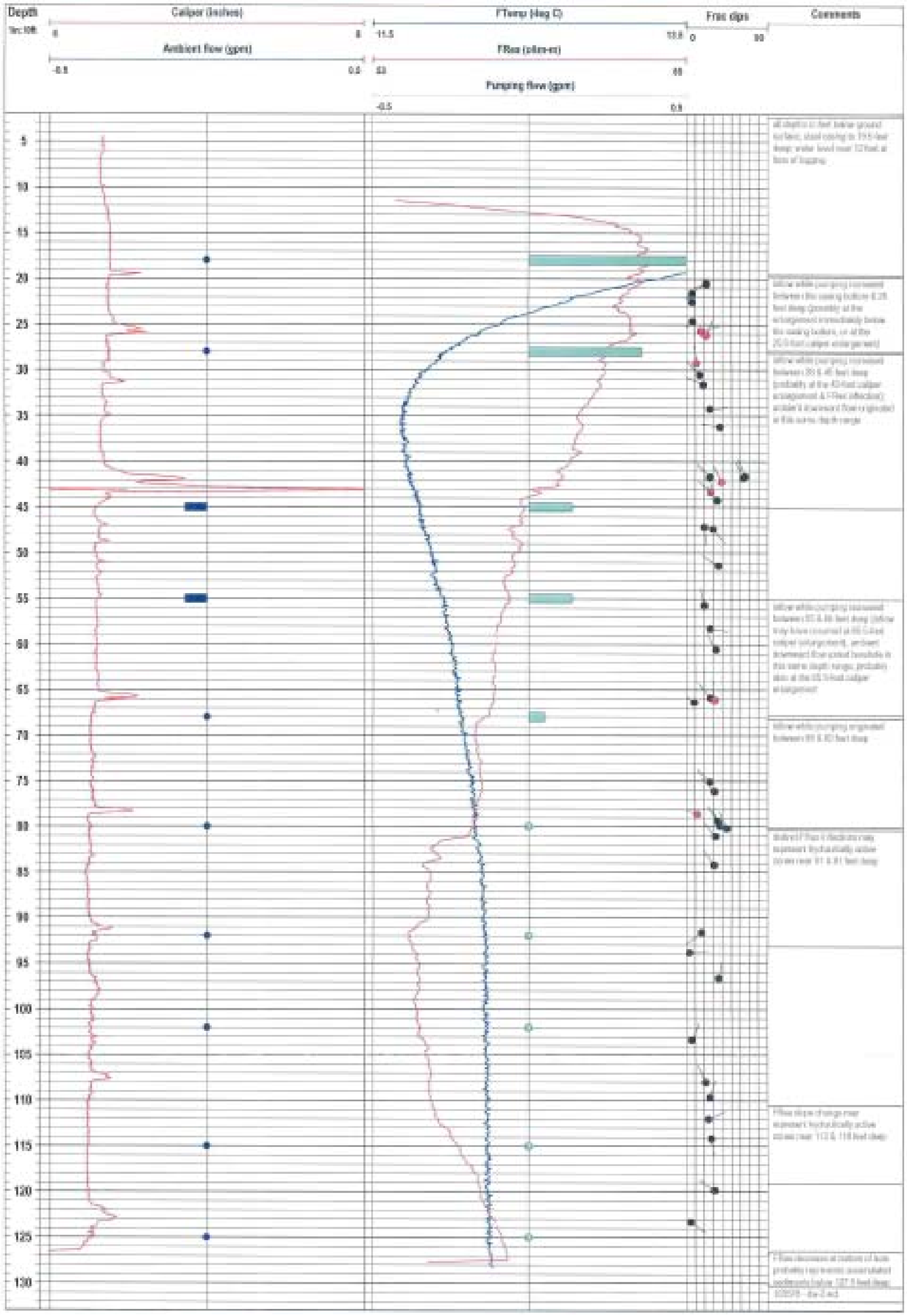


Figure 5. Geophysical logs of DW-2

Step Drawdown Tests

A step drawdown test has been conducted on each of four E-wells (E1, E2, E3 and E4) by pumping the well in a stepwise manner of increased flow rate. Drawdowns are measured in the pumped well at regular intervals in order to develop a curve of drawdown vs. time. These tests enable determination of a) the hydraulic behavior of the well including "well losses", b) an estimate of the aquifer transmissivity, and c) the pumping rate to be used for a longer duration constant rate pumping test.

