The Evolution of Planning, Performing, and Evaluating Aquifer Test Data for a Complex Fractured Bedrock Environment

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Abstract

In general, aquifer test data is underutilized and its value not appreciated. However, properly designed aquifer tests will provide vital hydrogeological and structural framework data during investigations and at calibration of the final Conceptual Site Model (CSM). However, aquifer test development must begin at the start of the project and continue during the investigation so that it can evolve with the data.

This case study is located within a small bedrock basin created by two reverse thrust faults. The site is located adjacent to the exposed contact between an Ordovician dolomite and Precambrian granitic gneiss. The contact strikes to the northeast and dips to the north-northwest at approximately 50 to 70 degrees. As a result of this geological setting, a complex, fractured crystalline/sedimentary bedrock aquifer system is present.

Discrete-fracture packer testing and two five day constant-rate pump tests were performed to evaluate fractured bedrock hydrogeological and structural frameworks. Hydraulic data was evaluated individually and comparatively using Cooper-Jacob and double porosity graphical analysis’ to determine aquifer properties, log-log time-drawdown plots to identify potential linear flow and extended well behaviors, and illustratively to identify structural relationships with flow regimes.

Aquifer values exhibited low-permeability and high-permeability fractured rock characteristics. Storativity values and drawdown data in the unconsolidated unit suggest the bedrock aquifer is semi-confined. Major flow channels at the site behave as ‘extended wells’ and demonstrate linear flow, whereas minor fractures demonstrated radial fracture flow. Thus, the hydrostratigraphic system is anisotropic and heterogeneous and composed of interconnected low-permeability fractures in a relatively impermeable rock matrix with a number of higher permeability fractures or fracture sets (major flow channels) that appear to have a prominent role in controlling groundwater flow.

This paper will present the evolution of planning, performing, and evaluating aquifer test data within a complex fractured bedrock environment.

Introduction

In general, aquifer testing and the available data produced by the tests are underutilized and their value not realized. This is due in part from poorly planned hydraulic investigations that concentrate on and rush to collect chemical data without first understanding the hydrogeologic system. This reverse investigation causes poor decisions to be made and data to be overlooked when it comes to aquifer testing. In fractured bedrock, a
critical opportunity is lost to understand the many structural relationships that exist at fractured bedrock sites.

Traditional aquifer tests can take many forms: slug testing, hydraulic packer testing, and system wide constant rate testing. In addition, there are non-traditional aquifer testing methods such as the heat-pulse flow meter (HPFW) application. This may in fact be one of the best aquifer test tools for fractured rock systems because it allows a vertical observation of groundwater flow during both non-pumping and pumping conditions. Thereby, allowing the user to understand relationships between low and high pressure zones.

Both the traditional and non-traditional methods have their advantages and disadvantages. Simpler sites may require one or perhaps a combination. Properly designed fractured bedrock aquifer tests will provide vital hydrogeological and structural framework data during investigations and at calibration of the final CSM. However, aquifer test development begins at the start of the project and continues during the investigation so that it can evolve with the data, and finally provide a calibration comparison to the CSM. If planned correctly, each aquifer test will provide information that will be used in planning the next tests. This case study will demonstrate how the planning, performing, and evaluating of aquifer test data within a complex fractured bedrock environment can maximize the amount of information collected that is typically overlooked.

Geology

The Site lies within the New Jersey Highlands region of the New England Physiographic Province. The region consists of gently eastward dipping thrust (or reverse) faults consistent with trends of other known Taconic-age thrust faults in the region. These thrust faults formed in a compressional tectonic regime that resulted in much less deformed Cambrian-Ordovician rocks that also distinguish the region. The present topography is the result of differential erosion of the uplifted surface. Many steep slopes coincide with fault planes, such as where Paleozoic rocks are faulted against Precambrian gneiss.

The regional topographic relief ranges from steeply sloped to gently rolling hills. The regional surface topography was formed by tributary erosion, which was controlled by bedrock structure and lithology. The resistant Precambrian crystalline rocks underlie the most pronounced ridges. The less resistant limestones, dolomites, and shales underlie the major tributary valleys. Bedrock exposures are, in general, very numerous in the uplands, although local areas are covered with glacial drift and/or till (FWENC, 2003).

