A New Rapid Method for Measuring the Vertical Head Profile

by Carl Keller

Abstract

This study describes a new technique for measuring the head profile in a geologic formation. The technique provides rapid, low cost information on the depth of water-producing zones and aquitards in heterogeneous aquifers, yielding estimates of hydraulic heads in each zone while identifying any potential for cross contamination between zones. The measurements can be performed in a typical borehole in just a few hours. The procedure uses both the continuous transmissivity profile obtained by the installation (eversion) of a flexible borehole liner into an open borehole and the subsequent removal (inversion) of the same liner from the borehole. The method is possible because of the continuous transmissivity profile (T profile described by Keller et al. 2014) obtained by measuring the rate of liner eversion under a constant driving head. The hydraulic heads of producing zones are measured using the reverse head profile (RHP) method (patent no. 9,008,971) based on a stepwise inversion of the borehole liner. As each interval of the borehole is uncovered by inversion of the liner, the head beneath the liner is allowed to equilibrate to a steady-state value. The individual hydraulic heads contributing to each measurement are calculated using the measured transmissivity for each zone. Application of the RHP method to a sedimentary bedrock borehole in New Jersey verified that it reproduced the head distribution obtained the same day in the same borehole instrumented with a multilevel sampling system.

Introduction

The measurement of the vertical head profile in a borehole is traditionally performed with either straddle packers in an open borehole or a multilevel sampling system (MLS) sealed in a borehole. The straddle packer technique involves the lowering of the packers to each interval to be measured while most of the borehole is open to cross connecting flow. The packers are inflated and the head in the straddled interval is measured as the water level in a vertical pipe or with a transducer in communication with the straddled interval. The packer method has several disadvantages. The procedure is time consuming and is seldom done for more than a few predetermined intervals in the borehole. Only in rare

circumstances is it done over continuous short intervals for the entire borehole (Quinn et al. 2015). Leakage of the straddle packer either at the contact with the borehole wall or through the formation to the open hole is often detected when pressure transducers are placed above and below the packers (Shapiro 2002; Quinn et al. 2016). The risk of entrapment of straddle packer systems due to borehole slough can prevent the use of straddle packers in less stable formations.

An MLS is a robust method for measuring the vertical head profile but the number of sampling intervals is limited. Without foreknowledge of the head distribution it is likely that relevant intervals will be missed when designing and installing an MLS. Some MLS systems are relatively expensive and often permanently installed (Black et al. 1986; Cherry et al. 2007; Meyer et al. 2016). If the head profile can be measured quickly at low cost, it can be used to guide MLS design or even packer testing. Optimizing the number and location of sampling intervals can result in better information and large cost savings.

Another head profile measurement method developed recently uses a blank liner to seal many pressure transducers distributed in the borehole prior to the sealing liner installation (newly developed and unreported). The time to install the transducers and liner, the wait for the formation to equilibrate, and the later removal of the liner and the transducers to read the head measurements requires several days. The cost of the many pressure transducers and the labor of the procedure are the disadvantages.

Straddle packer systems are also used to extract water samples and to estimate the transmissivity of each straddled interval and not only for head measurements. Leakage of the straddle packer systems can obscure the transmissivity and the water quality measurements (Shapiro 2002; Quinn et al. 2016). Straddle packers are only fully reliable when each packer is located in an aquitard in a smooth borehole. Packers also suffer from the need to oppose ambient hydrostatic loading in the wellbore during inflation, creating serious equipment issues when operated at more than 100 m of water level depth.

Another method for the efficient estimation of transmissivity and hydraulic head has been in use for several decades and is based on use of high-resolution flowmeter logs (Paillet 1998). This method uses vertical flow measurements made under two different quasi-steady flow conditions (usually static and pumped) to simultaneously fit a flow model to the two data sets to solve for both transmissivity and hydraulic head in each water-producing interval. Numerical codes are readily available at no cost (Day-Lewis et al. 2011) to do the flow modeling and the flow profiles can be obtained as part of a conventional well logging program. A disadvantage with this method is lack of dynamic measurement range such as those producing zones with transmissivity values two orders of magnitude less than the most productive zone cannot be detected and quantified. When borehole diameter is very ragged, resolution may not achieve even one order of magnitude.

Another approach uses a single wire-operated packer outfitted with a differential pressure transducer to measure the hydraulic head difference between the intervals above and below each packer station (Paillet et al. 1998). The water level values for individual measurement stations can be then be converted to hydraulic head values for intervals between packer stations. The estimate technique uses a graphical method to compare the profiles of hydraulic head in the upper and lower intervals as a function of packer station depth. The primary disadvantage of this approach is that it has only been demonstrated using an experimental prototype probe and the equipment needed to use this application is not readily available.

A technique for rapid high spatial resolution of hydraulic head and transmissivity can reduce the need for cumbersome and expensive straddle packer measurements. Water quality measurement can be left to other methods such as a MLS which allows efficient water sample collection but the location of water-producing intervals needs to be known before installation of such systems. Existing methods for quickly profiling boreholes to identify water-producing zones and estimate vertical hydraulic head gradients either require equipment such as a wire line packer that is not readily available or suffer from limits on the ability to detect less productive zones. The reverse head profile (RHP) method described here can simultaneously identify producing zones and estimate the transmissivity and head of those zones all in a single effective operation providing all the information needed to prevent cross contamination and to install water sampling equipment.