Step drawdown well testing was conducted in December 2003. In the analysis of the data we have followed the procedures described by Jacob Bear in his text entitled HYDRAULICS OF GROUNDWATER on pages 374 – 376 and pages 477 – 479.

The "well losses" are assumed to be caused by turbulent flow within and adjacent to the borehole for these "open-hole" completion bedrock wells. Therefore, they are also referred to as "Q-squared" losses. The equation used for data analysis is

$$s_w = BQ + CQ^2$$

where s_w is drawdown in the pumped well, Q is the well discharge, B is the formation-loss coefficient, and C is the Q-squared well-loss coefficient. B can be determined from the Theis Equation as $W(u)/(4\pi T)$, where $u = r_w^2 S/(4Tt)$, and therefore can be seen to be a function of both the well radius and time.

The execution plan was for each test to be initiated at a pumping rate of 3 gpm; after 60 minutes the pumping rate would be abruptly increased to 6 gpm and maintained at this rate for the next 60 minutes; finally the pumping rate would be abruptly increased to 9 gpm for the final 60 minutes of this 180 minute duration step test. Actual pumping rates for well E1 were 3.8, 6 and 7.7 gpm for the three steps, but the changes in pumping rate were made abruptly at the planned times.

Drawdown data from the step test of well E1 are shown in Figure 6. In the data analysis, to render the coefficient B constant for a given well, the incremental drawdown values selected for calculating the "specific drawdown" (s/Q) are selected at the same value of time after initiating the pumping rate of each step. This time has been chosen to be 60 minutes as shown on Figure 6.

Figure 7 shows the data analysis plot of specific drawdown, s/Q vs. discharge, Q, from all four step tests. This plot is used to determine the Q-squared well-loss coefficient C. It can be seen that data from wells E1 and E3 lie on a horizontal line and therefore exhibit no Q-squared loss (C = 0). Data for wells E2 and E4 have small C-coefficient values of 0.20 and 0.14 ft/gpm^2 respectively.

In preparation for 24-hr duration, constant rate pumping tests, the step drawdown test data is used to estimate the drawdown that will occur at the end of the 24-hr test. This will then allow the selection of an appropriate pumping rate for the test to avoid excessive drawdown in the pumped well. By extending the straight line on Figure 6, it appears that at E1 a 7.7 gpm pumping rate will produce a drawdown of 76 ft if we continued pumping for a total of 24 hrs.   The resulting 24-hr specific capacity would be 0.101 gpm/ft. With this specific capacity, a pumping rate of 10 gpm will produce 99 ft of drawdown (not deemed excessive for a borehole that is 400 ft deep) at a pumping time of 24 hrs. However this is not the correct drawdown for 10 gpm. In order to account for the additional Q-squared well loss in going from 7.7 to 10 gpm, we must add a quantity that represents the increased Q-squared well loss at 10 gpm (Q_i) over that projected at the 7.7 gpm (Q_{i-1}) rate. The equation that allows this calculation is developed as follows:

$$\text{Well Loss} = CQ_i^2 = C(Q_{i-1} + \Delta Q)^2$$
$$= CQ_{i-1}^2 + 2CQ_{i-1}\Delta Q + C(\Delta Q)^2$$

Since CQ_{i-1}^2 is already in the projection from the 7.7 gpm well discharge rate, only the last two terms $\{2CQ_{i-1}\Delta Q + C(\Delta Q)^2\}$ need to be added as extra well loss for the 10 gpm drawdown projection. For well E1, $Q_i = 10$ gpm, $Q_{i-1} = 7.7$ gpm and $\Delta Q = 2.3$ gpm, but since $C = 0$ for E1 there are no Q-squared losses, and there are no extra well losses to add.