Hydrogeology

The glacial sediment and bedrock hydrostratigraphic system identified at the Site is part of a basin-like structure. It trends northeast/southwest and is bounded by ridges created by the Highlands characteristic reverse thrust faults. The upper part of the hydrostratigraphic system, the glacial sediment hydrostratigraphic unit, is unconfined. The water table is approximately 4 to 5 feet bgs and has seasonal variations. The hydrostratigraphic system is bound vertically by low permeability, granitic gneiss bedrock. The dolomite and granitic
Gneiss bedrock hydrostratigraphic units are heterogeneous and anisotropic in nature. Groundwater flow is controlled in the glacial hydrostratigraphic unit and bedrock hydrostratigraphic units by primary porosity (pores between grains) and secondary porosity (fractures and enlarged bedding planes), respectively. The dolomite and granitic gneiss hydrostratigraphic units are semi-confined and the dolomite includes flowing artesian conditions northwest of the geologic contact in the valley of the system. The semi-confining conditions likely result from a low permeability glacial sediment depositional sequence above the weathered bedrock. Groundwater primarily flows through the granitic gneiss hydrostratigraphic unit fracture network to a highly fractured hydrostratigraphic interface zone at the dolomite/granitic gneiss contact (contact hydrostratigraphic unit). The low pressure head present at this interface redirects a portion of the groundwater flow in an upward direction along the contact and discharges groundwater into the unnamed tributary of the Wildcat Brook and possibly to the surface via seeps and springs in the vicinity of the contact outcrop. Since the hydraulic conductivity along the contact hydrostratigraphic unit is not high enough to redirect the entire groundwater flow regime, some of the groundwater continues along a flow path past the contact hydrostratigraphic to the fractured weathered dolomite hydrostratigraphic unit and then up through the glacial sediment. Eventually, the groundwater in the glacial sediment discharges to the Wildcat Brook and adjacent wetlands.

Aquifer Test Conceptual Planning

Aquifer test planning starts at the beginning of the project and continues throughout. Sometimes it needs to be expanded and sometimes needs to be reduced. Based on the complexities of this project, HPFM, short-term discrete pump testing and long term constant rate pump tests were used. The objectives of the HPFM testing were to identify fractures exhibiting high transmissive and low pressure head characteristics. The objectives of the discrete testing were to vertically profile the chemical concentrations in the fractures and to evaluate the short-term transmissivity of the fractures. Essentially, the discrete tests were performed on fractures that exhibited the potential for a low pressure head because groundwater flows from high pressure head to low pressure head. Thus, bulk transport of the dissolved contaminant would be through the low pressure head fractures. Final design of the constant rate test was based on the HPFM, discrete pump testing, rock coring and other down-hole geophysical results.

Initially, three separate three-day constant rate pump tests were proposed. However, results from the HPFM, discrete packer tests, literature review (Gernand and Heidtman, 1997; Kruseman and Ridder, 1989; Streltsova; and Walton, 1987), and other data obtained during the beginning stages of the investigation suggested a pump test duration of 5 to 10 days may be required to filter out potential gravity drainage of fracture intervals, daily cycles, earth tides, external influences, rainfall events, and determine hydrogeologic boundaries, and structural relationships that would not surface in this complex system during a shorter pumping period.

Based on that information, two 120-hour pumping tests in the bedrock aquifers were selected. The primary objective of the long term pump tests was to evaluate the structural-control relationship of the fractured bedrock and the hydrostratigraphic system.
Aquifer Test Performance

Vertical Cross-Flow Testing

Vertical groundwater cross-flows can be observed in open-bedrock boreholes whenever intersecting transmissive fractures show different pressure heads during ambient (non-pumping) conditions (Michalski and Klepp, 1990). The difference in pressure heads or vertical groundwater flow of water in the borehole can provide a map of fractures having a larger role in groundwater flow control and contaminant transport. HPFM logging and hydraulic packer tests were used to measure vertical cross-flows.