The RHP method described herein was invented in 2009 and the patent awarded in 2015. The first test was in 2010 at a site in Guelph, Ontario. Since then several more tests have been completed with good comparisons with independent measurements of head profiles. Since the RHP can only be performed when a continuous transmissivity profile has been performed, this study treats the utility of the combination of the two measurements. Once the transmissivity and head distribution are in hand it is easy to calculate the flow into and out of the open borehole to assess the probable cross connection if the borehole is left open.

The transmissivity profile and the RHP can be performed in the first day after the borehole is drilled and developed, which fits well with the EPA Triad approach for rapid site characterization. However, in many cases the transmissivity profile and RHP are carried out after NAPL FLUTe and FACT^{TM} measurements (Keller 2016 in publication review) are completed, which is several weeks after the borehole is drilled and lined with a blank liner to prevent cross contamination.

By measuring the head profile and the transmissivity profile immediately after the borehole is completed, one can gain knowledge of discrete aquifers, aquitards, artesian conditions and extreme gradients early in the site assessment process. This early knowledge can be very important to the location of subsequent holes, design of MLS systems, or choice of other measurement methods. The guidance provided by the early transmissivity and head profile can reduce cost significantly. If combined with early information on NAPL distribution and other contaminant distribution, the transmissivity and head information is even more valuable. The RHP method, examples of its use, and confirmation of the measurement results are provided hereafter.

RHP Method

First, a FLUTe transmissivity profile must be performed with a flexible liner to obtain the continuous transmissivity profile according to the method invented by Keller et al. (2014) (patent no. 7,281,422). Such a profile was obtained on August 25, 2015 at the Naval Air Weapons Center (NAWC) in New Jersey. The geologic situation is dipping, fractured mudstones of the Lockatong Formation of Triassic age, of the Newark Basin in West Trenton, New Jersey as described by Goode et al. (2014). The borehole was an HQ 100 mm cored borehole to 45.7 m. The result of the everting liner flow measurement per unit driving head (Figure 1) gives the volume of water per unit time per driving head (L/s/m) leaving the borehole under the driving head measured by a transducer located at the bottom of the borehole. The downward velocity of the everting liner is controlled by the flow rate out of the borehole which depends on the transmissivity below the descending liner. As the everting liner seals each flow path, the
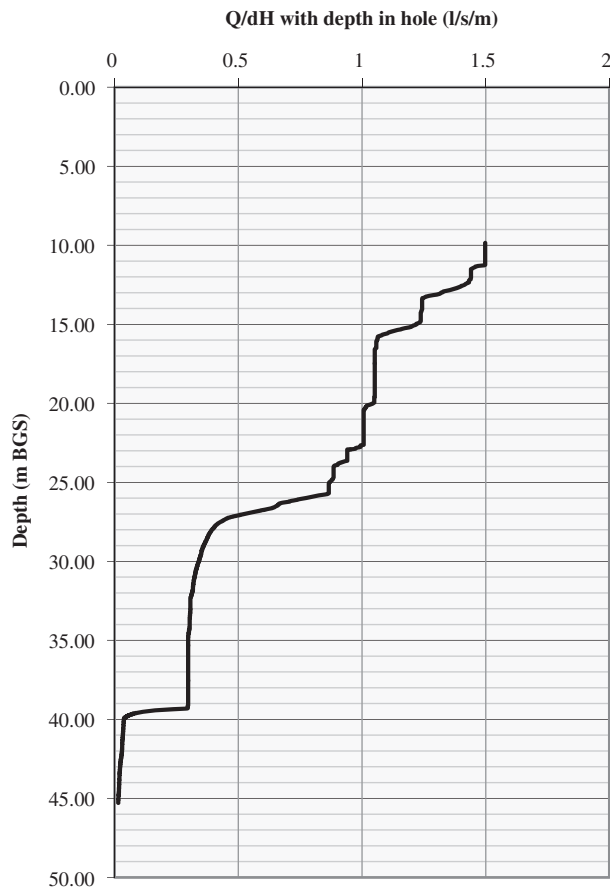
Figure 1. This is the original liner measurement of flow out of the borehole per unit driving head for a transmissivity profile in the 100 mm borehole at the NAWC site on August 24, 2015. The step changes in the plot are typically permeable intervals.
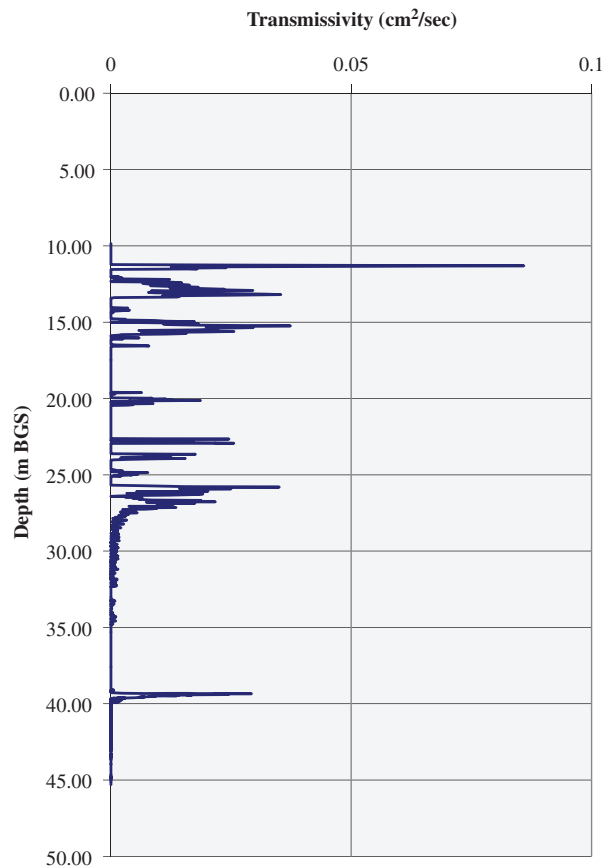