Using the above procedure for well E4 which has a C value of 0.14 ft/gpm^2 and a Q_{i-1} of 8.3 gpm produces the following. At 8.3 gpm the projected drawdown at 24 hours is 72 ft which yields a specific capacity of 0.116 gpm/ft. This specific capacity will produce 87 ft of drawdown at 10 gpm, however the calculated extra well loss for a ΔQ of 1.7 gpm is 4.4 ft. Therefore the expected drawdown after 24 hours of pumping at 10 gpm is 92 ft**.**

Figure 6
Step Test - E1

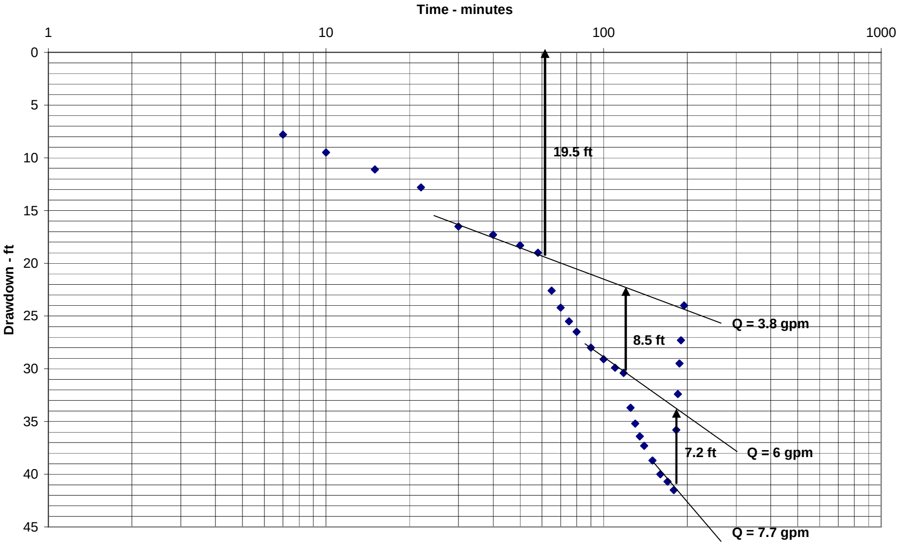
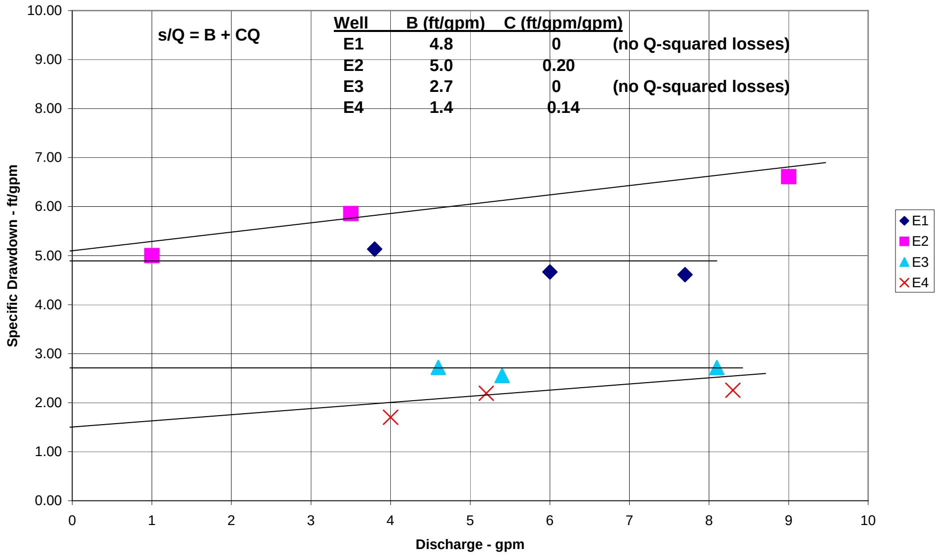


