HYDROGEOLOGIC CHARACTERIZATION OF A TILL MANTLED LEAKY FRACTURED BEDROCK AQUIFER

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A Project Presented

By

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ABSTRACT

HYDROGEOLOGIC CHARACTERIZATION OF A LEAKY TILL MANTLED FRACTURED BEDROCK AQUIFER

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In glaciated areas till can serve as a leaky aquitard for fractured bedrock aquifers. The characterization of a leaky till mantled fractured bedrock aquifer is presented. Multiple high resolution data sets were collected in response to unprecedented changes in the hydraulic head at a research site in eastern Massachusetts. Local scale aquifer and aquitard hydraulic conductivity, transmissivity and storativity values are determined through the analysis of purge recovery tests using Ostendorf and DeGroot (2010) and Cooper et al (1967) theories. The local scale parameters are in turn used to determine large scale aquifer transmissivity and storativity through an analysis of the drawdown due to irrigation pumping using Hantush (1960). It is confirmed that the till acts as a leaky aquitard to the fractured bedrock aquifer, with geometric mean hydraulic conductivities of 7.2E-9 m/s for the till and 1.6E-7 m/s for the bedrock. The storativity of the till is 2.7E-4 while that of the fractured bedrock is 6.7E-5. The transmissivity values determined through Cooper et al. (1967) overestimate the large-scale transmissivity of the aquifer by at most a factor of 3, as previously determined by Barker and Black (1983).
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1. INTRODUCTION

Glacial tills are widespread across the world and along with other glacial deposits are often parts of major groundwater resources (Stephenson et al. 1988). As glaciers advance previously deposited materials are often removed due to the scraping action of the glacier, exposing the underlying bedrock. Till is then deposited on the bedrock, resulting in till mantled bedrock systems. Tills, due to their generally low hydraulic conductivity, often serve as aquitards where the bedrock is weathered and fractured. The tills thereby influence the recharge of aquifers and control the downward or upward migration of contamination. A thorough understanding of the influence of the till and the fractured bedrock on each other is necessary in order to predict and manage leaky till mantled fractured bedrock aquifer systems and is becoming even more important as water sources become overtaxed.

This thesis presents results of a study of a leaky till mantled fractured bedrock aquifer system subjected to an unprecedented change in the historical steady hydraulic state of the drumlin due to large-scale drawdowns across the site induced by significant irrigation pumping on an abutting property. The local hydraulic behavior of the till and bedrock are determined through purge recovery tests analyzed using two methods: Ostendorf and DeGroot’s (2010) extension of Bouwer and Rice (1976) and Cooper et al. (1967). The large-scale irrigation pumping was analyzed using Hantush (1960). These three theories allowed for a thorough characterization of the leaky till mantled fractured bedrock aquifer system.

The presentation of the thesis is in the format of a journal article submission of approximately 10,000 word equivalents. Chapter 2 presents the manuscript. Chapter 3 presents a summary of
the research and recommendations for further work. The Appendix contains a poster presented at a conference attended during the time of this study.
2. **HYDROGEOLOGIC CHARACTERIZATION OF A LEAKY TILL MANTLED FRACTURED BEDROCK AQUIFER**

**INTRODUCTION**

Pleistocene tills are wide spread across the world and along with other glacial deposits are often parts of major groundwater resources (Stephenson et al 1988). Tills due to their generally low hydraulic conductivity often serve as aquitards and thereby influence the recharge of aquifers and control the downward or upward migration of contamination. Previous research on the performance of till aquitards has focused on clay-rich tills and characterization using pore water chemistry (e.g., Darling et al. 2013; Gardner et al. 2012; Hendry et al. 2004; Hiscock and Najafi, 2011). The research has also focused locally on the till, providing point specific characterizations and not larger scale information.

Research on sandy silt or silty sand till aquitards is relatively rare. Cherry et al (2004) only give one example of a non-clayey silt in their list of selected unlithified aquitards. While Gerber and Howard (2000) and Gerber et al (2001) did look at a large sandy silt till aquitard in Canada their focus was also on the till aquitard, not the interaction of the till and aquifer. Gerber and Howard (2000) used field data and a numerical model to determine a bulk hydraulic conductivity for a large sandy silt aquitard in Canada. Their focus was on the downward movement of contaminants through the aquitard and not the interaction between the aquitard and aquifer. Gerber et al (2001) found that the field-scale flow regime in till aquitards is not well understood and conducted a large scale field investigation, however their investigation also focused on flow paths within the till aquitard due to weathering and fracturing, not the interaction of the till and bedrock system.
The objective of this study was to characterize a till mantled fractured bedrock aquifer system which had been subjected to large scale drawdowns due to seasonal irrigation pumping from an abutting property. Unlike most of the published characterization of till aquitard the aquitard presented in this study is a sandy silt aquitard (Shelburne et al. 2000, Ostendorf et al. 2004). The current investigation is also unique in that a large scale areal and temporal characterization is possible due to the length and volume of irrigation pumping.

BACKGROUND

Site Overview

Scituate Hill is a glacial till drumlin overlying fractured Dedham granite located in the town of Cohasset, MA, approximately 25 km southeast of Boston as shown in Figure 1. The drumlin is elliptical in shape, with a major axis of approximately 1200 m oriented southeast and a minor axis of 800 m. The drumlin is 25 m in height rising to a maximum elevation of 55 meters above mean sea level. This study focuses on wells located primarily on the top, primarily flat, part of the drumlin (Figure 2) which serves as a salt storage facility for the MA Department of Transportation Highway Division (MassDOT). The drumlin has been the site of an extensive groundwater monitoring program conducted by the University of Massachusetts (UMass) Amherst since 1996 that is studying the fate and transport of deicing salt contaminated surface and groundwater (e.g., Shelburne et al. 2000, Poirier et al. 2004, Ostendorf et al. 2004, Ostendorf et al. 2006).

