Some contributions to the hydraulic characterization of fractured bedrock formations

Gonzalo Pulido

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SOME CONTRIBUTIONS TO THE HYDRAULIC CHARACTERIZATION
OF FRACTURED BEDROCK FORMATIONS

BY

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DISSERTATION
Submitted to the University of New Hampshire
in Partial Fulfillment of
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A mi familia:

Maria Isabel, Paula y

Sofía o Camilo....

a quien esperamos con amor.
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ABSTRACT

SOME CONTRIBUTIONS TO THE HYDRAULIC CHARACTERIZATION OF FRACTURED BEDROCK FORMATIONS

by

Gonzalo Pulido

University of New Hampshire, December 2003

During 3 years of investigation at the BBC field site, research has led to developments in bedrock monitoring, groundwater sampling, formation hydraulic testing, and the conceptual model of formation hydraulics. This dissertation presents a field device, two hydraulic test methods, and one method of hydraulic test analysis developed to assist in the hydraulic characterization of fractured bedrock formations. It also presents the use of these tools in the development of the Conceptual Hydrogeologic Model for a fractured bedrock formation contaminated with chlorinated solvents. The field device was named the Multipurpose Packer System (MPS), a discrete-interval isolation system for the sampling and hydraulic assessment of open wellbores completed in heterogeneous formations. A MPS prototype was successfully designed, fabricated, installed, and tested in a well. The MPS advantages included: the minimization of water quality biases and the ability to perform hydraulic tests at
isolated borehole intervals. The two field hydraulic tests were named the large drawdown slug test, and the gas injection test. Large drawdown slug tests are defined as those slug tests with initial drawdown larger than 5 m; these were demonstrated to be a valuable hydraulic test to: a) study well interconnectivity in heterogeneous formations, b) remove the need to pump large quantities of groundwater, c) quantify the storage coefficient for monitoring well field data, and d) assess tight formations. The gas injection test is a field technique for the characterization of hydraulic connections in fractured bedrock; the test is conducted below the water table by gas pressurizing an isolated interval of a borehole. The gas pressurization exceeds the pressure for water removal from the interval, thereby forcing gas to invade fractures that intersect the interval. The induced gas overpressure can be recorded in monitoring wells, allowing well interconnectivity to be described on a site-wide scale. A 1D Finite-Difference radial-flow model for interpretation of hydraulic tests was coded in a JAVA application named HyTests. It was successfully validated and extensively used in this research for identifying the hydraulic parameters of the fractured bedrock. Finally, the conceptual hydrogeologic model that was developed for the site identified: 1) the fractured bedrock connectivity with the other hydrogeologic units in the site, 2) The fractured bedrock hydraulic parameters, and 3) The fractured bedrock recharge mechanisms, flow patterns, and boundary conditions.
OBJECTIVES

The objective of this research was to develop tools for hydraulic characterization of fractured bedrock formations, and apply them to assist in the development of the conceptual hydrogeological model (CHM) of a site located in Portsmouth NH. The highly heterogeneous character of fractured bedrock formations requires: 1) the use of discrete-interval isolation systems for the sampling and hydraulic assessment of wellbores, 2) conducting hydraulic tests able to identify well interconnectivity, and 3) analysis of hydraulic test data with methods that do not rely on the conventional assumption of formation homogeneity.

The importance of this research resides in its contribution to the understanding of fractured bedrock formation hydraulics. This challenging subject is currently a cutting edge research topic in many areas, such as hydrogeology, rock mechanics, and environmental engineering.

DISSERTATION ORGANIZATION

Each chapter of this dissertation was written as a self-contained individual paper for submission to peer-reviewed journals. The obvious exceptions were the introduction and conclusion chapters, which encompass all of the research.

Chapter 2 is entitled Multipurpose Packer System (MPS). It describes the design, construction, testing, and use of the MPS. The MPS is a discrete-interval isolation system for the sampling and hydraulic assessment of open wellbores completed in heterogeneous formations.
Chapter 3 describes the Large Drawdown Slug Test (LDST), which is a hydraulic test method to extend the range of applicability of conventional slug tests by increasing the magnitude of the initial drawdown, elevating this hydraulic test to the confidence given to pumping test data.

Chapter 4 presents the gas injection test (GIT), a field technique for the characterization of hydraulic connections in a fractured bedrock formation. A GIT is conducted by gas pressurizing an isolated interval of a well completed in a fractured bedrock formation to a pressure larger than the static water column length in the interval, thereby forcing gas to invade fractures that intersect the isolated interval.

Chapter 5 discusses the design, implementation, validation, and the use of HyTests: A Numerical Model for Hydrogeologic Parameter Estimation. HyTests is a one-dimensional, finite difference groundwater flow model for hydraulic test interpretation. The model can account for actual hydraulic test conditions such as radial variability of hydraulic parameters, variable-flowrate pumping, and non-linear well hydraulic losses.

Chapter 6 synthesizes the use of the previously introduced tools for Developing a Conceptual Hydrogeological Model for a Fractured Bedrock Formation, which includes the identification of: 1) the fractured bedrock formation hydraulic connectivity with the other hydrogeologic units in the site, 2) The fractured bedrock formation hydraulic parameters, and 3) the fractured bedrock formation recharge mechanisms, flow patterns, and boundary conditions.
SITE HISTORY

The field site for this research was located at the Pease International Tradeport, Portsmouth, NH, the former Pease Air Force Base. More precisely, the field efforts were performed at site 32 where an underground storage tank received waste trichloroethylene (TCE) from 1956 to 1968. In 1983 site 32 was identified as a potential source for contamination, and a restoration program was initiated. Soil and groundwater TCE contamination was discovered in 1988, when the tank was removed. The selected remedial action for site 32 included: removal of contaminated soil; construction of seven extraction wells completed in the overburden and weathered bedrock strata (1991 to 1995); isolation of the overburden source area with a vertical barrier (sheet pile) built in 1996; groundwater pumping from within and below the sheet pile (overburden and weathered bedrock wells), and on-site treatment of the pumped water since 1997; and continuous long-term groundwater and treatment system monitoring to the present (USAF 1997a).

Since 1999, the Bedrock Bioremediation Center (BBC) at the University of New Hampshire has been studying the fractured bedrock formation underlying the overburden and weathered bedrock strata at site 32. The primary BBC objective was to isolate fracture zones and determine the nature of bioremediation processes in them.
REFERENCES


CHAPTER 2

MULTIPURPOSE PACKER SYSTEM
ABSTRACT

The Multipurpose Packer System (MPS) is a discrete-interval isolation system for the sampling and hydraulic assessment of wells completed in heterogeneous formations. The MPS consists of inflatable packers connected by threaded aluminum pipe, to isolate discrete intervals in the well. The packer to pipe couplings have sampling ports with miniature fittings. Pressure transducers and small diameter tubing are connected to the fittings and run through the aluminum pipe to a control board located at the wellhead. Data on hydraulic head, water sampling, and hydraulic testing can be collected for each isolated interval. An MPS prototype was successfully designed, fabricated, and installed in a 6" diameter, 200' deep well completed in a fractured bedrock formation contaminated with chlorinated solvents. The MPS isolated the intervals and was used successfully for hydraulic testing and water sampling. The MPS helps to minimize water quality biases. Additional research is being conducted to optimize the MPS design and its range of applications.

INTRODUCTION

Even though assuming homogeneity facilitates assessment of hydrogeologic phenomena, most hydrogeological environments are heterogeneous with respect to groundwater flow and transport processes.
fractured bedrock formations, each fracture zone can exhibit a different hydraulic head (Johnson et al., 2001) and even in homogeneous formations, contaminant plume dynamics are inherently heterogeneous (Smith et al., 1987).

Initially, clusters of monitoring wells were used for monitoring of heterogeneous hydrogeological sites. The main disadvantages of clusters are their high costs, extensive site disturbance, and purge water volumes (Robbins and Martin-Hayden, 1991). Nested monitoring wells address these limitations, but exhibit interval-sealing difficulties and concerns (US EPA, 1986).

Today, several patented instruments are available for discrete zone isolation and sampling. The FLUTe™ is a flexible-liner system that effectively seals and allows pressure measurements and water sampling from discrete intervals (Keller, 2002). The MR™ is a modular multiport system that employs a single, closed access tube with valved ports. Thus, different levels of a borehole are isolated within a single well casing (Hartten and Genau, 1995). The modular Waterloo Multilevel System (WMS™) includes a closed casing containing small diameter tubes, that connect each isolated monitoring port to the surface allowing groundwater sampling and hydraulic measurements (Cherry and Johnson, 1982). The Continuous Multichannel Tubing (CMT™) uses a custom-extruded flexible tubing to monitor as many as seven discrete zones (Einarson and Cherry, 2002). Each of these devices possesses unique advantages and disadvantages.

Since 1999, the Bedrock Bioremediation Center (BBC) at the University of New Hampshire has been studying a fractured bedrock formation contaminated with TCE and its progeny. The primary objective of the BBC is to isolate fracture
zones and determine the nature of bioremediation processes within them. This requires isolation and sampling of discrete zones in several bedrock wells (Pulido et al. 2003a). Consequently, FLUTE™ systems were installed in two wells. While providing good interval isolation, the FLUTE™ generated dissolved organic carbon resulting in bias of chlorinated contaminant concentrations (Ballestero et al., 2003). WM™ and CMT™ systems were available only up to well diameters of 4” (Solinst, 2002). Therefore, a Multipurpose Packer System (MPS, patent pending) was conceived, designed, constructed, and successfully tested to isolate discrete intervals, conduct hydraulic monitoring and testing, as well as water quality and microbial sampling in a fractured bedrock well.

MATERIALS AND METHODS

As with other multi-level devices, the MPS design is tailored to each well, based on well specifications and project objectives. The MPS is intended to be semi-permanently installed in the well during the data collection in the study site. An MPS prototype was designed and constructed for well BBC5 at the BBC’s bedrock site in Portsmouth, NH. Five intervals (I1 to I5) were isolated. Two of these (I2, I4) were identified as high hydraulic conductivity fracture zones, during previous straddle-packer hydraulic testing and borehole geophysics (Pulido et al., 2003a).
All MPS components were off-the-shelf items. The MPS prototype used inflatable packers (TAM™; Houston, TX) connected to aluminum pipe to isolate discrete intervals. The packer to pipe couplings were fabricated with ports containing miniature fittings (Beswick Engineering; Greenland, NH) to allow hydraulic and water quality sampling at each isolated interval. Pressure transducers (PDCR 1830 Druck™; New Fairfield, CT) and small diameter tubing (Freelin-Wade™; McMinnville, OR) were connected to the fittings and passed through the pipes to an aboveground control board. The board monitored hydraulic head, facilitated the collection of water samples, and permitted conducting hydraulic and tracer tests at each isolated interval (Figure 1).

The inflatable packers (P) were connected to 4" inside diameter (ID) aluminum pipe using stainless steel couplings. The deepest (P3, P4) and upper (P1, P2) packers were 2" ID and 4" ID, respectively. The larger packers were needed to accommodate all of the MPS tubing bundles to pass through them.

An injection, purging, and slug line (IPS), provided the MPS with the capability to inject a tracer, purge water, and perform slug tests. Similar to other MPS lines, it was 1/8" ID translucent polyurethane tubing. For each interval, the IPS line went from the ground surface, inside the aluminum pipe, down to the injection coupling (IC), located at the bottom coupling for each well interval. The IC had a ¼" thread to internally attach a stainless steel ¼" male elbow to a 1/8" tubing barb. Threaded tubing clamps were used to secure the IPS lines to the 1/8" barb fittings.
Figure 1. MPS Schematic and terminology
Figure 1. (Continuation)
The water sampling system provides the MPS with the capability to extract groundwater from each isolated interval. The system consisted of two lengths of 1/8" tubing: a pressurization line (color-coded orange), and a discharge line (color-coded blue). At the top of the designated isolated interval, the two lines were connected to each other with a stainless steel 1/8" barbed “T” fitting. The third branch of the “T” was connected to a stainless steel 1/8" check valve. The valve was connected to the water sampling coupling (WSC) by an elbow fitting. The WSC was the upper coupling of each isolated interval. This coupling had an internally installed ¼” elbow to thread to a pressure transducer (range (0 – 200) psi, accuracy 0.04% Full Scale).

Under normal conditions, the water sampling lines were full of water up to the hydraulic head elevation of the isolated interval. When gas (e.g., nitrogen) was applied to the pressurization line, the water volume contained in the water sampling lines was pushed out of the well through the discharge line. The check valve prevented flow back into from the formation from the isolated interval. When gas pressure was released, the check valve allowed water to flow from the formation’s isolated well interval into the water sampling lines until they were refilled. By repeating this process, the desired volume of water could be collected from the interval.

Each interval communicated with the surface by a bundle (B) consisting of a transducer cable, IPS, and water sampling lines. B1, B2, and B3 additionally contained IPS lines of diameters 1", ¼", and ½" that were connected to WSC1, WSC2, and WSC3, respectively, to study some of the MPS slug test features.
The 4" MPS bottom cap (WSC5) contained the IPS line port for l5. IC1 was located immediately above P1; WSC1 was located 10' above IC1. A drain bundle (a water sampling line with its check valve at the very bottom, inside the MPS) evacuated any water leaking into the MPS.

Above the ground surface, IPS and water sampling lines were connected to a control board. The pressure transducers were wired to a datalogger (CR10X Campbell Scientific; Logan, UT) for pressure data storage. The MPS was inflated with nitrogen by a single 1/8" ID clear polyurethane tubing that connected all packers. All tubing (sampling, testing, packer inflation) were provided with quick-disconnect brass valves, and normally capped to avoid interference signals between lines at the same interval. The overall cost of the BBC5 MPS prototype components was ~ $20,000.00 (US dollars, 2002) (including $6,000 for the transducers and datalogger).

**MPS Prototype Construction**

After decontamination of each MPS component, 200' of sheet plastic, long, was unrolled on the ground starting at the BBC5 casing. The MPS bundles were assembled on this. P4 was passed through B5 and the drain bundle, and these bundles were connected to WSC5 (Figure 2). Teflon tape was applied on every threaded fitting to minimize leaks. After threading and tightening WSC5 to P4, this MPS section was inserted into the well and held in place at the top of the casing (TOC) by a pipe clamp (Figure 3).
Figure 2. WSC5 detail prior to installation.

A. Transducer port threaded fitting
B. Water sampling and slug test ports (barbed fittings)
C. Transducer protective cover (removed at time of installation)
D. Water sampling “Tee”
E. Water sampling check valve
F. Drain (“Tee” and check valve)
G. Injection and slug test line
H. 4”x2” adapter for P4 packer.
Figure 3. WSC2 detail at top of casing.

A. ¼" slug test port  
B. Water sampling and slug test port  
C. Pressure Transducer (threaded into its port)  
D. Pipe clamp (holding aluminum pipe over well casing)

An aluminum tripod-cable-winch system was used to raise each new section of pipe or packer to be added to the MPS section already in the well (Figure 4). A 200 psi pressurization test was conducted each time a new packer was added, to test the integrity of the system.

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Figure 4. MPS installation equipment.

A. Aluminum tripod
B. Hand Winch
C. Stainless steel cable
D. Hook, chain, and clamp
E. 10'x4" Aluminum pipe
F. Tubing and transducer cables
When the MPS was fully installed in the well, the bundles were run from the top of casing through a 4" corrugated plastic hose, and directed to a shed to provide for year round protection. Inside the shed, pressure transducers cables were wired to the datalogger and the tubing bundles were connected and organized on a control board (Figure 5).

Figure 5. MPS control board detail.

A. Ball valve to hold inflation pressure
B. Quick-Disconnect valve and cap to prevent accidental MPS deflation.
C. MPS inflation pressure gage
D. 1/8” Quick-Disconnect valves
E. Wastewater collection funnel for water sampling
MPS Performance Tests

The packers in the MPS prototype were inflated by applying 150 psi. Before inflation, the BBC5 static water level (2.0' +/- 0.01') was measured with a water level sounder and the all transducer data logging was initiated. The actual top of casing-referenced depths for each WSC were calculated by adding the static water level to each of the stabilized pre-packer inflation pressure transducer readings (95.99', 112.17', 121.37', 141.55', and 163.09' below top of casing, for WSC1 through WSC5, respectively). Therefore, the packer inflation pressure (150 psi total for all packers) above hydrostatic pressure at the bottom of the MPS was ~80 psi.

Inflation and Sealing Tests

Inflation system integrity was confirmed after the MPS packers held the applied inflation pressure for two days. A sealing test was then conducted to determine the minimum inflation pressure required to prevent any hydraulic interconnection (short circuiting) between intervals. Experience with similar inflatable packers for hydraulic tests suggested packer inflation pressures of ~175 psi pressure at the nitrogen tank regulator gauge (89 psi above hydrostatic pressure), was a safe inflation pressure to seal between intervals down to 200' depth (Pulido et al., 2003a).

For the packer sealing experiment, the MPS was initially pressurized to 175 psi (gauge) that was then reduced in 25 psi steps until deflation. In each step, first l4 was pressurized with 70 psi (equivalent to 161.0' of water column)
through its IPS line (161.5' depth, top of casing) and then this pressure was released. Pressure in all intervals was recorded. Any I3 and I5 pressure responses to the I4 pressure signal were assumed to be a result of poor packer seals at the borehole wall.

The 175, and 150 psi tests displayed good seals (Figure 6). Slight disturbances were recorded at I3 and I5 when the packer inflation pressure was 125 psi. Significant pressure variations were detected at I3 for the packer inflation pressure of 100 psi. At 75 psi (zero pressure relative to hydrostatic conditions at the bottom of the MPS), the packers deflated and all intervals were hydraulically communicating. As a result, 150 psi (80 psi relative to MPS bottom hydrostatic pressure) was selected as the minimum safe inflation pressure for the MPS.

**Figure 6. Results of inflation and packer sealing tests. 05/12/03.** The MPS minimum safe inflation pressure was determined to be 150 psi.
 Slug Tests

The BBC5 MPS prototype was designed to conduct slug test research related to: initial slug size and duration, nonlinear effects of the slug test tubing, and slug test tubing diameter influence on field data and analyses (Chirlin, 1990). Most slug test settings reported in the literature measure the drawdown (H) by monitoring the free surface water level variation at the top of the slug test casing (Butler, 1998). When nonlinear phenomena exist, the formation water pressure is substantially different than the top of casing water level because of turbulent flow into the slug test casing (McElwee and Zenner, 1998).

The MPS used five, high reading frequency transducers, located directly at each isolated interval, in a port different than the IPS port, where the slug test pulse entered the formation. Hence, the influence of slug test magnitude and duration could be assessed because the transducer readings were not affected by the local flow effects in the injection line. Additional IPS lines were employed to determine the minimum IPS line diameter to obtain useful slug test results for quantitative analyses. The I2 to I5 MPS pressure transducers were connected to their respective WSC, located at the top of each interval; the I1 pressure transducer was located just above P1. Pressure transducers were set to record 8 pressure readings per second during slug tests. For I2, I3, and I4, the 1/8” IPS line was connected to the IC, located at the bottom of each respective well interval. The I1 IPS line was connected to IC1, located 10’ below WSC1. I1, I2, and I3 contained additional IPS lines (1”, ½”, and ¼” ID respectively) connected
to WSC1, WSC2, and WSC3 by ports located opposite to the transducer ports (Figure 1).

Slug tests at each isolated interval were conducted by first pressurizing the respective IPS line. When the pressure at the interval stabilized back to the original ambient value, a rising head slug test was produced by releasing the pressure from the IPS line. Rising slug test signals were generated at isolated intervals I2, I3, I4, and I5, by individually and independently applying 20 psi (equivalent to a water column $H_{\text{applied}} = 46'$) to their respective 1/8" IPS lines. Additional slug tests at I2 and I3 were conducted by applying the same 20 psi slugs to the 1/2" and 1/4" IPS lines (Figure 7). I1 was not included in this experiment because it did not have a top packer. If nitrogen had been applied to IPS1, it would have escaped to the atmosphere, bubbling through the well casing – MPS annulus.

All slug test initial drawdowns ($H_0$) were one or two orders of magnitude less than $H_{\text{applied}} (46')$ (Figure 7). This effect was primarily due to the small IPS line diameters. For a given $H_{\text{applied}}$, the volume of water effectively removed from the isolated interval during a slug test decreased with the square of the IPS line diameter (0.75, 0.19, and 0.04 ft³ for the 1/2", 1/4", and 1/8" IPS diameters, respectively). $H_0$ was proportional to that volume divided by the area of the annular space between the 4" aluminum pipe and the 6" well bore wall. Effectively, the observed $H_0$ was less than 10' for 1/4" and 1/2" IPS, and less than 1' for 1/8" IPS.
Figure 7. Slug test signals in the MPS intervals for various IPS diameters. All tests were initiated by applying 20 psi ($H_{\text{applied}} = 46'$) to the respective IPS line.

For slug tests conducted with a given $H_{\text{applied}}$ and IPS diameter, $H_0$ decreased when the isolated interval permeability increased (Figure 7). This can be explained by taking into account that to initiate a slug test at each interval, the IPS was depressurized; it took a finite time to release the nitrogen from each IPS line. During this time, a larger groundwater volume has reentered to the more permeable intervals (and their associated IPS lines). The slug test $H_0$ depended
on the IPS water level immediately after completion of nitrogen expulsion. Thus, Ho was larger for less permeable intervals. This was confirmed by the observed one order of magnitude lower Ho for I2 and I4 (high permeability), compared with I3, I5 Ho (low permeability) for the same IPS diameter.

**Water Sampling**

To assess the MPS water sampling system under extreme conditions, each water sampling line was pressurized at a high enough pressure to ensure complete removal of the water within it. Water samples were obtained from I1 to I5 by applying 70 psi (Ho applied = 161') to the water sampling lines. The water volume collected for each interval was then recorded. When nitrogen flowed out of the water sampling line, the applied pressure was released (Figure 8). I1 was almost unaffected after pressure release because of the large amount of water stored in it. Taking into account that the I1 static water level was ~ 2', and the top of P1 was 108', there was a water volume of approximately 11 ft³ stored in it. The 0.0141 ft³ (400 ml) sample volume was less than 0.09% of the I1 stored volume, and therefore no appreciable pressure decrease was expected.

The drawdown due to sampling increased with a decrease in interval permeability. This corroborated the conclusion formulated from slug tests. In this case, the impact of formation recovery on the observed Ho value was even more evident. The water volume extracted in each interval was approximately the same; therefore, if all intervals were impermeable, the pressure change should have been the same. However, I2, and I4 exhibited small drawdowns
because of their high permeability. In contrast, the less permeable intervals 13, and 15 had large drawdowns, indicating a larger hydraulic gradient was needed to send water from the formation to the well to replace the extracted sampled volume.