Figure 7
Well Losses and Specific Drawdown - Step Drawdown Test

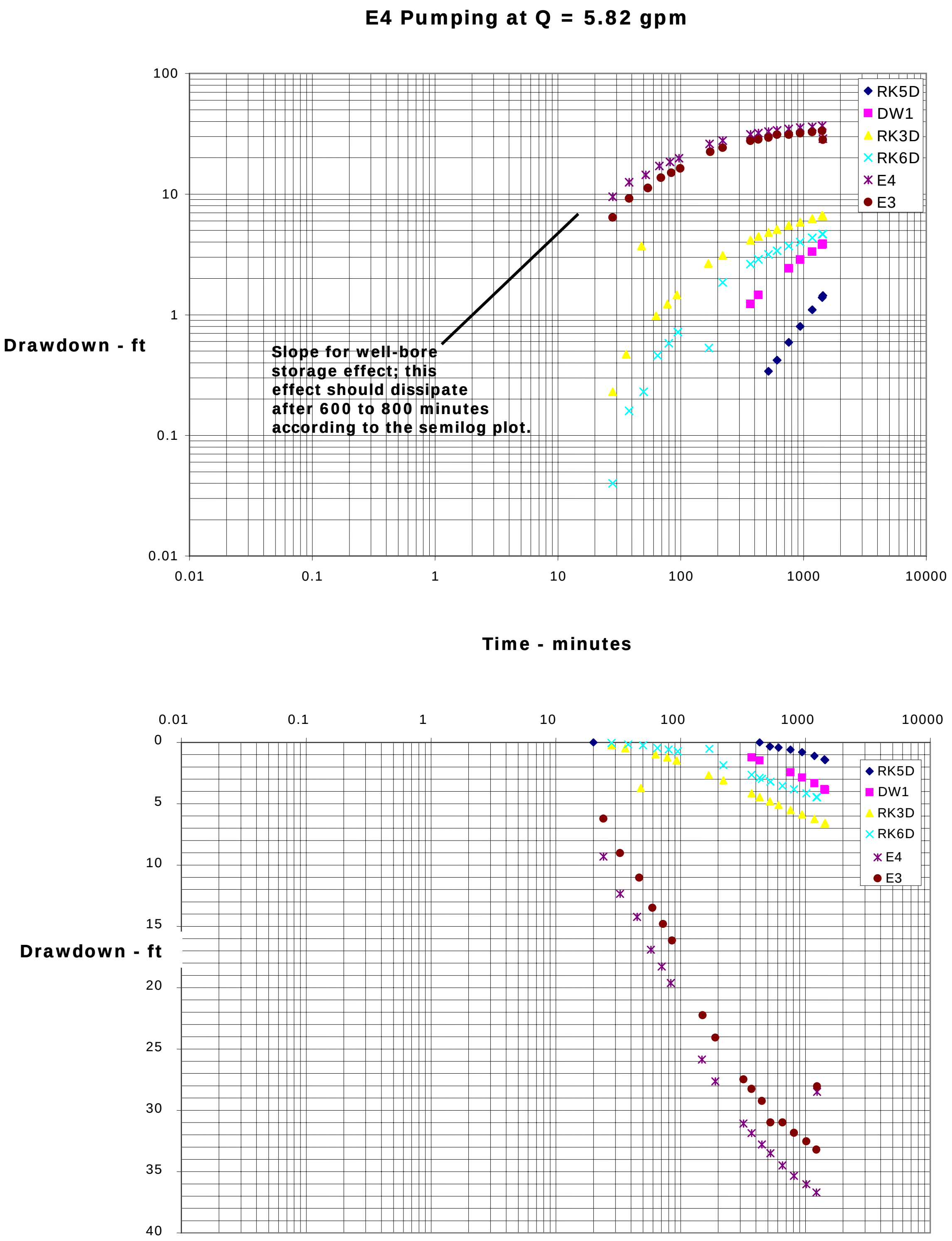


Constant Rate Pumping Tests

After completion of the step tests and completion of analysis of the step drawdown data, a 24-hr duration constant rate pumping test was conducted for each E-well. The selected pumping rate to be used for the constant rate tests was approximately 6 gpm. Observation wells surrounding each pumped well were selected for monitoring drawdown during the pumping test. Also, at a minimum, a 48-hr period of recovery was allowed at the end of each 24-hr pumping test to obtain additional data for analysis and to allow water levels to return to ambient conditions before the next test. As with the step tests, data was collected manually using electronic water level meters. The 24-hr duration for the hydraulic testing was selected because of known behavior of the aquifer from nearby pumping tests. If it were not for this other data, the short duration of these tests would no doubt be considered inadequate.

Observation well locations were selected such that they are situated at different distances and directions from each pumped well. This enables determination of the anisotropic properties of the bedrock aquifer. It was apparent from the results of a 10-day pumping test of wells nearby that there is a larger hydraulic conductivity in the NW-SE direction than in the SW-NE direction. Data is analyzed using the solution for areally anisotropic aquifers developed by Papadopulos and described in Walton's text entitled Groundwater Resource Evaluation.

Antecedent conditions for groundwater levels were monitored for a week prior to initiating the constant rate test to account for natural trends of groundwater recession. Expected results from the constant rate tests may include the effects of double porosity behavior and wellbore storage in addition to the anisotropy, and therefore plotted data was observed to detect these effects. Drawdown data were plotted on log-log paper as well as semilog paper, and the results from the test on pumping well E4 are shown in Figure 8.



Slope for well-bore storage effect; this effect should dissipate after 600 to 800 minutes according to the semilog plot.

Figure 8. Drawdown on log-log and semilog plots

These plots indicate that the effects due to wellbore storage persist for 600 minutes or more, and there is no apparent double porosity behavior.

Log-Log Plots