Twenty two monitoring wells clusters, two uncased bedrock observation wells, and one uncased bedrock supply well were constructed at the salt storage facility since August 1996. Each cluster consists of 2 or more closely spaced monitoring wells screened at different depths with at least
one installed at auger drilling refusal at the till/bedrock interface (henceforth referred to as deep
till wells) and at least one other screened through the water table, which is approximately 3 m
below ground surface. The monitoring wells were constructed of 25 mm radius PVC casing with
1.52 m long screens set in 49 or 110 mm diameter uniform sand packs between 2.1 and 5.3 m in
length. The wells were sealed with bentonite chips or high solids content bentonite grout to the
ground surface. The bedrock observation wells BW-1 and BW-3 were installed in October 2001
and May 2013 with 102 and 76 mm radius steel casing grouted 6 m into the bedrock,
respectively. The boreholes extend uncased for 14.4 m below the bottom of the casing. Based on
the till/bedrock interface found during installation of the deep till and bedrock wells, the
overlying till is 35 to 45 m thick in the study area and consists of two units: an upper 3 to 8 m
weathered brown till underlain by 25 to 35 m of unweathered gray till. The unweathered gray till
has a lower hydraulic conductivity due to the absence of weathering features such as fissures
(Shelburne et al. 2000, Poirier et al. 2004).

In terms of geotechnical classification, the brown and gray till show similar grain-size
distributions with all grains sizes present from clay (< 0.002 mm) up to boulders (> 300 mm) with
typical grain size distribution curves being nearly linear in semi-log space. Atterberg limits on
the fine grained portion all plot above the A-line in the CL or CL-ML range of a Casagrande
plasticity chart, indicating the fines are low plastic, inorganic clays; sandy and silty clays or silty
clays; or clayey silts and sands. In all cases, the natural water content is less than the plastic
limit with an average liquidity index equal to -0.4. Based on the results of the grain size analysis
and the Atterberg limits, the soil is classified as coarse grained using the Unified Soil
Classification System (USCS) with a specific classification of SC-CL.
**Hydraulic Transience**

The hydraulics at Scituate Hill has varied little since groundwater monitoring was initiated in 1996. As Figure 3 shows although seasonal variations are present, the greatest season variation in the G cluster was only 5 meters and well GB, which is a deep till well, varied even less. BW-3 is located within the G cluster (Figure 2). However, in 2011 two private bedrock wells were drilled offsite on a property abutting the southeast quadrant of the drumlin to serve as irrigation wells for a large residential complex (Figure 2). According to the well completion reports filed with the MA Department of Environmental Protection (DEP) the wells are of 75 and 90 mm radius, were drilled into the bedrock to depths of 244 m and 61 m, and had yields of 0.0041 and 0.0010 m$^3$/s at the time of installation for the far (IW-2) and near (IW-1) wells, respectively. The reports state that nearly all of the discharge was from a fracture zone located 40 to 50 m below the till/bedrock interface.

Figure 3 shows that the hydraulic head in BW-1 dropped more than 16 m between May and June 2011 due to the initiation of the newly installed irrigation wells. Figure 5a shows that the hydraulic head also decreased in the overlying till based on measurements from the set of wells located at Cluster G. The nominal steady state downward gradient at the site, as shown in Figure 5b increased significantly upon initial of the irrigation pumping. Drops were also measured in the wells located higher in the till unit. Due to the observed drawdowns it is assumed that the fractured bedrock aquifer is overlain by a leaky till aquitard.

**METHODS**

In order to fully characterize the till mantled leaky fractured bedrock aquifer system both the till and the fractured bedrock must be accurately analyzed. For this study high resolution hydraulic
head versus time data sets were collected for the deep till wells, BW-1, and BW-2 for the duration of the large amplitude and long term drawdown due to irrigation pumping. Additionally, purge recovery tests were conducted.

Instrumentation

Figure 2 shows the location of the wells used in this study which includes seven deep till wells (AB, BC, CB, DB, IB, LA, and QA) and two uncased bedrock observation wells (BW-1 and BW-2). Water levels were measured manually in the deep till wells and bedrock well BW-1 monthly or quarterly using an electronic sensor (Slope Indicator; Laramie, WY). After the dramatic changes in hydraulic head were observed in 2011 due to initiation of the irrigation pumping, vented, vibrating wire pressure transducers (Slope Indicator Corp.; Seattle, WA.) were installed in BW-1, BW-2, and the deep till wells prior to the summer 2013 irrigation pumping. The transducers were programmed to sample in 15 minute intervals. Once bedrock well BW-3 was installed in 2013 a transducer was also placed in this well. The transducers placed in the bedrock wells produced three high resolution sets of drawdown data resulting from the initiation of irrigation pumping on May 15, 2013 for IW-2 and May 21, 2013 for IW-1.

Purge Recovery Tests

Purge recovery tests were performed in early 2013 before the irrigation pumps were turned on for the summer season. Water levels in the wells were first manually measured with an electronic sensor for quality control purposes after which the wells were pumped using a Waterra purge pump (New England Environmental; Waltham, MA.). Pressure transducers, as described above, were used to measure the recovery with a 15 min recording interval. It was not possible to
perform a purge test in the bedrock water supply well BW-2 and therefore a large amplitude anthropogenic purge in May 2013 was used to analyze the hydraulic response of this well.