![Graph showing water sampling field curves.](image)

**Figure 8.** Water sampling field curves. Nitrogen lines were pressurized with 70 psi for each interval. The volumes of sample water collected from each sampling interval are shown in parentheses.

For the MPS water sampling protocol, the applied pressure was reduced to ensure that water inside the water sampling lines was not completely purged during each pressurization stroke. For the BBC5 MPS conditions, 40 psi
(Ho_{applied} = 92') was a safe pressurization value for all sample ports, although the pressure could be tailored for each interval. Subsequent tests indicated that pressurizing with 40 psi for one minute, and releasing it for another minute, produced a 7.32 inch$^3$ (120 ml) pumping stroke for all intervals.

**Using the MPS for Fracture Characterization**

The water pressures at each interval isolated by the MPS were continuously monitored for seven months by recording pressure at all five intervals with a frequency of one reading/minute. Unlike open boreholes, the environmental piezometric fluctuations recorded by the MPS correlated with ocean tides along the nearby neighboring shores (Figure 9) (Pulido et al 2003a). The MPS also assisted in detecting unexpected hydrogeological stresses at the site. For example, nearly instantaneous 0.3', 0.4' pressure decreases were recorded before midnight in I4 and I1, respectively, during a day without precipitation, sudden barometric pressure changes, or site activity (Figure 10). These signals could have been caused by instantaneous external loads, such as airplanes and heavy machinery movements in the neighbor airport. Also, I1 and I4 followed similar environmental trends, significantly larger than I2, I3, and I5 signals, and correlated with ocean water levels. This may indicate that the fracture zones intersected by these intervals extend to a larger scale than those fractures intersected by I2, I3, or I5.
Figure 9. Correlation between piezometric levels. BBC5 MPS, and open borehole wells, and tides recorded in New Castle, NH (NOOA, 2003)

Figure 10. MPS Environmental pressure trends and ocean water levels (04/13/03). There was no sudden barometric pressure change, precipitation, or activity at the site during this period.

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Vertical gradients

Pressure readings for each MPS interval under static conditions were used to study vertical gradients in BBC5 (Figure 11). Before the first MPS inflation, BBC5 was an open borehole, which “short-circuited” all intersected fracture zones until a well bore equilibrium was achieved, resulting in an apparent static water depth of 2.0' below top of casing. Eight hours after packer inflation, pressures stabilized at all intervals. II stabilized to a smaller depth (higher piezometric level) indicating that it was recharging the other intervals before MPS inflation (downward vertical flow). Very small vertical gradients existed between I2, I3, I4, and I5.

Figure 11. Vertical hydraulic gradients in five BBC5 intervals isolated with the MPS.
BBC5 vertical gradients were time dependent. For example, six days after packer inflation (the same day that the unexpected stresses were observed at l1 and l4), downward gradients l3-l4-l5, and l1-l2 were detected at midnight. A different pattern was observed at noon: l1 and l4 increased their static water depth, but l2, l3, and l5 exhibited little change. This generated an upward gradient l4-l5, and an almost zero gradient l2-l3.

The MPS was deflated after one month on order to conduct the previously described inflation and sealing tests (Figure 6). Before deflation, l3 had a static water depth 1' smaller than any other interval resulting in gradients of: l1-l3 upward, and l3-l5 downward. 30 minutes after MPS deflation, when pressure signals stabilized, gradient patterns persisted, but the l3 static water depth stabilized closer to the level of the others. Taking into account that l3 is a low hydraulic conductivity interval, this indicated that l3 was recharging the other intervals.

Well BBC5 exhibited vertical water flow 30 minutes after the MPS deflation indicating short-circuiting within the well bore. Figure 11 data series "05/12/03 (deflated)" corresponds to the time immediately before the large positive peak at the right hand side of Figure 6; after that, the MPS packers were reinflated. Figure 6 suggests that at this time, each interval had nearly recovered to its own static conditions; nevertheless, Figure 11 indicates that there were actually vertical flows at this time, from l3 to the other intervals.
Hydraulic Parameter Estimation

Extending the previous discussion about the impact of the slug test tubing diameter on slug test signals, the apparently instantaneous $H_o$ duration for most IPS tested diameters (Figure 7), lose that character when plotted on a log time scale (Figure 12). The 1/8" IPS generated $H_o < 0.02H_{\text{applied}}$, and yielded noisy slug test signals unusable for quantitative analyses. The ¼" IPS line generated $H_o = 0.15 H_{\text{applied}}$, exhibiting a good quality signal but a non-instantaneous $H_o$ duration (which prevented the accurate determination of the actual $H_o$ magnitude). The 3/8" IPS line generated $H_o = 0.33 H_{\text{applied}}$ with a near instantaneous $H_o$ duration, enabling performance and analysis of slug tests with $H_o < 45'$. As a result, the minimum recommended IPS line diameter is ½".

Figure 12. Independent slug test field curves. All tests were initiated by applying 20 psi ($H_{\text{applied}} = 46'$) to the respective IPS line.
The MPS can be used as a monitoring well for pumping tests and slug tests. For example, a discrete interval (112.25'-117.75') in BBC6, located 24.5' from BBC5, was isolated by a straddle packer system. The corresponding MPS field data matched a radial heterogeneous numerical model (Pulido and Ballestero, 2003) (Figure 13). The pumping test and slug test analyses consistently yielded $T=1.09$ ft$^2$/day within a 9.84' radius from BBC6, and $T=155$ ft$^2$/day beyond that radius. For both zones, $S$ was between 2E-4 and 7E-4. The hydrogeologic significance of these results is discussed in Pulido et al. (2003a).

Figure 13. MPS use as a monitoring well for a Pumping Test (PT) and Slug Test (ST) conducted on well BBC6.
Well Connectivity

When trying to maximize the slug test Ho for 1/8" IPS lines, the Ho_{applied} was increased beyond that for water removal from the IPS line, thereby forcing nitrogen to invade the isolated interval, and the intersecting fractures. The induced overpressure was recorded in BBC4 and BBC5 isolated intervals (Figure 14), and open borehole monitoring wells (Figure 15), allowing well interconnectivity to be described at a site-wide scale (within 400' from BBC5). This test was named a gas injection test, and is discussed in Pulido et al. (2003c).

![Graph of BBC5 Gas Injection Test](image)

**Figure 14.** Monitoring Well (MW) isolated interval pressure variations (right-hand scale) during the BBC5 gas injection test (left-hand scale). Well BBC4 is located 25' away from BBC5.

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Figure 15. Monitoring Well (MW) open-well pressure variations (right-hand scale) during the BBC5 gas injection test (left-hand scale). W6071, W6075, W6127, and BBC3 monitoring wells are located 402, 268, 47.5, and 225' from BBC5, respectively.

**FUTURE RESEARCH**

Based on the BBC5 MPS prototype experience, a standard MPS will additionally include automated water sampling pulses, and optimized MPS tubing diameters. Water sampling can be controlled with a solenoid valve to cyclically apply pressure for one minute, and then release it for the next minute (recovery). In this way, a pre-established sequence of pumping strokes can be applied to get the required sampling purge volume and perform a long term pumping test.

When the static water depth is shallow enough, connecting the IPS line to a peristaltic pump can significantly reduces the water purging time. In this case,
it is desirable to provide an IPC line diameter larger than 1/8", to reduce friction losses, and cavitation/degassing conditions in the suction line. The minimum recommended IPS line diameter was 1/2", dictated by the slug tests results. The MPS pipe diameter can be reduced from 4" (the additional IPS lines are not required in the next MPS). However, doing so, will increase the annular space between the MPS and the well wall, thereby extending interval purge times.

A site-wide tracer test is planned for the BBC site. The MPS will be used as a passive and active component of the test. By using its water sampling capabilities, the five isolated intervals can be periodically sampled in order to delineate multilevel arrival times of the tracer injected in a different well (passive). Additionally, a tracer can be injected at any MPS interval through the IPS line, and water sampling can be conducted from the other intervals and/or nearby wells in order to assess tracer flow paths in the fractured bedrock.

**CONCLUSIONS**

The MPS is a discrete-interval isolation system available for hydrogeologic studies. The only MPS components in continuous direct contact with the groundwater are: the packers, aluminum pipe, and stainless steel couplings. These materials minimize water quality biases due to sorption, desorption, and diffusion processes.

The MPS prototype demonstrated satisfactory interval sealing, hydraulic testing, and collection of water samples. It assisted in the assessment of piezometric level variations under ambient conditions; in particular, the
relationship between piezometric head and tidal water levels could be correlated. Currently, it is being used for hydrogeologic characterization of fractures and as an active and passive component of a site-wide tracer test.

The MPS prototype was used to study slug test performance, (e.g., the influence of slug duration and size, and the influence of the slug test tubing diameter on the field data). The MPS has been successfully used as a monitoring well for pumping tests and slug tests conducted in a neighboring well, allowing reliable T and S estimations. In addition, the gas injection test performed in the MPS made it possible to assess well interconnectivity at a site-wide scale.

Active research is being conducted on designing a second MPS based on the BBC5 MPS prototype experience. New features will include: increasing the IPC line diameter to 1/2", reducing the MPS aluminum pipe diameter from 4", and automation of water sampling pulses to enable the MPS systems to support long term pumping tests.

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CHAPTER 3

LARGE DRAWDOWN SLUG TESTS
ABSTRACT

Large drawdown slug tests (LDST) are defined as those slug tests with initial drawdown (Ho) > 5 m. LDST up to 18 m were conducted in discrete intervals at four wells completed in fractured bedrock. Water level responses were recorded in the test well and at monitoring wells located up to 70 m from the test well. When discrete intervals were isolated in monitoring wells, the measured monitoring well responses were above 30 cm, allowing quantitative estimation of hydraulic parameters by a finite difference, radial heterogeneous model. Transmissivity and storage coefficient estimates from LDST with monitoring wells were compatible with those estimates from pumping tests. LDST are a valuable hydraulic test to: a) study well interconnectivity in heterogeneous formations, b) alleviate the need to pump large quantities of groundwater and attendant associated disposal and logistical requirements, especially at contaminated sites, c) quantify the storage coefficient from monitoring well field data, and d) assess well interconnectivity of tight fractures.

INTRODUCTION

Hydraulic parameter estimation is required for many hydrogeologic studies. In projects ranging from groundwater exploration and management, to contamination and remediation studies, to site selection for hazardous waste repositories, transmissivity (T) and storage coefficient (S) values are typically
evaluated from pumping tests and slug tests. Pumping tests were the first site-scale quantitative hydraulic test used for hydrogeologic characterization (Theis, 1939). A pumping test yields an estimate of T from the time series of reduced head or drawdown and the flowrate (Q) of a test well. S can be estimated if drawdown time series are available in monitoring wells (Walton, 1970). The estimated values of T and S are fairly representative of the average hydraulic performance of the cylindrical portion of formation centered on the test well and with a radius equal to the monitoring well distance. Often in practice, these hydraulic characteristics are extrapolated into untested portions of the formation.

Pumping tests exhibit several disadvantages, depending of the kind of project under consideration. They are expensive, time consuming, labor intensive, and highly disruptive to the natural groundwater hydraulics at the site. They normally require several hours or days of pumping to get adequate data sets from the test well and monitoring wells. Depending on the well and formation, they may require significant personnel and equipment; heterogeneous formations require recording the hydraulic signals in several monitoring wells. At a contaminated site, all pumped groundwater must be collected and treated (Butler, 1998). Pumping test analytical methods most often require a constant discharge (Q), which is difficult to maintain under field conditions. Pumping test numerical methods account for, and allow the use of, a variable discharge rate, but require a time series discharge record using a recording flowmeter. In low-permeability formations, a very low discharge pump and a very sensitive
flowmeter are required, which increase the sophistication and cost of the test equipment.

To overcome these constraints, the slug test has been increasingly used for hydrogeologic assessments. The slug test was originally proposed by Hvorslev (1951) as a soil mechanics field experiment. The slug test is inexpensive, quick, and not very hydraulically disruptive. When the appropriate setting is selected (i.e., pressurized slug test discussed below), the slug test does not extract water from the tested formation: a great advantage when dealing with contaminated groundwater. Several analytical methods have been developed to solve the groundwater flow differential equation for a slug test, given certain boundary conditions (Cooper et al., 1967). The primary disadvantage of the traditional slug test is its limited scale of investigation.

Today, there is some reluctance to using slug tests (Butler, 1998) because they estimate T on a point-scale around the test well. Even if the analytical method addresses formation storativity, S estimates are questionable (Papadopulos et al., 1973). Slug tests suffer problems of non-uniqueness to a greater extent than pumping tests (Karasaki et al. 1988). This paper introduces a modified slug test that uses a large initial drawdown (Ho) to address the limitations just cited. Large drawdown slug tests (LDST) are based on increasing Ho to extend the radius of the hydraulic test around the test well to the point where quantifiable signals are recorded at a monitoring well. By using a finite difference radial model, T and S can be estimated from the test well and monitoring well field data.
No previous study was found in the literature to assess the influence of Ho on slug tests. Most authors do not include Ho values when reporting their field data examples. The established custom of reporting normalized field data (H/Ho) is based on the homogeneous diffusion equation solved by Cooper et al. (1967) assuming that the response to an instantaneous hydraulic stress is linear to Ho. If that assumption is correct, it is valid to use normalized drawdown (H/Ho) as the basic slug test variable. Therefore, in a homogeneous model, the formation response to an instantaneous stress is the same after normalizing the signal by the size of the imposed stress (Ho). This assumption is not valid when considering non-linear flow, formation heterogeneities, or non-instantaneous stress duration in field data (Shapiro and Hsieh, 1998).

LDSTs utilize Ho > 5 m; 5 mm is the maximum Ho value reported in the literature for traditional slug tests (McElwee and Zenner, 1998). Most authors use much lower Ho values. Cooper et al. (1967) used Ho = 42 cm for their field example, while Butler (1998) recommended performing repeated slug tests for various Ho values between 20 and 90 cm to assess the role of nonlinear mechanisms.

LDSTs have the added feature that they include pressure data from monitoring wells instead of just the test well, and hence can better estimate T and S. Black and Kipp (1977) were possibly the first to suggest the use of monitoring wells for slug tests. Novakowski (1989), developed type curves for analyzing slug test monitoring well signals. Belitz and Dripps (1999) described slug tests performed with six monitoring wells in a shallow unconfined aquifer.

**MATERIALS AND METHODS**

Since 1999, the Bedrock Bioremediation Center (BBC) at the University of New Hampshire has been studying a fractured metamorphic rock formation that is contaminated with TCE and its progeny. The contamination occurred in the overburden and migrated downward into the bedrock. The field site is located at the Pease International Tradeport (Portsmouth, NH), the former Pease Air Force Base. A primary project objective is to isolate fracture zones and determine the nature of microbial biodegradation of the solvents occurring in the fractures. Wells constructed by the U.S. Air Force were predominantly completed in the upper (weathered) portion constituting the top 3 to 8 m of the bedrock, whereas wells installed by the BBC were completed below in the competent (fractured) bedrock: from below the weathered zone down to depths of 60 m below ground surface. A hydraulic testing program, which included more than 200 slug tests and 10 pumping tests, was performed as part of the site hydraulic characterization. Hydraulic tests were conducted on five fractured bedrock 15.24 cm (6-inch) diameter wells, with total completion depths ranging between 30 and 60 m. During each hydraulic test, pressure signals were recorded at the test well and all other fractured bedrock wells at the site, plus at five screened weathered-rock wells (completion depths ranging from 14 to 23 m (Figure 16). After
hydraulic tests were completed in BBC4 and BBC5, these wells were outfitted with discrete zone isolation systems to prevent in-well vertical cross contamination between fracture zones (Pulido et al., 2003).

Figure 16. Monitoring Network Location Map. Origin at Coordinates 64504m North, 369865m East, referred to NH state plane coordinate system.
**Slug Test Performance**

The discrete zones selected for hydraulic testing were isolated with a pneumatic straddle packers system (YEP-4.75/6.00 Roctest™; Plattsburgh, NY; gland length 1 m) as shown in Figure 17. The length of the isolation interval for hydraulic testing was 1.0 or 1.67 m. Within the isolation interval was a perforated 5 cm (2-inch) internal diameter (ID) brass pipe coupled with the solid pipe of the packers. The coupling at the base of the bottom packer pipe was capped. The top packer pipe was connected to 5 cm ID threaded aluminum pipe that extended to above the top of the well casing (TOC). Three pressure transducers (Roctest™ PWS vibrating wire; range 0-517 kPa (0-75 psi); accuracy 0.5% full scale; maximum frequency 1 reading each 3 seconds) were included in the system; one just above the top packer, a second in the center of the isolated interval, and a third next to the bottom cap. All three transducers were located on the outside of the 5 cm pipe.

The upper and lower transducers were used to check the seal between the inflated packers and the wall of the test well; the central transducer records pressure in the isolated zone during hydraulic tests. Packers were inflated with Nitrogen gas (N₂). An inflation pressure ~620 kPa (90-psi) in excess of the hydrostatic pressure in each tested interval was sufficient to maintain high integrity packer seals; the deepest BBC well was 62 m, therefore the minimum pressure in the N₂ tank regulator was 62 m * 9.8 kPa/m + 620 kPa = 1228 kPa. For simplicity, the inflation pressure in the regulator gauge was set to 1379 kPa (200 psi) for all tested intervals. This pressure met or exceeded the 620 kPa (90
psi) above ambient hydraulic pressure required yet did not exceed manufacturers specifications for maximum packer pressurization.

Figure 17. Hydraulic test instruments associated with the installation of the straddle-packer at well BBC3

A. Aluminum tripod  
B. Hand winch  
C. Top pressure transducer  
D. Isolation interval with central pressure transducer  
E. Bottom pressure transducer  
F. Top packer  
G. Bottom Packer  
H. N₂ tank for slug tests and packer inflation  
I. Waste water drum for pumping tests
The aluminum pipe at the top of casing was capped with a "T" fitting as shown in Figure 18. A high sensitivity pressure transducer (PDCR 1830 Druck™; New Fairfield, CT; range 0-345 kPa (0-50 psi); accuracy 0.04% full scale; frequency 64 readings/s) was installed inside the aluminum pipe to a depth below the static water level, expected during the programmed Ho values. This transducer recorded the slug test signals for quantitative analyses. For rising slug tests, the aluminum pipe was pressurized with nitrogen (N$_2$) gas; for falling slug tests the aluminum pipe was depressurized with a vacuum pump. The 2.5 cm (1 inch) wellhead fitting accommodated the slug test transducer cable, the gas line, and a 2.5 cm quick-release ball valve for the pressure release to initiate the ST.

Rising slug tests were performed by setting the straddle packer to the desired test depth and inflating the packers. The N$_2$ line was connected to the packer inflation filling at the wellhead. The slug test (Druck) transducer frequency was set to 8 readings/s, and upper, central, and lower transducers (RocTest) to 1 reading/ every 5 seconds. The quick-release valve was left open until all the pressure transducer readings stabilized. The valve was then closed and the N$_2$ tank regulator was set to the programmed pressure for displacing the desired Ho in the test interval. After this pressurization, when all transducer pressure signals had stabilized, the quick-release valve was opened thereby starting the slug test. After one minute, the slug test transducer frequency was decreased to 1 reading every 5 seconds, and after five minutes all transducer
frequencies were set to 1 reading per minute. Aslug test was considered complete when the water level stabilized in the aluminum pipe, or after 30 minutes duration when testing tight intervals.

**Figure 18. Slug test well head detail**

A. 5 cm (2 inch) diameter aluminum pipe extending from the packer string.
B. 2.5 cm (1 inch) diameter quick opening ball valve
C. N₂ line
D. High frequency pressure transducer cable
E. Three medium frequency pressure transducer cable
F. Stainless steel cable supporting the packer string during repositioning
In the same well intervals, pumping tests were conducted for comparison purposes with the hydraulic parameter estimates of the LDSTs. An electric submersible pump was lowered inside the 5 cm diameter aluminum pipe, down to just above the isolated interval or to a depth greater than the expected drawdown for the pumping test. The central transducer signal was set to a frequency of 1 reading every 5 seconds. Given the low pumping rates (less than 100 ml/s), the flowrate was measured volumetrically each 15 minutes or more frequently when flowrate changes were observed. Recovery data was also collected for pumping tests.

All monitoring wells were instrumented with 0-103 kPa (0 – 15 psi) Druck pressure transducers, and set for one 1 reading per minute during hydraulic testing. All pressure transducers were wired to CR10X Campbell Scientific™ dataloggers (Logan, UT).

**LDST CONCEPTUAL INTERPRETATION**

The complete set of tests for hydraulic characterization of the site, including rising and falling slug tests and short and long pumping tests, was analyzed and reported by Pulido et al. (2003). Several representative LDSTs are presented in this paper to demonstrate the capabilities of the method for hydraulic characterization.

A 30 LDST sequence was conducted over the course of 6 hours in an isolated interval (33.6-37.7 m) in BBC3 (Figure 19). Ho values were gradually
increased from 60 cm up to 18.9 m. LDST with Ho > 5 m generated water level responses clearly distinguishable from environmental water level fluctuations in the weathered bedrock well 6029 (10 cm (4-inch) in diameter, screened interval 9.7-12.8 m), located 63 m from BBC3.

![Figure 19. Successive LDSTs in one interval of test well BBC3 and responses in monitoring well 6029, located 63 m from BBC3.](image)

Another LDST sequence performed in BBC4 (isolated interval 46.1-47.7 m) with Ho values between 0.6 and 15.8 m generated signals in weathered bedrock well 6127 (10 cm diameter, screened interval 20.5 - 23.6 m) located 16.1 m from BBC4 (Figure 20). These two data sets demonstrate several useful features of the LDST. The LDST can assess well interconnectivity in heterogeneous formations. For example, while the monitoring well in Figure 19 is
four times further away from the test well than in Figure 20, the response signal in Figure 19 is four times larger. These test also confirm the Ho-duration issue discussed by Chirlin (1990): at each individual LDST, the initial (negative) drawdown during pressurization was persistently lower than the initial (positive) drawdown during release (Figures 19 and 20). This is because pressurization was transmitted to the isolated interval in a gradual way, and a significant formation response occurs during this process. Consequently, the pressurization pulse does not conform to the conceptual model of an instantaneous slug and is not useful for quantitative analysis. On the contrary, the 2.5 cm quick-release valve opening results is a near-instantaneous pressure release.

