Pumping Test Analysis in a Fractured Crystalline Bedrock

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Abstract

Groundwater flow in fractured bedrock is controlled by the location, orientation and aperture of individual fractures as well as by the interconnectedness of the individual fractures into a network. The interconnectedness of individual fractures can be determined through pumping tests. It has been noted that, during a pumping test, the hydraulic response at observation wells in fractured bedrock is different from the hydraulic response observed in unconsolidated porous media (Tiedeman and Hsieh, *Ground Water* 39:68-78, 2001).

A 24-hour pumping test was performed in a crystalline bedrock groundwater system. The pumping well is a 15-cm diameter, 30-m deep open bedrock borehole which intersects a significant transmissive fracture(s) at only one depth interval over the 23-m uncased portion of the borehole. Borehole geophysical logging of the pumping well indicated two open fractures at a depth of 15 m below ground surface: a fracture dipping west-northwest at an angle of 8° from the horizontal, and a fracture dipping northwest at an angle of 36°. The geophysical logging data identified this zone as containing one or more transmissive fractures, but were not able to resolve if one or both of these fractures contributed groundwater to the borehole. The pumping rate was varied during the course of the pumping test, from 4 liters per minute (L/min) to 7 L/min to 0 L/min and then to 2 L/min. Within 50 minutes of raising the pumping rate to 7 L/min, the water level in the well dropped below the 15-m depth of the transmissive fracture(s), leading to rapid dewatering of the borehole. This verified the initial hypothesis that significant transmissive fracture(s) occurred at only one depth in the open borehole.

Piezometric heads in 14 observation wells were measured every 10 minutes and recorded with a datalogger. Based on review of these data, 11 of the 14 wells are categorized into one of three major well groups that represent hydraulically interconnected fracture sets. Group 1 wells are high-transmissivity wells that include the pumping well. Group 2 wells are moderate-transmissivity wells that are adjacent to and qualitatively similar to the Group 2 wells. Both Group 1 and 2 wells showed rapid hydraulic responses to changes in pumping rate. The main difference between Group 1 and 2 wells is the magnitude of the drawdowns. Group 3 wells are moderately transmissive wells that show both qualitatively and quantitatively different behavior from the Group 1 and 2 wells. Unlike Group 1 and 2 wells, Group 3 wells exhibited delayed responses to changes in pumping rates. Three of the 14 wells exhibited behavior that could not easily be included in one of the three well groupings.

Background

Traditional analysis of pumping test data includes fitting observation well drawdown data to analytical solutions for solving aquifer transmissivity, hydraulic conductivity and storage coefficient. Analytical solutions, including the Theis solution, are based on assumptions derived for porous media aquifers, including uniform thickness, infinite extent and steady state conditions. The practice of fitting drawdown data in response to pumping in fractured bedrock aquifers often leads to difficulties in matching data to analytical solutions, due to the differences between flow in porous media and flow in discrete fractures.

For bedrock aquifers exhibiting low storativity and porosity, minor stresses in the aquifer caused by pumping can lead to significant drawdown responses in nearby observation wells, whereas other wells will not respond to the stress. This is believed to reflect the interconnected network of a fracture architecture whereby specific monitoring wells tap a same network, and other wells are outside of the network. The differences in observation well drawdown data can therefore be used to indicate the presence or absence of a fracture network, regardless of distance from the pumping well.

Unlike pumping tests in porous media, the drawdown response in observation wells in fractured bedrock aquifers is not highly dependent upon the distance between the observation well and the pumping well. As illustrated by Tiedeman and Hsieh (2001), observation wells screened within a high-transmissivity fracture zone will produce similar drawdown behavior, regardless of their distance to the pumping well. Tiedeman and Hsieh (2001) show that, within a fracture zone, observation wells exhibit similar times of initial drawdown response and similar maximum drawdowns. By grouping wells with similar drawdown behavior, fracture zones can be defined. A "primary" interconnected fracture zone can be defined to include wells in which the drawdown response curves essentially mimic that in the pumping well. Additional fracture zones are defined based on a delay in response and smaller peak drawdown values.

Site Description

The study site is topographically positioned on a relatively flat hilltop just north of a regional surface water divide (Figure 1). The ground surface elevation at the site is approximately 41 meters above mean sea level (masl) and slopes to the northeast, where a wetland is present representing a regional groundwater discharge area. Because the site is located within an urban area, the ground surface is largely capped by buildings and paved parking areas, thereby limiting groundwater recharge across the study area. Unconsolidated deposits at the site are classified as a glacial till, however the water table is located approximately 3 meters to 6 meters into bedrock.

Bedrock at the site consists of a metamorphic sequence of intensely sheared parent rocks, including diorite, gabbro, altered basalt and schist. Regional bedrock structure and fractures are dominated by northeast-trending features with secondary northwest-trending conjugate features. Numerous healed fractures were observed in core samples suggesting that at one time the bedrock was moderately to highly fractured. Visual inspection of natural fracture surfaces in rock cores revealed the presence of chlorite, a common clay mineral produced from the weathering of ferro-mangnesium-rich bedrock. Structurally, site bedrock fracturing can be grouped into three distinct categories based on their order of frequency; 1) small scale foliation planes along mineral contact surfaces, generally trending northeast and dipping northwest; 2) medium to large scale sub-horizontal stress relief fractures; and 3) large-to very large-scale, sand-filled, high-yield, regional northeast-trending fractures.

From a hydraulic perspective, the first set of fractures attributed to mineral contact surfaces generally exhibit low transmissivity. The second set of fractures has higher transmissivities than the foliation planes and is believed to represent openings within the bedrock resulting from unloading stresses following deglaciation. These features were generally located within the upper 30 meters of bedrock. The third type of fracture was only observed at two wells at the site, located approximately 300 meters downgradient of the pumping test area.