The first aquifer test performed was vertical groundwater cross-flows using HPFM. Logging and testing was performed in seven boreholes. The logging was performed under non-pumping and then pumping conditions. The HPFM is capable of measuring vertical flow in a borehole under both non-pumping and pumping conditions. Under non-pumping (or ambient) conditions, vertical flow within the borehole can be determined and in-flow (borehole groundwater flowing into the hydrostratigraphic unit) and out-flow (hydrostratigraphic unit groundwater flowing into the borehole) fractures can be identified, similar to the pressure head difference method discussed below. Under pumping conditions, fracture flow response may differ from ambient conditions and provide an understanding of fracture participation during long term pumping.

Discrete Packer Testing

Fifty-two discrete hydraulic packer tests were performed on a total of 14 boreholes to evaluate potential fractures. During single packer use at the bottom of the boreholes, the packer interval and interval above the packer were monitored using pressure transducers. During double packer use, the packer interval and intervals above and below the packer were monitored using pressure transducers. Pumping rates ranged from less than 1 gallon per minute (gpm) to over 20 gpm.

Constant-Rate Pump Testing

As a result of the initial aquifer testing and other investigation results, a monitoring well and piezometer network was installed. Well clusters were installed where monitoring of multiple fractures in one location was required. Due to the artesian conditions and formation instability, multi-port wells were determined not to be appropriate.

Four step tests were performed to determine pumping rates for long term pump tests. As a result, two constant-rate 120-hour (5-day) pump tests were performed in two areas under consideration for permanent or temporary hydraulic control wells. The constant pump rate for each test of eight gallons per minute was selected based on the extrapolated drawdown of the step tests.

The water levels in 29 monitoring wells and piezometers were electronically and manually measured during each of the pump tests from overburden and bedrock
hydrostratigraphic units. For monitoring wells and piezometers with flowing artesian conditions, either dedicated self-contained data loggers or clear tube extenders were used.

**Aquifer Testing Results**

*Vertical Cross-Flow Testing (HPFM)*

Figure 1 illustrates a typical example of the information acquired during HPFM testing. In this borehole (BR-16), under ambient conditions, the data suggests the 240 to 258 feet bgs in-flow fracture interval is a potential major flow channel.

Borehole BR-14 was installed through the dolomite, the fractured contact between the dolomite and the granitic gneiss and the granitic gneiss to a depth of 700 bgs. HPFM results illustrated that a large majority of the groundwater entering the borehole flowed from the dolomite and granitic gneiss hydrostratigraphic units to the contact hydrostratigraphic unit between 200 and 240 feet bgs. In addition, under ambient and pumping conditions, no flow was observed between 540 feet bgs and the bottom of the borehole (700 feet bgs).

The HPFM results from seven boreholes identified seven fracture sets that exhibited characteristics of a major flow channel and also provided important information regarding the no to low flow fracture characteristics within the deeper bedrock. This early aquifer tests data provided the necessary foundation for updating the CSM and a spring board for the next aquifer test: discrete fracture packer testing.

*Discrete Packer Evaluation*

Discrete packer testing provides a means for stressing and measuring individual fractures within a hydrostratigraphic system over a short duration and also provides an opportunity for static head measurements above, within, and below the packer interval just after the packers are inflated. Transmissivity values were calculated in the field using the Cooper-Jacob method (Cooper and Jacob, 1946). Due to the small aperture of the fractures, the short duration can provide reliable data for analysis.

Two significant results were observed. First, the tested fractures can be separated into two distinct groups according to their transmissivity values, as illustrated in Figure 2. One group of fractures has transmissivity values greater than 26.7 ft²/day, while the other group has transmissivity values less than 13.4 ft²/day. Therefore, it is likely the group with the larger transmissivity values may be hydraulically inter-connected. Secondly, the transmissivity values ranged from 0.0 ft²/day for fractures with no response to 1,604.3 ft²/day. This indicates at the fracture level there is a substantial difference from fracture to fracture. Thus, the large range of transmissivity values from the packer tests provides a more accurate representation of the fracture network’s ability to potentially transmit water (Muldoon and Bradbury, 2005).