In principle, the monitoring well responses to LDSTs can be used for quantitative estimation of hydraulic parameters. However, the maximum monitoring well response was 2 and 6 mm, respectively (Figures 19 and 20; the transducer accuracy is +/- 1.5 mm). These small variations are enough to demonstrate hydraulic connectivity, but compromise the accuracy of any model that uses this monitoring well data to estimate hydraulic parameters. In addition, the monitoring well storage of water will affect test results (Novakowski, 1989). Therefore, it is desirable to isolate discrete zones in a monitoring well during an LDST in order to increase monitoring well signal size allowing for quantitative analysis.
Figure 20. Various LDST in an interval of test well BBC4 and responses in monitoring well 6127, located 16m from BBC4.

A sequence of 2 slug tests and 9 LDSTs was conducted in BBC5 isolated interval 45.5-47.2m. Ho values between 1.8 m to 17.7 m generated 60 cm responses in the isolated interval 38.8-40.4m in BBC4, located 7.6 m away (Figure 21). All of these monitoring well LDST responses were large enough for quantitative analysis. Additionally, the complete sequence could be analyzed as a single pulse interference test (Johns, 1998), after correction of environmental water level trends in the monitoring well (McElwee, 2002).
LDSTs can be useful for well interconnectivity assessment of tight fractures; those fractures essentially closed or filled, and therefore almost impermeable (Bredehoeft and Papadopoulos, 1980). For example, 12 isolated intervals in test well BBC6 exhibited the step-like shape signals typical of slug tests in tight fractures: the applied 69kPa (10 psi) N₂ pressure was dissipated at such a slow rate that it required several hours to recover to initial conditions. Consequently, the pressure was released after 30 minutes had elapsed. The pressure signal returned to the initial value without initiating a slug test curve.

Figure 21. LDST sequences in one interval of test well BBC5 and responses in an isolated interval of monitoring well BBC4, located 7.6 m from BBC5.
However, the BBC6 slug test pressurization phase in 4 of the isolated intervals were detected in monitoring wells BBC3 and 6075 located 70 m and 80 m from BBC6, respectively (Figure 22). The seemingly impermeable test intervals in BBC6 were actually hydraulically connected to the fractured bedrock well (BBC3) and the weathered bedrock well (6075). The data showed the BBC6-BBC3 connectivity (i.e., the signal response size) was stronger than that of BBC6-6075. The connectivity in BBC6 at 28.8 m was one order of magnitude larger than the other three intervals. The arrival time of the peak signal generated by the same 69kPa pressurization in BBC6 was different for each interval, indicating different connection paths in the fracture network.
Figure 22. Monitoring well BBC3 and 6075 responses to LDST conducted in tight intervals of BBC6.
As a first approximation, slug test and LDST field data were fitted to the radial homogeneous model proposed by Cooper et al. (1967). This allowed estimation of $T$ and $S$ values from open borehole slug tests by superimposing the field data onto type-curves depending on the $\alpha$ and $\beta$ dimensionless parameters defined as:

$$\alpha = \frac{r_w^2 S}{r_c^2}$$  \hspace{1cm} (1)$$

$$\beta = \frac{Tt}{r_c^2}$$  \hspace{1cm} (2)$$

where $r_w$ and $r_c$ refer to the well radius at the tested zone and the slug test casing radius, respectively. As discussed by Karasaki (1987), $\alpha$ represents the ratio of formation storativity to the slug test casing storage and has an inverse relation with the slug test radius of influence. $\beta$ has an inverse relation with the slug test total duration. This duration is proportional to the slug test casing storage and inversely proportional to $T$.

Figure 23 presents two typical field data sets fitted to Cooper type-curves. The open borehole slug test conducted in BBC3 ($H_o=80$ cm) yielded field data that matched the $\alpha=1E-5$ type-curve and estimates of $T = 8.6$ m$^2$/day and $S=1E-6$. The satisfactory fit to the Cooper type-curve implies that a radial flow homogeneous model was a suitable representation for these slug test conditions. In contrast, the straddle packer slug test performed in BBC5 ($H_o=1.85$ m) did not
fit to the type-curve set. This set would need to be extended to unrealistically low 
S values to match the straddle packer slug test field data.

Figure 23. Slug test hydraulic parameter estimation by the Cooper type-curve.

Most of the slug tests conducted at the site used a straddle packer system 
with isolated interval lengths of 1.0 m or 1.67 m, depending on the configuration 
of the packer system (Pulido et al., 2003). Systematically, the field data slope 
(H/Ho vs. time) was higher than any Cooper type-curve, thus precluding using 
this method for T and S estimations. Hyder et al. (1994) reported similar 
phenomenon for slug tests conducted in partially penetrating wells for which the 
hydraulics during straddle packer slug tests is similar. They developed a type 
curve method of analysis for partially penetrating wells assuming homogeneous 
conditions.
The observed divergence from the Cooper method for straddle packer slug tests, was also discussed by Hayashi et al. (1987) when $b_1$, the ratio of the test interval length ($B$) to the well bore diameter ($2r_w$) is small. Assuming an homogeneous medium, they noted that spherical flow in the formation near the tested interval becomes significant when $b_1 < 20$. Effectively, the same trend was found in Figure 24 when single packer slug tests were conducted in BBC3 to isolate progressively smaller intervals from the packer to the bottom of the well ($B = 16.7$ m (open borehole), 10.7 m, 4.3 m, and 1.12 m; with $H_0$ values of 0.80 m, 1.20 m, 1.24 m, and 1.26 m, respectively).

![Figure 24. Slug test field data as a function of $b_1$, the ratio of test interval length to well bore diameter.](image)

When the slug test $H_0$ was progressively increased for a given test interval, the normalized $H/H_0$ field data for each test were not coincident, as
would be expected from the homogeneous linearity assumption of the Cooper method. Instead, the data plots were shifted towards larger times as Ho was increased. Figure 25 shows this trend for 13 slug tests conducted in BBC5 (isolated interval 45.5-47.2 m). The observed shift was probably not caused by the larger time required to release the N\(_2\) from the slug test casing for larger Ho values because that took less than one second for all Ho.

![Normalized slug test data in test well BBC5 and its dependence on Ho.](image)

**Figure 25.** Normalized slug test data in test well BBC5 and its dependence on Ho.

McElvee and Zeneer (1998) and McElvee (2002) reported field data dependency on Ho associated with turbulent flow next to and within the test well. Their normalized field curves increased slope as Ho increased. Although the BBC5 data exhibited a temporal offset, the normalized field curves clearly maintained a constant slope with increasing Ho (Figure 25). If turbulent flow
existed at the early times because of the large Ho values, the field curve would have exhibited a clear change of shape at the time when the transition to laminar flow was established at the later times. There was no evidence of deviation from laminar (Darcian) flow in the BBC5 curves (Figure 25).

Karasaki et al. (1987) analyzed the expected slug test curves when the test well intersects a subhorizontal fracture that is part of an interconnected fracture system. They reasoned that the flow in the intersected fracture is radial and at some distance, where the fracture becomes more interconnected with the fracture system, the flow becomes spherical (as expected when testing a discrete interval in an homogeneous formation). They developed type curves that clearly show the effects of the change in flow geometry from the inner to the outer region. When the total storativity next to the test well is very small, the type curves are shifted horizontally without any noticeable transition from the inner to the outer region. The shift to larger times increases with the ratio between the inner and outer permeabilities.

The type curves presented by Hyder et al. (1994), Hayashi et al. (1987) and Karasaki et al. (1987), are not meant to be complete sets of curves for slug test analyses. The application of these methodologies requires developing specific type-curves for the particular hydrogeological conditions expected at the site. Even with customized type-curves, it is likely that field data will not fit a particular type-curve. Either an analytical technique that does not rely on curve matching or a flexible numerical technique are more advantageous for the kind of slug test field data considered in the fractured bedrock wells at the BBC site.
The need for a model to estimate hydraulic parameters of fracture network formations motivated the development of HyTests (Pulido and Ballestero, 2003). HyTests is a finite-difference radial heterogeneous model that, when given T and S values, solves the groundwater flow differential equation at any radius from the test well. Hydraulic parameters can be iteratively modified until the model responses match the field data. HyTests allows different hydraulic parameter sets for concentric cylinders around the test well, which enables the assessment of the effect of the scale of investigation in heterogeneous media (Shultz et al., 1999).

The homogeneous model failed to reproduce field data; when it fit the early data, it diverged for the later times and vice versa (Figure 26). In contrast, a two-zone radial heterogeneous model matched the field data with a Mean Percent Error (MPE) of the modeled drawdowns of 1.52 +/- 1.03% relative to Ho. The MPE is the arithmetic average of the model deviations from the measured drawdowns, relative to the maximum measured drawdown for the monitoring well during the hydraulic test. Almost all this error occurred in the later times of the slug test, after more than 75% of recovery had been achieved.

A sensitivity analysis was performed for the heterogeneous models for the smaller Ho slug test of Figure 25. The model was very sensitive to the inner zone T (2.1m²/day); in contrast, the model revealed only that the outer zone T > 10 m²/day (Figure 27). The inner zone final radius (r=2.0 m) was accurately estimated because it was shown to be a very sensitive parameter (MPE increased dramatically with small deviations from r=2.0 m). The outer zone final

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radius was the model radius, where the model was set to an impermeable barrier, to represent an infinite formation extension from the test well. The actual extension of the drawdown cone was estimated by gradually reducing the outer zone radius until model MPE started to increase; the analyzed slug test influence extended ~ 100 m around the test well (Figure 28). The model was not very sensitive to the inner zone S (S>1E-4) and insensitive to the outer zone S (Figure 29). The inner zone S was found to be smaller than 1E-4 (Figure 29). A more accurate S estimate is obtained when using monitoring well data. It should be underscored that the results for the test well were not unique: a larger radius inner zone with a smaller T can result in a similar MPE. This non-uniqueness of the direct solution model can only be overcome by concurrent solutions using monitoring well data.

![Graph showing hydraulic parameter estimation](image)

**Figure 26.** Hydraulic parameter estimation for the smallest Ho slug test shown in Figure 25, by homogeneous and radial heterogeneous models. Test interval length B=1.67m.
Figure 27. Sensitivity Analysis for T estimates

Figure 28. Sensitivity Analysis for radius estimates
A two-zone radial heterogeneous model was used to analyze all the slug test field data of Figure 25. It was found that the inner zone radius increased with the Ho magnitude, indicating a larger penetration distance for the LDSTs. The estimated inner and outer zone T values were constant for all Ho and generated modeled curves with MPE < 3%. In comparison, the same slug test field data were analyzed using the Cooper method by matching the early or the later data. In both cases, the T estimate decreased as Ho increased. The Cooper early time T estimates were similar to numerical, inner zone T estimates. The late time Cooper T estimates were close to the geometric average of inner and outer T (7.5 m²/day) (Table 1).
Table 1. Comparison of T estimates by the Cooper method and a two-zone radial heterogeneous model. The single well slug test field data is shown in Figure 26.

<table>
<thead>
<tr>
<th>Ho [m]</th>
<th>Transmissivity [m²/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Two zone radial heterogeneous</td>
</tr>
<tr>
<td></td>
<td>Inner radius [m]</td>
</tr>
<tr>
<td>1.85</td>
<td>0.1</td>
</tr>
<tr>
<td>3.39</td>
<td>0.3</td>
</tr>
<tr>
<td>3.62</td>
<td>0.2</td>
</tr>
<tr>
<td>4.79</td>
<td>0.4</td>
</tr>
<tr>
<td>6.17</td>
<td>0.5</td>
</tr>
<tr>
<td>6.47</td>
<td>0.4</td>
</tr>
<tr>
<td>7.60</td>
<td>0.5</td>
</tr>
<tr>
<td>9.80</td>
<td>1.0</td>
</tr>
<tr>
<td>11.60</td>
<td>1.5</td>
</tr>
<tr>
<td>13.67</td>
<td>1.5</td>
</tr>
<tr>
<td>14.14</td>
<td>2.0</td>
</tr>
<tr>
<td>15.26</td>
<td>2.0</td>
</tr>
<tr>
<td>17.70</td>
<td>2.0</td>
</tr>
<tr>
<td>Pumping test</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Values in shade cells are the same for all rows.

The possible presence of turbulent flow for large Ho values was explored by analyzing the drawdown cone and the Reynolds Number (Re). HyTests calculates and allows modeling the drawdown cone at any time during the hydraulic test modeling. For Re calculations, HyTests conceptualizes the flow as occurring between parallel plates. The distance between the plates is the fracture aperture (Bf). Darcian flow (laminar flow) exists to Re=1000 (Marsily, 1986). HyTests calculates the Re at any radius r, avoiding the use of the (unknown) fracture aperture:

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where \( V_r \, [\text{m/s}] \) is the Darcian velocity, \( K_r \, [\text{m/s}] \) corresponds to the hydraulic conductivity, \( i_r \, [\text{m/m}] \) represents the hydraulic gradient, and \( \nu \, [\text{m}^2/\text{s}] \) is the water kinematic viscosity. Once the numeric model is solved, \( V_r \) and \( i_r \) are known for each radius \( r \), thereby allowing calculation of \( R_e \).

The drawdown cone and the \( R_e \) variation for the largest \( H_o \) of Figure 25 were analyzed for two modeling times (Figure 30). At \( t=0.1\text{s} \) the drawdown cone extended \(< 90 \text{ cm} \) from the test well; at \( t=5\text{s} \), it extends to the inner zone radius. At all times, \( R_e < 1000 \), indicating that laminar flow existed for the duration of the LDSTs of Figure 25.

![Figure 30. Cone of depression and flow regime for the largest Ho slug test in Figure 25.](image-url)
When isolated interval monitoring well signals were provided, the LDSTs resulted in T and S estimates equivalent to those obtained from pumping tests, but with considerably less time, instrumentation, and personnel requirements. As evidence of this, both hydraulic tests (pumping test and LDST with Ho = 12.68 m) were conducted in an isolated interval of BBC6 (Figure 31) and monitoring well signals were recorded in isolated intervals of BBC4 and BBC5 (Figures 32 and Figure 33, respectively). By using a radial heterogeneous model, the pumping test and LDST analyses predicted the same T and S values (Table 2), demonstrating the consistency in estimating T and S between LDSTs and pumping tests.

Figure 31. Pumping Test (PT) and LDST conducted in an isolated interval of BBC6.
Figure 32. Monitoring well BBC4 isolated interval responses to the BBC6 Pumping Test (PT) and LDST shown in Figure 31.

Figure 33. Monitoring well BBC5 isolated interval responses to the BBC6 Pumping Test (PT) and LDST shown in Figure 31.
Table 2. BBC6 pumping Test (PT) and LDST Comparative Results. (See Figures 31-33 for field data).

<table>
<thead>
<tr>
<th></th>
<th>Test well BBC6 PT</th>
<th>Monitoring Wells BBC5 PT</th>
<th>Monitoring Wells BBC4 PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from BBC6  [m]</td>
<td>0</td>
<td>7.62</td>
<td>7.62</td>
</tr>
<tr>
<td>Depth Top [m]</td>
<td>34.21</td>
<td>36.94</td>
<td>43.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom [m]</td>
<td>35.89</td>
<td>42.34</td>
<td>45.08</td>
</tr>
<tr>
<td>Inner Zone T [m²/day]</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.0E-04</td>
<td>2.0E-04</td>
</tr>
<tr>
<td>Zone S [ ]</td>
<td></td>
<td>2.0E-04</td>
<td>2.0E-04</td>
</tr>
<tr>
<td>Radius [m]</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Central Zone T [m²/day]</td>
<td>N/A</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>Zone S [ ]</td>
<td></td>
<td>7.0E-04</td>
<td>2.0E-04</td>
</tr>
<tr>
<td>Radius [m]</td>
<td></td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Outer Zone T [m²/day]</td>
<td>14.40</td>
<td>14.40</td>
<td>14.40</td>
</tr>
<tr>
<td>Zone S [ ]</td>
<td></td>
<td>7.0E-04</td>
<td>2.0E-04</td>
</tr>
<tr>
<td>MPE [%]</td>
<td>8.16</td>
<td>8.47</td>
<td>6.19</td>
</tr>
<tr>
<td>SD [%]</td>
<td>4.06</td>
<td>10.9</td>
<td>4.05</td>
</tr>
</tbody>
</table>

Shaded cells not applicable (N/A) (two-zone model)

The radial heterogeneous model was a first approximation that successfully matched the entire hydraulic test data set from the fractured bedrock formation at the BBC site, meaning that all the modeled curves matched the field data with mean percent errors smaller than 10% (Pulido et al., 2003). Nevertheless, more sophisticated models are required to capture the fracture network heterogeneity in hydraulic tests analyses (Pulido and Ballestero, 2003). For example, the radial heterogeneous model predicted a gradual start for the BBC5 response to the pumping test conducted in BBC6, however a sudden start for the early time response in BBC5 was observed, indicating more complex hydraulics prevailed (Figure 33).
CONCLUSIONS

LDSTs extend the range of applicability of conventional slug tests, elevating them to the confidence given to pumping test data. By increasing the magnitude of Ho, LDSTs generate water level responses at those monitoring wells that are hydraulically interconnected with the test well. When discrete intervals are isolated in the monitoring well, responses to LDSTs are sufficiently magnified to permit quantitative evaluation of T and S as in pumping tests. However, LDSTs have the advantage of not pumping water and dramatically reducing the required time for testing. LDSTs conducted on tight fractures revealed a detectable hydraulic connection to a well located 70 m from the test well.

Slug tests and LDST field normalized data for the BBC wells completed in fractured bedrock, in general did not fit to radial homogeneous models, nor to Cooper type-curves in particular. When Ho increased, the normalized data shifted to increasing times without any change in slope, indicating formation heterogeneity (T) with a constant S. LDSTs can also be used in porous media, as long as the pressurized slug test instrumentation is provided to allow high enough Ho to produce response signals in monitoring wells.

A finite difference radial heterogeneous model was successfully used to analyze the slug test and LDST data for this formation, the inner zone T being at least one order of magnitude lower than the outer zone. The inner zone properties were interpreted as representative of single fractures intercepted in
the tested well interval and interconnected with the fracture network system at some distance from the test well (outer zone). The estimated inner zone radius increased for larger Ho values. No evidence of turbulent flow was found for the analyzed LDSTs. If turbulent flow exists, a model that includes this hydraulics would need to be adapted to the LDST data.

The use of isolated interval monitoring well data together with test well data for LDSTs, allowed reliable estimation of S, and the radius and T values of the outer zone. LDST demonstrated to be consistent with pumping tests in terms of hydraulic parameter estimation.

Overall, including LDSTs as part of hydraulic testing activities on hydrogeologic projects will contribute positively to improving the hydrogeological conceptual model of a site.

ACKNOWLEDGEMENTS

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CHAPTER 4

GAS INJECTION TESTS
ABSTRACT

The gas injection test (GIT) is a field technique for the characterization of hydraulic connections in fracture networks. A GIT is conducted below the water table by gas pressurizing an isolated interval of a borehole completed in a fractured bedrock formation. During the test, a gas pressure in excess of the pressure for water removal from the interval is used: therefore the gas dewateres the interval by forcing water into the fractures that intersect the tested interval. After pressure release, the groundwater imbibes the gas phase until static conditions are restored. The pressure responses to the drainage and imbibition processes can be recorded in monitoring wells, allowing well interconnectivity to be described on a site wide scale. Three GITs conducted in a metamorphic fractured bedrock formation afforded the assessment of major flow paths, the extent of hydraulic connections within > 120 m of the tested wells, and estimated the depth of the hydraulically active fractures intersecting the tested intervals.

INTRODUCTION

Hydraulic Tests at Pease Site

Since 1999, the Bedrock Bioremediation Center (BBC) at the University of New Hampshire has been studying a fractured metamorphic rock formation that is contaminated with TCE and its progeny. The field site is located at the Pease International Tradeport, Portsmouth, NH (formerly Pease Air Force Base). The
primary project objective is to isolate and characterize fracture zones and
determine the nature of microbial degradation occurring in them. Most of the site
wells installed prior to 1999 were completed by the U.S. Air Force in the
overburden (consisting of layers of sands, marine clay and silt, and glacial tills)
and the weathered bedrock. The BBC wells are completed as open boreholes in
the (fractured) competent rock belonging to the Kittery formation (Figure 16). A
hydraulic testing program, including more than 200 slug tests, and more than 10
pumping tests, was performed as part of the site hydraulic characterization.
Straddle packer slug tests were conducted in five fractured competent bedrock
wells (15.2 cm diameter, ranging in depths between 21 and 61 m).

Transmissivity (T) profiles were developed for each BBC well, based on
the straddle packer slug tests. During each hydraulic test, pressure signals were
recorded at nearby fractured bedrock wells, and five weathered bedrock wells
(ranging in depth from 14 to 24 m). After straddle packer hydraulic tests were
completed in wells BBC4 and BBC5, discrete-multilevel isolation systems, with
pressure transducers at selected intervals, were installed in these two wells in
order to prevent vertical cross contamination of fractures with the chlorinated
solvents within in the boreholes. The isolation system used in BBC4 was a
FLUTE™ system (Santa Fe, NM), which isolated seven intervals; two of them (P6
and P7) included pressure transducers. A multipurpose packer system (MPS)
was installed to isolate and monitor pressure in five intervals in BBC5 (Pulido et
al., 2003 a).
One of the primary objectives of the hydraulic characterization of the site was the well interconnectivity assessment. This was accomplished by pumping tests, slug tests and gas injection tests (GIT). A GIT is a field experiment consisting of injecting gas into the tested formation, in contrast to pumping test and slug test that involve water flow only.

A GIT uses the same principle as the standard test method for permeability of rocks by flowing air (ASTM, 2003), except that the latter is conducted in a small sample of rock under lab conditions. This standard method is designed to measure the intrinsic rock permeability coefficient, \( k \) [m\(^2\)]:

\[
k = \frac{2Q_e \mu L}{(P_i^2 - P_e^2) A}
\]

where \( Q_e \) [m\(^3\)/s] is the air flowrate through the sample; \( P_i \) and \( P_e \) [Pa] are the entrance and exit pressure of air, respectively; \( L \) [m] is the length of specimen; \( A \) [m\(^2\)] is the cross-section area of specimen; and \( \mu \) [Pa.s] is the dynamic viscosity of air at the temperature of the test. The intrinsic permeability can be used to evaluate the hydraulic conductivity \( K \) [m/s]:

\[
K = \frac{k \rho g}{\mu}
\]

where \( \rho \) [kg/m\(^3\)] is the water density and \( g \) [m/s\(^2\)] is the gravitational acceleration (Marsily, 1986).