It can be seen from the log-log plot for E4 (plots for the other E-wells are similar) that all of the data curves tend to follow the general shape of the Theis “Type Curve”. This is an indication of radial flow behavior in the aquifer, and also suggests that the fractures are well-connected in all directions. It can also be seen that the log-log data curves for the extraction well E4 tends to approach a straight line with unit slope (one log cycle of drawdown for one log cycle of time) at small times. This is to be expected because of the “well-bore storage” effect. This phenomenon is most visible during very early times. This effect is more obvious on the semilog plots, which are discussed below. Also the length of time that well-bore storage effects are significant is more easily determined from the semilog plots.

The drawdown in E3 when it is the pumped well (figure not shown) shows straight-line “half-slope” behavior for time between 10 and 100 minutes (“half-slope” means an increase in drawdown of half a log-cycle for a time change of one log-cycle). This is an indicator of linear or parallel flow as opposed to radial flow, and often occurs in fractured bedrock aquifers. Linear flow can be caused by a pumping well intersecting a vertical or near-vertical fracture such that flow to the well, at least initially, is dominated by the linear flow along that single fracture. Linear flow behavior can also be caused by a pumping well intersecting a horizontal or near-horizontal fracture, which has water flowing into it in a linear fashion from the lower permeability rock matrix on either side. It should be noted that at late times the drawdown data for all wells tend to follow the Theis Type Curve for radial flow.

The magnitude of drawdown in wells E3 and E4 are of similar magnitude. Since they are a considerable distance apart, this would suggest there is a highly transmissive fracture connecting them. This would appear to be the feature that is causing the early time linear flow behavior of well E3. However, when E4 is the pumped well this half-slope drawdown behavior in not evident. Instead it appears that both E3 and E4 only exhibit the well-bore storage effect.

Semilog Plots

The semilog data plot shows two distinct behaviors, one for the pumped well and another for the observation wells. The data for the pumping well exhibits the distinctive shape indicative of well-bore storage. This shape is a backwards S-shaped “hump” that merges into the classical straight line predicted by the Cooper-Jacob approximation to the Theis curve. The data collected in the pumped well appears to be dominated by well-bore storage with only a few points at larger time showing the true straight line behavior which is parallel to the straight line of the drawdown data for the deep observation wells (Note: the straight line behavior on the semilog plot of drawdown vs. time indicates radial flow to the pumped well). It is easier to see the straight line behavior on the semilog plot than to determine exactly what portion of the data on the log-log plot matches the Theis Type Curve.