Figure 2. Individual transmissivity values in the NAWC hole 100 mm borehole calculated for each increment traveled by the liner in a half second (6660 data points).

remaining transmissivity below the liner is less than before the liner sealed the flow path and the liner descent rate is reduced. One can define a transmissivity of each increment of the borehole as the flow rate out of each interval divided by the head difference driving the flow. The total transmissivity T_{tot} of the borehole is determined from the sum of transmissivities of each interval (ΔT_i) of the borehole. This method initially assumes that there is no vertical gradient along the borehole so that the difference between the original open borehole water level and the measured head in the borehole beneath the liner is the head difference driving the flow below the liner. If hydraulic head differences between flow zones are later found to approach that of the water level difference driving the liner emplacement, the results need to be corrected as addressed below.

The actual caliper log was used for the borehole diameter which provides better definition of the flow rate in Figure 1 than if a constant borehole diameter is assumed when a caliper log is not available. Figure 2 is a plot of the transmissivity deduced from Figure 1 for each borehole interval traversed by the liner during every half second (6660 data points).

If one integrates the data from Figure 2 from the bottom of the borehole to the top, one obtains the transmissivity of the borehole below each depth on the vertical axis (Figure 3). Therefore, the transmissivity below 24.6 m is 1.65 cm²/s and that below 38.3 m is 0.56 cm²/s. The transmissivity in the interval is the difference 1.084 cm²/s between the two elevations. From Figure 3, one can obtain the transmissivity of any interval in the borehole. This kind of transmissivity data is generally useful and essential to the RHP method. Until that kind of data was available, straddle packers, flowmeter measurements, and MLSs were the only common options for a formation head profile.

The transmissivity profile shown in Figure 1 was performed in 0.9 h, and then the hole was left sealed by the liner. That typically leaves the rest of the day to do the RHP. However, the RHP in this borehole was performed the following morning.

If the transmissivity data in Figure 2 are integrated over 0.15-m intervals, one obtains Figure 4. Figure 4 is the result that one would expect if one had performed 300 separate 0.15-m straddle packer tests. In almost any situation, it is impractical to do that many packer tests. From Figure 4, it is easy to recognize the major flow zones in the borehole at the high transmissivity intervals.

In order to do a RHP, it is necessary to decide which borehole intervals are to be measured. Using Figure 4, each high flow zone was defined as an interval of interest.
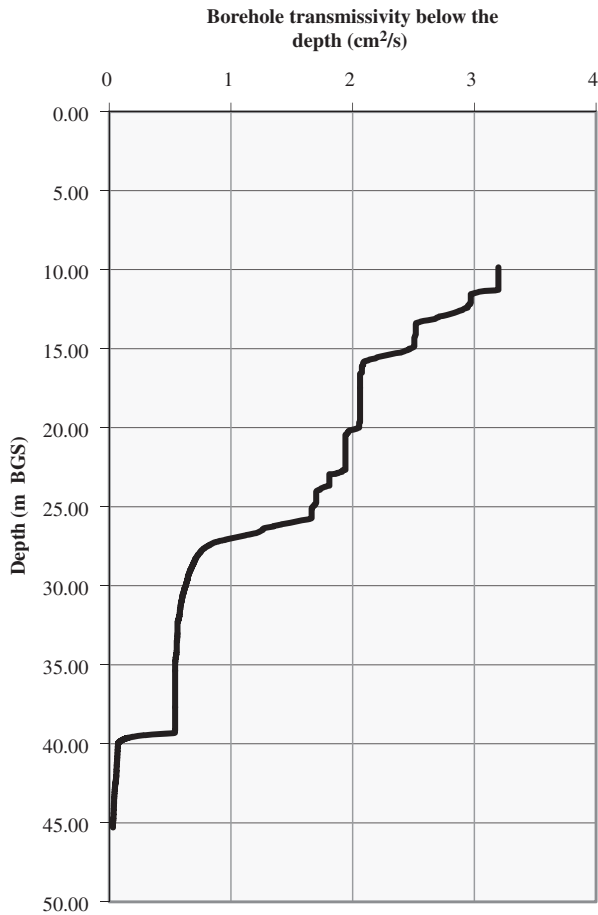
Figure 3. The integral of Figure 2 data from the bottom of the hole to the top. This graph is a measure of the transmissivity of the borehole below each depth on the vertical axis. Major drops in the curve are the high flow zones. The difference in the graph between any two elevations is the transmissivity of that interval.