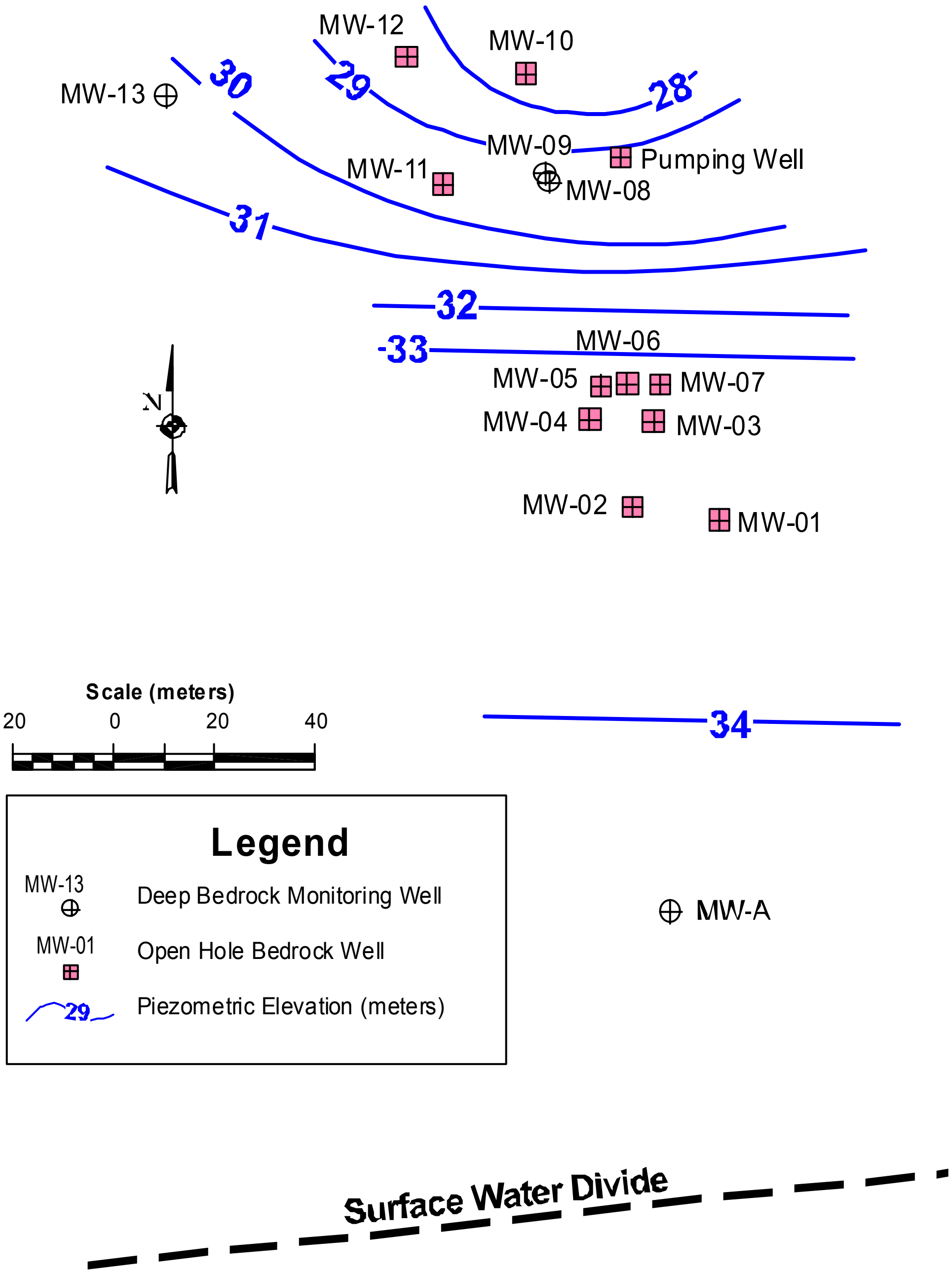

Figure 1. Site Plan Showing Bedrock Piezometric Elevations (in meters above mean sea level)

A borehole geophysical log for the pumping well is depicted in Figure 2. Eleven fractures were identified by the acoustic televiewer. Many of the fractures had dip angles greater than 50° from the horizontal. However, these fractures were not associated with significant caliper openings or measurable flow inside the borehole using the heat-pulse flowmeter. Two northwest-dipping, sub-horizontal fractures identified at a depth of approximately 15 m (Figure 2) were associated both with a significant decrease in borehole integrity (as indicated by the caliper measurement) and a noticeable change in the vertical flow rate measured by the heat-pulse flowmeter.