With E1 as a pumping well (figure not shown) the drawdown for deep (~400 ft) observation wells are approximately 5 times the drawdown magnitude for shallow (~100 ft) observation wells. This reflects the fact that shallow wells do not intercept the deep water yielding fractures that are intercepted by both the pumped well and the deep observation wells. Instead the shallow wells are connected through the vertical hydraulic conductivity of the bedrock which is apparently much smaller than the lateral hydraulic conductivity.

With E2 as a pumping well, as with the E1 pumping test, one of the shallow wells has very little drawdown compared with the deeper observation wells. However, one of the other shallow wells shows nearly the same drawdown as its paired deep well, which indicates that at this particular location there is a good hydraulic connection vertically in the bedrock aquifer. This is just one more indication of the heterogeneity of a fractured bedrock aquifer.

Aquifer characteristics, storage coefficient (S) and transmissivity (T) have been determined from the semilog drawdown vs. time plots using the Cooper-Jacob approximation. Those values are presented in following table. The average value of transmissivity for the deep bedrock aquifer is approximately 300 gpd/ft (40 ft^2/day), and the average value for storage coefficient is approximately 3×10^{-4}. The average values obtained from each of the four pumping tests are given below.

Pumping Well	No. of Obs. Wells	Transmissivity, T gpd/ft (ft^2/day)	Storage Coefficient
E1	2	215 (28.7)	5.1×10^{-4}
E2	5	283 (37.8)	1.2×10^{-4}
E3	4	313 (41.8)	1.4×10^{-4}
E4	3	422 (56.4)	4.1×10^{-4}
	Averages:	310 (41)	3×10^{-4}

There appears to be an increase in transmissivity values from E1 to E4, which is SW to NE across the site. There is also an indication, as previously mentioned, that the bedrock aquifer is anisotropic, with a larger hydraulic conductivity in the NW-SE direction than in the NE-SW direction. This is evident in some of the data from the 24-hr tests analyzed below, but is most evident and confirmed from the data of the 72-hr test described later.

Anisotropic Transmissivity Calculations

As expected, the drawdown data exhibited behavior indicating anisotropy in the horizontal plane, that is, and elongated cone of depression in the NW-SE direction. Therefore specialized methods for determining the directional tranmissivities have been used (method of Papadopulos published in 1965 as presented in the 1970 text Groundwater Resource Evaluation by William Walton). This data analysis method involves plotting drawdown vs. time on semilog graph paper to determine "zero drawdown" intercepts, and then solving a set of simultaneous equations for the hydraulic characteristics. This procedure was followed to analyze the data from 24-hour constant rate pumping test of well E2. The analysis revealed that there is a maximum transmissivity of 78.4 ft^2/day and a minimum transmissivity of 12.85 ft^2/day. The direction of the maximum transmissivity is along a NW-SE line, and the direction of the minimum is perpendicular to this direction along a NE-SW line. This corresponds with the direction of the elongated cone of depression from the 72-hour test (described below). It can also be seen that the value of the average transmissivity determined from the Cooper-Jacob analysis (41 ft^2/day as presented above) is approximately equal to the average of the maximum and minimum values. The value of storativity from the Papadopulos analysis is 1×10^{-4} which is nearly the same as the average value from the Cooper-Jacob analyses of 3×10^{-4}.

72-Hr Pumping Test Of The Four E-Wells

The constant rate test of the four E-wells pumping simultaneously was conducted for a pumping duration of 72 hours (4320 minutes), with each well producing approximately 5.5 gpm for a combined total extraction rate of 22 gpm. Before initiating this test, antecedent monitoring of groundwater levels was conducted for a period of 5 days; the water levels were essentially constant prior to initiating the 72-hr pumping test.