The boundaries of those intervals were picked at borehole depths of 45.5, 43.2, 38.3, 24.7, 21.6, 19.4, 13.3, and 10.0 m (plotted as horizontal dashed lines in Figure 4). These intervals were selected to include the major flow zones. Lower transmissive intervals may separate aquifers of different head and therefore these selected boundaries lie in low transmissivity zones. The boundary depths below the surface are where the liner inversion will be halted as described hereafter.

The transmissivity of each interval was determined from the difference between the values of Figure 3 at each of those depths. Table 1 shows the stop depths (Z_i), the transmissivity values (T_i) at each depth, and the difference of the transmissivity values which are the ΔT_i values for each interval. The intervals are numbered from the bottom of the borehole to the surface.

RHP Procedure

The horizontal dashed lines in Figure 4 are the stop depths of Table 1 which bound the intervals over which the formation hydraulic head was measured. The
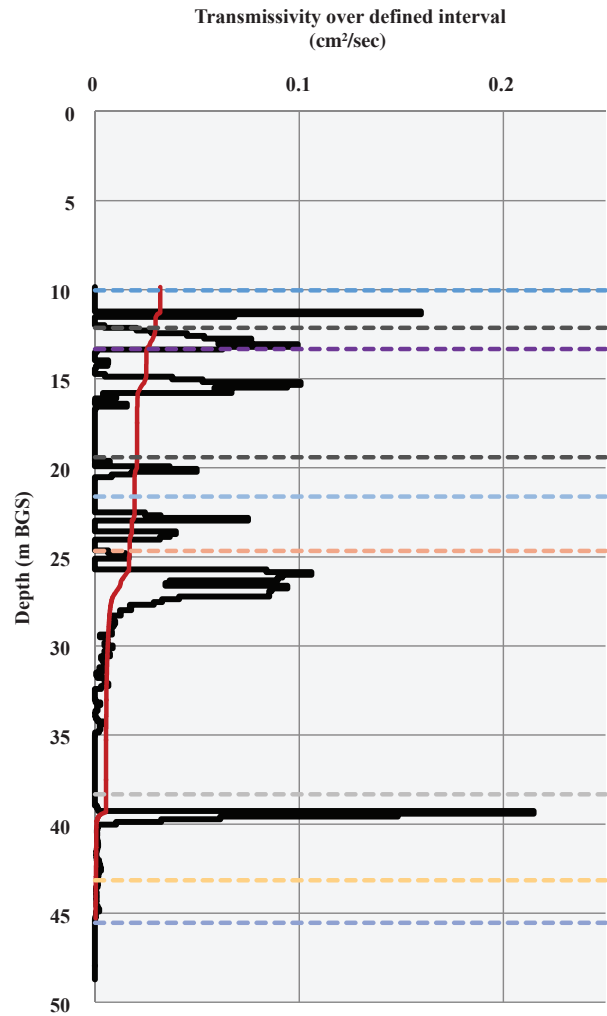

Figure 4. This is the integral of the data of Figure 2 in each 0.15-m interval. This is the equivalent of three-hundred 0.15-m straddle packer tests. The red line is an estimate of the reliability of the values (1% of the value of Figure 3). The horizontal dashed lines were picked as the stopping points for the RHP.

boundaries should be selected using all information available (e.g., the transmissivity profile and any other geologic information) that may define intervals of potentially different head. Exceptionally long intervals should be avoided. The head in the formation for each interval is defined as F_i.

When the transmissivity profile was completed, the final liner position in the borehole was as shown in Figure 5 at Z_1. The liner was near the bottom of the borehole. The transmissivity profile is halted when the remaining transmissivity beneath the liner is very low. That is usually when the liner descent rate has slowed to less than 0.0003 m/s. The measurement can be continued to a greater depth, but the remaining transmissivity is usually considered unimportant to the site characterization. The pressure transducer shown in Figure 5 was placed at the bottom of the borehole prior to the transmissivity profile to record the head history in the borehole during the transmissivity profile.