*Discrete Fracture Hydraulic Connections*
During the short term hydraulic packer tests in the bedrock hydrostratigraphic units, the drawdown in surrounding monitoring wells and open boreholes was measured throughout the tests to determine if a hydraulic relationship exists between the fracture being tested and the surrounding monitoring wells and open boreholes.

During the performance of packer tests in the dolomite hydrostratigraphic unit, little to no drawdown was observed in the surrounding wells and boreholes. This suggests that, at least in the dolomite hydrostratigraphic unit, the hydraulic interconnectivity between fractures is minimal and groundwater is transmitted mainly through select major flow channels. However, the lack of drawdown in the observation well and boreholes may be because the fracture interval was not stressed enough during the packer test to have a wide areal extent.

During the performance of packer tests in the granitic gneiss hydrostratigraphic unit at borehole location BR-14(g), drawdown was observed in observation boreholes at the Site. In fact, the deeper the packer interval, the more of a hydraulic connection was observed. This is likely due to fewer fractures and lower hydraulic conductivity. Due to the low pumping rate, minimal pumping time due to rapid drawdown, and very slow recovery after pumping, this zone is still classified as a low-permeability hydrostratigraphic unit with considerable hydraulic connections.

In-Well Cross-Flow and Packer Testing Comparison

The evaluation of the HPFM logging identified seven potential major flow channels. When matching the in-flow fracture intervals with their transmissivity results from the packer testing, the potential major flow channels fall within the higher transmissivity modal distribution identified in Figure 2, except for the 75 to 100 foot interval in PZ-3. Based on this analysis of multiple data sets, a total of six in-flow fractures are considered major flow channels.

In addition, the HPFM logs from borehole BR-14(g) and PZ-3 illustrate no vertical flow under ambient and pumping conditions present below 540 and 280 feet bgs, respectively. This data, combined with the high RQD in the cores and several unsuccessful hydraulic packer test attempts below these depths where no to very low flow was encountered, suggest the presence of a low-permeability granitic gneiss hydrostratigraphic unit below these depths, thus providing the vertical boundary of the hydrostratigraphic system at the Site.

Pumping Test Analysis

The data from two 120-hour (5-day) pump tests were analyzed to characterize the fractured bedrock hydrostratigraphic units below the site. Aquifer Test Pro version 4.0 (WHI, 2005) was utilized to fit the drawdown data collected from observation wells and piezometers associated with the two tests. The pump test data evaluation included analytical methods and assumptions, hydrostratigraphic hydraulic properties, time-drawdown plot analysis, fracture pattern and drawdown relationships, tributary gauge measurements, and conclusions.
Pump test data can be interpreted with several different conceptual models, such as equivalent porous medium (EPM), single fracture, and/or double porosity (Gernand, 1997). These conceptual models were considered and evaluated during data analysis of the two pumping tests. However, only the double porosity method was considered in the final analysis. The double porosity approach characterizes the fractured aquifer as two components: (1) fractures with high transmissivity and low storativity, and (2) rock blocks with low transmissivity and high storativity. In a classic double porosity response, the early and late time drawdown data can be plotted on separate Theis curves connected by intermediate time data correlating to the beginning of flow out of rock blocks into fractures. Very early time data at the pumping well may plot linearly as single-fracture flow (Streltsova, 1988) if not masked by wellbore storage effects (Gernand, 1997).

**Hydrostratigraphic Unit Hydraulic Properties**

The hydrostratigraphic unit hydraulic properties were calculated with the double porosity theory by the Aquifer Test Program. These hydraulic properties include transmissivity (square feet per day (ft$^2$/day)), hydraulic conductivity (feet per day (ft/day)), specific storage, sigma and lambda.

In the dolomite hydrostratigraphic unit, transmissivity values range from 13 ft$^2$/day to 500 ft$^2$/day, with an average value of 167 ft$^2$/day. In the granitic gneiss hydrostratigraphic unit, transmissivity values range from 25 ft$^2$/day to 800 ft$^2$/day, with an average value of 197.5 ft$^2$/day. There are no correlations between transmissivity and either distance or direction to the pumping wells, suggesting the hydrostratigraphic system behaves heterogeneous across the Site.