A simple linear plot of drawdown vs. time for deep bedrock wells showed that water levels returned to starting equilibrium levels at a time of approximately 12000 minutes (200 hours), or 128 hours after cessation of pumping. The water levels then remain constant for the duration of monitoring, or for 9 days after pumping ceased. It is apparent that no correction for natural water level fluctuation is required for these tests (a lucky break).

The cone of depression for the deep wells at a time of 4000 minutes has been prepared and is presented as a map in Figure 9**,** using data taken from the semilog drawdown plots. It can be seen that even though the wells are aligned in the NE-SW direction the contours defining the cone of depression are elongated in the NW-SE direction. This indicates that the bedrock aquifer is anisotropic with a larger hydraulic conductivity in the NW-SE direction than in the NE-SW. Figure 10 shows the drawdown cone for the shallow wells, the anisotropy is even more pronounced here than for the deep wells.

As previously mentioned, there is a local fracture feature that connects wells E3 and E4 such that they tend to act as a horizontal well connecting their two locations. This creates a very effective hydraulic containment feature, as the groundwater levels between the two wells will be almost at the same level as the water in the wells themselves.

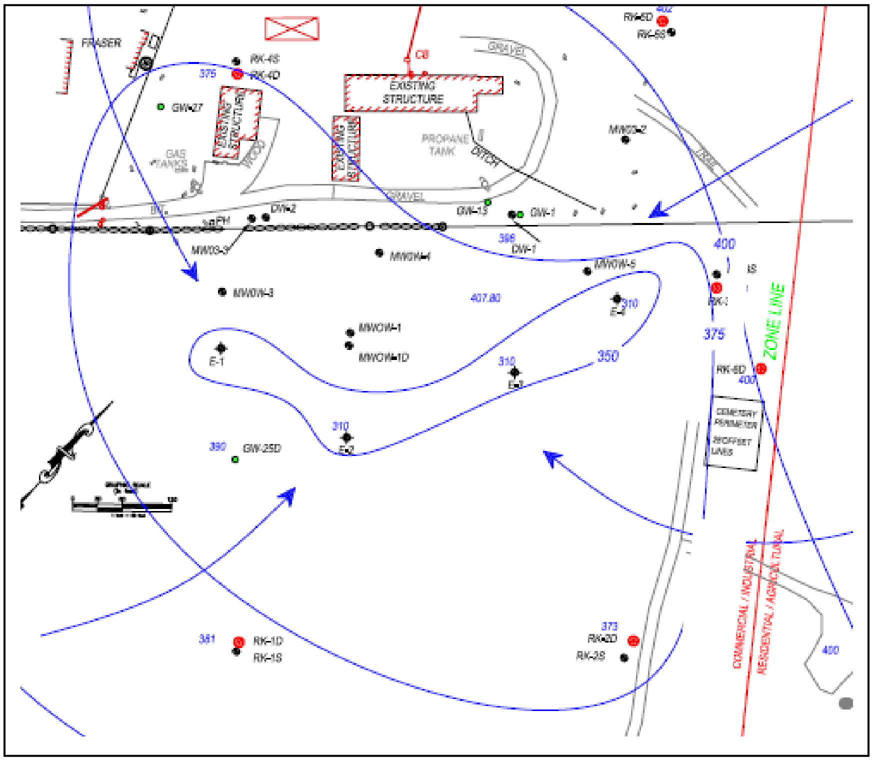


Figure 9. Drawdown cone around pumping wells at t = 4000 minutes

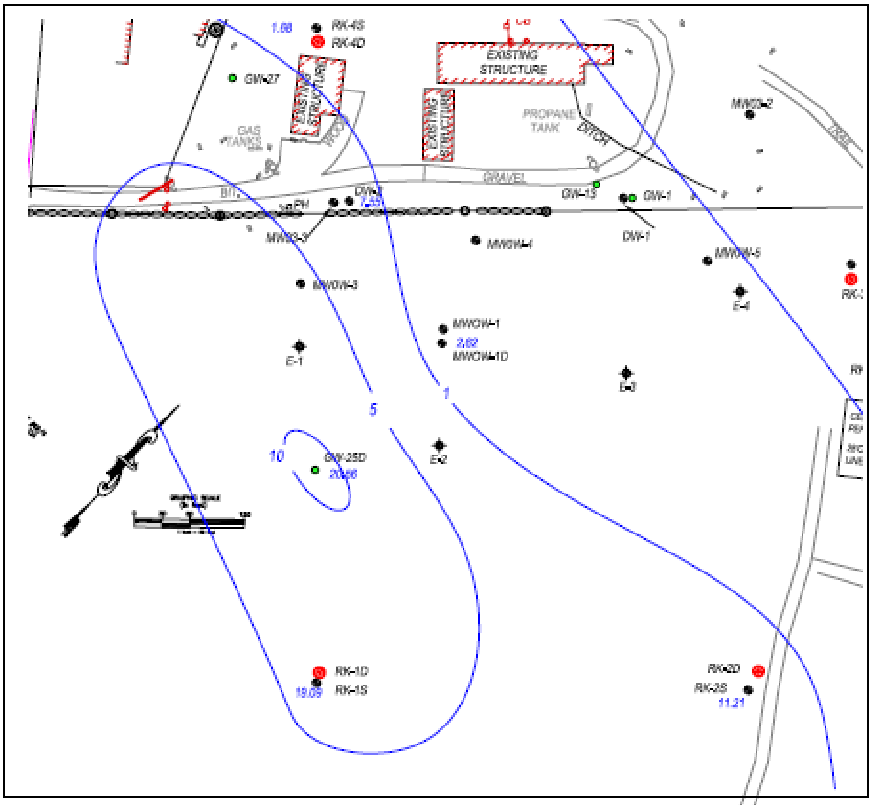


Figure 10. Shallow bedrock cone of depression at t = 4000 minutes

Conclusions

The pumping tests reported herein have allowed us to make the following conclusions regarding groundwater flow and aquifer response to pumping:

- The E-wells are very efficient as shown by the step drawdown tests, and little to no extra “well loss” is associated with their completions
- The bedrock aquifer is well connected laterally and response to pumping is observed in all directions from a pumping well; this implies that the groundwater flow can be controlled by pumping at the site