THEORY

This section presents the theory used for interpreting the various sets of data collected at the site and includes: 1) both Ostendorf and DeGroot (2010) modified Bouwer and Rice (1976) and Cooper et al. (1967) for interpretation of purge recovery tests performed in the bedrock and deep till wells, and 2) Hantush (1960) for interpretation of the influence of the large drawdown irrigation pumping on the bedrock and deep till wells. Table 1 presents a summary of the input and output parameters for the three models. For all models, a kinematic viscosity of 1.3E-6 m²/s was used due to the observed groundwater temperature of 10°C in the bedrock wells (White 2008). Numerical optimization was performed using a golden section search as first described by Kiefer (1953). For optimizations with multiple search parameters the golden section searches were nested.

**Purge Recovery**

The overdamped slug test theory of Bouwer and Rice (1976) models the exponential response of the hydraulic head in a partially penetrating well when subjected to an instantaneous disturbance. The response is governed by the exponential decay constant $\lambda$ which can be used to estimate the local hydraulic conductivity $K$ of the aquifer given

$$\lambda = \frac{2LK}{r_c^2 \ln\frac{r_E}{r_p}}$$  \hspace{1cm} (1)
with $L$ and $r_p$ the length and radius of the sand pack or uncased borehole length, $r_c$ the radius of the casing, and $r_E$ the equilibrium radius. Ostendorf and DeGroot (2010) extended the theory to account for the presence of background head trends by introducing a linear rate of varying background hydraulic head $\kappa$. Given an initial disturbance amplitude $A$ the resultant model of drawdown or drawup $s$ is

$$s = A \exp(-\lambda t) + \frac{\kappa}{\lambda} [\lambda t + \exp(-\lambda t) - 1]$$  \hspace{1cm} (2)

with $t$ time from the beginning of the recovery. Equations (1) and (2) are used to estimate the hydraulic conductivities of both the fractured bedrock as well as the overlying till. This model was used to determine the hydraulic conductivity of the till and fractured bedrock. For this investigation the fractured bedrock hydraulic conductivity is denoted as $K$ while that of the till is denoted as $K'$.

The slug test theory of Cooper et al (1967) is another method for modeling the exponential response of the hydraulic head in a well when subjected to an instantaneous disturbance. Unlike Bouwer and Rice, Cooper et al can produce estimates of the hydraulic conductivity as well as the storativity of the formation. The solution for the normalized drawdown is

$$\frac{s(t)}{s_0} = \frac{8\alpha_{Cooper}}{\pi} \int_0^\infty \exp \left( - \frac{\beta u^2}{\alpha_{Cooper}} \right) \frac{1}{u\Delta(u)} du$$ \hspace{1cm} (3a)

$$\alpha_{Cooper} = \frac{r_p^2 s}{r_c^2}$$ \hspace{1cm} (3b)

$$\beta = \frac{TT}{r_c^2}$$ \hspace{1cm} (3c)
\[ \Delta(u) = \left[ uJ_0(u) - 2\alpha_{\text{Cooper}}J_1(u) \right]^2 + \left[ uY_0(u) - 2\alpha_{\text{Cooper}}Y_1(u) \right]^2 \]  

with transmissivity \( T \) and storativity \( S \). \( J_0 \) and \( Y_0 \) and \( J_1 \) and \( Y_1 \) are zero- and first-order Bessel functions of the first and second kind, respectively. What is referred to as simply \( \alpha \) in Cooper et al. is referred to as \( \alpha_{\text{Cooper}} \) in this work in order to prevent confusion between their grouped parameter and compressibility. This method was used to determine the storativity of the till \( S' \) and the transmissivity \( T \) of the fractured bedrock as well as local estimates of the storativity of the fractured bedrock \( S \). A visual estimate of transmissivity \( T \) was determined from type curves followed by a two-parameter search for the storativity \( S \) and transmissivity \( T \). As Cooper et al. is designed only for testing in fully-penetrating wells in confined aquifers the sand pack lengths \( L \) were used as the aquifer thickness to estimate \( K' \).

**Bedrock Drawdown from Irrigation Pumping**

Hantush and Jacob (1955) and Hantush (1960) present two models for the analysis of drawdown in an aquifer overlain by a leaky aquitard, both of which are based on the previous work of Jacob (1946). The Hantush and Jacob (1955) model does not take the storage of the aquitard into account, while the Hantush (1960) model does. The implication of not taking release of water from storage into account is that the drawdown across the aquitard varies linearly, which as Batu (1998) argues is “certainly not the case at small values of time.”

The Hantush and Jacob (1955) model of drawdown of an aquifer due to pumping is

\[ s(r, t) = \frac{Q}{4\pi T} W(u, \beta) \]  

\[ u = \frac{r^2 s}{4 T t} \]
\[ W(u, \beta) = \int_u^{\infty} \frac{1}{y} \exp \left( -y - \frac{\beta^2}{4y} \right) dy \]  

(3c)

\[ \beta = r \sqrt{\frac{K'}{Tb'}} \]  

(3d)

with constant discharge from the pumping well \( Q \), transmissivity \( T \), storage \( S \), time since pumping began \( t \), distance between the pumping well and the observation well \( r \), and aquitard thickness \( b' \). Aquifer thickness \( b \) is determined through the optimization of \( T \) with the given \( K \).