A GIT is conducted in an isolated interval of a well, each fluid phase governed by the physics of multiphase flow of immiscible fluids: conservation of
mass law, modified Darcy's law, equation of state, capillary pressure, and the 
relation between phase saturations (Marsily, 1986). During the pressurization 
phase, the tested interval is subjected to a gas pressure higher than the static 
pressure of the fracture network at the zone intersected by the tested interval. 
Therefore the groundwater (wetting fluid) is forced away from the fracture 
network by the gas (non-wetting fluid). The release phase of the GIT starts when 
the gas pressure is released from the isolated interval. Hereafter the water 
displaces the gas from the fracture network by imbibition mechanisms. The 
drainage and imbibition phases follow different pressure histories (hysteresis). 
These mechanisms can be represented by the serial bundle of tubes model 
(Ganoulis, 1988), each tube representing the fracture aperture at each 
considered distance from the well. The hydrodynamics of both GIT phases can 
be assessed by the extended Darcy's law for steady state multiphase flow 
(Ganoulis, 1988):

\[ \bar{v}_i = \frac{k_i}{\mu_i} (\nabla P_i + \rho_i g \nabla z) \]  

(3)

where \( \bar{v}_i \) [m/s] is the Darcian velocity of phase \( i \); \( k_i \) is the relative 
permeability of phase \( i \), and the other terms have the same meaning explained in 
Equation (1) and (2), relative to the phase \( i \).

Mishra et al. (1987) reported field experiments and techniques of analysis 
for calculating hydraulic properties of unsaturated fractured formations by 
injecting gas into an isolated section of a borehole that intersects the fracture(s) 
of interest. These methods could be adapted for the analysis of the GIT release
phase because of the fracture network zone invaded by the gas during the GIT pressurization phase is essentially under unsaturated conditions after the gas pressure is released. Their results plot linearly when the square of the pressure drop ($\Delta P^2$) between the injection borehole and a monitoring well, is presented using a logarithmic time scale. The slope of this curve is used to evaluate the hydraulic conductivity.

**GAS INJECTION TEST PERFORMANCE**

A GIT was performed during a hydraulic test in the BBC5 MPS isolated interval I4, located from 42.9 to 49.4 m below top of casing. The MPS included inflatable packers connected to aluminum pipe that isolated discrete intervals in the well (Figure 34). The packer to pipe couplings were fabricated with ports containing miniature fittings. Pressure transducers and small diameter tubing were connected to the fittings and ran through the pipes up to the surface, where a control board permitted monitoring hydraulic head, water sampling, and conducting hydraulic and tracer tests at each isolated interval (Pulido et al., 2003b). The isolated well volume at each interval was an annular cylinder with the outer diameter (OD) equal to the well bore diameter (15.2 cm), and the inner diameter (ID) equal to the MPS aluminum pipe OD (10.2 cm). The annulus length was equal to the distance between the bottom of the top packer and the top of the bottom packer in the tested interval. The BBC5 MPS isolated five intervals (I1 to I5); two of them (I2 and I4) were previously characterized as high hydraulic conductivity zones (Figures 35 and 36). At the bottom of each MPS
interval, there was a 3.175 mm diameter ID plastic tubing, which traveled to the ground surface. At the top of each MPS interval, there was a pressure transducer (range 0-1379 kPa, accuracy 0.04% full scale, maximum reading frequency 8 pressure of readings/s).

Figure 34. BBC5 Gas injection test setting (see text for descriptions of variables).
Figure 35. BBC well transmissivity profiles established by straddle packer slug tests. Depths measured from Top of Casing (TOC)
The complete pressure history in I4 was recorded when pressurizing the I4 tubing with nitrogen ($N_2$) (Figure 37).

Figure 36. BBC5 interval 4 Acoustic Televiewer log (Depths referenced to top of casing [m]).
Figure 37. BBC5 GIT conducted at fractured bedrock interval I4 (43.0-49.4m).

A. 69.9 kPa (7.1 m of H₂O) applied pressure, and increased to 137.9, 275.8, 344.7, and 413.7 kPa (14.1, 28.1, 35.2, and 42.2 m, respectively)
B. Pressure increased to 482.6 kPa (49.2 m)
C. Pressure increased to 517.1 kPa (52.8 m)
D. Pressure increased to 551.6 kPa (56.2 m)
E. \( P_e = 47.5 \) m. \( H_b = 5 \) m. [No instrument manipulation]
F. \( P_f = 46.5 \) m. [No instrument manipulation]
G. \( P_g = 46.2 \) m. GIT sudden, total \( N_2 \) pressure release
H. \( P_h = 45.7 \) m. Flat zone starts
I. \( P_i = 45.7 \) m. Recession zone starts
J. Recession curve continues until 19:40, when the I4 static water level is re-established to pre-GIT level

Between points a-b, the tubing pressure was increased in a step-wise fashion moving sequentially from 137.9, 275.8, 344.7, to 413.7 kPa of \( N_2 \), without releasing it between steps. For each step, pressure transients of less than 3 cm of water were recorded by the transducer. Because the I4 injection tubing cross-
sectional area (7.76E-2 cm²) was negligible in comparison to the interval's annular area (101 cm²). A 413.7 kPa (42 m of water) pressurization in the I4 tubing pushed 332 cm³ of water from the injection line into the isolated interval fractures. This volume induced an observed overpressure equivalent to 332 cm³ / 101 cm² = 3 cm of water. After each response, the I4 pressure returned to the ambient (static) value.

The static water column length (Wc_i) in the bottom of I4, at the point where the tubing entered the interval, was Wc_i = (49.6 - 0.9 m) = 48.7 m (Figure 34), equivalent to 479.9 kPa. Therefore, when 482.6 kPa of N₂ pressure (equivalent to an applied hydraulic head of H_{applied}=49.1 m) was applied at point b, the tubing water was completely replaced with N₂, and some N₂ entered the interval. Because of its lower specific gravity, N₂ flowed to the top of the annular space, where the transducer was located. The transducer recorded this process as a sudden ~30 cm pressure increase at point b, that stabilized (horizontal pressure history) to point c, indicating that pressure equilibrium between the N₂ and the water in I4 was reached after the water level inside the interval decreased 30 cm.

Point b represented the initiation of a GIT. The applied pressure in excess of the static water column length was termed the GIT head: H_{GIT} = (H_{applied} - Wc_i). Thus, H_{GIT} represented the energy available for N₂ to displace groundwater from the tested interval; H_{GIT} = (49.1-48.7 m)=40 cm at point b, similar to the observed pressure increase at point b (30 cm) (Figure 37).

Point c corresponded to the time when the applied pressure was increased to 517.1 kPa (H_{applied} = 52.7 m), or H_{GIT} = (52.7-48.7 m)= 4.0 m.
However, the transducer recorded a sudden pressure increase of ~60 cm over the pressure at point c, followed by a slightly positive slope curve reaching to point d (Figure 37). This suggested that during c-d the l4 water level decreased 60 cm until it reached a fracture, and after that N₂ was flowing into the intersecting fracture. This process was accelerated when the N₂ pressure in the regulator was increased to 551.6 kPa ($H_{\text{applied}} = 56.2$ m), after point d ($H_{\text{GIT}} = 56.2 - 48.7 = 7.5$ m). A sudden pressure increase of ~45 cm followed by a nearly linear pressure increase was observed from d to e. The total pressure increase during the GIT ($H_b$) was the transducer pressure difference between points a-e ($H_b = 5.0$ m) (Figure 37). During d-e, the water level inside l4 was continuously decreasing, as evidenced by the recorded pressure increase in the transducer. At point e, the pressure increase ceased because the water level decreased to the level of a major fracture intersection. Thus, the transducer recorded a sudden pressure decrease following the path e-f, as a consequence of the enhanced fracture flow path available for the N₂ phase. The invasion rate stabilized after point f following a low slope pressure decrease (f-g), because of the larger volume of the fracture network occupied by N₂. During d-g, the 551.6 kPa ($H_{\text{applied}} = 56.2$ m) regulator pressure remained constant; N₂ flow could be heard from the N₂ tank and the regulator pressure decreased from 10343 to 2578 kPa.

The pressure applied to l4 was completely released at point g when the l4 tubing was disconnected from the N₂ tank. This resulted in only an initial ~60 cm sudden pressure decrease in the l4 transducer following the path g-h. l4
pressure was stable during the short period h-i; thereafter, it slowly decreased by the linear path i-j, nearly parallel to the previous line f-g, representing the gradual upward relocation of the trapped N₂ into the fracture network, because of its low specific gravity. Eventually, l4 recovered its static pressure more than eight hours after the GIT started.

At each time during b-g, N₂ invaded the fracture network. This process was governed by the density difference between the gas phase (N₂) and the liquid phase (groundwater). N₂ must have invaded groundwater in the upper fracture network zone near BBC5 l4 because of it is the lighter density. It must have followed viscous fingering mechanisms (Marsily, 1986).

The GIT pressure curve can assist in determining the location and relative permeability of the hydraulically active fracture zones in the tested interval. For example, at point c the l4 water level stabilized after decreasing 30 cm (Figure 37), corresponding to \( (43 + 0.3) \) m = 43.3 m from top of casing (Figure 36), indicating no fracture intersecting the top 30 cm of the interval. At point d, the l4 water level decreased another 60 cm (without stabilizing to \( H_{\text{GIT}}=4 \) m), equivalent to \( (43+0.3+0.6) \) m = 43.9 m from top of casing. In agreement, the acoustic televiewer log indicated a near horizontal fracture at that depth (Figure 36). The almost linear pressure increase d-e indicated that the l4 water level was continuously falling without encountering additional permeable fractures; in addition, the fracture at 43.9 m deep exhibited low permeability: this was inferred by the shape of the pressure history d-e. At point e, the total water level decrease was 5 m, corresponding to 48 m from top of casing. The sudden
pressure decrease after point e, indicates that the fracture intersecting I4 at 47.8
intersected with a more permeable zone away from the well.

The extent of a formation stressed by a GIT can be estimated by
calculating the N₂ volume injected into the fracture network during the test. The
N₂ volume injected between d-g was estimated using the gas-state equation for
N₂: \( P_0 \cdot V_0 \cdot T_1 = P_1 \cdot V_1 \cdot T_0 \), where \( P \) and \( V \) represent the gas absolute pressure
and volume, at any two thermo- dynamic states 0 and 1, respectively. GIT N₂
injection occurred between states b and g (Figure 37). Assuming isothermal
conditions, the gas-state equation between b-g simplifies to: \( P_b \cdot V_b = P_g \cdot V_g \).
At state b, the N₂ inside the tank, occupied a volume \( V_b = \pi \cdot r_{tank}^2 \cdot H_{tank} = \pi \cdot (0.10 \text{ m})^2 \cdot 0.61 \text{ m} = 0.0197 \text{ m}^3 \), at an absolute pressure \( P_b = (10342.5 - 2578.0) \text{ kPa} / 9.8 \text{ kN/m}^3 \) (specific weight of water) + 10.3 \text{ m} \) (standard atmospheric
pressure) = 802.6 \text{ m} \). At any time between b-g, the N₂ relative pressure should
have been approximately 48.7 \text{ m} \), the static water column length, equivalent to an
absolute pressure \( P_g = (48.7 + 10.3 \text{ m}) = 59.0 \text{ m} \). Replacing \( P_b, V_b, \) and \( P_g \) values
in the gas-state equation, the estimated volume \( V_g \) surrounding the hydraulically
interconnected fracture network invaded by N₂ was 0.27 \text{ m}^3 \).

The GIT gas volume injected into the fracture network, generated a 30 \text{ cm},
one-hour long pressure response in other BBC5 isolated intervals, and in isolated
intervals of BBC4, located radially 7.6 \text{ m} \) from BBC5 (Figure 38). Additionally, it
generated detectable, six-hour long site wide pressure responses at open
borehole monitoring wells. The GIT pressurization phase took < 15 minutes, but
> 8 hours were needed for static pressure recovery (Figure 39).
Figure 38. Monitoring Well (MW) isolated interval pressure variations (right-hand axis) during the BBC5 GIT (left-hand axis).

Figure 39. Open-borehole Monitoring Well (MW) pressure variations (right-hand axis) during the BBC5 GIT (left-hand axis). The BBC5 GIT appears as a near instantaneous $H_2 = 5.0$ m pressure pulse applied around 9:00h, and took until 20:00h for complete stabilization.

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The GIT results infer the fracture connectivity in monitoring wells surrounding BBC5 (Figure 40) shows the BBC5 GIT interpretation. BBC5 11, 12, 13, 15, and BBC4 P6 and P7 intervals were connected hydraulically to 14 (Figure 40). The hydraulically active fracture locations and orientations in wells BBC4 and BBC5 were identified by straddle packer slug tests (Figure 35) and acoustic televiewer logs. The acoustic televiewer indicated fracture attitude (strike and dip), while the overburden and weathered bedrock depth and thickness was obtained from well drilling records (Figure 40). Similar damped responses observed in monitoring well intervals were interpreted as the BBC4 and BBC5 interconnections occurring through other fractures of the fracture network, rather than the fracture originating in BBC5 14. The hydraulic connection of the fracture network extended at least 122 m south of BBC5 14, as indicated by the strong pressure responses at wells W6127 (weathered bedrock) and W6071 (fractured bedrock).
ALTERNATE GIT CONFIGURATION

Two more GITs were conducted; the first one in BBC5 I5 (49.7 – 60.4 m below top of casing), and the second one in BBC6 (isolated interval 39.6-41.3 m). Contrary to the BBC5 I4 GIT, these new GITs had their injection line entering on the top of the interval. The BBC5 I5 had its injection line entering at 49.7 m depth (Figure 34). The GIT pressure history in the tested interval and in the other four isolated intervals of BBC5 (Figure 41) exhibited trends similar to those obtained during the BBC5 I4 GIT (Figure 38).

![Figure 41](image.png)

Figure 41. BBC5 GIT conducted at fractured bedrock interval I5 (49.7-60.2 m) on 10/24/03.

A. 68.9 kPa (7.03 m of H_2O) applied pressure, and increased to 137.9, 206.9, 275.8, 344.8, 413.7 and 482.7 kPa (7.0, 14.1, 21.1, 28.1, 35.2, 42.2, and 49.2 m, respectively)
B. Regulator pressure increased to 551.6 kPa (56.3 m)
C. Regulator pressure increased to 620.5 kPa (63.3 m) and maintained for the duration of the test

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Point b was the initiation of the I5 GIT ($H_{\text{applied}}=56.3 \text{ m}$; $H_{\text{GIT}}=(56.3-48.6 \text{ m}) = 7.7 \text{ m}$; $N_2$ tank pressure = 13790 kPa). The pressure increase after point b was 2.6 m, indicating an intersecting fracture at a depth $(49.7+2.6 \text{ m}) = 52.3 \text{ m}$, which was confirmed with the acoustic televiewer log (not shown). At point c, pressure was set and maintained constant to $H_{\text{applied}}= 63.3 \text{ m}$ [$H_{\text{GIT}}=(63.3-48.6 \text{ m}) = 14.7 \text{ m}$], larger than the I5 length. $N_2$ was continuously flowing from the tank into the intersecting fracture, and invading the fracture network around BBC5 as evidenced in the pressure increase at all BBC5 isolated intervals (Figure 41). The I5 pressure increased following path c-d-e, until the I5 water level reached the bottom of the well (60.2 m of pressure at point e, meaning that no other hydraulically conductive fracture was present below 52.3 m. Beyond point e the applied pressure was maintained constant ($H_{\text{applied}}= 63.3 \text{ m}$), but I5 pressure was observed to gradually decrease; at the same time, the other isolated intervals continued increasing pressure, confirming of the progressive invasion of the fracture network by $N_2$. After point f ($H_{\text{applied}}= 63.3 \text{ m}$; $N_2$ tank pressure = 6895 kPa) I5 exhibited a constant pressure, and the other intervals started to decrease pressure, indicating that the $N_2$ invading phase found a high permeability flow path. The pressurization was maintained overnight (Figure 42). Immediately before point g (~22 hours after GIT initiation at point b), the $N_2$ tank pressure was 1172 kPa, and the I5 applied pressure had fallen from 63.3 m (point f) to 51.4 m (point g) following a linear trend f-g. The $N_2$ volume that entered into the fracture network between b-g was $\sim 0.43 \text{ m}^3$. Contrary to the BBC5 I4 GIT, a strong response was observed in all isolated intervals immediately after the pressure
was released from the g at point g. g pressure dropped 44.4 m over a 45 minutes period after point g, followed by a 7-minutes duration, slug test like curve, until the static water level was recovered. Therefore, the injection line entering on the top of the interval facilitated the expulsion of the gas phase from the fracture network after the pressure was released from the injection line.

![Graph showing pressure release phase](image)

**Figure 42. BBC5 I5 GIT including the pressure release phase.**

The BBC6 GIT used a straddle packer system (Figure 43). In this case, the 1.67 m long isolated interval was a perforated, 5.1 cm ID brass pipe connected to solid pipe through the upper and lower packers. Below the bottom packer, the pipe was capped. The top packer was connected to 5.1 cm ID threaded aluminum pipe that extended above the top of casing.
Three pressure transducers (RocTest™, Plattsburgh NY; vibrating wire, 0 - 517.1 kPa nominal range, 200% full scale over range, frequency 1 reading / 3s, and accuracy of 0.5% full scale) measured pressures above, below, and within the isolated interval. The top transducer was lashed to the outside of the aluminum pipe and located above the top packer. The bottom transducer ran through the two packers and was lashed to the bottom cap below the lower packer. The central transducer was located in the isolated interval, outside the
perforated pipe. This transducer recorded the pressure in the isolated interval during hydraulic testing. An additional transducer (same specifications as the others, but 0 – 172.4 kPa, nominal range) was set inside the aluminum pipe, 13.4 m below the top of casing to get more precise water column variation measurements inside the aluminum pipe during the GIT. The cable of this transducer passed through a 2.54 cm Tee-fitting which capped the aluminum pipe. The Tee-fitting also held a 3.175 mm diameter N₂ tubing for pressurizing the isolated interval and a 2.54 cm diameter quick-release ball valve to facilitate a near-instantaneous gas pressure release.

Before the BBC6 GIT, the static water level in the isolated interval was 0.79 m below top of casing. The top of the isolated interval was 39.6 m below top of casing, thus \( W_{ci} = (39.6 - 0.79) \) = 38.8 m. Initial N₂ tank pressure was 13790 kPa. For 47 minutes, the injection line was pressurized in 68.9 kPa (7.0 m of H₂O) steps using the N₂ tank regulator (Figure 44). The first two pressurization steps (\( H_{applied}=7.0 \) and 14.1 m) generated the signals typical of a pressurization phase of a slug test: a sudden peak pressure followed by a logarithmic recovery to static conditions. The same trend was observed in the isolated interval transducer when the third step was applied (\( H_{applied}=21.1 \) m). Nevertheless, in this case, the aluminum pipe transducer signal continuously increased because the transducer depth (13.4 m below top of casing) was less than \( H_{applied} \). Thus, the water level inside the aluminum pipe was below the transducer, which was measuring the N₂ pressure increase inside the aluminum pipe. The subsequent two pressurization steps (\( H_{applied}=28.1 \) and 35.1 m) exhibited similar curves.
The GIT started when a N$_2$ pressure of 413.7 kPa ($H_{\text{applied}} = 42.2$ m, $H_{\text{GIT}} = (42.2 - 38.8$ m) = 3.4 m) was applied. At this pressure, the N$_2$ had enough energy to entirely displace water from the isolated interval 39.6 – 41.3 m, and to start to invade the fracture network along the intersecting fracture. A pressure increment less than the interval length ($H_{\text{GIT}} < 1.67$m) would have allowed determining the depth of the upper most hydraulically active fracture(s).

Continuous N$_2$ flow was heard exiting the N$_2$ tank. The aluminum pipe transducer signal was lost for $H_{\text{applied}}$ larger than 42 m, because the applied pressure exceeded the maximum range of the transducer.
When the N$_2$ pressure was increased to 482.6 kPa ($H_{\text{applied}} = 49.2$ m, $H_{\text{GIT}} = 10.4$ m), the isolated interval pressure increased to 42.5 m. This indicated that the excess pressure energy (49.2-42.5m) = 6.7m was driving N$_2$ into the fracture network through the fracture intersecting this interval. The N$_2$ pressure was then increased to 551.6 kPa ($H_{\text{applied}} = 56.2$ m, $H_{\text{GIT}} = 17.4$ m). Thereafter, the pressure history curve was very similar to portion d-g of the BBC5 GITs (Figures 37 and 41). The pressure in the BBC6 interval increased from point d until it reached a maximum of 44.6 m at point e ($H_{b}=(44.6-39.4m)=5.2$ m). Point e was interpreted as the time when the N$_2$ invading phase reached a fracture network zone with enhanced permeability (possibly the weathered bedrock). The quick pressure decrease e-f was associated with the sudden volume surge of the N$_2$ phase. After point f, the low slope pressure decrease was a consequence of the continuing flow of the N$_2$ phase into the fracture network.

The N$_2$ pressure was released at point g, by opening the quick-release valve. Prior that, the N$_2$ regulator pressure was 4137 kPa. In contrast to the eight hour recovery period observed after pressure release in the BBC5 15 GIT (Figure 39), the BBC6 GIT showed a near instantaneous pressure release from the isolated interval, followed by a recovery typical of a slug test (Figure 45). The five-minute period with zero pressure recorded in the isolated interval immediately after pressure release (point g), indicated that the reentering water was below the central transducer. The aluminum pipe transducer started to record pressures larger than zero 23 min after the N$_2$ pressure release, indicating the instant when the water level inside the injection line recovered to the depth of
13.4 m below top of casing. Static conditions returned 55 minutes after pressure release. The N₂ volume that entered into the fracture network during the GIT in BBC6 was ~ 0.45 m³.

Figure 45. The BBC6 GIT, including the pressure release phase.

The BBC6 GIT history was clearly reproduced in the isolated interval I3 of BBC5 (36.8 – 42.3 m) located 7.6 m from BBC6 (Figure 46). The other four BBC5 isolated intervals and the top and bottom intervals in BBC6 recorded damped pressure responses on the order of 60 cm. On a site-wide scale, pressure variations less than 3 cm were detected in open borehole fractured bedrock wells BBC1 and BBC3 (located 47.2 m and 70.7 m, respectively, from BBC6) (Figure 47).
Figure 46. Monitoring well isolated interval pressure variations due to the BBC6 GIT.
Figure 47. Monitoring Well (MW) open borehole pressure variations (right-hand axis) to the BBC6 GIT (left-hand axis). Wells BBC1 and BBC3 are located 47.2 m and 70.7 m from BBC6, respectively.