- In general, vertical hydraulic conductivity is smaller than horizontal, but there is a vertical hydraulic connection throughout the bedrock aquifer; and one location where a deep/shallow observation well pair was installed, the vertical hydraulic conductivity appears to be nearly as great as the horizontal
- The bedrock aquifer exhibits anisotropic behavior with the transmissivity being greater in the NW-SE direction than in the NE-SW direction
- In addition to anisotropy, the aquifer tests reveal a trend of increasing transmissivity across the site from SW to NE
- The hydraulic connection between two of the extraction wells indicates that the two wells are connected by a highly transmissive fracture; the behavior of the water levels during pumping reveals that these two wells act as if they were connected by a horizontal well, thus assuring containment and capture of the area between them

References

1. Bear, J., (1979), Hydraulics of Groundwater, McGraw-Hill, Inc., 567 pp.

2. Walton, W. C., (1970), Groundwater Resource Evaluation, McGraw-Hill, Inc., 664 pp.

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Dr. Murray has more than 40 years of consulting, applied research, and academic experience in hydrology and remedial engineering, and is a registered Professional Engineer. He has conducted surface water quality and quantity studies, and hydrogeologic investigations to characterize aquifers for both groundwater supply and groundwater cleanup. He has served as expert witness for court cases involving contaminant migration and site cleanup. Dr. Murray has held positions as a Professor of Civil Engineering, National Laboratory Research Hydrologist and Consulting Engineer.

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Ms. Farnsworth has been providing environmental services to clients for more than 20 years. She formed her own company, MyKroWaters, Inc. in 1994 and is a certified WBE business enterprise providing a full array of environmental consulting services in the areas of environmental and OSHA Compliance; Environmental Management Systems; ISO 14000 program development; environmental site evaluation; site investigation and characterization; and remediation design, implementation and operation. She is a member of the LSP Board in Massachusetts.