The calculated hydraulic conductivity values range from 0.06 ft/day to 1.93 ft/day, with an average value of 0.66 ft/day for the dolomite hydrostratigraphic unit, from 0.06 ft/day to 3.4 ft/day, with an average value of 0.62 ft/day for the granitic gneiss hydrostratigraphic unit, and from 0.65 ft/day to 15.0 ft/day, with an average value of 5.90 ft/day for the contact hydrostratigraphic unit. The dolomite and granitic gneiss values indicate a low hydraulic conductivity and fall within the range of typical hydraulic conductivity values found in igneous and metamorphic rocks (Brassington, 1988). Given the fractured nature of the contact, the higher hydraulic conductivity average is expected. The storativity values for the fractured dolomite, granitic gneiss, and contact hydrostratigraphic units suggest semi-confined conditions.

Two other parameters, sigma ($\delta$) and lambda ($\lambda$), are dimensionless parameters associated with the double porosity theory. They can be used to characterize the flow from the rock matrix to the fractures. Sigma is a ratio of specific storage between the rock matrix and fractures, and lambda is the interporosity flow coefficient (WHI, 2005). For a given value of lambda, varying sigma changes the time duration of the flat part of the curve, which is the late time Theis curve translated horizontally (WHI, 2005). The average calculated values for sigma are 177 and 254 for the dolomite and granitic gneiss hydrostratigraphic units, respectively. Sigma is slightly higher in the granitic gneiss hydrostratigraphic unit, but is still
within the same order of magnitude as in the dolomite hydrostratigraphic unit. This suggests there is no significant difference in the specific storage ratio between the dolomite and granitic gneiss hydrostratigraphic units. The average calculated values for lambda are 0.15 and 0.20 for the dolomite and granitic gneiss hydrostratigraphic units, respectively. The slightly higher lambda value for the granitic gneiss hydrostratigraphic unit indicates water will drain from fractures quickly and then flow from the blocks. The slightly lower value of lambda indicates this transition will be slower within the dolomite hydrostratigraphic unit.

*Evaluation of Time-Drawdown Curves in the Overburden and the Bedrock*

Five overburden monitoring wells and one overburden piezometer were monitored during the 5-day pump tests in the glacial sediment hydrostratigraphic unit. The drawdown contours suggest the glacial sediment and bedrock hydrostratigraphic units are hydraulically connected.

The time-drawdown plots, which were used for curve fitting and calculating of hydraulic properties, were also used to evaluate time-drawdown data on a log-log plot of time versus drawdown. Pumping well time-drawdown curves were analyzed to evaluate the effects the bedrock structure may have on the hydrostratigraphic system hydraulics and identify potential major flow channels.

The first two hours of drawdown data plotted linearly for both pumping wells (Figure 3). This suggests single fracture flow conditions may exist near the pumping wells (Gernand, 1997). The pumping well drawdown curves are consistent with linear flow in a fracture set which is significantly more transmissive than the remaining fractures. These plots show drawdown is becoming steady-state after approximately the first two hours of pumping, suggesting a recharge boundary was reached during this time. In this case, the recharge boundary is the contact hydrostratigraphic unit.

After the early-time drawdown data, the middle and late time-drawdown data for observation wells matched well with the double porosity method. This suggests the hydrostratigraphic system can be characterized by spatially well-connected fractures at the Site scale.

*Relationships of Drawdown to Fracture Patterns*

Geometric spatial analysis of the pump test drawdown data was performed to evaluate fracture patterns and the heterogeneity of hydrostratigraphic units. An elliptical cone of depression can illustrate the direction of enhanced drawdown which closely parallels a dominant fracture set (Gernand, 1997). Maximum drawdown contours for both pumping tests were prepared to illustrate flow in the bedrock hydrostratigraphic units as two-dimensional (horizontal). The cone of depression for both pump tests (PZ-3 and BR-14PW) is elongated along the direction of the contact, which strikes southwest and northeast. The elongated cone of depression along the contact indicates the contact may behave as an extended well. For purposes of discussion, the pump test data from pump test BR-14PW is provided in Figure 4 to illustrate this response.
The drawdown shape for pump test PZ-3 was only slightly elliptical along strike. This slight elliptical shape appears to be the result of the 400 feet of open borehole in the pumping well. The drawdown results from the large linear open-hole pumping well would then illustrate a general composite view of the hydrostratigraphic system. This elliptical shape suggests radial groundwater flow. As for the drawdown shape for pump test BR-14PW, the elliptical shape is very strong in the contact strike direction, suggesting the contact hydrostratigraphic unit has a higher hydraulic conductivity than the dolomite and granitic gneiss hydrostratigraphic units.