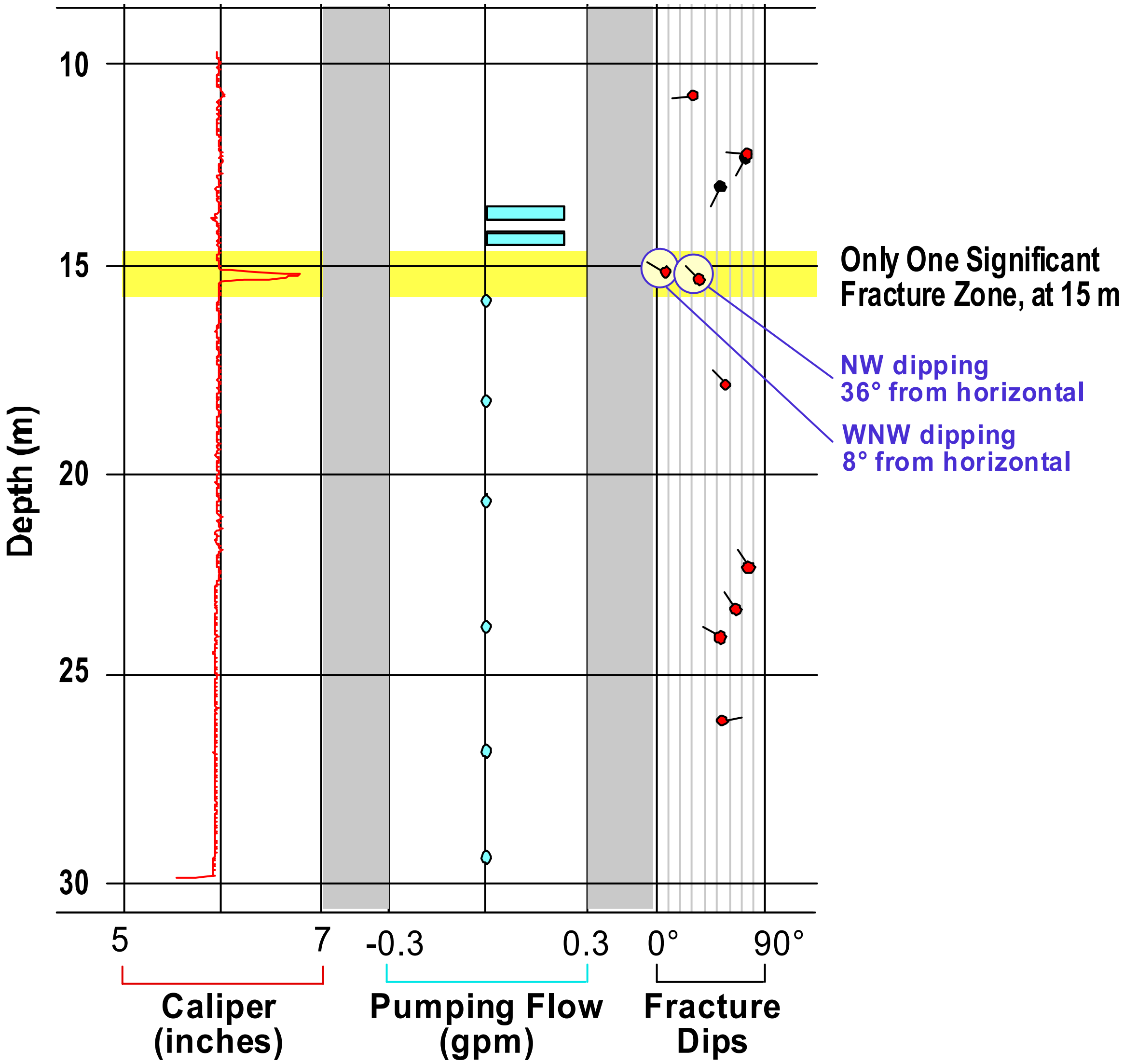

Figure 2. Borehole Geophysical Log of Pumping Well

Methodology

Aquifer Testing

On 8 and 9 January 2002, a 24-hour pumping test was conducted. Groundwater elevations were monitored at the pumping well and the 13 wells listed in Table 1 prior to, during and after the pumping event.

Bedrock Monitoring Wells in Study Area

Table 1 summarizes construction details for observation wells used during the 24-hour pumping test. Wells comprised either 5-cm PVC wells (MW-08, MW-09 and MW-13) or open bedrock boreholes (MW-01 through MW-07, MW-10 through MW-12). The open boreholes have saturated lengths of between 12 meters and 20 meters.

Table 1. Summary of Well Construction Details

Well ID	Well Diameter (mm)	Total Well Depth (m)	Screen Length (m)	Screen Interval Elevation (m ASL)	
				Bottom	Top
Pumping Well	100	30	Open hole	10	33
MW-01	100	24	Open hole	16	38
MW-02	100	25	Open hole	16	37
MW-03	100	24	Open hole	16	35
MW-04	100	18	Open hole	23	36
MW-05	100	18	Open hole	23	35
MW-06	100	24	Open hole	16	35
MW-07	100	18	Open hole	22	34
MW-08	50	27	3	13	16
MW-09	50	19.5	4.6	21.3	25.9
MW-10	150	30	Open hole	10	31
MW-11	150	30	Open hole	10	34
MW-12	50	30	Open hole	10	30
MW-13	50	23	3	18	21

Results

Baseline Hydraulic Response Comparison

Groundwater elevations at the pumping well, MW-08 and MW-09 experienced similar head fluctuations in the days prior to the pumping test (see Figure 3). MW-01 also appears to be in the same fracture zone, in spite of its distance from the pumping well. All four of these wells show an increase in groundwater elevation following a rain event on 6 and 7 January 2002. Monitoring wells MW-02, MW-03, MW-05 and MW-06 experienced fluctuations in groundwater elevations that are similar, but less than the pumping well. MW-13 showed even more damped fluctuations; however it generally appears to respond to the same hydraulic perturbations as the pumping well.

Groundwater elevations at monitoring wells MW-10, MW-11 and MW-12 experienced fluctuations similar to the pumping well throughout the monitoring period, however early time small-scale fluctuations lead to a decrease in head over a six-hour period in the early hours of January 7, 2002. This sharp drop in head is followed by a period of gradual increase.

Pre-pumping groundwater elevations at monitoring well MW-07 did not show a similar trend to the other wells. MW-07 showed a steady increase in groundwater elevation over the four-day period that is thought to be attributed to borehole equilibration following a recent sampling event.