Table 1

Parameters Used in the Calculation of the Head Distribution in the Formation and the Flow into the Borehole

Interval No. in Order of Measure	Z_i, Stop Depths (m bgs)	T_i	ΔT_i	BH_i (m)	RHP, F_i (m)	RHP WT (m bgs)	Open Hole Flow (L/h)
1	45.629	0.031	0.031	43.102	43.102	2.591	−3.388
2	44.344	0.043	0.013	43.034	42.867	2.826	−2.447
3	40.737	0.542	0.499	42.976	42.971	2.722	−78.464
4	31.490	1.702	1.160	43.185	43.283	2.409	−51.944
5	23.134	1.941	0.240	43.197	43.278	2.414	−11.169
6	20.505	2.061	0.120	43.225	43.682	2.011	11.803
7	16.365	2.549	0.488	43.327	43.759	1.934	61.618
8	12.733	2.967	0.418	43.356	43.533	2.160	18.840
9	11.083	3.199	0.232	43.408	44.068	1.624	55.150

Notes: Z_i, stop depths in the borehole where the inversion is halted; T_i, transmissivity values from the transmissivity profile (Figure 3); ΔT_i, transmissivity values in each interval; BH_i, equilibrium heads measured at each stopping depth; F_i, formation heads calculated relative to the bottom of the borehole; RHP WT_i, hydraulic head values for each interval; Open Hole Flow, flow into and out of the borehole using the RHP values and the open borehole head (negative sign indicates outflow). Intervals are numbered from the bottom of the borehole. These results are from the iteration of the transmissivity profile with the RHP head values to account for vertical head differences driving flow along the borehole.
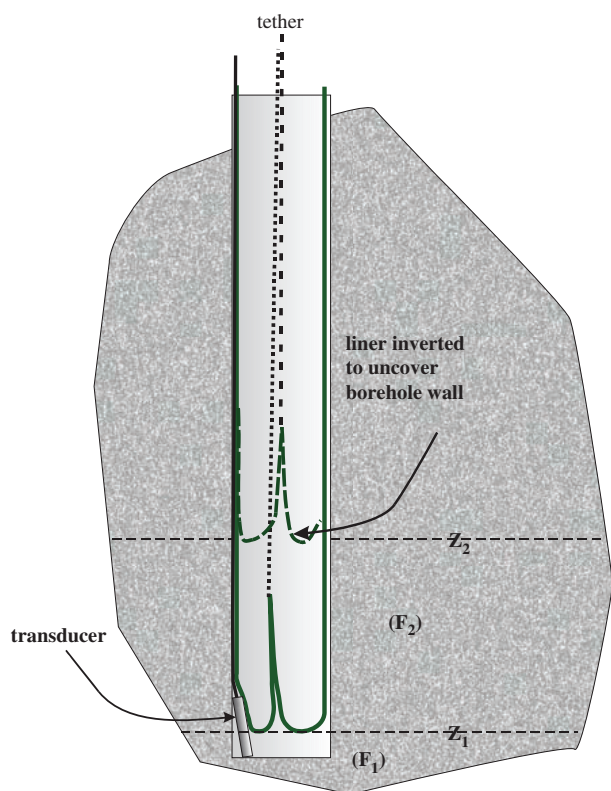

Figure 5. The green outline shows the position of the liner when the transmissivity profile was halted near the bottom of the hole at the depth Z_1. The first inversion of the liner (dashed green line) then uncovers a new portion of the borehole to the position Z_2.

After the transmissivity profile was completed and the liner descent halted, the pressure transducer was allowed to equilibrate to the head in the open hole beneath the liner. That head is then assumed to be the formation head in the remaining unsealed interval of the open hole. That open interval is defined as the first interval

in Table 1. The transducer pressure upon equilibration is defined as BH_1, the equilibration head in the borehole beneath the stationary liner at Z_1 (Figure 5). Therefore the equilibration head $BH_1 = F_1$, the formation head in that first interval. This is the initial condition of the RHP. One can write the flow equation for Q between the borehole and the formation in this first interval when equilibrium has been achieved as:

$$Q_1 = \Delta T_1 (F_1 - BH_1)\ 2\pi / \ln R = 0, \quad \text{or,} \quad F_1 = BH_1 \tag{1}$$

where ΔT_1 is the transmissivity in the formation over the open interval below the liner, F_1 is the formation head, BH_1 is the equilibration head beneath the liner, and $\ln R$ is the log of the ratio of the radius of influence to the radius of the borehole. The term $2\pi / \ln R$ is not important for the rest of this description, is assumed to be constant, and cancels out of all such flow equations where there is no net flow. This equation yields the familiar result that the water level (blended head) in a borehole open to multiple flow zones is the transmissivity-weighted average of the hydraulic head in those zones. The value of ΔT_1 is determined from the final liner velocity just before the transmissivity profile was halted. The RHP analysis assumes that the formation head is constant over each measurement interval ($Z_i - Z_{i-1}$). If there is any doubt, a test of this assumption would be to select smaller intervals in the borehole to see if that makes any difference in the results.

From this initial condition, the RHP is performed as follows:

The tether at the surface is untied and connected to a winch (or FLUTe linear capstan as described at http://flut.com/Equipment/equip.html). The tether and inverted liner tension are increased in order to invert the liner to a new depth Z_2 as listed in the Table 1. The borehole depth was 45.7 m for this example. The inversion

is then halted until the transducer pressure has equilibrated to a new head BH_2. This new geometry is shown in Figure 5. New flow equations can be written for the first interval, Q_1 and also for the newly uncovered interval of the borehole, Q_2, using the new equilibration head value, BH_2, and since $Q_1 + Q_2 = 0$, resulting in

$$F_2 = \Delta T_1 \left(BH_2 - F_1 \right) / \Delta T_2 + BH_2 \qquad (2)$$

Then the procedure is repeated. The liner is inverted to a new higher elevation, Z_3, and halted until the pressure transducer equilibrates to a new head, BH_3.