According to Gernand (1997), the elliptical drawdown curves are indicative of angled fractures in bedrock environments. As Figure 4 illustrates, elliptical drawdown contours are present during both pump tests, confirming the acoustic teviewer logs that indicate a predominant southwest-northeast trending strike dipping 45 to 75° to the north-northwest. Therefore, the highly fractured make-up of the contact hydrostratigraphic unit appears to be a structural influence on the hydrostratigraphic system’s hydraulic response.

At the end of the 5-day pump tests, BR-14PW produced more total drawdown of 133 feet than PZ-3 with 72.27 feet drawdown. The reason for the difference in total drawdown between the two pumping tests is because BR-14PW is screened in the contact hydrostratigraphic unit, which behaves as an extended well with a different hydraulic conductivity. In addition, drawdown was measured in all directions and to a distance as far as 567 feet (PZ-4) and 620 feet (BR-1) away from pumping wells BR-14PW and PZ-3, respectively. Drawdown was also observed at different well depths ranging from 23 feet in piezometer PZ-1 to 540 feet in monitoring well BR-14(g). This suggests vertical hydraulic connections exist throughout the hydrostratigraphic system.

Based on these results, the hydrostratigraphic system can be characterized as anisotropic and heterogeneous with groundwater flow through spatially well-connected fractures strongly influenced by the contact hydrostratigraphic unit.

Conclusions

The structural features in the dolomite and granitic gneiss hydrostratigraphic units are the weathered zones and fractures along gneiss foliations and banding, the weathered and fractured bedding planes and fractures in the dolomite, and the contact between the two geologic units. These structural features are the location of the major groundwater flow channels and also control groundwater movement in the hydrostratigraphic units underlying the Site.

The transmissivity and hydraulic conductivity values determined from the aquifer tests are representative of low-permeability fractured igneous and metamorphic rock. The storativity values, and the presence of drawdown in the glacial sediment hydrostratigraphic unit during the pump tests, indicate the bedrock hydrostratigraphic units are semi-confined. Additionally, transmissivity values for both pump tests ranged from 13 to 800 ft²/day. This range was within the range of the discrete packer testing range for transmissivity. They
provided a tighter range of transmissivity values that provide a larger general view of the hydrostratigraphic system hydraulics.

After one hour of pumping during the pump tests, steady-state conditions were observed surrounding the pumping wells, suggesting the contact hydrostratigraphic unit behaves as an extended well. This is also supported by the elliptical drawdown observed along the contact strike. Steady-state conditions were not attained outside the pumping well vicinity. In addition, the drawdown curves for the observation wells adjacent to the pumping wells plotted linearly during the first two hours of the pump tests, suggesting the presence of single fracture flow.

Based on the drawdown contours from the BR-14PW pump test, one major flow channel was observed: the contact hydrostratigraphic unit. This major flow channel will have a greater likelihood of increased contaminant transport than the lower permeability fractures, and the low to impermeable granitic gneiss hydrostratigraphic unit will act as a vertical boundary for the hydrostratigraphic system.

During the pumping tests, the observation wells exhibited linear flow near the contact hydrostratigraphic unit (an extended well) during the first hour of pumping and radial flow through interconnected fractures after the first hour of pumping.

The HPFM, pumping and packer test results strongly indicate an anisotropic and heterogeneous hydrostratigraphic system composed of many interconnected low-permeability fractures in a relatively impermeable rock matrix, with a number of higher permeability fractures or fracture sets (major flow channels) that have a more prominent role in controlling groundwater flow.