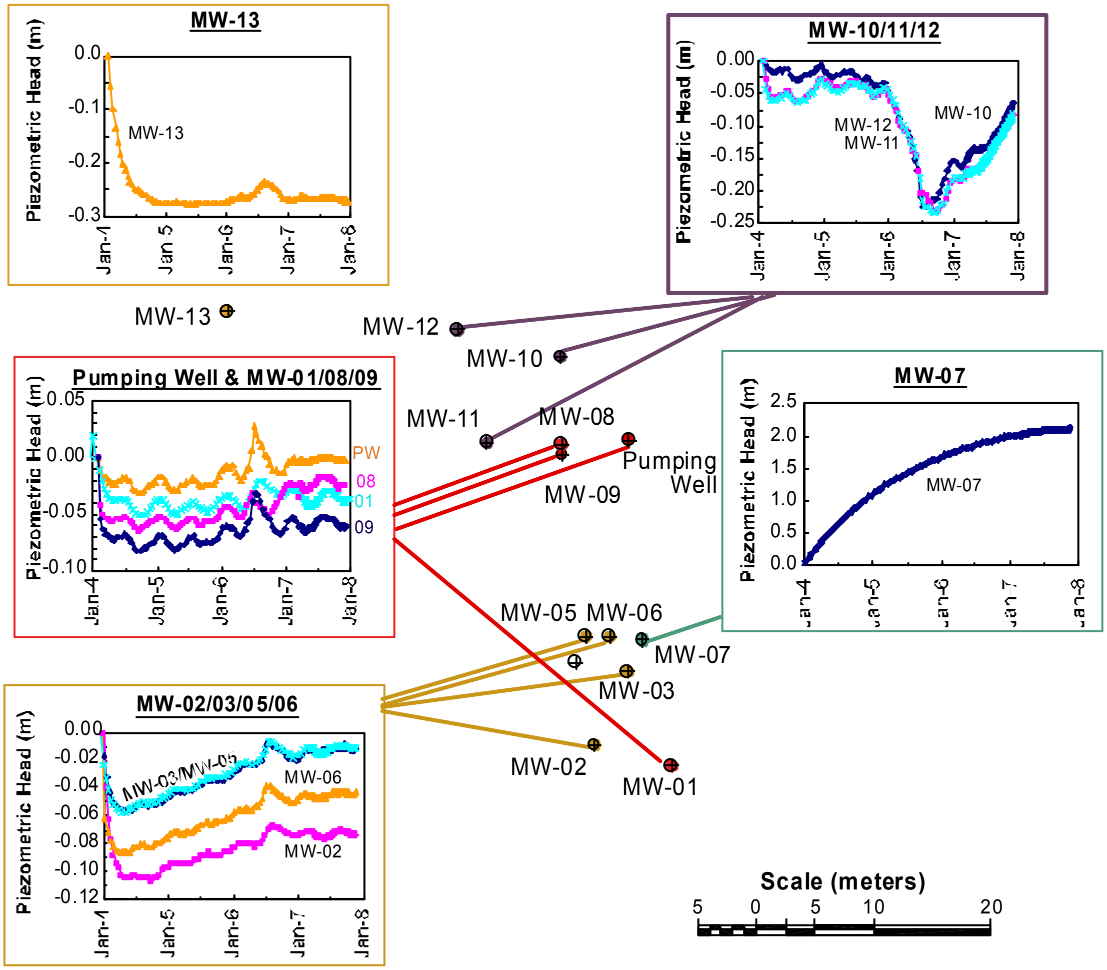

Figure 3 Piezometric Data From Prior to Pumping Test

Pumping Rate

The applied pumping rate varied throughout the course of the test. After pumping at an initial rate of 4.2 L/min for two hours, the pumping rate was raised to 7.2 liters per minute (L/min) for 40 minutes, after which time the water level in the pumping well began to rapidly decline. It became apparent that the primary water-bearing fracture(s) at the pumping well occur(s) at a depth of approximately 15 m below ground surface (see Figure 2). Therefore, in the analysis of the pumping test data, it is assumed that the fractures which contributed the vast majority of water to the well occur at a depth of approximately 15 m. When the water level in the well fell below 15 m, it was assumed that the 15-m-depth fracture(s) continued to produce water which trickled into the hole, and that no additional water was withdrawn from deeper fractures. Therefore, to compute the amount of water that was produced by the fracture, the volume rate of drawdown was subtracted from the volume of water extracted from the hole, as shown in Table 2.

Table 2. Calculated Extraction Rates from Pumping Well Fracture Zone

Day	Time		Elapsed Time (min)		Measured Pumping Rate (L/min)	Drawdown Rate in Well (L/min)[1]	Effective Pumping Rate (L/min)
	Start	End	Start	End			
Jan 8	9:56	12:16	0	140	4.2	NA[2]	4.2
	12:16	12:56	140	180	7.2	NA	7.2
	12:56	13:45	180	229	7.2	1.5	5.7
	13:45	14:15	229	259	0.9	-1.1	2.1
	14:15	17:23	259	447	3.1	0.2	2.9
	17:23	18:16	447	500	0	-1.4	1.4
	18:16	21:15	500	679	0	-0.04	0.04
Jan 9		10:30	679	1474	1.7	NA[2]	1.7

Note: [1] Only when the water elevation in the well fell below the fracture level of 15 m below ground surface.
[2] NA = not applicable because water level is equal to or above fracture level

Drawdowns in Observation Wells

Drawdown response data are presented as the reduction in water level after initiating pumping (time zero). Figure 4 shows the drawdown in the pumping and observations wells during the 24-hour pumping test and two days of water level recovery. Drawdown responses were recorded at 14 wells (MW-01 through MW-13 and the pumping well). A pumping rate of 7.2 L/min resulted in over-pumping of the extraction well, and the water level in the well fell below the elevation of the main fracture zone after 180 minutes of pumping (see Figure 5). Adjustments in the pumping rate permitted the continuation of the test for a period of 24 hours.