The data indicated that the intervals 39.6 – 41.1m and 36.9 – 42.3m in BBC6 and BBC5, respectively, most likely intersect the same fracture (Figure 48). This was supported by the coincident shapes of pressure signals observed in both intervals during the GIT. The other BBC5 isolated intervals, as well as the top and bottom isolated intervals in BBC6, must be hydraulically interconnected with this fracture through the fracture network, as suggested by their damped responses during the GIT. The BBC3 response was a narrow 30-minute peak coincident with the BBC6 pressure signals; indicating a pressure increase in the fracture network connection BBC6-BBC3 during the GIT.
pressurization phase, and a recovery of ambient pressure synchronized with the GIT pressure release phase (Figure 47). This was interpreted as an efficient hydraulic connection between BBC6 and BBC3. The BBC1 response, on the contrary, was a two hour, wide bell-shaped pressure variation (Figure 47), suggesting that at the time of GIT pressure release, some N2 was trapped in the fracture zone around BBC1 and slowly relocated into the fracture network.

Figure 48. BBC6 GIT interpretation.
FUTURE RESEARCH

The effect of the GIT overpressure in the field formation stress around the tested interval must be addressed to avoid irreversible modification of the hydrogeologic environment after conducting a GIT. The fracture aperture modification during the discussed GITs was negligible. The maximum overpressures ($H_{\text{GIT}} \times$ specific weight of water) generated in the intersecting fracture zone were 72 kPa and 170 kPa during the BBC5 and BBC6 GITs, respectively. In the corresponding isolated intervals, the static water pressures ($W_d \times$ specific weight of water) were 418 kPa and 388 kPa. The total stress existing in the isolated intervals (interval depth $\times$ specific weight of sediment or rock $\sim 1.8 \times 9.8$ kN/m$^3$) under ambient conditions were 753 kPa and 700 kPa, respectively. Thus, the GIT overpressure represented 6% and 15% of the prevailing pressure in the fractures under normal conditions.

The GIT could be conducted using compressed air instead of $N_2$. Nevertheless, in sites where microbiologic studies are under progress, air injection must be avoided because it could drastically change the microbial activity. In some field sites, the GIT can be inappropriate because of the high disruption of the natural conditions during the gas invasion and gas release phases.

The development of GIT analytical models will greatly improve the test’s applicability for fracture network characterization. Any GIT model should be based on the GIT pressurization and release pulses. If the pressure response is linear when shown in the logarithmic scale (Figure 49), it suggests that simplified
theoretical models could be developed for overall fracture network permeability estimates.

Figure 49. BBC5 I4 GIT signal on logarithmic scales.

CONCLUSIONS

A GIT is a field technique for the characterization of hydraulic connections in a fracture network. During the test, an isolated interval of a well completed in a fractured bedrock formation is pressurized using an inert gas until $H_{\text{applied}}$ is larger than the length of the static water column for the interval ($W_c$). This forces gas into fractures intersecting the isolated interval. The energy available for the gas migration is $H_{\text{GIT}} = (H_{\text{applied}} - W_c)$. Interpretation of the pressure data is greatly assisted by responses in adjacent monitoring wells because the gas has a higher mobility and buoyancy than the liquid phase into the fracture network.
GITs conducted at isolated intervals in BBC5 and BBC6 revealed important information about the fracture network in the competent rock. Fracture network hydraulic connections were detected > 120m away from the wells (which were 7.6 m distant from each other). The BBC5 l4 GIT used a 3.175 mm-diameter injection line, situated at the bottom of the isolated interval. This configuration was useful in determining the depth of the hydraulically active fractured zone intersecting the isolated interval by observing the maximum pressure increase ($H_b$). It also caused ~ 0.27 m$^3$ of N$_2$ to be trapped in the fracture network, affecting the tested well signals for 8 hours after the GIT started. The BBC5 l5 GIT (3.175 mm-diameter injection line) and the BBC6 GIT (5.1cm-diameter injection line), used injection lines located at the top of the isolated interval. Approximately 0.43 and 0.45 m$^3$ of N$_2$, respectively, were injected into the fracture network during the pressurization phase and later released back through the injection line in a nearly instantaneous way. This configuration can provide a determination of the depth of the most hydraulically active fracture(s), when fine pressure increment steps are used.

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REFERENCES


CHAPTER 5

HYTESTS: A NUMERICAL MODEL FOR HYDROGEOLOGIC PARAMETER ESTIMATION
ABSTRACT

HyTests is a JAVA application used to aid the interpretation of groundwater well hydraulic test field data. It is a tool for hydraulic evaluation of a formation in terms of: hydrogeologic units (confined, semiconfined, and unconfined behavior), hydraulic parameters (hydraulic conductivity or transmissivity and storativity), and boundary conditions in the test well and at the external border (impermeable or constant head boundary). HyTests is a 1D finite-difference radial-flow model designed for pumping test and slug tests interpretation in homogeneous or radially heterogeneous formations. HyTests is a direct model, which predicts the drawdowns in monitoring well, and statistically compares them with observed data. The input data can be interactively updated until a satisfactory fit is obtained. HyTests includes several field conditions that are not addressed by conventional methods. HyTests was successfully validated against synthetic and field data hydraulic tests reported in the literature. HyTests was used extensively to analyze pumping test and slug test field data from 5 wells completed in a metamorphic fractured bedrock formation and allowed a consistent interpretation of the hydraulic parameters for the site. HyTests can be downloaded at http://www.unh.edu/erg/bbc.
INTRODUCTION

Theis (1939) developed the first analytical method for confined formation pumping test data analysis. Hantush (1966) included leakage effects in semi-confined formations. Papadopoulos et al. (1967) considered the well bore storage of the test well. Newman and Witherspoon (1972) developed an analytical method for unconfined formations considering delayed yield. All of these methods estimate hydraulic conductivity (K) and when field data is available in one or more monitoring wells, the storativity can also be estimated.

Cooper et al. (1967) developed an analytical method for slug test data by solving the groundwater flow differential equation for the test well. The Cooper method estimates transmissivity (T) in the small scale around the test well. In principle, it also estimates storage coefficient (S), but with little accuracy because it only uses test well data.

Several limitations of these analytical methods prevent their use for quantitative analysis of hydraulic tests (pumping tests and slug tests) in fractured bedrock formations to estimate hydraulic parameters. This is because the methods assume homogeneity: a hypothesis clearly inappropriate for many fractured rock systems. The methods also do not allow for the possibility of non-linear flow in the vicinity of the test well during a hydraulic test. In addition, they assume static water level conditions exist before the initiation of the hydraulic test. However, when testing tight formations it is common that the hydraulic test starts under dynamic conditions (i.e., non-equilibrium). Pumping test analytical methods require constant flowrate (Q) throughout the duration of each pumping
step, which is difficult to maintain under field conditions, especially in tight formations. Lastly, many analytical solutions cannot address the effects of precipitation events, which can significantly affect the field data, especially during long term pumping tests.

HyTests is designed to address most of the constraints of the existing analytical methods. It works as a finite difference direct model that solves the groundwater flow differential equation at discrete distances from the test well (where the pumping test or slug test is conducted) for a selected set of input values of hydraulic parameters and boundary conditions. These input parameters can be iteratively modified until the model responses match hydraulic test field data. HyTests was developed as part of the hydraulic characterization of a fractured bedrock metamorphic formation that is contaminated with TCE and its progeny (Pulido et al., 2003).

**NUMERICAL MODEL**

Any numerical or analytical hydraulic test two-dimensional model based on Darcy's Law, solves the transient, saturated groundwater flow differential equation:

\[ \frac{\partial}{\partial x} \left[ T_x \left( \frac{\partial s}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ T_y \left( \frac{\partial s}{\partial y} \right) \right] = S \frac{\partial s}{\partial t} + q \]

(1)

Where: \( s \) is drawdown [m]; \( T_x \) and \( T_y \) are the components of transmissivity (T [m²/s]) in the x and y directions, respectively; \( t \) is elapsed time since initiation of the hydraulic test; \( S \) is the dimensionless storage parameter (storage
coefficient or specific yield) of the formation; and \( q \) [m/s] is the inflow per unit area representing water entering the system at the point \((x, y)\). In general, \( h \), \( T \), \( S \), and \( q \) can vary at each point \((x, y)\) of the formation.

When radial symmetry exists, Equation (1) can be rewritten in polar coordinates at any distance \( r \) from a test well, to obtain the one-dimensional (1D), radial, groundwater flow differential equation:

\[
\frac{\partial}{\partial r} \left( r \frac{\partial S}{\partial r} \right) + \frac{T}{r} \frac{\partial S}{\partial r} = S \frac{\partial S}{\partial t} + q(r,t)
\]

HyTests employs the finite-difference approach proposed by Rushton (1979): the hydrogeologic formation is represented as a set of concentric cylinders around the test well (Figure 50). The radial groundwater flow finite-difference equation is obtained from Equation (2) by applying a mass balance to each cylinder:

\[
\frac{s_{n+1,t} + \Delta t - s_{n,t} + \Delta t}{H_n} + \frac{s_{n-1,t} + \Delta t - s_{n,t} + \Delta t}{H_{n-1}} = \frac{s_{n,t} + \Delta t - s_{n,t}}{TR_n} + q
\]

\[
H_n = \frac{\Delta a^2}{B_n K_n}
\]

\[
TR_n = \frac{\Delta t}{S_n r_n^2}
\]

where: \( s_{n,t} \) is the drawdown in node \( n \) at time \( t \); \( q \) is the inflow per unit area in radius \( r_n \) at time \( t \); and \( K_n \) and \( S_n \) are the hydraulic conductivity and storativity.
at node \( n \), respectively. \( \Delta a = \ln(r) \) is introduced in Equation (4) to allow node spacing to increase logarithmically from the test well. \( H_n \) and \( TR_n \) are the flow and temporal hydraulic resistances, respectively; they are convenient idealizations that relate Equation (3) to an electrical circuit, using the physical analogy between Darcy's and Ohm's Laws (Figure 51).

**Figure 50. Radial finite difference mass balance.**

**Figure 51. Analogous electric circuit to the radial finite difference ground water flow model.** The mass balance in node \( n \) at time \( t+\Delta t \) is equivalent to
a current balance in node n surrounded by electric resistances $H_n$ and $TR_n$, which represent transmissivity and storativity, respectively. Given the drawdown in each node n at any time t, and the hydraulic parameter set required to compute the hydraulic resistances for each cylinder, Equation (3) can be written for n unknown drawdowns for the next time step ($\Delta t$). HyTests uses the Gaussian elimination method for solving this system of linear equations (Burden, 1997).

Impermeable or constant level boundary conditions at the node N, located at the maximum model radius, are specified by setting $H_N=0$, or $s_N=0$, respectively. The flowrate $Q(t)$ extracted from the test well (n=0), and the water stored in the test well casing, are simulated by modifying $H_0$, and $TR_0$:

$$H_0 = \frac{-Q}{2 \pi r^2 \Delta a}$$  \hspace{1cm} (6)

$$TR_0 = \frac{2 \Delta t \Delta a}{r_{casing}^2}$$  \hspace{1cm} (7)

Turbulent flow in any node n, is modeled by modifying $H_n$:

$$H_n = H_a \left(1 + F \left(\frac{V}{V_i}\right)^m\right)$$  \hspace{1cm} (8)

Where: F and m are the turbulent coefficient and exponent, respectively; $V$ is the average horizontal velocity in the test well at the current time; $V_i$ is the initial horizontal velocity in the test well. In this way well resistance (well loss) can be incorporated into the model.

Leakage from a semi-confining stratum at any node n is represented by:
where: $K'$ and $B'$ are the hydraulic conductivity and thickness of the aquitard, respectively (Marsily 1986).

HyTests can accommodate radial heterogeneous conditions; the hydraulic parameter values can vary with the distance from the test well, but are constant for a specific distance at any orientation angle. This is a useful first approximation to hydraulic test analyses on heterogeneous formations, such as fractured bedrock formations.

HyTests is a direct solution model for estimation of $T$ and $S$. Meaning that the user specifies values for the hydraulic parameters, and the model predicts the hydraulic head (drawdown) around the test well at different times. $T$ and $S$ modified until the computed heads adequately match the observed heads. Several hydrogeologic conditions are included in the input hydraulic parameter set (Figure 52). HyTests solves Equation (3) to yield spatial and temporal head data. This synthetically generated hydraulic test curve is statistically compared to field data in order to evaluate goodness-of-fit. Although automatic optimization techniques can be implemented, iterative use of HyTests informs the user of the overall influence of each parameter in the hydraulic test performance. A quick start guide for HyTests usage is included as an appendix.
VALIDATION

Initially, HyTests was validated against analytical solutions to Equation (1). For a confined aquifer, Theis (1935) stated:

\[ s = \frac{Q W(u)}{4 \pi T} \]  
\[ u = \frac{r^2 S}{4 T t} \]  
\[ W(u) = \int_{u}^{\infty} \frac{e^{-r}}{r} \, dr \]  

(10)

Rusthon (1979) selected a convenient hydraulic parameter set to generate synthetic drawdown time series from Equation (10). If \( r_{\text{well}} = r_{\text{casing}} = 1\times10^{-5} \text{ m} \), \( r_{\text{model}} = 1\times10^{-5} \text{ m} \), \( K = 1\times10^{-8} \text{ m/day} \), and \( B = 2.5\times10^{-5} \text{ m} \), \( S = 1\times10^{-2} \), and \( Q = \pi \times 1\times10^{-2} \text{ m}^3/\text{day} \) for 1E6 days, this equation simplifies to:

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\[ s = W(u); \quad u = \frac{r^2}{t} \]  

Clearly, this hydraulic parameter set is not physically realistic, but it does subscribe to the mathematical domain, and therefore allows the generation of synthetic \( s \) data directly from tables of \( u \) vs. \( W(u) \) (Walton, 1970).

\( s \) predictions in the test well (modeled as a monitoring well located 1 mm away from the center of the well and in a monitoring well located 1 m from the test well, were obtained with HyTests using Rushton's hydraulic parameter set as the input data. In this case, the "field \( s \) values" were the \( s(t) \) synthetic values predicted with Equation (11).

HyTests successfully reproduced the analytical values. It matched the Theis analytical solution with an MPE < 0.4% for the test well and monitoring well (Figure 53). The same hydraulic parameter set was compared to the Hantush analytical solution for semi-confined formations; just two more parameters were required for this comparison: the aquitard hydraulic conductivity (\( K' = 1.5625 \) m/day) and the aquitard thickness (\( B' = 625 \) m). For this case, the MPE was less than 0.8% for the test well and monitoring well (Figure 54). The same hydraulic parameter set was also used to compare the HyTests results to the Papadopoulos analytical solution for large diameter wells (\( r_{\text{well}} = 1 \) m). In this case, the MPE was 0.2% (Figure 55).
Figure 53. HyTests validation against the Theis (1939) analytical solution for confined formations, and their respective Drawdown Percent Error (DPE) distribution (DPE is defined in Equation A4). Hydraulic parameter set: $r_{\text{well}} = r_{\text{casing}} = 1E^{-5}$ m, $r_{\text{model}} = 1E^{-5}$ m, $K = 1E^{-8}$ m/day, and $B = 2.5E^{5}$ m, $S = 1E^{-2}$, and $Q = \pi \times 1E^{-2}$ m$^3$/day for 1E6 days. Test Well (TW) is represented as a Monitoring Well located 0.001 m from center of pumping well. Test well Mean Percent Error (MPE) = 0.089 +/- 0.05 %. Monitoring well MPE = 0.33 +/- 0.14 %. n = 60.
Figure 54. HyTests validation against the Hantush (1966) analytical solution for semi-confined formations and their respective DPE distribution. Hydraulic parameter set: \( r_w = r_c = 1E-5 \text{ m}, r_{model} = 1E5 \text{ m}, K = 1E-8 \text{ m/day}, B = 2.5E5 \text{ m}, S = 1E-2, K' = 1.5625 \text{ m/day}, B' = 625 \text{ m}, \) and \( Q = \pi \times 1E-2 \text{ m}^3/\text{day} \) for 1E6 days. Test Well (TW) is represented as a monitoring well located 0.01 m from center of pumping well; MPE=0.3+/-0.2%, \( n = 11 \). Monitoring Well located 0.5m from the test well; MPE = 0.8+/-0.5%. \( n = 5 \).
Figure 55. HyTests validation against the Papadopoulos (1967) analytical solution for large diameter wells in confined formations and their respective DPE distribution. Hydraulic parameter set: $r_{\text{well}} = r_{\text{casing}} = 1$ m, $r_{\text{model}} = 1E5$ m, $K = 1E-8$ m/day, $B = 2.5E5$ m, $S = 1E-2$, $r_{\text{well}} = 1$ m, and $Q = \pi \times 1E-2$ m$^3$/day for 1E6 days. MPE=0.22+/−0.19 %. n = 28.

HyTests exceeded precision and accuracy of Theis’ method when it was applied to a pumping test field data set analyzed by Walton (1970) and to a slug test field data set used by Cooper et al. (1967). Walton (1970) analyzed a pumping test with a monitoring well using the Theis method, obtaining an MPE=2.1+/−1.0 %. HyTests matched the same field data with a MPE of 1.02+/−0.58 % (Figure 56). The Cooper and HyTests methods fitted the slug test field data with MPEs of 2.05+/−1.06 % and 1.65+/−1.32 %, respectively (Figure 57).
Figure 56. HyTests validation against the Theis (1939) method for a pumping test analyzed in Walton (1970), and their respective DPE distribution. Hydraulic parameter set: $r_{well} = r_{casing} = 2.5 \times 10^{-2}$ m, $r_{model}=1 \times 10^4$ m, $K=22.9$ m/day, $B = 5.48$ m, $S=1.8 \times 10^{-5}$, and $Q = 1198$ m$^3$/day for 500 minutes. Monitoring well located 251 m from the test well. MPE=1.02±0.58 %.

Theis method hydraulic parameter estimate are: $K=22.87$ m/day, $B = 5.48$m, $S=2 \times 10^{-5}$. MPE=2.1±1.0 %, $n = 22$.
Figure 57. HyTests validation against the Cooper (1967) method for a slug test analyzed in Cooper et al. (1967) and their respective DPE distribution. Hydraulic parameter set: $r_{well} = r_{casing} = 0.152 \text{ m}$, $r_{model} = 10 \text{ m}$, $K = 0.450 \text{ m/day}$, $B = 98 \text{ m}$, and $S = 3\times10^{-3}$. MPE = 1.65$\pm$1.32%. Cooper method hydraulic parameter estimate are: $K = 0.467 \text{ m/day}$, $B = 98 \text{ m}$, $S = 1\times10^{-3}$. MPE = 2.05$\pm$1.06%. $n = 21$.

**FIELD EXAMPLE**

The complete set of hydraulic tests analyzed by HyTests in a BBC fractured bedrock formation is presented in Pulido et al. (2003). Two selected pumping tests and slug tests conducted in the same isolated well interval are presented here to demonstrate some of HyTests capabilities.
A variable flowrate pumping test and a slug test were conducted in an isolated interval of a well completed in the competent fractured bedrock; these tests were analyzed using HyTests. Both the pumping test and slug test data provided the same hydraulic parameter estimate (Figure 58). The high pumping test MPE (8.16 +/- 4.16 %) was expected because of the highly scattered drawdown field data. HyTests allowed representing the flow in the formation with a two-zone radial model, which was required for matching the field data.

![Pumping Test (PT) and Slug Test (ST) hydraulic parameter estimation by HyTests. A pumping test and a slug test were conducted on well BBC6 fractured bedrock interval (34.36-36.04 m) generated the same hydraulic parameter set: \( r_{\text{well}} = 0.00762 \text{ m}, r_{\text{casing}} = 0.0254 \text{ m}, r_{\text{model}} = 1000 \text{ m}, \) inner zone radius 3 m, \( K = 0.0605 \text{ m/day}; \) outer zone \( K = 8.64 \text{ m/day}. \) For both zones \( B = 1.67 \text{ m}. \) Pumping test MPE = 8.16+/−4.06 %; slug test MPE = 3.14+/−2.01.](image)

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The pressure responses in an isolated interval monitoring well helped to reliably estimate S and refine the heterogeneous model used to analyze the test well data (Figure 59). Significantly, HyTests was used to estimate T and S from slug test monitoring well signals. The hydraulic parameter compatibility between the pumping tests and slug tests estimates demonstrated HyTests' versatility to reproduce different hydraulic tests.

![Graph](image)

**Figure 59.** Pumping Test (PT) and Slug Test (ST) hydraulic parameter estimation from monitoring well isolated interval responses by HyTests. BBC4 interval (43.5 – 45.08 m) responses to a pumping test and a slug test conducted in on well BBC6 interval (34.36-36.04 m). A three zone radial heterogeneous model was required for pumping test and slug test fitting: \( r_{\text{well}}=0.00762 \text{ m} \), \( r_{\text{casing}}=0.0254 \text{ m} \), \( r_{\text{model}}=1000 \text{ m} \). Inner zone radius 3 m (pumping test), and 2 m (slug test), \( K=0.0605 \text{ m/day} \). Central zone radius 10 m; \( K=0.605 \text{ m/day} \). Outer zone \( K=8.64 \text{ m/day} \). For all zones \( S = 1E^{-4} \), \( B = 1.67 \text{ m} \). Pumping test MPE = 8.16+/−4.06 %; slug test MPE = 8.25+/−7.71.

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HYTESTS USAGE

Using HyTests to select an hydraulic parameter set that matches hydraulic test field data is an iterative process that is dependent on both the user's understanding of the meaning and impact of each hydraulic parameter in Equation (1), and the hydrogeological setting under consideration. Initial estimates for $T$ and $S$ can be obtained from analytical type curve solutions. Spreadsheets were developed to optimize the required procedures involved in the type curve methods. These are available as part of the downloadable HyTests installation package. Nevertheless, when starting with any predefined set, a reasonable initial fit may be achieved in only a few iterations, provided some basic hydrogeological criteria are applied when modifying the hydraulic parameter sets.

$T$ is the most sensitive parameter in the model. It determines the magnitude of modeled drawdowns. The order of magnitude of $S$ greatly influences the slope of the temporal drawdown curve, even in a single well pumping test. Boundary effects are indicated by sudden changes in the field data trend in the later times of a pumping test. Turbulent flow near the test well may be inferred from the Reynolds number or when a satisfactory fit for the pumping phase is lost during the recovery phase of a multi-step pumping test. The type of formation influences the shape of the field test drawdown curve and provides clues as to whether additional parameters must be considered (e.g., infiltration recharge, or aquitard properties).
If the model still does not fit the data, heterogeneous flow should be suspected and the HyTests' hydraulic resistance in one or more nodes can be modified (Equation 8). Caution should be exercised when increasing the degree of heterogeneity of the model. The more complex the model, the larger the number of parameters that need to be estimated. The accuracy of each data set can only be guaranteed when field data are available for monitoring wells.