The short term solution for the Hantush (1960) model of drawdown due to pumping is

\[ s(r, t) = \frac{Q}{4\pi T} H(u, \beta') \quad (t < b'S'/10K') \]  

(4a)

\[ H(u, \beta') = \int_u^{\infty} \frac{e^{-y}}{y} \text{erfc} \left( \beta' \sqrt{\frac{u}{y(y-u)}} \right) dy \]  

(4b)

\[ \beta' = \beta \sqrt{\frac{S'}{2S}} \]  

(4c)

with storage of the aquitard \( S' \). The long term solution, for \( t > b'S'/K' \), is equal to the 1955 model given in Eq. 3. Hantush (1960) suggested that a spline function could be used to merge the short and long term solutions and accordingly, an exponential spline function was developed for this study as described in more detail in Appendix A. This theory allows for larger-scale determinations of \( S \) and \( T \). Since the two irrigation wells had different initiation dates a superposition solution was used to model the influence of this difference on the response of the site monitoring wells. The reported yields of 0.0041 and 0.0010 m\(^3\)/s at the time of installation
for the far (IW-2) and near (IW-1) wells respectively are the flow values assumed for any modeling of the hydraulics.

RESULTS

This section presents the results of the hydrogeological characterization of the till mantled leaky fractured bedrock aquifer system. Bouwer and Rice (1976) with the Ostendorf and DeGroot (2010) extension for background trends was used to interpret the purge recovery tests to determine the hydraulic conductivity of the overlying till, $K'$. The same purge recovery tests were also analyzed using Cooper et al (1967) in order to determine the bedrock transmissivity $T$ as well as the bedrock and till storativity, $S$ and $S'$. In all cases the till thickness $b'$ was assumed equal to 30 m. The $T$, $K'$, and $b'$ values were in turn used with Hantush (1960) to analyze the large, long-term drawdown due to the offsite irrigation well pumping to derive larger scale estimates of $S$ and corrected values of $T$.

**Purge Recovery Tests – Deep Till**

The results of the purge recovery tests in the deep till are summarized in Table 2. Figure 6 plots examples of recovery $s$ versus time data for purge tests performed in six of the deep till wells. Wells BC, CB, DB and IB have similar recoveries while wells AB and LA recovery more slowly. Figure 6 also plots the optimized Ostendorf and DeGroot (2010) theory fit to the data using an average ambient head trend $\kappa$ of 8.6E-7 m/s as determined from optimizing the individual deep till recoveries with a $\kappa$ loop. The calibrated hydraulic conductivity values range from 4.7E-9 to 1.9E-8 m/s with a geometric mean of 7.1E-9 (Table 2). Figure 7 plots examples of normalized recovery $s'/s_0$ where $s_0$ is the initial water level disturbance versus a dimensionless time parameter $Tt/r_c^2$. Figure 7 also plots the optimized Cooper et al (1967) theory fit to the data.
The storativity of the till $S'$ ranged from 5.4E-6 to 5.0E-2 with a geometric mean of 2.7E-4, implying an $\alpha'$ range of 2.6E-10 to 2.4E-6 Pa$^{-1}$ with geometric mean of 1.2E-8. The transmissivity of the till $T'$ ranged from 1.8E-8 to 9.5E-8 m$^2$/s with a geometric mean of 4.1E-8 m$^2$/s resulting in a hydraulic conductivity $K'$ value range of 7.1E-9 to 4.4E-8 m/s with a geometric mean of 1.7E-8 m/s. In terms of $\alpha'$ the wells tested can be grouped into wells with high $\alpha'$ and wells with low $\alpha'$ with the exception of well IB. Wells AB, BC, CB, and LA have $\alpha'$ values ranging from 2.6E-10 to 1.1E-8 with a geometric mean of 1.3E-9 Pa$^{-1}$ while wells DB and IB have $\alpha'$ of 3.9E-7 and 2.4E-6 with a mean of 9.7E-7 Pa$^{-1}$.

**Purge Recovery Tests – Bedrock**

Table 3 presents results of the purge recovery tests performed in the bedrock and Figure 8 plots recovery $s$ versus time data for purge tests performed in BW-1 and BW-2. Figure 8 also plots the optimized Ostendorf and DeGroot (2010) theory fit to the data. The calibrated hydraulic conductivity values were 1.0E-7 and 1.6E-7 m/s for BW-1 and BW-2, respectively (Table 3). Figure 9 plots normalized recovery $s/s_0$ versus a dimensionless time parameter $T/t_{rc}^2$ for tests run in BW-1 and BW-2. Figure 9 also plots the optimized Cooper et al (1967) theory fit to the data. The storativity of the bedrock $S$ was 1.5E-5 and 6.0E-5 implying compressibility of the bedrock $\alpha$ was 1.1E-10 and 3.1E-10 Pa$^{-1}$ for BW-1 and BW-2, respectively. The transmissivity $T$ values were 2.3E-6 and 6.5E-6 m$^2$/s implying hydraulic conductivity $K$ values of 1.6E-7 and 3.3E-7 m/s. For these values the thickness of the aquifer was assumed to be 14.4 m for BW-1 as this is the uncased interval and 20 m for BW-2.

**Large-Scale Bedrock Drawdown Due to Irrigation**
Table 4 presents results of the Hantush (1960) calibrations and Figure 10 plots the drawdown measured in BW-1 and BW-2 due to the 2013 irrigation well pumping. Figure 10 shows a drawdown of about 11 m in BW-1, similar to that measured in 2011 (Figure 4), and a larger drawdown of 18 m in BW-2. This higher resolution 2013 data set indicates that IW-1 started up 6 days earlier than IW-2 as shown by the inflection in the early stages of the drawdown curves. Additionally, the leveling off of the drawdown with time implies leakage from the overlying till aquitard. Figure 11 plots the 2012 irrigation pumping induced drawdown measured in some of the deep till wells. In all cases the magnitude of the drawdown, ranging from 5 to 18 m, is significantly larger than the historical seasonal hydraulic head variation in the deep till (Figure 3).