Pumping drawdown and recovery response data indicate that the pumping well and MW-09 tap the same highly conductive fracture. Except for the 5-hour period during which the water level in the pumping well was below its transmissive fracture, the two well drawdowns were essentially identical. The extreme similarity in responses at these wells occurred even though the pumping well is an open bedrock well, with a saturated depth of 20 meters, while MW-09 is a 50-mm PVC monitoring well with a 4.6-meter screen.

MW-08, MW-11, and MW-12 are also hydraulically connected to the pumping well, and drawdowns in these observation wells follow closely the drawdown in the pumping well. These wells responded rapidly to changes in pumping rate. All wells show two drawdown periods, with the drawdown during the first period (up to about 500 minutes) higher than during the second period (from 700 to 1500 minutes).

MW-10, by contrast, experiences a more diffuse response to the pumping well, and shows a gradually increasing drawdown until 1500 minutes into the test (i.e., soon after pumping ceased), after which the groundwater elevation in the well recovers. MW-13 shows a similarly diffuse response, with increasing drawdown until 1500 minutes into the test. However, the drawdown at MW-13, located 40 meters to the west of the pumping well is less than MW-10, but is very similar to that in six bedrock wells (i.e., MW-01 through MW-06), located approximately 30 meters to the south of the pumping well. Both the timing and drawdowns in these six wells are similar. They exhibit an initial drawdown response after 500 minutes of pumping, with drawdown peaks at 1500 minutes.

MW-07 shows drawdown behavior similar to the other wells in its vicinity, but the drawdown in this well is noticeably lower. Since the water level in this well was increasing at the start of the test, indicating non-steady state conditions prior to the start of pumping (see Figure 3) the drawdown response for this well are the least reliable in determining fracture interconnectedness.

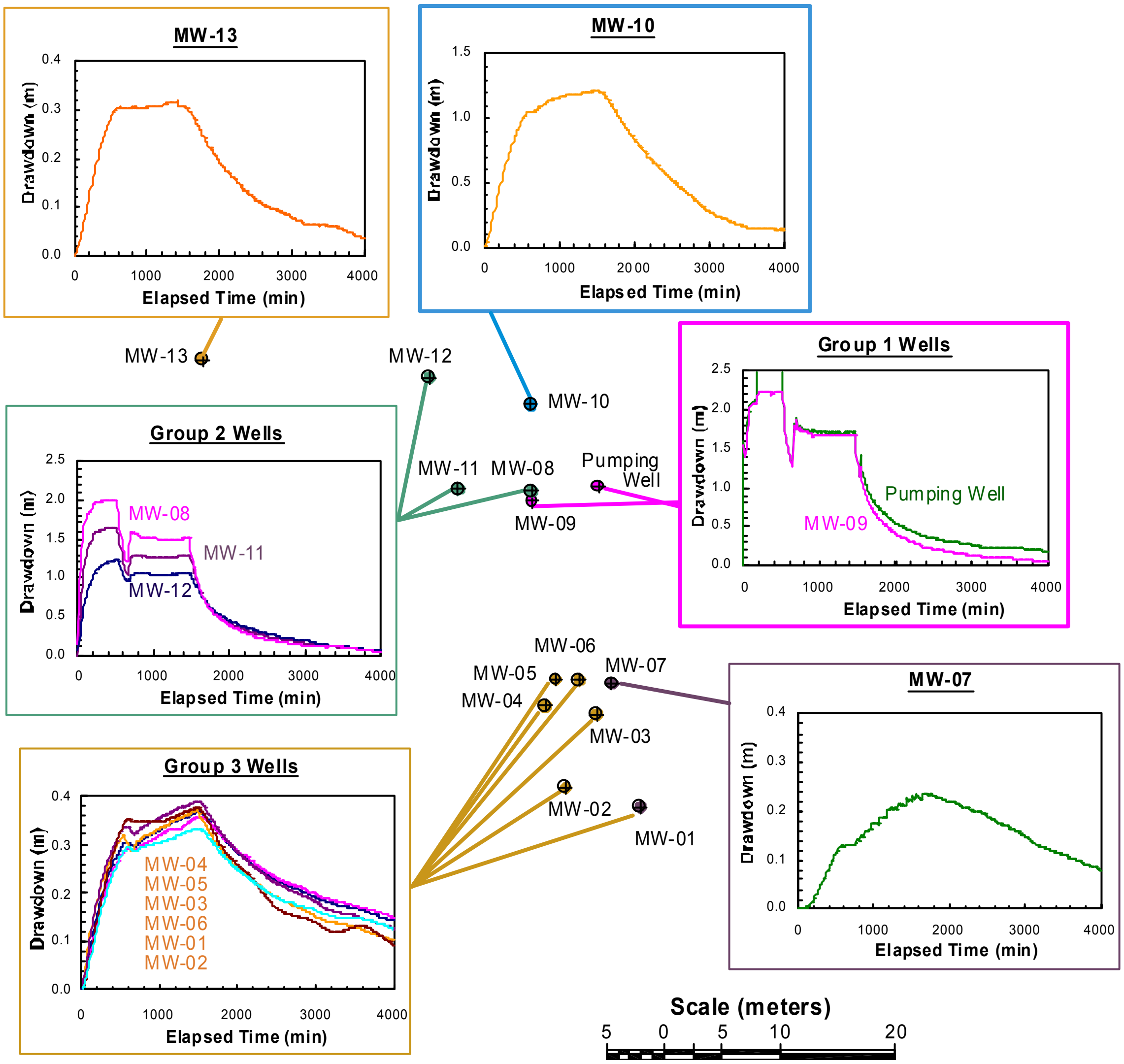

Figure 4 Drawdown Data

Fracture Connectivity Groupings

Pre-recovery drawdown data from all 14 wells are shown in Figure 5. Based on the drawdown data (Figures 4 and 5), two primary fracture zones were identified. The identified fracture zones are shown in Figure 6.