A homogeneous model has low non-uniqueness problems, because the shape of the drawdown curve is rigid. When a heterogeneous model is used, it may be possible to find several node set combinations that match the field data. The correct set can be identified if there are additional data, such as monitoring well readings. For example, when analyzing a single well hydraulic test, the maximum recommended degree of heterogeneity must be represented by a two-zone radial model. Certainly, three or more zones would also fit the field data, but the accuracy of each node set in the case of a single well hydraulic test is highly questionable and can only be increased by utilizing data from additional monitoring wells.

**FUTURE RESEARCH**

HyTests will be extended by adding models for the analyses of hydraulic tests in formations of increasing geological/geometric complexity. A 2D finite element horizontally heterogeneous model has already been developed for HyTests following the approach explained by Istok (1989), and is currently under validation tests. This model could be the basis for a fracture network model.
which will analyze discrete fractures as interconnected disks in 3D space (Adler et al., 1999). A layered heterogeneous model will allow hydraulic test interpretation for stratified porous-media formations. A 3D finite element model will include 3D spatial variability of the hydraulic parameters.

CONCLUSIONS

HyTests simulates the drawdown-time series from hydraulic parameter sets. Simulated results are graphically displayed, and are statistically compared with hydraulic test field data. The hydraulic parameter values can be interactively updated until the simulated drawdown-time series achieve a satisfactory fit to the hydraulic test field data, accounting for actual hydraulic test conditions (e.g., radial dependence of hydraulic parameters, variable-flowrate pumping tests, and well hydraulic losses). HyTests was successfully validated and calibrated with data from the Theis, Hantush, and Papadopulos methods (pumping tests) and the Cooper method (slug tests). The accuracy of the estimated hydraulic parameter set depends on the quality and quantity of field data. Monitoring well data reduce non-uniqueness effects and increase reliability of heterogeneous models.

ACKNOWLEDGEMENTS

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CHAPTER 6

DEVELOPING A CONCEPTUAL HYDROGEOLOGICAL MODEL FOR A FRACTURED BEDROCK FORMATION
A conceptual hydrogeological model (CHM) was developed for a metamorphic fractured bedrock formation contaminated with TCE and its progeny. This formation is located in Portsmouth, NH. Hydrologic inputs included precipitation, tides, and two years of water level data from monitoring wells. The hydraulic characterization of the site included: a 15 day site-scale pumping test; 10 straddle-packer pumping tests, more than 200 slug tests at isolated depth intervals in wells; and groundwater level monitoring during drilling. The more relevant CHM elements identified were: 1) the fractured bedrock formation was an interconnected fracture network hydraulically connected with the weathered bedrock and the overburden strata. 2) The hydraulic parameters of the fractured bedrock formation, identified by hydraulic tests, were best represented by a radial heterogeneous model. 3) The fractured bedrock formation in the site was under semiconfined conditions because of the overburden strata. 4) The fracture network at the site was an active component of the regional fractured bedrock formation groundwater flow. 5) The regional fractured bedrock formation recharge zone was located to the northwest of the site; the groundwater flow in the site was toward the east, and discharged to the ocean through fractured bedrock formation outcrops.
INTRODUCTION

The field site for this research was located at Pease International Tradeport, Portsmouth, NH, (formerly Pease Air Force Base). More specifically, in Site 32, where an underground storage tank received waste trichloroethylene (TCE) from 1956 to 1968 (Figure 60). In 1983, Site 32 was identified as a potential source for subsurface contamination and a remedial investigation/feasibility study was initiated. Soil and groundwater contaminated with TCE was discovered in 1988, when the tank was removed. The record of decision specified: removal of contaminated soil; construction of seven extraction wells completed in the overburden and weathered bedrock strata (1991 to 1995); isolation of the overburden source area with a vertical (sheet pile) barrier built in 1996; groundwater pumping with treatment from within and below the sheet pile (active since 1997); and continuing long-term groundwater and treatment system monitoring (USAF 1997a).

Since 1999, the Bedrock Bioremediation Center (BBC) at the University of New Hampshire has been studying the fractured bedrock formation underlying the overburden and weathered bedrock strata at Site 32. The primary objective of the BBC is to isolate fracture zones and determine the nature of biodegradation of TCE and its progeny occurring within them. The development of a Conceptual Hydrogeological Model (CHM) was required to plan and conduct future evaluations of in situ biodegradation methods and technologies in the fractured bedrock at the site. The CHM included the identification of fractured bedrock formation hydrogeological features, such as well interconnectivity,
hydrogeological parameters, lateral extension of the fracture network, recharge mechanisms, and boundary conditions.

Figure 60. Location Map of Site 32 (USAF, 1997b).
HYDROGEOLOGICAL HYPOTHESIS

A CHM is a simplified representation of a hydrogeologic formation, including hydro-stratigraphic units, hydrological inputs, hydraulic parameter estimates, boundary conditions, and flow directions. A CHM is developed by integrating geologic, geophysical, hydrologic, and water chemistry information; it improves the hydrogeologic understanding of the site, assists flow and transport field experiments, and constitutes the hypothesis for mathematical models, which can be used for hydrogeological predictions. A CHM is usually summarized in a scheme representing the more relevant hydrogeological features (Anderson and Woessner, 1992).

Five hydro-stratigraphic units were identified during the feasibility study conducted at Site 32: upper sand, marine clay and silt, lower sand, and glacial till, weathered bedrock, and the fractured bedrock (Figure 61). The marine clay and silt was identified as an aquitard between the upper sand and the lower sand/glacial till. The estimated hydraulic conductivity (K) in the overburden was 3E-2, 8.5E-4, and (1.2E-2 to 1.6E-1) m/day, for the upper sand, marine clay and silt, and lower sand/glacial till units, respectively. The estimated K in the weathered bedrock and fractured bedrock was 6.2E-1 and 9.1E-3 m/day, respectively (USAF 1997a).

The potentiometric contours in the upper sand, lower sand/glacial till, weathered bedrock, and fractured bedrock were obtained before and after
Figure 61. Geologic cross section of Site 32 (USAF, 1997b).
startup pumping from the sheet pile (Figures 62 and 63, respectively). The groundwater flow across the site remained consistently eastward. Under pumping conditions an upward vertical gradient from the fractured bedrock to the weathered bedrock and the lower sand/glacial till was observed, preventing the spreading of the dissolved plume into the fractured bedrock. The contaminated fractured bedrock was excluded from the remedial action because of its technical impracticability (USAF 1997a).

**GEOLOGY**

Five (BBC) wells were drilled at the site into the competent fractured bedrock, with final depths ranging from 20 to 61 m below ground surface. According to the drilling logs for each BBC well, the overburden thickness ranges from 7 to 18 m and consists of clay, sand, and glacial till. The upper bedrock surface is highly weathered, to depths of 3 to 10 m. The weathered bedrock overlies the more competent (fractured) bedrock.

The fractured bedrock is part of the Kittery Formation, which consists of altered layers of metasandstone (quartzite) and metashale, predominantly phyllite (Novotny, 1969). The Kittery Formation contains many preserved, tightly folded, sedimentary structures that can be used to interpret stratigraphic sequencing. Abundant outcrops of the Kittery Formation were mapped in the neighboring shores (Figure 64). Jointing and fracturing are common in the Kittery Formation, due to the brittle behavior of the quartzite. The strike and dip at Site 32 are ~ 55° to the northeast and ~ 70-75° to the northwest, respectively.
Figure 62. Potentiometric contours on February 1997, before starting the groundwater extraction system. Measurements in feet. (USAF, 1997b)
Figure 63. Potentiometric contours on March 1997, after starting the groundwater extraction system. Measures in feet. (USAF, 1997b)
The jointing and folding have a northeast-southwest trend. There are abundant diabase dikes, trending to the northeast that intruded into the formation in the late Triassic. The majority of the faults in the formation at the site are sinistral strike-slip faults trending to the northeast-southwest (Rickerich, 1983).

Figure 64. Geologic map of the Great Bay area (Novonty, 1969), and Site 32 location.
Each BBC well was continuously cored in the fractured bedrock with a 10 cm diameter diamond core bit. Examination of the cores revealed open fractures, microfractures, and many mineral veins. These features contain a variety of minerals (e.g., calcite, quartz, and pyrite). Real-time drilling parameters were recorded at wells BBC4, BBC5, and BBC6, including: drill rate, thrust pressure, torque, rotation speed, drilling water pressure, and input/output drilling water flow. Geophysical logging of the boreholes included: video, fluid resistivity, fluid temperature, single point resistivity, spontaneous potential, natural gamma, caliper, normal resistivity, full-waveform sonics, acoustic televiewer, optical televiewer, heat pulse flowmeter, and omni-directional radar (Figure 65). The combined information provided by the lithologies, drilling parameter records, and geophysical logs assisted the selection of intervals within the boreholes to isolate for hydraulic testing.

![Geophysical logs](image)

**Figure 65.** BBC5 selected geophysical logs.
RECHARGE MECHANISMS

The regional fractured bedrock formation potentiometric contours indicated a recharge zone to the northwest of Site 32, discharging to the surrounding shores (Figure 66). The absence of surface bodies of water in the recharge area (i.e., rivers, lakes) indicated that precipitation is the most probable source of recharge, by infiltration through the abundant fracture correlated lineaments ("significant lines in the earth's face", Hobbs (1904)) and outcrops detected in the recharge and discharge zones (Figures 64 and 66).

The BBC monitoring well network for Site 32 was initiated on October 13, 2000. Initially, this network consisted of wells 6013, 6029, and 6075 completed in weathered bedrock, and instrumented with pressure transducers to record water levels each minute. During October 2001, the monitoring network was augmented to include weathered bedrock well 6127 and fractured bedrock wells 6071, BBC1, BBC3, and BBC4. In addition, several overburden and weathered bedrock wells in and around the sheet pile were instrumented during a site-wide pumping test. After BBC5 and BBC6 were completed, they were also incorporated into the monitoring network (Figure 67).
Figure 66. Bedrock potentiometric contours (Roseen et al., 2001) and Fracture correlated lineaments (Dengan and Clark, 2002). Measurements in feet MSL.
Figure 67. Monitoring network location map. Origin at Coordinates 64504 m North, 369865 m E, referred to NH state plane coordinates system.

Figure 68 shows the monitoring well water level variations and the corresponding meteorological data for the year 2000, recorded at the Pease climatological station (PSWC, 2003). BBC3 drilling generated strong signals in the monitoring wells, indicating hydraulic connectivity between fractured bedrock and weathered bedrock wells. In addition, the precipitation events clearly affected the water level in the weathered bedrock wells, suggesting infiltration recharge.
through the northern bedrock outcrops, as discussed below. Similar charts were developed for each instrumented well on a monthly, yearly, and aggregate basis. Water levels were measured from the top of casing (TOC) for each well; therefore, the larger the reported water level value the deeper the piezometric level.

![Graph showing water levels and other data over time](image)

Correlative statistical tests (Pearson test, Dixon and Massey (1983)) were conducted to assess the relationship between monitoring well water levels and: precipitation, temperature, and atmospheric pressure changes (Table 3). 24-hour average values were used for monitoring well water levels and each weather parameter. All data from drilling and hydraulic testing dates were excluded from these data sets in order to focus on ambient relationships. For water level correlation with precipitation, daily water level changes were compared with 24-hour precipitation on the same day. For all monitoring wells except BBC1, water level changes were negatively correlated with precipitation, meaning that the water level increased during precipitation events.

<table>
<thead>
<tr>
<th>Weather Parameter</th>
<th>Monitoring Wells</th>
<th>Weathered</th>
<th>Fractured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of data points</td>
<td>6013 6029 6075</td>
<td>BBC1 BBC3 BBC6 6071</td>
</tr>
<tr>
<td></td>
<td>Pearson's Coefficient Tabulated</td>
<td>303 404 299</td>
<td>221 177 40 256</td>
</tr>
<tr>
<td></td>
<td>Pearson's Coefficient Calculated</td>
<td>0.10 0.10 0.10</td>
<td>0.10 0.17 0.26 0.10</td>
</tr>
<tr>
<td></td>
<td>Are Water Levels (WL) and T correlated?</td>
<td>YES YES YES</td>
<td>YES YES YES YES</td>
</tr>
<tr>
<td></td>
<td>Number of data points</td>
<td>445 576 438</td>
<td>478 400 61 528</td>
</tr>
<tr>
<td></td>
<td>Pearson's Coefficient Tabulated</td>
<td>0.07 0.07 0.07</td>
<td>0.07 0.07 0.21 0.07</td>
</tr>
<tr>
<td></td>
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<td>-0.38 -0.44 -0.41</td>
<td>0.26 -0.44 -0.53 -0.36</td>
</tr>
<tr>
<td></td>
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<td>YES YES YES</td>
<td>YES YES YES YES</td>
</tr>
<tr>
<td></td>
<td>Number of data points</td>
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<td>214 167 24 232</td>
</tr>
<tr>
<td></td>
<td>Pearson's Coefficient Tabulated</td>
<td>0.17 0.10 0.17</td>
<td>0.17 0.17 0.34 0.17</td>
</tr>
<tr>
<td></td>
<td>Pearson's Coefficient Calculated</td>
<td>0.07 0.31 0.24</td>
<td>-0.89 0.29 0.68 0.32</td>
</tr>
<tr>
<td></td>
<td>Are WL changes and AP changes correlated?</td>
<td>NO YES YES</td>
<td>YES YES YES YES</td>
</tr>
</tbody>
</table>
Precipitation days were excluded from the temperature and atmospheric pressure statistical tests to avoid confounding the data (Dixon and Massey, 1983). Depths to water in wells were positively correlated with temperature, meaning that high temperature months (which also are the dry season -July through August) exhibited deeper water levels. Therefore, the local (site) fracture network was hydraulically connected to the larger, more regional fractured bedrock formation: discharging to the ocean even during periods of low recharge. Water level changes between two consecutive days were compared with atmospheric pressure changes between the same consecutive days. In five monitoring wells, water level changes positively correlated with atmospheric pressure changes. As detailed in McWhorter and Sunada (1977), this suggests confined conditions in the formation, because the water level in the monitoring wells is affected by atmospheric pressure changes, but the confining strata prevent such direct influence of the atmospheric pressure changes in underlying regions of the formation. In contrast, wells completed in an unconfined formation exhibit little to no correlation with atmospheric pressure changes. Well 6013 was not statistically correlated with atmospheric pressure changes. Well BBC1 exhibited a different and contrary statistical trend compared to the other monitoring wells for rainfall and atmospheric pressure changes; one possible explanation is because its low permeability could have delayed its response to the daily changes in weather parameters.

Figure 69 shows the environmental trends in monitoring wells during three consecutive days (i.e., no field activity). When there was 4.6 mm of precipitation
during the second day, the water levels in weathered bedrock wells 6127 and 6029 increased in response to the regional infiltration recharge through the northern fractured bedrock outcrops. The water levels in BBC1 and in the five isolated intervals of BBC5 were negatively correlated with tides. All BBC5 intervals, as well as BBC1 water levels, were negatively correlated with tides, whereas weathered bedrock wells 6029 and 6127 were not correlated (Table 4), indicating that the fractured bedrock was hydraulically connected with the ocean, as suggested by the Kittery Formation outcrops in the nearby estuary shores (Figure 64). Any possible tidal effect in the weathered bedrock was through the hydraulic connections with the fractured bedrock.

Figure 69. Groundwater and ocean water level variations on August 4-6, 2003. Tide data for New Castle, NH (NOAA, 2003).
Table 4. Correlation of groundwater and ocean water levels.
(95% level of confidence)

<table>
<thead>
<tr>
<th>Well</th>
<th>Calculated Pearson Coefficient</th>
<th>Are ground water and ocean water levels Correlated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>6029</td>
<td>-0.09</td>
<td>No</td>
</tr>
<tr>
<td>6127</td>
<td>-0.01</td>
<td>No</td>
</tr>
<tr>
<td>BBC1</td>
<td>-0.28</td>
<td>Yes</td>
</tr>
<tr>
<td>BBC3</td>
<td>-0.19</td>
<td>No</td>
</tr>
<tr>
<td>BBC5 I1</td>
<td>-0.33</td>
<td>Yes</td>
</tr>
<tr>
<td>BBC5 I2</td>
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<tr>
<td>BBC5 I3</td>
<td>-0.33</td>
<td>Yes</td>
</tr>
<tr>
<td>BBC5 I4</td>
<td>-0.33</td>
<td>Yes</td>
</tr>
<tr>
<td>BBC5 I5</td>
<td>-0.33</td>
<td>Yes</td>
</tr>
</tbody>
</table>

n=70  Tabulated Pearson Coefficient = 0.2

A site-wide pumping test was conceived to assess the hydraulic connections and vertical gradients between overburden, weathered bedrock, and fractured bedrock units. On October 26, 2001, the sheet pile extraction wells (completed in the overburden and weathered bedrock strata) that had been operating for years were shut down, and the recovery signals from all site wells (overburden, weathered bedrock, and fractured bedrock) were recorded for one week at which time stabilization was achieved (i.e., constant were water levels). On November 2, 2001, the extraction wells were started again, and all the monitoring well signals were recorded until they stabilized. The site-wide hydraulic connection between overburden, weathered bedrock, and fractured
bedrock was confirmed by the drawdown observed in wells representative of each stratum (Figure 70).

*Figure 70. Drawdown curves in selected wells after re-starting pumping from the sheet pile extraction wells.*

Both the steady-state potentiometric contours in the overburden, weathered bedrock, and fractured bedrock before pumping was suspended and after it was reinitiated, showed a downward vertical gradient from the overburden (higher potentiometric value) to the weathered bedrock (lower potentiometric...
value) and an upward vertical gradient from the fractured bedrock to the weathered bedrock (Figure 71). The sheet pile pumping induced local recharge from the overburden and fractured bedrock towards the weathered bedrock.

Figure 71. Steady-state piezometric contours in the overburden, Weathered Bedrock (WB), and Fractured Bedrock Formation (FBF), before suspending pumping from the sheet pile extraction wells (Oct.26/2001, at 1:00 AM), and after restarting pumping (Nov. 03/2001, at 1:00 AM). Measures in ft. Elevations referred to mean sea level.
At the end of the interval when pumping was interrupted (i.e., approximate ambient baseline conditions), the overburden, weathered bedrock, and fractured bedrock units were in near hydraulic equilibrium, resulting in no significant net vertical flow (Figure 72).

Figure 72. Steady-state piezometric contours in the overburden, Weathered Bedrock (WB), and Fractured Bedrock Formation (FBF), before re-starting pumping from the sheet pile extraction wells (November 02/2001, at 1:00 AM). Measures in ft. Elevations referred to mean sea level.
The TCE concentration profiles for each BBC well consistently exhibited a decrease in concentration with depth (Figure 73), indicating that a hydraulic connection exists between overburden, weathered bedrock, and fractured bedrock. The TCE downward gradients were interpreted as the footprints of the DNAPL dissolved plume, which sank into the fractured bedrock, even under upward hydraulic gradient conditions between the fractured bedrock and the weathered bedrock.

![Figure 73. TCE concentration profiles in BBC wells.](image)

FLOW PATTERNS AND BOUNDARY CONDITIONS

A recharge path into the fractured bedrock was evident from the water level responses in the five isolated intervals of BBC5 during a large precipitation
event (3.5 cm of rainfall between 18:00 h and 24:00 h of June 26, 2003, calendar day #177). A vertical gradient in BBC5 from the intermediate interval (13) to the upward and downward extremes was evident (Figure 74). The well responses occurred 8 hours after the precipitation, supporting the recharge hypothesis instead of water level increase due to the gravitational load imposed by the fallen rain itself. In addition, the weight of the 3.5 cm precipitation layer was negligible in comparison with the weight of the more than 10 m thickness of overburden above the fractured bedrock. The water levels increase more than 20 cm, a consequence of the storage coefficient (S), which is defined as the ratio of the volume change in a unit horizontal area of formation to a unit change of piezometric level (Marsily, 1986). However, the water levels in the five isolated intervals at BBC5 increased more than 60 cm and no significant variation in S was detected between BBC wells. Taking into account the fractured bedrock formation cone of depression around the sheet pile (Figure 71), the larger incremental change in the BBC5 water level indicated that the fracture network around the sheet pile was storing the infiltrated water from a larger area of the fractured bedrock formation, through the hydraulically active fractures. Hence, the observed infiltration recharge into the fractured bedrock formation was not local, because of the adverse (upward) vertical gradient, but regional through the interconnected fractures (e.g., fracture intersecting BBC5 13).
The regional fractured bedrock formation potentiometric contours provided evidence of groundwater flow to the east at Site 32, toward the ocean (Figure 66). This was consistent with the baseline site-wide fractured bedrock potentiometric contours, and those measured immediately after start up of the sheet pile groundwater extraction system (Figures 62 and 63). The fractured bedrock groundwater discharge to the ocean has also been confirmed by thermal imagery and conventional groundwater exploration techniques (e.g., piezometric mapping) (Roseen, 2002).
HYDRAULIC PARAMETERS

Even though the primary objectives of the sheet pile pumping test were the assessment of hydraulic connectivity and vertical gradients between hydrogeological units, it also provided for hydraulic parameter estimation for the overburden and weathered bedrock strata. The field data after re-starting pumping from the extraction wells was used for the sheet pile pumping test quantitative analysis. The estimates must be considered only as a first approximation because of the several field conditions departing from the usual assumptions required for pumping test analyses (Walton, 1970). For example, there were seven extraction wells, each one with its own screen length, depth, target strata, and pumping regime (flowrate and schedule). They were conceptualized as one well located in the centroid of the extraction well network, pumping at a constant rate equal to the summation of all individual flowrates. The screen was assumed to intersect the glacial till / lower sand and weathered bedrock units (~5 m thick, overlaid by ~1 m thick marine clay and silt, Figure 61). The hydraulic conductivity \((K)\) and storage coefficient \((S)\) values evaluated from overburden and weathered bedrock monitoring wells were considered as representative of the glacial till / lower sand, and weathered bedrock units, respectively. It must be underscored than the drawdown observed in the fractured bedrock monitoring wells were representative of the hydraulic path between the pumping well and the fractures intersecting these monitoring wells. Thus, the hydraulic unit tested during the sheet pile pumping test was basically
the weathered bedrock unit and the fractures intersecting it. Therefore, the K and S values from fractured bedrock monitoring wells must be considered more representative of the weathered bedrock, than the fractured bedrock unit itself.

The monitoring well signals consistently matched Hantush type curves (Marsily, 1986), indicating that the marine clay and silt unit acted as a semiconfining layer for the lower glacial till / lower sand, weathered bedrock, and fractured bedrock (Table 5).