As shown in this paper, proper planning, performance, and evaluation of aquifer test data provides a complete and accurate characterization of a complex fractured bedrock environment.

References

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Biography

Mr. Malaniak received a BS in Biology and Chemistry from Rutgers University in 1994 and a M.S. in Geoscience from Montclair State University in 2004. He is a registered professional geologist and certified professional geologist. He currently is the supervising hydrogeologist with Tetra Tech EC, Inc. in Morris Plains, New Jersey. The last several years Mr. Malaniak has developed a geoscience intern program through local university’s, provides technical supervision and direction for geoscience related projects, specifically for complex fractured bedrock hydrogeological investigations in New Jersey and New York, and directs a variety of remedial investigations and actions in the metropolitan area.

David Li, Senior Hydrogeologist at Tetra Tech EC, Inc., Langorne, PA. He received a M.S in Engineering from University of Guelph, Canada, and a M.Sc. in Hydrogeology (Numerical Modeling) from University of Waterloo, Canada 1994. His skills are in numerical methods (modeling) of flow and transport in either porous media or fractured media.

Mr. Jamieson has over 26 years of experience in hydrogeology and geology. As the National Geosciences Discipline Leader, Mr. Jamieson is responsible for the technical qualifications of 80 geosciences personnel (geologists, hydrogeologists and geophysicists) and the quality of work products they produce. He has been the hydrogeology lead on numerous projects involving dissolved, DNAPL and LNAPL contamination characterization and remediation including investigation design and implementation, 3-D groundwater modeling, pre-design pump testing and analysis, and groundwater capture system design.
Figure 1. Illustrates groundwater flow within an open borehole under ambient conditions. The groundwater is observed to enter the borehole from the granitic gneiss hydrostratigraphic unit between 310 feet bgs and the bottom of the borehole at 324 feet bgs, flow upward, and exit the borehole into the granitic gneiss hydrostratigraphic unit between 254 and 248 feet bgs. Under ambient conditions, groundwater flow is observed entering the borehole from the granitic gneiss hydrostratigraphic unit between 160 and 180 feet bgs, flowing upward and downward, exiting into the granitic gneiss hydrostratigraphic unit between 130 and 150 feet bgs and 240 and 258 feet bgs.
**Notes:**

*Two packer tests in BR-14g were below sea level and had no apparent flow. Their elevations were -82.8' and -112.8' MSL.*

*Five apparent no flow zones were encountered in PZ-3 at elevations of 444.59', 434.59', 304.59', 253.09', and 132.09' MSL.*

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**Figure 2.** The fracture transmissivity values from the discrete packer tests are separated into two distinct groups. One group of fractures has transmissivity values greater than 26.7 ft²/day, while the other group has transmissivity values less than 13.4 ft²/day. Therefore, it is likely the group with the larger transmissivity values may be hydraulically inter-connected. Secondly, the transmissivity values ranged from 0.0 ft²/day for fractures with no response to 1,604.3 ft²/day. This indicates at the fracture level there is a substantial difference from fracture to fracture. Thus, the large range of transmissivity values from the packer tests provides a more accurate representation of the fracture network’s ability to potentially transmit water (Muldoon and Bradbury, 2005).
Figure 3. The first two hours of drawdown data plotted linearly for both pumping wells. This suggests single fracture flow conditions may exist near the pumping wells (Gernand, 1997). The pumping well drawdown curves are consistent with linear flow in a fracture set which is significantly more transmissive than the remaining fractures. This plot shows drawdown is becoming steady-state after approximately the first two hours of pumping, suggesting a recharge boundary was reached during this time. In this case, the recharge boundary is the contact hydrostratigraphic unit. Prior to the recharge boundary effects, the time-drawdown data for the pumping wells show the slopes ranging from 0.5 to 8.0 and 3.5 to 8.0 log cycles of drawdown per log cycle of time for pumping wells BR-14PW and PZ-3, respectively. These slopes suggest the wells are near a high permeability fracture.
**Figure 4.** The cone of depression is elongated along the direction of the contact, which strikes southwest and northeast. Based on the differences in well construction for each of the pumping wells, the elongated cone of depression along the contact indicates the contact may behave as an extended well.