The data in Figure 10 were modeled using Hantush (1960) with a spline fit between the short and long term solutions (Appendix A) and superposition to account for the different start time of the irrigation pumps. Input parameters consisted of a till thickness $b' = 30$ m and the site geometric average of $K' = 7.2\times 10^{-9}$ m/s (Table 2). The very large 15 min sampling data set was reduced by using 8 hr average values to reduce computation time. Data on pumping rates for the two irrigation wells was not available and thus the yield for these two wells that was filed with MA DEP was used for modeling purposes with $Q = 0.0041$ for IW-2 and $0.0010$ m$^3$/s for IW-1.

Figure 10 plots the calibrated drawdown curves for BW-1 and BW-2. The transmissivity and storativity values for the fractured bedrock aquifer are $1.2\times 10^{-6}$ and $2.4\times 10^{-6}$ m$^2$/s and $5.0\times 10^{-5}$ and $9.1\times 10^{-5}$ for BW-1 and BW-2, respectively.

**EVALUATION OF RESULTS**

*Deep Till Properties*
As Table 2 shows there is little variation within the hydraulic conductivity results using either the Ostendorf and DeGroot (2010) or Cooper et al (1967) methods. The hydraulic conductivity determinations using Cooper et al (1967) with a mean value of 1.7E-8 m/s tend to be approximately twice as large as those determined using Ostendorf and DeGroot (2010) with a geometric mean value of 7.2E-9 m/s. This may be due to the fact that Cooper et al does not take background head trends into account. Table 5 presents a comparison of the results from the large amplitude purge recovery tests conducted for this study and the small amplitude slug tests from Poirier et al (2004). The hydraulic conductivity values are from Poirier et al. (2004) while the compressibility values are from a reanalysis of the data for only hydraulic conductivities were calculated. The results of the large and small amplitude tests are consistent with each other with the exception of wells IB and LA which disagree by one and two orders of magnitude. Despite these differences the geometric mean values of 1.7E-8 m/s from this study and 4.2E-8 m/s from Poirier et al (2004) are in agreement. The values determined for this study are in the range of hydraulic conductivity for a glacial till given by Freeze and Cherry (1979) of $10^{-12}$ to $10^{-6}$ m/s.

The values of $S'$ from the Cooper et al (1967) analysis of the purge recovery tests varied across four orders of magnitude with a geometric mean of 2.7E-4. Due to the wide range of $S'$ values determined from the Cooper et al. analysis of small amplitude slug test data from Poirier et al. (2004) was used to double check the accuracy of the purge tests. Table 5 presents this comparison. The results from the two different data sets are generally consistent, with means of 2.7E-4 from the large amplitude purge tests performed for this study and 1.2E-4 for the small amplitude slug tests before by Poirier et al (2004). The geometric mean $\alpha'$ from the Cooper et al.
(1967) tests is 1.2E-8 Pa⁻¹ which is higher than the estimate of 3E-9 Pa⁻¹ obtained by Ostendorf et al. (2004) and more similar to the value of 3E-8 Pa⁻¹ reported by Keller et al. (1989).

**Bedrock Properties**

The hydraulic conductivity values for BW-1 and BW-2 as determined using Ostendorf and DeGroot (2010) were 1.0E-7 and 1.6E-7 m/s, respectively. These values agree with an earlier estimate of 1.7E-7 m/s (Doherty, 2003) as well as the Freeze and Cherry (1979) range for fractured igneous and metamorphic rocks of 5E-9 to 1E10-4 m/s. Boutt et al. (2010) estimated a hydraulic conductivity of 4.0E-6 m/s in crystalline bedrock 50 km northwest of Scituate Hill. The hydraulic conductivity values from the purge recovery tests confirm that the till serves as an aquitard to the fractured bedrock aquifer. As shown in Table 4, the calibrated storativity values are 5.0E-5 and 9.1E-5 for BW-1 and BW-2, respectively. These values are on the low end of the range given by Freeze and Cherry (5E-5 to 5E-3). Assuming aquifer thicknesses of 14.4 m and 20 m for BW-1 and BW-2, as explained earlier, results in specific storage values of 3.5E-6 and 4.6E-6 m⁻¹. These values are on the low end of the range for fissured and jointed rock given by Batu (1998) after Domenico and Mifflin (1965) of 3.28E-6 to 6.89E-5 m⁻¹.

The bedrock compressibility values of 3.6E-10 and 4.7E-10 Pa⁻¹ respectively for BW-1 and BW-2 as determined by using the assumed thicknesses mentioned previously and Hantush (1960) compare favorably with those determined by using Cooper et al. (1967) of 1.1E-10 and 1.2E-10 Pa⁻¹. The mean α value of 4.0E-10 Pa⁻¹ is an order of magnitude greater than a local estimate of the compressibility of sound Dedham granite of 2.2E-11 Pa⁻¹ as found by Leet and Ewing (1932) in an abandoned quarry 20 km west of the site and is in the lower range for jointed rock given by Freeze and Cherry (10⁻⁸ to 10⁻¹⁰ Pa⁻¹, 1979). Although the calculated α values are approximately
equal to the compressibility of water of 4.4E-10 Pa\(^{-1}\) (White 2008) due to the assumed low porosity of the bedrock the effect of the compressibility of water on the storativity is regarded as negligible.