Table 5. Sheet pile pumping test results.

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<thead>
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<th>Strata</th>
<th>Well</th>
<th>S</th>
<th>T</th>
<th>K</th>
<th>K_{average}</th>
<th>K'</th>
<th>K'_{average}</th>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>m/day</td>
<td>m/day</td>
<td>m/day</td>
<td>m/day</td>
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<td>7.7E-03</td>
<td>0.23 +/- 0.26</td>
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<td>0.0018 +/- 0.00296</td>
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<td>1.0E+00</td>
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<td>9.9E-04</td>
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<td>4.07</td>
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<td>9.9E-04</td>
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<td>5.0E-02</td>
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<td>6.0012 +/- 0.000246</td>
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<td>BBC4 P7</td>
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<td>0.99</td>
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</tbody>
</table>

Aquifer thickness (B)= 5m; Aquitard thickness (m')=1m
Values in shade cells are the same for all rows

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The K values for the overburden (0.23 +/- 0.26 m/day) and the
semiconfining layer (0.0018 +/- 0.00029 m/day) were inside the published ranges
for glacial till / sand and clay / silt, respectively (Marsily, 1986). K estimates were
generally consistent with those previously reported by USAF (1997a). Storage
coefficient (S) values were typical of confined and semiconfined formations.

The hydraulic parameter estimation of the fractured bedrock was
addressed by an extensive set of pumping tests and slug tests conducted in
discrete intervals of the fractured bedrock wells, with monitoring wells in the
weathered bedrock and in the fractured bedrock (open borehole and isolated
intervals). Besides the conventional methods of analyses, they were interpreted
with a numerical radial heterogeneous model that closely matched the field data.
Therefore, they yielded reliable estimates of the hydraulic parameters
representative of the fractured bedrock.

The Transmissivity (T) profiles of each BBC well were obtained using
straddle packer slug tests for isolated interval thickness of B= 1.67 m and B=1.06
m. S was estimated from monitoring well responses to pumping tests and slug
tests in selected intervals of each BBC well. After hydraulic tests were
completed in BBC4 and BBC5, discrete zone isolation systems were installed in
these two wells to prevent cross contamination between the intersected fracture
zones.

The materials and methods used for conducting and analyzing hydraulic
tests in the project are detailed in Pulido et al. (2003b). A radial heterogeneous
model was required to fit the slug test and pumping test field data because they
did not fit to conventional homogeneous models such as Cooper et al. (1967) and Theis (Marsily, 1986). A numeric model named HyTests was developed, validated, and used for hydraulic parameter estimation for all hydraulic tests at each isolated interval (Pulido and Ballestero, 2003).

Slug test field data were fitted to a radial heterogeneous model with mean percent error MPE < 3% (relative to the maximum drawdown during the hydraulic test) for all the BBC wells. The modeled pumping tests generated higher MPE (~10%) due to the more scattered field data. A two-zone radial heterogeneous model was used to analyze single well hydraulic tests. When monitoring well measurable responses were obtained, a three-zone model was required to get compatible T and S estimates for the test well and the monitoring well field data. In general, the inner zone T was two to three orders of magnitude less than the outer zone T. The inner zone T values were interpreted as those of just the fractures that intersected the tested interval. Whereas the outer zone T represented more of a porous media (the overall fractured formation). The estimated radius of the inner zone increased with the initial displacement (Ho) value of the slug test, indicating a larger slug test penetration into the tested formation for larger Ho values.

Figure 75 summarizes the T profiles in the inner zone for each BBC well obtained from 1.67 m interval straddle packer slug tests, and confirmed at selected intervals with pumping tests. Most slug tests had signals just in the test well. In this case, the heterogeneous model was highly sensitive to T and to the radius of the inner zone, but relatively insensitive to T of the outer zone and S

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values. When there were quantifiable monitoring well responses to slug and pumping tests, the sensitivity of the model to these latter parameters significantly increased, and the estimated parameter set for the inner and outer zones generated curves that simultaneously fitted the field data in the test well and monitoring well.

Figure 75. Fractured bedrock formation wells transmissivity profiles. Test length B = 1.67 m. T values were estimated in the inner zone of a radial heterogeneous numeric model (Minimum detectable T = 0.007 m²/day)
BBC1 was found to be the lowest permeability fractured bedrock well: its open borehole never encountered the Kittery formation, but rather was entirely in a dike. The only two intervals with fractures (12.1-13.8 m, and 14.1-15.9 m) resulted in inner zone T values of 0.007 m²/day and 0.05 m²/day, respectively. Both intervals yielded an inner radius of 20 cm, and an outer zone transmissivity of 14.4 m²/day. The tighter of these two BBC1 intervals was used to conduct a single well pumping test, that resulted in the same T estimates as the corresponding slug test (MPE =9.5 +/- 7.93 %). No monitoring well signal was detected during the pumping test, even in well 6029, located only 10 m from BBC1. Based on the hydraulic tests in BBC1 (that were standard for this project), the detection limit for T with the methodology and equipment, was 0.007 m²/day, corresponding to K = 4.2 mm/day (1.67m interval length).

Three sets of slug tests were performed in BBC3. 1.67 m interval slug tests were conducted along the entire depth and 1.06 m interval slug tests were performed only at selected intervals to refine the previous T estimates (Table 6). After that, single packer slug tests were conducted starting with the bottom 1.67 m and increasing the test interval ultimately to the entire well bore (Table 7). The bottom 1.67 m interval was the most permeable and was used to conduct a series of 33 slug tests with increasing Ho values. The estimated T was constant for all Ho, however the inner zone radius continuously increased for Ho larger than 3.7m. Rising and falling slug tests were performed at most of the tested intervals of the three sets, yielding the same results for both. Subsequently,
rising slug tests were used because they resulted in a cleaner signal, and allowed significantly increased Ho values.

Table 6. BBC3 straddle packer slug test results

<table>
<thead>
<tr>
<th>Tested interval thickness = 1.67 m</th>
<th>Tested interval thickness = 1.06 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth [ft]</td>
<td>Ho</td>
</tr>
<tr>
<td>Top Bottom</td>
<td>[m]</td>
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<tr>
<td>17.60 19.28</td>
<td>1.43</td>
</tr>
<tr>
<td>0.48</td>
<td>F</td>
</tr>
<tr>
<td>0.71</td>
<td>F</td>
</tr>
<tr>
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<td>F</td>
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</tr>
<tr>
<td>1.08</td>
<td>R</td>
</tr>
<tr>
<td>21.87 23.55</td>
<td>1.23</td>
</tr>
<tr>
<td>0.31</td>
<td>R</td>
</tr>
<tr>
<td>0.80</td>
<td>F</td>
</tr>
<tr>
<td>0.90</td>
<td>F</td>
</tr>
<tr>
<td>23.39 25.07</td>
<td>1.38</td>
</tr>
<tr>
<td>1.06</td>
<td>R</td>
</tr>
<tr>
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<td>R</td>
</tr>
<tr>
<td>0.91</td>
<td>F</td>
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<tr>
<td>0.34</td>
<td>F</td>
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<tr>
<td>24.61 25.29</td>
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<td>R</td>
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<td>F</td>
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<td>R</td>
</tr>
<tr>
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<td>R</td>
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<tr>
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<tr>
<td>4.33</td>
<td>R</td>
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R=Rising, F=Falling

Outer zone T = 14.4 m²/day for all tests

Inner zone radius = 0.2 m for all tests except (*)=0.30 m, (**)= 0.48 m.

MPE < 3% for all modeled slug test

Values in shaded cells are the same For all rows

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Table 7. BBC3 single packer slug test results.

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<tr>
<th>Top Thickness [m]</th>
<th>Ho [m]</th>
<th>Model</th>
<th>T [m²/day]</th>
<th>Tested Interval: (33.5 - 35.2) m</th>
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<td>0.31R</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3.78R(**)</td>
<td>2.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.93F</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.05F(*)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.68F</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.52F</td>
<td></td>
</tr>
</tbody>
</table>

For all slug test analyzed with heterogeneous models:

Outer zone T = 14.39 m²/day

Inner zone radius = 0.20 m, but (*)=0.30 m, (**)=0.49 m

Values in shaded cells are the same for all rows

R=Rising, F=Falling
The 1.67 m and 1.06 m interval T profiles consistently demonstrated a higher T zone below 29 m. The 4.69 m interval single-packer slug tests resulted in T estimates similar to the summation of the three bottom 1.67 m interval slug tests, which covered the same well interval. However, 11.4 m and 17.19 m intervals predicted T values larger than the sum of the individual 1.67 m interval T estimates (Tables 6 and 7). The straddle packer slug tests, and the 4.69 m interval single packer slug tests fitted to a two-zone radial heterogeneous model indicating that they were testing an individual fracture. Conversely, 11.4 m interval and 17.2 m interval single packer slug tests fitted to a homogeneous model indicating that they were testing the overall fractured formation. Effectively, the 17.2 m interval slug tests estimated T=8.65 m²/day, similar to the outer zone T (14.4 m²/day).

A highly permeable interval in BBC3 was selected to conduct a pumping test, which resulted in measurable responses in three (weathered bedrock) monitoring wells, located within 63 m from BBC3. This data indicated there was a hydraulic connection between the fractured bedrock and the weathered bedrock. The pumping test was conducted at a nearly constant flowrate (50 ml/s), so the Jacob's homogeneous analytical method could estimate T and S (Marsily, 1986). The two-zone radial heterogeneous model used for the corresponding slug tests at the same interval resulted in equivalent T estimates, but with a larger inner zone radius. For the monitoring well, the Jacob model T was on the same order of magnitude as the outer zone T obtained with the heterogeneous model (Table 8). For the pumped well, the Jacob model T was the same order of magnitude.
as the geometric mean $T$ of the two zones. The numerical radial heterogeneous model was preferred over the Jacob model because it also fit the slug test field data for the same interval, including the allowance for flowrate variation, and provided a statistical measure of the model deviation from the scattered field curves.

Table 8. BBC3 pumping test results

<table>
<thead>
<tr>
<th></th>
<th>Test Well BBC3 (*)</th>
<th>Monitoring Wells (**)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance to BBC3 [m]</strong></td>
<td>0.00</td>
<td>23.47 63.40 37.80</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top [m]</td>
<td>31.32</td>
<td>10.06 9.75 9.66</td>
</tr>
<tr>
<td>Bottom [m]</td>
<td>32.39</td>
<td>16.15 12.80 12.71</td>
</tr>
<tr>
<td><strong>Jacob Model (Homogeneous)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T$ [m$^2$/day]</td>
<td>3.28</td>
<td>26.15 23.88 26.45</td>
</tr>
<tr>
<td>$S$ [J]</td>
<td>N/A</td>
<td>6.9E-04 1.5E-04 8.7E-05</td>
</tr>
<tr>
<td><strong>Inner Zone (Heterogeneous)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T$ [m$^2$/day]</td>
<td>0.36</td>
<td>0.36 0.36 0.36</td>
</tr>
<tr>
<td>$S$ [J]</td>
<td>N/A</td>
<td>8.0E-04 2.0E-04 2.5E-04</td>
</tr>
<tr>
<td>Radius [m]</td>
<td>0.35</td>
<td>0.35 0.35 0.35</td>
</tr>
<tr>
<td><strong>Outer Zone (Heterogeneous)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S$ [J]</td>
<td>N/A</td>
<td>8.0E-04 2.0E-04 2.5E-04</td>
</tr>
<tr>
<td><strong>MPE [%]</strong></td>
<td>4.90</td>
<td>3.18 7.28 4.87</td>
</tr>
<tr>
<td><strong>SD [%]</strong></td>
<td>3.30</td>
<td>2.21 4.41 3.33</td>
</tr>
</tbody>
</table>

(*) Isolated interval (**) Open Borehole N/A: not applicable

Table 9 summarizes the BBC4 slug test results. A (variable flowrate) pumping test performed in a high permeable interval generated responses at weathered bedrock well 6127. By using the radial heterogeneous two-zone model, the same $T$ estimates were obtained as the corresponding slug tests, but with a much larger inner zone radius (Table 10). The BBC4 $T$ profile exhibited two high permeability intervals below 40 m.
Table 9. BBC4 slug test results.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Ho [m]</th>
<th>Inner Zone</th>
<th>T [m²/day]</th>
<th>Radius [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>Bottom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.29</td>
<td>27.97</td>
<td>0.75F</td>
<td>0.12</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.49R</td>
<td></td>
<td>1.01</td>
</tr>
<tr>
<td>27.97</td>
<td>29.64</td>
<td>0.60F</td>
<td>0.09</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.28R</td>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td>31.01</td>
<td>32.69</td>
<td>1.03F</td>
<td>0.12</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.28R</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>32.54</td>
<td>34.21</td>
<td>0.47F</td>
<td>0.17</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.49R</td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td>34.37</td>
<td>36.04</td>
<td>0.71R</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.06F</td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td>36.50</td>
<td>38.18</td>
<td>0.68R</td>
<td>0.22</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.44F</td>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.92R</td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>38.33</td>
<td>40.01</td>
<td>0.62F</td>
<td>0.23</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.69R</td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td>39.85</td>
<td>41.53</td>
<td>0.58R</td>
<td>0.29</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.32F</td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td>41.68</td>
<td>43.36</td>
<td>0.67F</td>
<td>1.30</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.96F</td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.35R</td>
<td></td>
<td>0.37</td>
</tr>
<tr>
<td>44.12</td>
<td>45.80</td>
<td>0.54F</td>
<td>0.38</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.75R</td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.90F</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>46.10</td>
<td>47.78</td>
<td>0.69R</td>
<td>0.94</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.30R</td>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.03R</td>
<td></td>
<td>0.61</td>
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<tr>
<td></td>
<td></td>
<td>4.27R</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>49.15</td>
<td>50.83</td>
<td>0.47R</td>
<td>0.43</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.60F</td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.47R</td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

R=Rising, F=Falling
MPE < 3% for all modeled slug test
Outer zone T = 14.4 m²/day for all modeled slug test
Values in shaded cells are the same for all rows
Table 10. BBC4 pumping test results.

<table>
<thead>
<tr>
<th>Distance from BBC4 [m]</th>
<th>BBC4 (*)</th>
<th>6127 (**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Top [m]</td>
<td>0.00</td>
</tr>
<tr>
<td>Bottom [m]</td>
<td></td>
<td>47.76</td>
</tr>
<tr>
<td>Inner Zone</td>
<td>T [m²/day]</td>
<td>0.94</td>
</tr>
<tr>
<td>S [ ]</td>
<td>N/A</td>
<td>8.5E-04</td>
</tr>
<tr>
<td>Radius [m]</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Outer Zone</td>
<td>T [m²/day]</td>
<td>14.40</td>
</tr>
<tr>
<td>S [ ]</td>
<td>N/A</td>
<td>8.5E-04</td>
</tr>
<tr>
<td>MPE [%]</td>
<td>5.3</td>
<td>2.04</td>
</tr>
<tr>
<td>SD [%]</td>
<td>5.6</td>
<td>0.96</td>
</tr>
</tbody>
</table>

(*) Isolated interval  (**) Open Borehole

BBC5 slug tests also matched the two-zone radial heterogeneous model, however the inner zone and outer zone T estimates were larger than for any other BBC well (Table 11). The more transmissive interval was used to conduct slug tests with increasing Ho, confirming the corresponding increase of the estimated inner zone radius. This same interval was used to conduct a pumping test, which yielded monitoring well responses in open borehole well 6127 and isolated intervals in well BBC4. The same two-zone model used for the corresponding slug tests was obtained from the test well signal, however a three-zone radial heterogeneous model was required to fit the monitoring well field data. A third zone, located between the inner and outer zones used for the slug tests analysis, yielded T values intermediate between those of the inner and outer zones (Table 12). The BBC5 T profile indicated the presence of two high permeability intervals below 33 m.
Table 11. BBC5 slug test results.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Ho [m]</th>
<th>Inner Zone T [m²/day]</th>
<th>Radius [m]</th>
<th>Outer T [m²/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>Bottom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31.14</td>
<td>32.81</td>
<td>2.97</td>
<td>0.14</td>
<td>0.90</td>
</tr>
<tr>
<td>33.88</td>
<td>35.55</td>
<td>3.19</td>
<td>1.44</td>
<td>0.90</td>
</tr>
<tr>
<td>36.93</td>
<td>38.60</td>
<td>2.53</td>
<td>0.14</td>
<td>0.70</td>
</tr>
<tr>
<td>39.97</td>
<td>41.65</td>
<td>1.87</td>
<td>0.07</td>
<td>0.50</td>
</tr>
<tr>
<td>45.46</td>
<td>47.14</td>
<td>1.85</td>
<td>0.43</td>
<td>0.13</td>
</tr>
<tr>
<td>50.34</td>
<td>52.01</td>
<td>0.00</td>
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<td></td>
</tr>
<tr>
<td>53.39</td>
<td>55.06</td>
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<td></td>
</tr>
</tbody>
</table>

MPE < 3% for all modeled slug test

Values in shaded cells are the same for all rows
Table 12. BBC5 pumping test results.

<table>
<thead>
<tr>
<th>Distance from BBC5 [m]</th>
<th>Test Well</th>
<th>Monitoring Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BBC5 (*)</td>
<td>BBC4 (*)</td>
</tr>
<tr>
<td>Depth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top [m]</td>
<td>0.00</td>
<td>7.62</td>
</tr>
<tr>
<td>Bottom [m]</td>
<td>45.46</td>
<td>23.90</td>
</tr>
<tr>
<td></td>
<td>47.14</td>
<td>25.4</td>
</tr>
<tr>
<td>Inner Zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T [m²/day]</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>S [ ]</td>
<td>N/A</td>
<td>7.0E-04</td>
</tr>
<tr>
<td>Radius [m]</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Central Zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T [m²/day]</td>
<td>N/A</td>
<td>5.77</td>
</tr>
<tr>
<td>S [ ]</td>
<td></td>
<td>7.0E-04</td>
</tr>
<tr>
<td>Radius [m]</td>
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</tr>
<tr>
<td>Outer Zone</td>
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<td></td>
</tr>
<tr>
<td>T [m²/day]</td>
<td>144.19</td>
<td>144.19</td>
</tr>
<tr>
<td>S [ ]</td>
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<td>7.0E-04</td>
</tr>
<tr>
<td>MPE [%]</td>
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<td>3.7</td>
</tr>
<tr>
<td>SD [%]</td>
<td>3.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

(*) Isolated interval (**) Open Borehole
N/A: Not applicable Values in shaded cells are the same for all rows

For the BBC6 slug tests, a two-zone heterogeneous model with the inner zone radius increasing with Ho, matched the field data (Table 13). BBC6 isolated interval (34.2 -35.9 m) was selected to conduct pumping and slug tests, which yielded measurable responses at five isolated intervals in BBC5, three isolated intervals of BBC4, and the open borehole well 6127.
Table 13. BBC6 slug test results.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Ho</th>
<th>Inner Zone Depth [m]</th>
<th>T [m²/day]</th>
<th>Radius [m]</th>
</tr>
</thead>
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<td>Top Bottom</td>
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<td>[m]</td>
<td>[m²/day]</td>
</tr>
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<td>0.02</td>
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<tr>
<td></td>
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<td>2.03</td>
<td>0.30</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>1.83</td>
<td>0.19</td>
<td>0.50</td>
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<td>1.74</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.83</td>
<td>0.50</td>
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</tr>
<tr>
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<td></td>
<td>3.05</td>
<td>0.60</td>
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</tr>
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<td>3.29</td>
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<td>0.60</td>
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<td>0.10</td>
<td>0.80</td>
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</tr>
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<tr>
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<td>1.01</td>
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<td>11.95</td>
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<td>11.89</td>
<td>10.00</td>
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<td>11.70</td>
<td>10.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Depth [m] Ho Inner Zone Depth [m] T [m²/day] Radius [m] Depth [m] Ho Inner Zone

<table>
<thead>
<tr>
<th>Top Bottom</th>
<th>[m]</th>
<th>T [m²/day]</th>
<th>[m]</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>42.60</td>
<td>44.27</td>
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<td></td>
</tr>
<tr>
<td>45.64</td>
<td>47.32</td>
<td>1.92 0.01 0.30</td>
<td></td>
</tr>
<tr>
<td>47.02</td>
<td>48.69</td>
<td>0.00</td>
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</tr>
<tr>
<td>48.39</td>
<td>50.06</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>49.76</td>
<td>51.44</td>
<td>8.56 0.01 1.00</td>
<td></td>
</tr>
<tr>
<td>51.13</td>
<td>52.81</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>52.35</td>
<td>54.03</td>
<td>3.54 0.01 0.30</td>
<td></td>
</tr>
<tr>
<td>52.50</td>
<td>54.18</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>53.97</td>
<td>55.55</td>
<td>7.57 0.27 0.80</td>
<td></td>
</tr>
<tr>
<td>55.25</td>
<td>56.92</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>56.62</td>
<td>58.29</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>57.99</td>
<td>59.66</td>
<td>2.31 0.00 0.30</td>
<td></td>
</tr>
<tr>
<td>59.33</td>
<td>61.01</td>
<td>2.50 0.01 0.30</td>
<td></td>
</tr>
</tbody>
</table>

Outer Zone Transmissivity = 14.4 m²/day for all tested intervals

MPE < 3% for all modeled slug test

Values in shaded cells are the same for all rows

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In general, a consistent $S$ estimate between $2E-4$ and $8E-4$ was obtained from wells completed in weathered bedrock and fractured bedrock (Table 14). A radial heterogeneous model with $T$ increasing from the test well, was required to fit slug test and pumping test field data. The $T$ estimates generated from the two hydraulic tests were equivalent. The inner zone $T$ was interpreted as the transmissivity of isolated fracture(s), while the formation overall $T$, represented by the outer zone $T$ (i.e., the resultant of fracture interconnectivity). The inner zone radius was related to the distance where the isolated fracture at the well bore had interconnected with other fractures. For slug tests, this radius increased with $H_0$, and was even larger for pumping tests, because a larger imposed stress demanded that more distant fractures were involved. The simple radial heterogeneous model (two- or three-zone) fit the slug test and pumping test field data reasonably well and resulted in a consistent set of $T$ and $S$ predictions to be used as initial estimates for hydraulic calculations.