Writing three flow equations, one for each interval, $Q_1 + Q_2 + Q_3 = 0$, and,

$$F_3 = \left(\Delta T_1 \left(BH_3 - F_1 \right) + \Delta T_2 \left(BH_3 - F_2 \right) \right) / \Delta T_3 + BH_3 \qquad (3)$$

This procedure can be repeated, each time adding a new interval and equilibrating to a new borehole head, BH_i. Each time the liner is stopped, one can calculate a new formation head, F_i, from the previously calculated values of F_{i-1} and the measured BH_i and the T_i values obtained from Figure 3. Note in general,

$$F_i = \left(\Delta T_1 \left(BH_i - F_1 \right) + \Delta T_2 \left(BH_i - F_2 \right) \right.$$
$$\left. + \Delta T_3 \left(BH_i - F_3 \right) \ \ldots \ldots \right) / \Delta T_i + BH_i \qquad (4)$$

The result is the formation head profile shown in Figure 6 (green squares). Note that the sum of products in Equation 4 is divided by ΔT_i. If ΔT_i is a small transmissivity, it is not so well measured in the FLUTe transmissivity profiling method as is explained by Keller et al. 2014. Therefore, the division by a less well-measured value of ΔT_i can lead to a larger error in F_i than for other intervals. The data reduction procedure flags those formation heads calculated for relatively low ΔT intervals as devisors in Equation 4 and they are identified on the plot as red squares.

Results

The explicit measurements listed in Table 1 were used with the above formulation to generate the head profile shown in Figure 6 (green squares). The stopping points defining the boundaries of the measured intervals are also plotted as the horizontal dashed lines. The vertical red line defines the open borehole water table also called the blended head. It is noteworthy that several of the upper intervals have heads higher than the blended head and are therefore inflow zones into the open borehole. The red square is a low transmissivity interval subjected to relatively large measurement error as described above and discussed in the next section.

Hydrologic Adjustments to the Low ΔT Interval Heads

Since the transmissivity profiling method only resolves the transmissivity within about one percent of
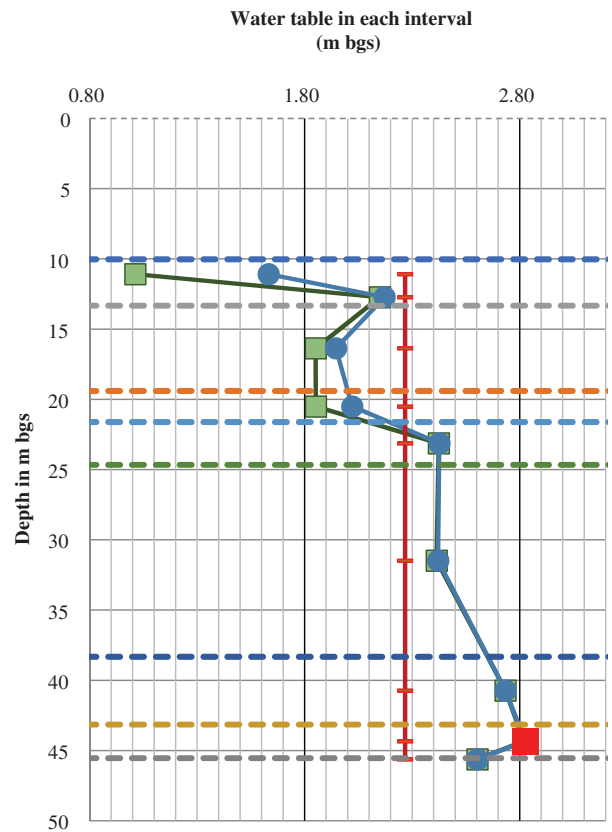

Figure 6. The plot of the RHP values deduced from the RHP in the 100 mm borehole at the NAWC site. The green squares are the direct calculation from the measured equilibrium heads and first transmissivity profile. The blue dots are the RHP values after use of the RHP values in the transmissivity profile calculation (the first iteration). The vertical red line is the original blended head in the borehole. The red plot points are for intervals with very low transmissivity values and therefore less reliable head calculations. The horizontal dashed lines are the stopping points.

the transmissivity below a given depth, the transmissivity of differences would be less reliable. The data reduction procedure identifies those intervals for which the ΔT_i is less than a defined fraction of the transmissivity beneath the top of each interval or less than a defined minimum value judged to be the limit of the transmissivity profile method. Two percent was used in the calculation for Figure 6 for the first fraction and $0.02 \, \text{cm}^2/\text{s}$ for the transmissivity limit which led to the red square identification of Figure 6. Because the red squares lie in low ΔT intervals and the head calculations above and below the red points are better defined, it is logical to assume that the heads in the low ΔT intervals lie between the head above and below the low transmissivity interval. A simple improvement/adjustment in the head estimate in the low transmissivity interval would be to pick a value that lies on the line between the two intervals above and below the red data points. In effect, this is simply a matter of smoothing the vertical head profile to remove excursions associated with values subject to large measurement error.