**Drawdown Modeling**

Figure 12 presents the measured drawdown due to irrigation pumping in wells BW-1 and BW-2. Figure 12 also presents the predicted drawdown using the Hantush (1960) model with the transmissivity values determined for BW-1 and BW-2 using Cooper et al (1967). The predicted quasi steady-state value for both wells is lower than the measured value. Due to the nature of the exponential decay of Eq. 3 when the value of \( u \) is very small due to very large time values the steady state drawdown is reached and given by

\[
W(0, \beta) = 2K_0(\beta) \tag{5a}
\]

\[
s(r, t) = \frac{Q}{2\pi T} K_0 \left( \frac{Tt}{r^2} \right) \tag{5b}
\]

where \( K_0 \) is the modified Bessel function of second kind of zero order. The drawdown is governed by the transmissivity, not the storativity, and an overprediction of the drawdown implies the transmissivity values are too great. The results shown in Figure 10 are from using Hantush (1960) with the decreased transmissivity values shown in Table 4, which are smaller than those from Cooper et al. (1967, Table 3) by factors of 1.9 and 2.7 for BW-1 and BW-2. That Cooper et al (1967) overestimates transmissivity for fractured bedrock was previously determined by Barker and Black (1983) who found that if standard homogeneous analysis methods are applied to fissured aquifers the transmissivity is a slight overestimate by a factor of up to 3.
Figure 13 presents the measured drawdown due to irrigation pumping in wells BW-1 and BW-2. Figure 13 also presents the predicted drawdown curves for BW-1 and BW-2 if both wells were modeled using the mean of the individual Hantush (1960) fits presented in Figure 10 and Table 4. The drawdown in BW-1 is overpredicted by approximately 4 meters, while that of BW-2 is underpredicted by approximately 1 meter. The inability of the model to correctly predict drawdown in both wells is most likely due to the differing construction details of the wells. As previously mentioned BW-1 only has an uncased interval of 14.4 m, while BW-2 has an uncased interval of at least 125 m. Boutt et al. (2010) found that hydraulically active fractures are generally found in the top 100 m in fractured rock 50 km northwest of the research site, with the occurrence of flowing fractures decreasing with depth. This means that BW-1 is most likely not hydraulically connected to some of the deeper fractures in the bedrock and therefore has less drawdown and a lower transmissivity.

*Parametric Analysis of Influence of Irrigation Pumping*

Due to the influence of transmissivity on the quasi steady-state drawdown analysis, a parametric analysis of the influence of the hydraulic conductivity of the till, transmissivity of the fractured bedrock, the storativity of the bedrock and the storativity till was carried out for BW-2. The results of this study are presented in Figure 14. In each case one parameter was changed while all other values were kept at the values from the initial optimization (Table 4). It is shown that the storativity of the till and bedrock do not influence the steady-state drawdown due to pumping, however they do influence the shape of the drawdown curve prior to the steady-state condition. Higher storativity values for both units lead to a greater release of water initially, resulting in a faster drawdown of the aquifer, and vice versa for lower storativity values.
The transmissivity and hydraulic conductivity both have a strong influence on the steady-state drawdown value. Decreasing transmissivity values result in decreasing drawdown while increasing transmissivity values initially results in increased drawdowns but later leads to decreased drawdowns. This is due to the influence of the two transmissivity terms in Eq. 5b. The hydraulic conductivity of the till only appears once in Eq. 3 and has a more direct and highly influential effect on the drawdown with higher conductivity values results in lower drawdown values due to increased leakage from the aquitard.

**Additional Drawdown Prediction**

An uncased bedrock well with construction similar to that of BW-1, BW-3, was constructed in May 2013 in order to provide a third data set for analysis. The location of the well is shown in Figure 2. The transducer in the well failed shortly after installation resulting in an approximately one and a half month gap in the drawdown data (Figure 15). In order to test the previous conclusions an attempt was made to fit the model to this incomplete data set. The resulting fit, obtained using the geometric mean $S'$ value of 2.7E-4, is shown in Figure 15. Transmissivity was estimated at 4.9E-6 m²/s and storativity of the bedrock was estimated at 9.1E-5. While the storativity value is the same as that of BW-2, the transmissivity value is twice that of BW-2 which in turn is twice that of BW-1. These values were determined using a $b$ value of 14.4 m for this is the uncased interval of the well.

**CONCLUSIONS**

This paper presents successful methods for characterizing a sandy silt till mantled fractured bedrock aquifer. Three separate methods of analysis are used and their results are in mutual
agreement. Bouwer and Rice slug test theory (1976) as modified by Ostendorf and DeGroot (2010) is used to determine the hydraulic conductivity of both the till and the fractured bedrock, confirming that the sandy silt till serves as an aquitard for the fractured bedrock aquifer. Hantush leaky aquitard drawdown theory (1960) is used to determine the storativity bedrock as well as large-scale estimates of the transmissivity of the bedrock aquifer and confirms that the till is a leaky aquifer with storage release from a finite aquitard. The theory accurately models the response of the aquifer even though it is composed of fractured bedrock. Cooper et al slug test theory (1967) allows for an independent estimate of the storativity of the till and fractured bedrock.