The pumping well and four observation wells, MW-08, MW-09, MW-11 and MW-12, show similar hydraulic responses. These wells responded immediately to the pumping stresses and behave as if they exist within the same fracture zone. The two wells with the most pronounced response to each change in pumping stress, the pumping well and MW-09, are believed to intersect the same fracture zone and are classified as Group 1 wells. Nearby wells MW-08, MW-11 and MW-12 showed similar behavior, but exhibit lower drawdowns than Group 1 wells; these are therefore Group 2 wells. In addition to having lower drawdowns than the Group 1 wells, the Group 2 wells also have significantly lower sustainable pumping rates than the Group 1 wells.

South of the Group 1 and 2 wells, MW-01 through MW-06 show very similar behavior, indicating that they are located within the same fracture zone. These six wells are termed the Group 3 wells. The Group 3 fracture zone is separate from the Group 1/2 fracture zone as indicated in the nearly 0.8 meters of difference in peak drawdown and by the more diffuse responses to individual changes in pumping perturbation.

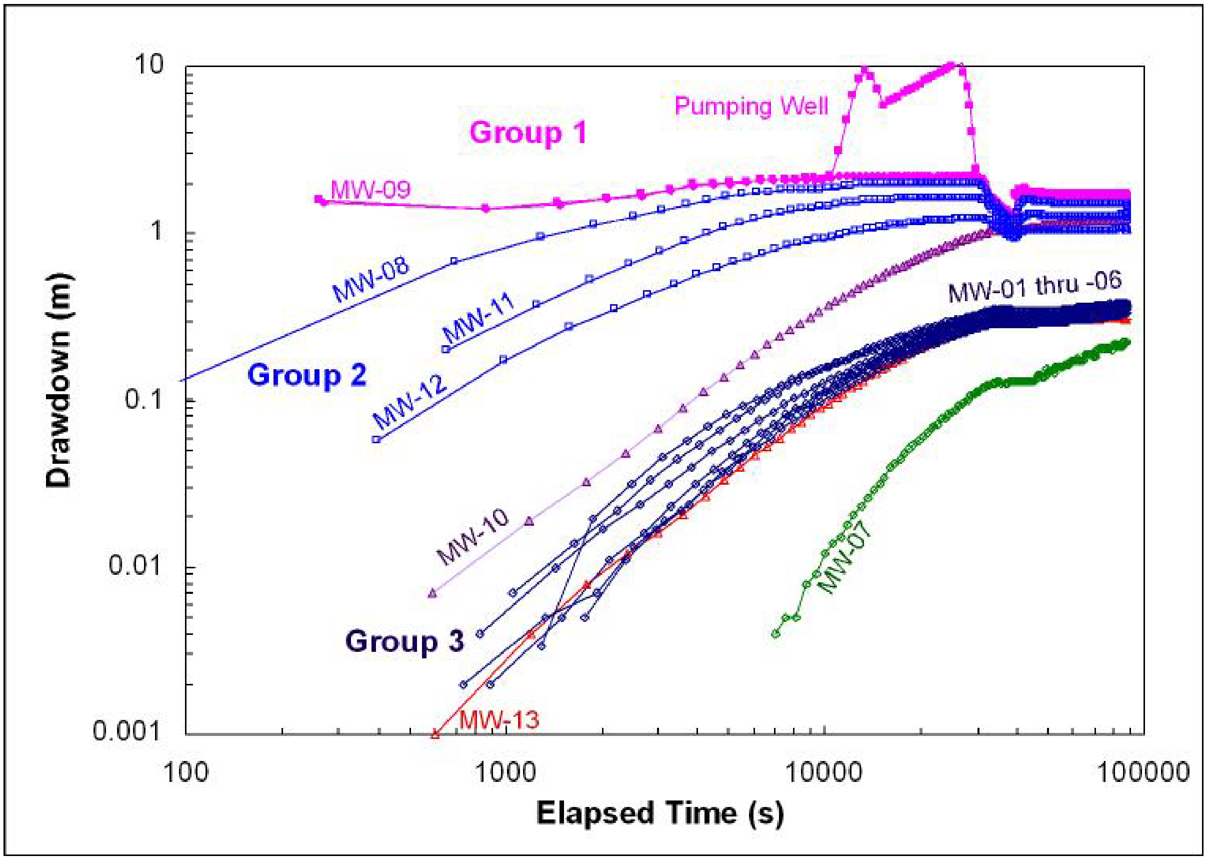

Figure 5. Drawdowns Recorded in Deep Bedrock Wells During 24-Hour Pumping Test, Pre-Recovery Data

MW-10, located adjacent to the Group 2 wells, responded more slowly to pumping stresses and was therefore not included in Group 2. However, because the late-time drawdown at MW-10 approached that of the Group 2 wells, the fracture zone that is tapped by MW-10 is presumed to be hydraulically connected to the Group 2 fracture zone (see Figure 6).