Correction of the Transmissivity Profile with the Measured Head Distribution

Because the transmissivity profile technique described by Keller et al. (2014) assumes the blended head in the open borehole is the formation head throughout the borehole depth, the transmissivity values will have some inherent error if the formation head distribution is very different from the water table in the open hole. However, with the head profile just deduced from the RHP method, a better assumption is to use the RHP head as the formation head in the transmissivity calculation of Keller. That was performed for this borehole. The result is shown in Figure 6 as the dark blue line with blue dots. The comparison of the two curves on Figure 6 shows the most significant change in the RHP was in the uppermost interval with only modest changes in the deeper intervals.

Flow Into and Out of the Borehole

The last measurement should produce the same head in the borehole as the blended head in the open hole because the last equilibrium position was in the casing (at 10.0 m bgs). In that case, it is useful to use the last blended head, BH_9 in this example, to calculate the flow occurring into or out of the open borehole by using the formation heads deduced from the measurement for the hydraulic head in each flow zone, the last equilibrium head as the open borehole water level, and the ΔT_i of each interval. The resulting flows are shown in Figure 7. The flow into the borehole is generally above 22 m. The flow out of the hole occurs primarily below 30 m with a large outflow at the single large fracture at 39 m (see Figure 4, the transmissivity profile). It is also noteworthy that the borehole flow is about one borehole volume every 2.5 h. Therefore, substantial cross connecting flow is expected when the borehole is open. The borehole flow calculation can be used to calculate a synthetic borehole flow log as described in "confirmation of the method."

Comparison of the RHP at the NAWC to Other Measurements

Ideally, the RHP would be compared to the measured head in a multilevel head measurement system immediately after the RHP. For the measurement above on August 25, 2015, there was no measurement of the actual head profile until March 17, 2016. The head distribution measured was after a heavy winter snow fall and a very heavy Spring rain 3 d prior to the installation of a Water FLUTe MLS. The head distribution measured 7 months later in the sealed borehole is shown in Figure 8 as the light blue curve with × plots in comparison with the RHP (dark blue curve and dots). The blended head in the open hole (vertical blue line) was 0.6 m higher than in August (vertical red line). Because of the 7-month delay and the large change in the hydrologic state the comparison is not considered a confirmation of the method. The two profiles (measured vs. RHP) are displaced by the amount of the blended head values and of a similar gradient, but it is also likely that the intermittent pump-and-treat pumping nearby has also shaped the head distribution with depth.
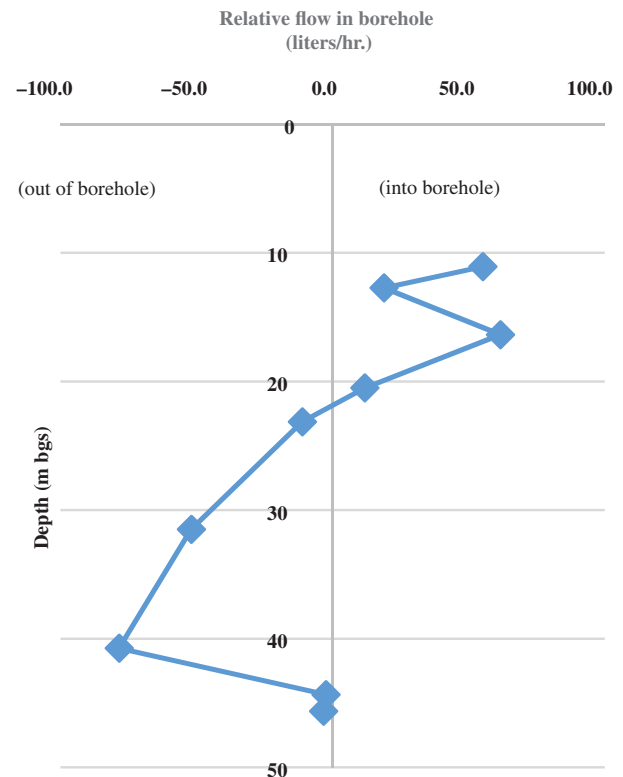

Figure 7. Calculated flow into or out of the 100 mm borehole (positive is into the borehole) using the calculated RHP values (Figure 7), the transmissivity for the intervals (Figure 3), and the equilibrium borehole head measured for the borehole at the highest liner position. The large flow out of the borehole is at the highly transmissive zone at 39 m (a gaping fracture on the video log).