Based on the Bouwer and Rice (1976) results for the deep till wells and the Cooper et al (1967) transmissivity values for the bedrock wells the hydraulic conductivity of the till \( K' \) and fractured bedrock \( K \) were found to be 7.2E-9 and 1.0E-7 m/s, respectively. The storativity of the till \( S' \) and fractured bedrock \( S \) were found to be 2.7E-4 and 7.1E-5, respectively. The storativity of the till was determined using Cooper et al (1967), while the storativity of the bedrock was determined using Hantush (1960) based on prior estimates using Cooper et al (1967). The storativities result in compressibility values of 9.0E-9 and 4.0E-9 Pa\(^{-1}\) for the till and fractured bedrock, respectively.

Although the drawdowns induced by the irrigation pumping occur across a large area using global average values of transmissivity and storativity does not result in accurate modeling of the drawdown behavior. Instead local values of transmissivity and storativity are used. This is most likely due to the differing construction details of the wells investigated resulting in different
amount of connectivity to hydraulically active fractures. This determination was made possible due to the large number of high resolution data sets acquired at the site. The findings from this research can be applied to fractured bedrock aquifers in glaciated areas around the world where material overlying the bedrock has been stripped and replaced by a layer of till.

Recommendations for future work includes modeling the upward attenuation of the large scale drawdown in the till aquitard. A correct calibration of the attenuation will add the coefficient of vertical consolidation to the list of important aquifer and aquitard parameters determined through this investigation. The attenuation can be modeled thanks to the dataset from the G well cluster (Figure 5). Determining the coefficient of vertical consolidation will also allow for modeling of the aquifer/aquitard system at a given radius and a given elevation into the till, such as the drawdown curves from the deep till wells (Figure 11). Additionally the recovery of the aquifer/aquitard system will be modeled. Data from 2012 suggest that the system recovers at a slower rate than it is drawn down implying a more complex solution than a simple mirror injection well is required (Figure 11).
APPENDIX

Spline Function

As stated earlier, there are short and long term solutions for the Hantush 1960 model. For this study the exponential spline function \( F \) is adopted, where

\[
s(r, t) = \frac{Q}{4\pi T} F \left( \frac{K' t}{b' s'} \right)
\]

\[
F \left( \frac{K' t}{b' s'} \right) = W(u, \beta) \left[ 1 - \exp \left( \frac{K' t}{b' s'} \right) \right] + H(u, \beta') \exp \left( \frac{K' t}{b' s'} \right)
\]

This solution departs from the short term behavior of Eq. 3 and asymptotically approaches the long term behavior of Eq. 4 as the drawdown across the aquitard develops. Figure 16 shows the spline between the two term solutions for one of the wells in this study. Due to the fact that there are two pumping wells the full equation used to the study is given by

\[
s(r, t) = \frac{Q_{IW-1}}{4\pi T} F_{IW-1} \left( \frac{K' t_1}{b' s'} \right) + \frac{Q_{IW-2}}{4\pi T} F_{IW-2} \left( \frac{K' t_2}{b' s'} \right)
\]

where \( t_1 \) and \( t_2 \) are the initiation times for pumping from the far and near wells, respectively.
ACKNOWLEDGEMENTS

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REFERENCES


**TABLES**

Table 1: Summary of input and output parameters for Ostendorf and DeGroot (2010), Cooper et al (1967), and Hantush (1960).

<table>
<thead>
<tr>
<th>Model</th>
<th>Input</th>
<th>Output</th>
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<tbody>
<tr>
<td>Ostendorf and DeGroot (2010)</td>
<td>$s(t)$ from purge test, well parameters</td>
<td>$K'$ –deep till</td>
</tr>
<tr>
<td>Cooper et al. (1967)</td>
<td>$s(t)$ from purge test, well parameters</td>
<td>$T$ and $S$– bedrock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T'$ and $S'$ - deep till</td>
</tr>
<tr>
<td>Hantush (1960)</td>
<td>$s(r,t)$ from long-term irrigation pumping, $Q$, well parameters</td>
<td>$S$ - bedrock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$S'$ – deep till</td>
</tr>
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</table>
Table 2: Summary of Purge Recovery Tests using Ostendorf and DeGroot (2010) and Cooper et al. (1967) for the deep till wells.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>λ [s⁻¹]</td>
<td>T' [m²/s]</td>
</tr>
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<td>1.2E-08</td>
</tr>
<tr>
<td>BC</td>
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</tr>
<tr>
<td>CB</td>
<td>3.5E-05</td>
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<tr>
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</tbody>
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Table 3: Summary of Purge Recovery Tests using Ostendorf and DeGroot (2010) and Cooper et al. (1967) for the uncased bedrock wells.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>λ [s⁻¹]</td>
<td>T [m²/s]</td>
</tr>
<tr>
<td>BW-1</td>
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<td>1.4E-06</td>
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<tr>
<td>BW-2</td>
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Note: Values with an asterisk (*) were determined using an assumed aquifer thickness b of 20 m.
Table 4: Summary of Hantush (1960) results for the uncased bedrock wells

<table>
<thead>
<tr>
<th>Well</th>
<th>T [m²/s]</th>
<th>K' [m/s]</th>
<th>b' [m]</th>
<th>S [-]</th>
<th>S' [-]</th>
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<tr>
<td>BW-1</td>
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<tr>
<td>BW-2</td>
<td>2.4E-06</td>
<td>7.2E-09</td>
<td>30.0</td>
<td>9.1E-05</td>
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Table 5: Comparison of Lukas (large-scale purge tests) and Poirier et al. (2004) (small-scale slug tests) Cooper et al (1967) test results.