Likewise, the drawdown at MW-07 was considerably less than in the Group 3 wells. However, changes in the rate of drawdown are noted for each key change in pumping rate that is evident in Group 3 drawdowns (see Figure 4). It is surmised that the discrepancy between the drawdown at MW-07 and at Group 3 wells is the fact that MW-07 was sampled prior to the pumping test. Well recovery from the sampling event was occurring throughout the course of the pumping test. As a consequence, drawdowns in MW-07 were less than might have occurred if the well had not been sampled. Therefore, the fracture map (Figure 6) indicates the high probability that MW-07 is one of the Group 3 wells.

Finally, MW-13, the most distant of the observation wells, shows drawdown behavior that is similar to that at MW-10. However, due to the distance between these wells, they have not been grouped together.

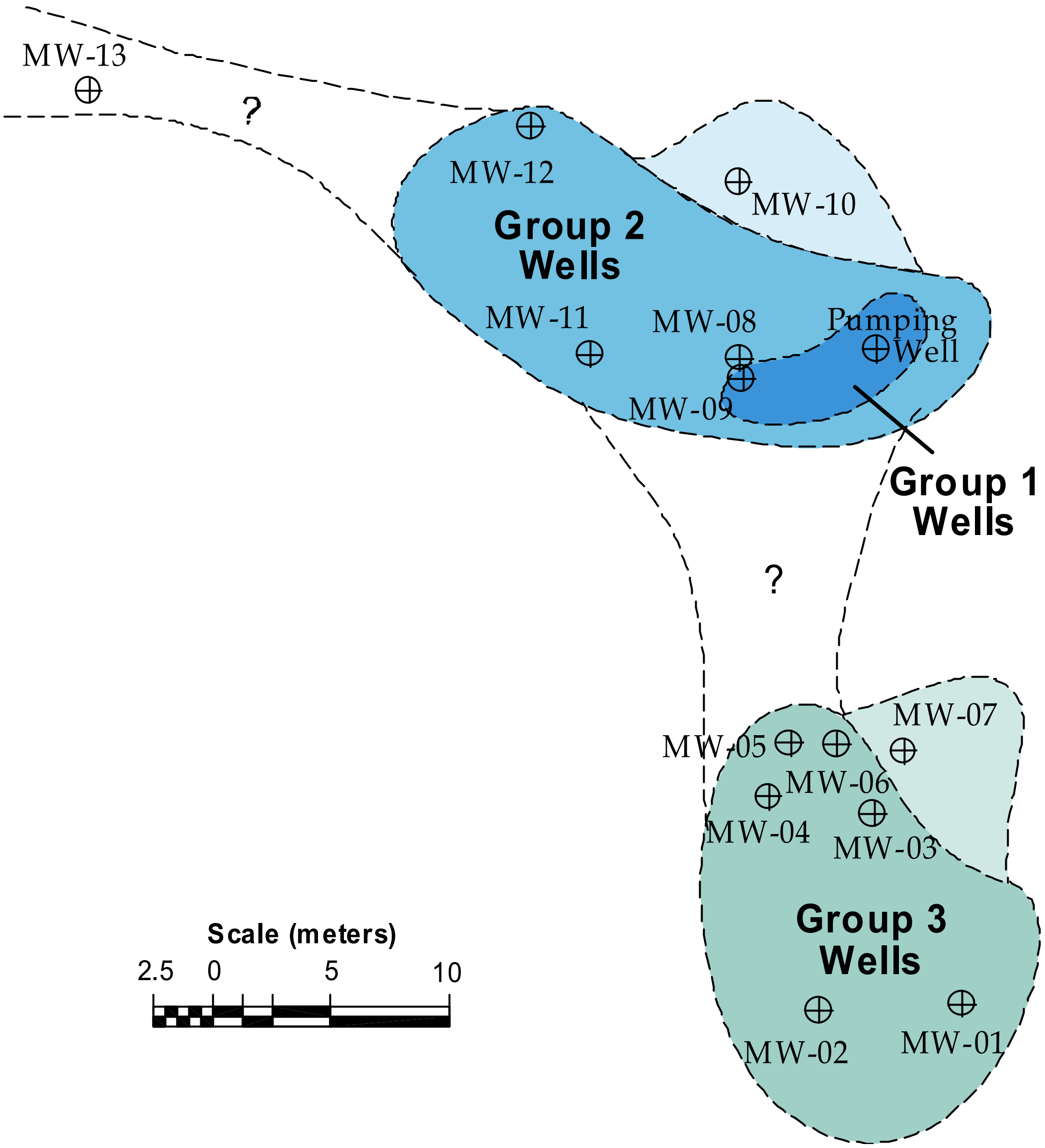

Figure 6. Fracture Interconnectivity Map

Theis Analysis of Wells in Groups 1 and 2

It is clear from the data that observation wells in fractured bedrock do not behave in the same manner as wells in porous media. Observation wells that tap the same fracture zone show similar drawdown rates, regardless of their distance to the pumping well. For this reason, a Theis-type analysis of the complete drawdown data set was not possible. However, a Theis analysis was performed for the observed drawdowns in the Group 1 and 2 wells (i.e., those that were most closely interconnected with the pumping well).

Figure 7 presents the drawdowns recorded in the Group 1 and 2 observation wells (not including the pumping well) and a best-fit Theis-type solution. Although the gross features of the drawdown curves are captured by the Theis-type solution, significant deviations are evident in Figure 7. For instance, the early-time drawdown data is over-predicted by the Theis equation. This is most likely because of well-bore storage effects (Gringarten, 1982). The measured primary porosity of the bedrock at the site is 0.7%. Therefore, the monitoring wells themselves, particularly the 15-cm diameter open holes, play an important role as a storage reservoir within the bedrock aquifer. For instance, MW-603 contains 400 liters of groundwater, equivalent to the water contained in over 60 m^3 of unfractured bedrock. Late time drawdown data are also poorly predicted by the Theis solution. During the recovery period, the Theis solution often underpredicts drawdown.