**WELL INTERCONNECTIVITY**

The water level responses to BBC well drilling and hydraulic testing in the monitoring wells provided data to infer the hydraulic connections between wells. For example during BBC5 drilling, its hydraulic connectivity with fractured bedrock wells BBC1 and 6071, and also with weathered bedrock wells 6013, 6029, 6075, and 6127 was evident (Figure 76). No measurable response was obtained in BBC1 (BBC4 was not instrumented during BBC5 drilling).
Table 14. BBC6 Pumping Test (PT) and Slug Test (ST) comparison.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Test Well</th>
<th>Monitoring Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BBC6 (*)</td>
<td>BBC5 (*)</td>
</tr>
<tr>
<td></td>
<td>PT ST</td>
<td>PT ST</td>
</tr>
<tr>
<td>Distance from BBC6 [m]</td>
<td>0</td>
<td>7.62</td>
</tr>
<tr>
<td>Top [m]</td>
<td>34.21</td>
<td>36.94</td>
</tr>
<tr>
<td>Bottom [m]</td>
<td>35.89</td>
<td>42.34</td>
</tr>
<tr>
<td>Inner Zone</td>
<td>T [m^2/day]</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>S [ ]</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Radius [m]</td>
<td>3.00</td>
</tr>
<tr>
<td>Central Zone</td>
<td>T [m^2/day]</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>S [ ]</td>
<td>7.0E-04</td>
</tr>
<tr>
<td></td>
<td>Radius [m]</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td>S [ ]</td>
<td>7.0E-04</td>
</tr>
<tr>
<td></td>
<td>MPE [%]</td>
<td>8.16</td>
</tr>
<tr>
<td></td>
<td>SD [%]</td>
<td>4.06</td>
</tr>
</tbody>
</table>

(*) Isolated interval  (**) Open Borehole  N/A: not applicable

Clearly, the monitoring well signals during pumping tests of the BBC wells confirmed hydraulic connections (Tables 8, 10, 12 and 14). Even when the monitoring well signals were not large enough for quantitative analysis, they were useful to infer well interconnectivity. For example, the BBC5 hydraulic tests generated detectable responses in the monitoring wells (Table 15). As expected, the pumping test yielded larger water level variations in the monitoring wells. Major hydraulic connections intersecting three BBC5 intervals were evident (bold font). As detailed in Pulido et al. (2003b), large drawdown slug tests yielded monitoring well responses that confirmed hydraulic connections. Gas injection tests conducted in BBC5 and BBC6 allowed the interpretation of the hydraulic...
connectivity between isolated intervals, and between the test well and the more distant monitoring wells (Pulido et al., 2003c).

Figure 76. Monitoring well water level responses to BBC5 drilling.
Table 15. Maximum water level responses [m] during BBC5 Pumping Tests (PT) and Slug Tests (ST).

<table>
<thead>
<tr>
<th>Tested Interval [m TOC]</th>
<th>Type of test or Ho [m]</th>
<th>Q [ml/s]</th>
<th>Top [m]</th>
<th>Bedrock Wells</th>
<th>Weathered Bedrock Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>BBC1</td>
<td>BBC3</td>
<td>BBC4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P1</td>
<td>P5</td>
<td>P6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.0 30.7</td>
<td>PT</td>
<td>0.8</td>
<td>&lt;TDL</td>
<td>&lt;TDL</td>
<td>0.01</td>
</tr>
<tr>
<td>31.1 32.8</td>
<td>ST</td>
<td>3.0</td>
<td>&lt;TDL</td>
<td>&lt;TDL</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02</td>
<td>0.05</td>
<td>0.30</td>
</tr>
<tr>
<td>33.9 35.6</td>
<td>ST</td>
<td>13.4</td>
<td>&lt;TDL</td>
<td>&lt;TDL</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
<td>0.06</td>
<td>0.27</td>
</tr>
<tr>
<td>35.4 37.1</td>
<td>PT</td>
<td>1.0</td>
<td>&lt;TQL</td>
<td>NR</td>
<td>0.12</td>
</tr>
<tr>
<td>36.9 38.6</td>
<td>ST</td>
<td>12.8</td>
<td>NR</td>
<td>&lt;TDL</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28.6</td>
<td>0.04</td>
<td>NR</td>
</tr>
<tr>
<td>38.5 40.1</td>
<td>PT</td>
<td>11.0</td>
<td>&lt;TDL</td>
<td>0.06</td>
<td>0.21</td>
</tr>
<tr>
<td>40.0 41.7</td>
<td>ST</td>
<td>13.7</td>
<td>&lt;TDL</td>
<td>&lt;TDL</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.6</td>
<td>&lt;TDL</td>
<td>0.10</td>
</tr>
<tr>
<td>45.5 47.1</td>
<td>ST</td>
<td>17.7</td>
<td>&lt;TDL</td>
<td>&lt;TDL</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Distances to BBC5 [m] 53.7 68.6 7.6 7.6 7.6 7.6 0.1 100 43.6 86.5 14.4

NR=No Recorded. TDL=Transducer Detection Limit. TQL=Transducer Quantification Limit. Bold fonts indicate the responses in the more permeable tested intervals.

CONCLUSIONS

Figure 77 summarizes the CHM developed for the fractured bedrock formation underlying Site 32. The fractured bedrock was hydraulically connected with to the weathered bedrock and overburden. The latter acted as a semiconfining layer. The weathered bedrock and fractured bedrock S values were characteristic of confined or semiconfined formations. The more conductive fractures were located after 30 m below ground surface. The fracture network at the site was part of the regional groundwater flow in the fractured bedrock.

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with its recharge zone to the northwest of the site (infiltration due to precipitation) and its discharge zone in the shores located to the east of the site (outcrops).

The fractured bedrock is an interconnected fracture network with hydraulic connections to weathered bedrock and overburden. This is supported by the sheet pile pumping test, the contaminant profiles, and the hydraulic tests on the wells completed in fractured bedrock.

The hydraulic parameters of the fractured bedrock formation at the site were identified by slug tests and pumping tests. The field data fit a radial heterogeneous model, with $T$ increasing from the test well. The inner zone $T$
was representative of isolated fractures; the outer zone \( T \) was associated with the larger scale of the fractured bedrock formation (more of a porous media). The radius of the inner zone increased with the size of the disturbance induced by the hydraulic test.

The overburden acted as a semiconfining layer for the fractured bedrock in the site. This was concluded from the sheet pile pumping test. In addition, the fractured bedrock formation \( S \) estimates were characteristic of a confined or semiconfined formation. The correlation between fractured bedrock well water level changes and atmospheric pressure changes also support this conclusion.

The fracture network at the site was hydraulically connected to the regional fractured bedrock groundwater flow. This is indicated by the correlation between fractured bedrock well water levels at both hourly ocean water levels and regional dry and wet seasons.

The fractured bedrock formation at the site is recharged very slowly by infiltration due to precipitation as indicated by the correlation between fractured bedrock groundwater levels and rainfall. Consistently, the regional recharge zone located northwest of the site, exhibited abundant fracture correlated-lineaments and outcrops, providing hydraulic paths to fractured bedrock groundwater flow to the site. Local infiltration to the fractured bedrock was prevented by the upward hydraulic vertical gradient from the fractured bedrock to the weathered bedrock under normal conditions at the site (continuous sheet pile pumping). Even with baseline conditions, local infiltration was unlikely because of the low permeability of the semiconfining layer (i.e., marine clay and silt) and the negligible vertical
gradients between the hydrogeological units at the site under the latter conditions.

This conceptual hydrogeological model can be further delineated by the results of the geochemical, geological, and geophysical studies currently under development. It will serve as a framework for the next site research efforts; in particular, for a planned site scale tracer test, and for a mathematical model which will include the fracture network character of the formation.

**ACKNOWLEDGEMENTS**

This research was performed under US EPA contract CR 827878-01-0. The authors would also like to acknowledge the collaboration of the U.S. Air Force and the Pease Development Authority during the BBC project. The authors would also like to express their gratitude to Dr. Wallace A. Bothner, and his Ph.D. candidate Jose Casas, for their contributions in the geologic description.
REFERENCES


This dissertation presented groundwater instrumentation, field hydraulic tests, and a method of hydraulic test analysis; all developed to assist in the hydraulic characterization of fractured bedrock formations. It also presented the implementation of these tools for the delineation of the Conceptual Hydrogeologic Model (CHM) of a fractured bedrock formation.

Chapter 2 presented the Multipurpose Packer System (MPS), a discrete-interval isolation system for hydrogeologic studies. The MPS uses inflatable packers connected to aluminum pipe to isolate discrete intervals in a well. One MPS innovation is the packer to pipe couplings that have ports with miniature fittings. Pressure transducers and small diameter tubing are connected to the fittings and run through the aluminum pipe up to the well head, where a control board permits monitoring hydraulic head, water sampling, and the performance of hydraulic testing for each isolated interval. The only MPS components in continuous direct contact with the groundwater are: the packers, aluminum pipe, and stainless steel couplings. These materials minimize water quality biases due to sorption, desorption, and diffusion processes.

The MPS prototype demonstrated satisfactory interval sealing, hydraulic testing, and water sampling. It assisted the assessment of piezometric level variations under ambient conditions; in particular, the MPS data reflected the effect of tides on piezometric levels. Currently, it is being used for hydrogeologic characterization of fractures, delineation of chemical and microbiological gradients, and as an active and passive component of a site-wide tracer test.
The MPS prototype has already permitted the study of ST performance, such as: the influence of slug duration and size, and the influence of the ST tubing diameter on the field data. The MPS was successfully used as a monitoring well for PT and ST conducted in a neighboring well, allowing reliable estimates of T and S. In addition, the GIT performed in the MPS made it possible to assess well interconnectivity at a side-wide scale.

Chapter 3 introduced the *large drawdown slug test* (LDST), which extends the range of applicability of conventional ST, elevating it to the confidence given to PT data. By increasing the magnitude of the imposed hydraulic signal (Ho), LDST generate water level responses at monitoring wells that were hydraulically interconnected with the test well. When monitoring well discrete- intervals are isolated, monitoring well responses to LDST are magnified sufficient to permit estimation of T and S, in an analogous way as the PT, but avoiding water pumping and dramatically reducing the required testing time. LDSTs conducted on tight discrete intervals resulted in a detectable hydraulic connectivity to a well located 70 m from the test well. This increases the volume of aquifer investigated by the LDST compared to that for traditional ST.

ST and LDST field normalized data for the fractured bedrock formation under consideration, in general did not fit to radial groundwater homogeneous flow models nor to Cooper type-curves in particular. When Ho is increased, the normalized data shifts to increasing times without any change in the slope of the data plot. This was interpreted as formation heterogeneity (T) yet S consistency. LDST can also be used in porous media, as long as the pressurized ST
instrumentation is provided to allow Ho increases to where response signals are detected in monitoring wells.

A finite difference radial heterogeneous model was successfully developed and used to analyze the ST and LDST for this formation. In the heterogeneous model, the inner zone T was at least one order of magnitude lower than that the outer zone. The inner zone properties can be interpreted as representative of a single fracture intercepted in the tested interval, that gets interconnected with the fracture network system at some distance from the test well (outer zone). The estimated inner zone radius was found to increase for larger Ho values. No evidence of turbulent flow nearby the test well was found for the analyzed LDSTs, but in the event of turbulent flow, a model that includes such hydraulics can adapt to LDST data.

The use of isolated interval monitoring well data together with test well data for LDST allowed reliable S estimates, as well as the radius and T values of the outer zone (far field properties). The consistency between hydraulic parameter estimation with PT and LDST was demonstrated.

Chapter 4 deals with the gas injection test (GIT), a field technique for the characterization of hydraulic connections in a fracture network. A GIT is conducted by gas pressurizing an isolated interval of a well completed in a fractured bedrock formation to a pressure \( H_{\text{applied}} \) larger than the static water column depth in the interval \( W_{\text{ci}} \), thereby forcing gas to invade fractures intersecting the isolated interval. The energy available for this invasion is \( H_{\text{GIT}} = H_{\text{applied}} - W_{\text{ci}} \). The GIT interpretation is greatly assisted by reactions in monitoring
wells, which are enhanced by a GIT because the higher mobility and buoyancy trend of the gas invading the liquid phase into the fracture network.

Two GITs conducted at isolated intervals of wells BBC5 and BBC6 allowed several relevant fracture network features to be revealed. Fracture network hydraulic connections were detected over more than 120 m from these two wells (which were 7.6 m distant from each other). The BBC5 GIT used a 3.175 mm-diameter injection line, which entered at the bottom of the isolated interval. This configuration was useful in determining the depth of the hydraulically active fractured zone intersecting the isolated interval by observing the maximum pressure build up ($H_b$); also, it caused about 0.26 m$^3$ of N$_2$ to be trapped into the FN, affecting the tested well signals for about 8 hours after GIT initiation. To the contrary, the BBC6 GIT used a 51 mm-diameter injection line, which entered at the top of the isolated interval. Approximately 0.45 m$^3$ were injected into the FN during the GIT pressurization phase, and released back through the injection line in a nearly instantaneous way after the gas pressure release. This setting would require finer pressure increment steps to determine the depth of the hydraulically active fracture(s).

The HyTests mathematical model is discussed in chapter 5. It simulates the drawdown-time series from hydraulic parameter sets. Simulated results are graphically displayed, and statistically compared with hydraulic test field data. The hydraulic parameter values can be interactively updated until the simulated drawdown-time series achieve a satisfactory fit to the hydraulic test field data, taking into account actual hydraulic test conditions such as radial dependence of
hydraulic parameters, variable-flowrate PT, and well hydraulic losses. HyTests was successfully validated and calibrated with published examples of the Theis, Hantush, and Papadopulos methods (PT), as well as the Cooper method (ST).

The accuracy of the estimated hydraulic parameter set depends on the quality and quantity of field data. Monitoring well data reduce non-uniqueness results, and increase the reliability of heterogeneous models.

As an example of the integrated use of these previous contributions, the conceptual hydrologic model of the site is developed in chapter 6. The more relevant elements identified are: 1) the fracture bedrock formation was an interconnected fracture network hydraulically connected with the weathered bedrock and the overburden strata. 2) the fracture bedrock formation hydraulic parameters identified by hydraulic tests were best represented by a radial heterogeneous model. 3) the fracture bedrock formation at the site was under semiconfined conditions due to the overburden strata. 4) the fracture bedrock formation at the site was an active component of the regional fracture bedrock formation groundwater flow. 5) the regional fracture bedrock formation recharge zone was located to the northwest of the site; the fracture bedrock formation groundwater flow in the site was to the east, and discharged to the ocean through fracture bedrock formation outcrops or submerged under sediment.

**RECOMMENDATIONS FOR FUTURE RESEARCH**

The BBC5 MPS prototype experience should guide the design of a second MPS. New features can include: increasing the diameter of the injection, purging
and slugs line to 1.27 cm, reducing the MPS casing diameter, and automation of water sampling pulses to enable the MPS systems to support long term, near continuous pumping tests.

A natural LDST extension can be to conduct a series of interfering LDSTs. This means initiating a new LDST prior the previous LDST signal being dissipated. The corresponding LDST signals in the tested well and in monitoring wells can diminish the uniqueness problems when testing heterogeneous formations.

The development of GIT analytical models will greatly improve its applicability for fracture network characterization. Any GIT model should be based on multiphase flow of immiscible fluids: conservation of mass, modified Darcy’s law, the equation of state, capillary pressure, and the relation between phase saturations (Marsily 1986). The GIT pressurization/release pulses plot as straight lines when shown in the appropriate scales, suggesting that simplified theoretical models could be developed for overall fracture network permeability estimates.

HyTests needs to be extended to add models to analyze hydraulic test in formations of increasing complexity of geologic/geometric settings. A 2D Finite Element horizontally heterogeneous model already exists within HyTests, but awaits validation. It will be the basis for a Fracture Network Model, which will analyze discrete fractures as interconnected disks in the 3D space. A Layered Heterogeneous Model will allow hydraulic test interpretation in stratified porous–
media formations. 3D Finite Element Model will model 3D spatial variability of the Hydraulic parameters.

The presented CHM can be further detailed and refined by the results of the geochemical, geological, and geophysical studies currently under development. It will serve as a framework for subsequent efforts at the site; in particular, for a planned site scale tracer test and for a mathematical model that includes the fracture network characteristics of the formation.
In order to be an alternative to analytical methods, a numerical model must be coded in a user-friendly environment. In the case of interpreting groundwater data, a numerical model should allow hydraulic test data analysis in a comparable time and with similar effort as the analytical models. For this reason, HyTests is written in Java, a powerful, platform independent, computer programming language which provides full graphical interfaces for editing and updating data sets, analyzing results, and conveniently saving input data as well as intermediate and final results.

HyTests installation instructions and a quick-reference user manual are provided as part of the HyTests installation package, downloadable at http://www.unh.edu/erg/bbc. HyTests uses the International System of units.

HyTests is a menu-driven program. The main menu provides options for File operations and Input hydraulic test data to obtain modeling Results, and to access the on-line Help (Figure A1). Menus are accessed through pull-down icons on the computer screen.
Figure A1. HyTests main menu

The File submenu options can: create a New file for a hydraulic test analysis; Open an existing file; Save the current file; save the file with a different name (Save As...); perform a New Analysis with the current data set; Close the current file; and Exit from the HyTests application. The Input submenu options include: Model, for entering the numerical model settings; Wells, for incorporating the hydraulic test field data; and Nodes, for defining hydraulic parameter values in the numeric spatial mesh. The Results submenu options includes: Solve the numeric model; Summary, to display results; Spatial Mesh and Time Mesh for viewing the meshes used for the numeric calculations. The Help submenu contains options for: describing What HyTests is?; explaining Using HyTests; displaying literature References, and providing general information About HyTests.

HYTESTS INPUT REQUIREMENTS

Each New file or New Analysis starts by specifying the numerical model settings in the model window (Figure A2). The only Type of Model available in the current version of HyTests is the Radial Heterogeneous model. The temporal and spatial numerical meshes are specified by entering the Time Steps per Cycle, the Well Radius in the tested interval, the Casing Radius in the drawdown zone, the maximum Model Radius, and the Spatial Steps Per Cycle.
Hydraulic test data are input to the model via the wells window. The drawdown time series for each monitoring well can be imported from a text file or input in the table provided (Figure A3A). HyTests can simulate any defined pumping schedule during the hydraulic test (Figure A3B). The maximum pumping time entered into the flowrates table defines the maximum model time. Therefore, slug tests and pumping tests with recovery must be specified with a zero flowrate final step and the maximum desired modeling time.

Hydraulic parameters are input in the nodes window (Figure A4). HyTests allows the specification of any number of Node Sets, each one with a different hydraulic parameter set. This incorporates the formation radial heterogeneity into the model. The node sets are concentric cylinders of increasing Final Radius. By convention, the first node set corresponds to the test well. In this case, the nodes window allows for the specification of an Initial Drawdown value. For slug tests, this is the size of the slug (Ho); for pumping tests starting
with static conditions, this value is zero, but a non-zero value can be input to indicate non-equilibrium initial conditions.

A) Single well and flowrate table

B) Multiple wells and drawdown table

Figure A3. Well windows
While the numeric model is being solved, the modeling control window is displayed (Figure A5). If inconsistent hydrogeological conditions are generated at any time during the solution process (such as a test well drawdown larger than the formation bottom depth), HyTests will cancel the modeling run and will ask the user to correct input data.
During each time step solution, the current modeling progress and current flowrate are shown in the time mesh. Modeling can be controlled by the Start/Pause/Continue on-screen button. When the option Show Current Iteration Results is enabled, current values for drawdown, Darcian velocity, and Reynolds number in the test well are displayed at each iteration time. The Modeling Speed slider is useful when it is important to Save Current Results at selected Current Iteration Times. In this case, the current values of drawdown, Darcian velocity, and Reynolds number for each spatial node can be exported to a text file for post-processing analyses.

The drawdown profile at each time step is used by HyTests to evaluate Darcian velocity at each spatial node \( n \):

\[
V_{Darcy} = K_n \frac{\hat{s}_{n+1} - \hat{s}_n}{r_{n+1} - r_n} \tag{A1}
\]

Where: \( K_n \) is the hydraulic conductivity, \( \hat{s}_n \) is the current (approximate) drawdown and \( r_n \) is the radial distance from the node \( n \) to the test well.
HyTests evaluates the Reynolds number \( (R_e) \) at each node, based on the formation thickness (B) (to represent parallel plate flow in a fracture of aperture B):

\[
R_e = \frac{V}{u} = \frac{T}{u} \left( \frac{\delta_{n+1} - \delta_n}{r_{n+1} - r_n} \right)
\]

(A2)

Where: \( u \) [m²/s] is the kinematic viscosity. A plane fracture exhibits laminar flow for \( R_e < 1000 \). When representing porous media, \( R_e \) must be evaluated based on pore diameter instead of B, and laminar flow exists for \( R_e < 10 \) (Marsily, 1986).

While the numerical model is being solved for each time step, the hydrogeological scheme is updated showing the current drawdown cone, as well as \( V_{Darcy} \) and \( R_e \) spatial profiles (Figure A6).

![Figure A6. Modeling progress window](image-url)
The summary window is displayed after numeric calculations are successfully completed (Figure A7). By checking any monitoring well in the View Results column, the results window is shown for the selected well (Figure A8).

![Figure A7. Summary window.](image)

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The model results are graphically and statistically compared with the drawdown-time series data measured in the field. At each field data point i, the model accuracy is measured by the drawdown percent error (DPE) (Miller and Miller, 1993). The DPE is defined as the deviation of the modeled drawdown $\hat{s}_i$ from the measured drawdown $s_i$, relative to the maximum measured drawdown for the monitoring well $s_{\text{max}}$, during the hydraulic test.
\[ DPE_i = \left| \frac{s_i - s_f}{s_{\text{max}}} \right| \times 100 \]  \hspace{1cm} (A3)

DPE is preferred over the Root Mean Square error (which would be obtained by replacing \( s_{\text{max}} \) by \( s_i \) in the denominator of Equation 12), to avoid inconsistencies when \( s_i = 0 \). The DPE biases towards large drawdowns, however, it is the larger drawdowns that are the more relevant when deciding if the current matching is acceptable.

HyTests measures the model accuracy in each monitoring well by calculating the drawdown mean percent error (MPE), from its \( n \) readings:

\[ MPE_{\text{MW}} = \frac{\sum_{i=1}^{n} DPE_i}{n} \]  \hspace{1cm} (A4)

The model precision for each monitoring well is measured by the monitoring well standard deviation (MWSD) of the MPE values:

\[ \text{MWSD} = \sqrt{\frac{\sum_{i=1}^{n} (DPE_i - MPE_{\text{MW}})^2}{n-1}} \]  \hspace{1cm} (A5)

The overall model percent error (OMPE) measures the fit of the model to the field data for each monitoring well, weighted by the number of readings (\( n_w \)):

\[ OMPE = \frac{\sum_{w=1}^{MWF} MPE_{w} \times n_w}{\sum_{w}^{MWF} n_w} \]  \hspace{1cm} (A6)