<table>
<thead>
<tr>
<th>Well</th>
<th>Tester</th>
<th>T [m²/s]</th>
<th>K [m/s]</th>
<th>S [-]</th>
<th>a [Pa⁻¹]</th>
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<tr>
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<tr>
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<td>Poirier</td>
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<td>5.2E-06</td>
<td>2.0E-10</td>
</tr>
<tr>
<td>BC</td>
<td>Lukas</td>
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<tr>
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<td>Poirier</td>
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<tr>
<td>CB</td>
<td>Lukas</td>
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<td>2.1E-08</td>
<td>2.7E-04</td>
<td>1.1E-08</td>
</tr>
<tr>
<td></td>
<td>Poirier</td>
<td>3.4E-08</td>
<td>1.4E-08</td>
<td>2.1E-03</td>
<td>8.7E-08</td>
</tr>
<tr>
<td>DB</td>
<td>Lukas</td>
<td>9.5E-08</td>
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</tr>
<tr>
<td></td>
<td>Poirier</td>
<td>9.7E-08</td>
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<td>4.1E-03</td>
<td>1.9E-07</td>
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<tr>
<td>IB</td>
<td>Lukas</td>
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</tr>
<tr>
<td></td>
<td>Poirier</td>
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<td>1.4E-07</td>
<td>1.5E-02</td>
<td>7.2E-07</td>
</tr>
<tr>
<td>LA</td>
<td>Lukas</td>
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<tr>
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<td>Poirier</td>
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<td>Geometric Mean</td>
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<tr>
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<td>Poirier</td>
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<td>4.2E-08</td>
<td>1.2E-04</td>
<td>5.4E-09</td>
</tr>
</tbody>
</table>

Note: Lukas values are from the current study, Poirier values are from the data collected for Poirier et al (2004)
Figure 1: Location of the research site
Figure 2: Detailed map of the research site

Figure 3: Hydraulic Head levels in the G-Cluster from 2002 to 2009.
Figure 4: Hydraulic Head in BW-1 from August 2011 to November 2012.
Figure 5: Attenuation of Drawdown in Till Aquitard. Elevations are for the midpoint of the screened interval.
Figure 6: Observed (circles) and predicted (lines) drawdown from Ostendorf and DeGroot (2010) Purge Recovery tests in the till.
Figure 7: Observed (circles) and predicted (lines) normalized drawdown for the Cooper et al (1967) analysis of the till wells.
Figure 8: Observed (circles) and predicted (lines) drawdown for the uncased bedrock wells using Ostendorf and DeGroot (2010).

Figure 9: Observed (circles) and predicted (lines) normalized drawdown from Cooper et al. (1967) analysis for the bedrock wells.
Figure 10: Observed (circles) and predicted (lines) hydraulic head from Hantush (1960) drawdown analysis of BW-1 and BW-2.
Figure 11: Observed drawdown and recovery in the deep till wells in 2012.
Figure 12: Observed (circles) and predicted (lines) hydraulic head in the uncased bedrock wells from Hantush (1960) drawdown analysis with Cooper et al (1967) $T$ values.

Figure 13: Observed (circles) and predicted (lines) hydraulic head in the uncased bedrock wells from Hantush (1960) drawdown analysis using mean BW1 and BW2 $T$ and $S$ values.
Figure 14: Results of the parametric study of the Hantush (1960) on the influence of drawdown from (a) storativity of the till, (b) storativity of the bedrock, (c) transmissivity of the bedrock, and (d) hydraulic conductivity of the till.
Figure 15: Observed (circles) and predicted (line) hydraulic head in BW-3.
Figure 16: Illustration of the spline function showing the short term solution (solid black line) and the spline solution (dashed red line).
3. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Scituate Hill, a glacial till drumlin located in Cohasset, MA has been the site of an extensive groundwater monitoring program since 1996. The monitoring program involved sampling trips during which the water levels across the site were measured and water samples were taken for water quality analysis; at first quarterly and then monthly. In 2012 there was an unprecedented drop in the hydraulic heads measured in the deep till and bedrock wells across the site. Due to this change in the hydraulics more transducers were deployed in order to obtain multiple high resolution data sets which could in turn be used to model the response of the till aquitard fractured bedrock aquifer system. By estimating local scale aquitard and aquifer parameters using the theories of Ostendorf and DeGroot (2010) and Cooper et al. (1967) and estimating large scale aquifer parameters using the Hantush (1960) theory the till mantled leaky fractured bedrock system was able to be characterized.

The hydraulic conductivity of till and bedrock were determined to be 7.2E-9 and 1.0E-7 m/s, respectively, confirming that the till acts as a leaky aquifer to the fractured bedrock aquifer. The mean transmissivity values were 1.6E-8 and 1.8E-6 m²/s and mean storativity values were 2.7E-4 and 7.1E-5 for the till and fractured bedrock, respectively. Although drawdowns were induced across the site by the irrigation pumping global mean values of transmissivity and storativity did not result in accurate modeling of the drawdown behavior. This is most likely due to differing construction details of the bedrock wells investigated in the study presented. This implies that BW-1 is not hydraulically connected to the entire fractured bedrock aquifer.
It is recommended that future work focus on better characterization and understanding of the fractured nature of the bedrock. An unanswered question resulting from the work is what the nature of the fractures is, and how exactly they influence the different amounts of drawdown seen at the different wells. A greater understanding of the bedrock fractures will help to explain the differences in transmissivity and drawdown between BW-1 and BW-2, as well as the significantly higher transmissivity needed in order to model the drawdown in BW-3.
APPENDIX: LIST OF PRESENTATIONS