Although the Theis solution does not capture all of the drawdown behavior observed during the pumping test, the best-fit values of transmissivity and storage coefficient will be presented here for completeness. The best-fit value of transmissivity is 1.8×10^{-5} square meters per second (m^2/s), and the best-fit storage coefficient is 9×10^{-5}. Both the transmissivity and storage coefficient are within the range of values reported by Tiedeman and Hsieh (2001) for a similar geological setting.

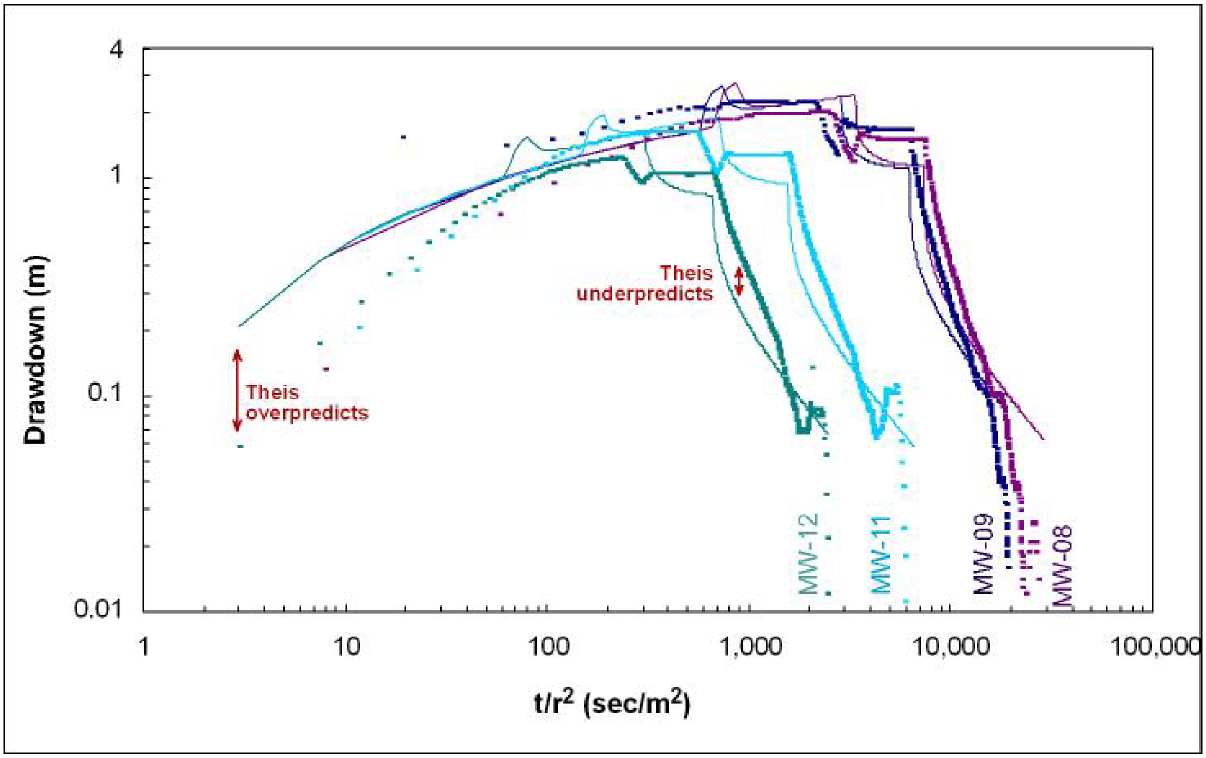

Figure 7. Drawdown during Pumping Test with Theis Radial Flow Solution ($T=1.8 \times 10^{-5}$ m^2/s, $S=9 \times 10^{-5}$)
Group 1 and 2 Wells Only

Summary

A 24-hour pumping test was successful in evaluating interconnectivity of fractures at a crystalline bedrock site. Drawdown data from 13 observation wells and the pumping well were analyzed using the rapidity of the hydraulic response, the magnitude of the peak drawdown and the geographic location of the well. Eleven of the 14 wells are categorized into one of three major well groups that represent hydraulically interconnected fracture sets. Group 1 wells are high-transmissivity wells that include the pumping well. Group 2 wells are moderate-transmissivity wells that are adjacent to and qualitatively similar to the Group 1 wells. Both Group 1 and 2 wells showed rapid hydraulic responses to changes in pumping rate. The main difference between Group 1 and 2 wells is the magnitude of the drawdowns.

Group 3 wells are moderate-transmissivity wells that show both qualitatively and quantitatively different behavior from the Group 1 and 2 wells. Unlike Group 1 and 2 wells, Group 3 wells exhibited delayed responses to changes in pumping rates. Because of the delayed rate of hydraulic response, early time drawdowns (i.e., at times less than 500 minutes) are generally lower than later-time drawdowns (i.e., at times between 500 and 1500 minutes).

Three of the 14 wells exhibited behavior that could not easily be included in one of the three well groupings. MW-07 is likely a member of Group 3. However, because this well was sampled prior to the pumping test,. Its drawdown behavior is different from the other Group 3 wells. MW-13 likely represents an insufficiently characterized fracture zone. The third well, MW-10, is a low-yielding well in the vicinity of the Group 2 wells.

References

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