Time Required for the Measurement

This describes how the measurements were performed on August 24 and 25, 2015. The transmissivity profile was performed in the afternoon of the 24th in 0.9 h after the FLUTe liner with a NAPL FLUTe and FACT system had been removed from the borehole and those contaminant mapping systems were removed from the inverted liner. The RHP was performed the next morning using the same flexible liner in 2.5 h. Most of the time needed was to allow the pressure transducer to equilibrate to determine the BH_i values for each interval. However, only about 15 min was sufficient for equilibration of each interval. In that time, we can use the transducer data to calculate the asymptote of the equilibration. The data of the last 10 min of each equilibration interval were used to determine the long-term asymptote.

While the transmissivity profile and RHP can be performed in the same day, the prior removal of a sealing liner is usually required and may require more time for the removal, transmissivity profile, reverse head measurement, and reinstallation of the blank liner. It is also useful in many cases to be able to perform geophysical measurements in the same hole after the RHP and before the final reinstallation of the sealing liner. The sealing liner is often then left in place until a monitoring well installation is to be done in the same borehole.
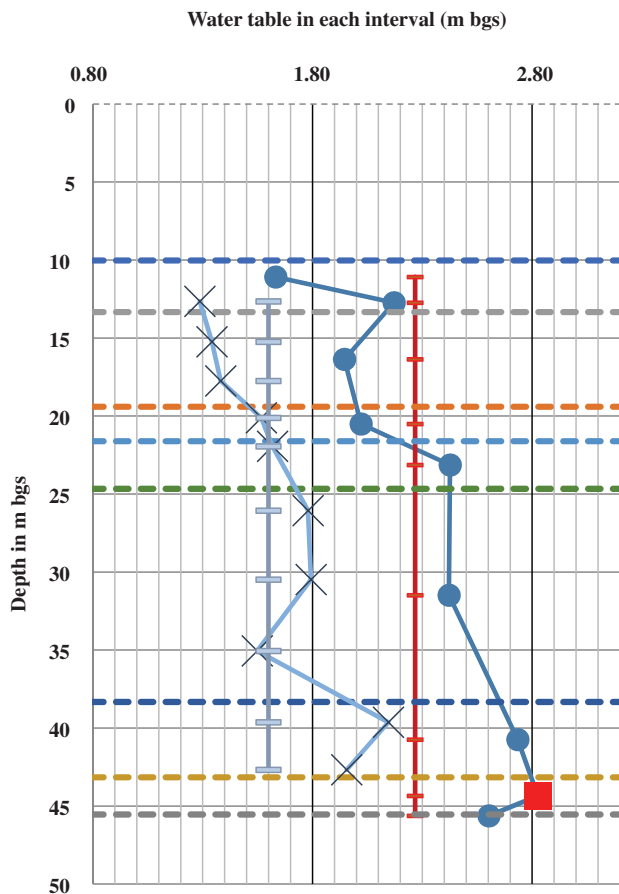
Water table in each interval (m bgs)

Figure 8. The RHP result (dark blue curve) calculated with the refined transmissivity profile in the NAWC borehole. The light blue (×) head values were measured with a Water FLUTe™ MLS in the same hole, but 7 months later (March 17, 2016) after heavy snow and rainstorms. The vertical blue line is the open borehole water table 7 months later. The offset of the blended heads (red to blue vertical lines) in the open hole is similar to the offset of the head distributions 7 months later, but otherwise the two curves are significantly different. The average gradients are very similar. Pump and treat wells were also operational during the 7-month interval and would influence the head distribution.

It has been observed in more recent installations that a longer wait is necessary for lower transmissivity boreholes for a sufficient equilibration of the head beneath each stopping elevation. The time to approach equilibration is examined by Flach et al. 2000 for flowmeter testing. In that study, the time to equilibration was found to depend directly on the radius of the borehole squared, the storativity of the formation, and inversely on the transmissivity of the borehole. The transducer reading measured for the RHP method can be observed during the measurement to better determine the time required to sufficiently approach equilibration. The total transmissivity for the NAWC borehole was $3\,\text{cm}^2/\text{s}$. The ability to extrapolate to the asymptote of equilibration is better the nearer the head measured is to equilibrium, since the borehole is nearer a steady-state flow condition and flow modes are more nearly laminar.

Confirmation of the Method

A more definitive test of the RHP method was performed in a 154-mm diameter borehole to 30.5 m at a second fractured rock site in New Jersey on December 21, 2015. The geologic situation was bedrock beneath the site consisting of the Passaic Formation of the late Triassic age predominantly of sandstone with shale beds and lenses of conglomerate. Bedding planes and joints were identified throughout shallow bedrock. The transmissivity profile had been performed several months before and the blank liner had been left in place with the transducer at the bottom of the hole. When a Water FLUTe multilevel system was to be installed, the blank liner was removed while performing the RHP measurements. A Water FLUTe multilevel flexible liner system was installed immediately. After the formation head was allowed to stabilize, the water table at each of four sampling intervals was measured in the MLS system on the same day as the RHP and compared to the head distribution measured with the RHP. The result is shown in Figure 9. The agreement is excellent. The RHP values were then used to update the transmissivity profile. However, since the driving head for the transmissivity profile was well above the head variations in the formation, the change was negligible in the new RHP with the revised transmissivity values. The total second borehole transmissivity was about $1\,\text{cm}^2/\text{s}$ and sufficient equilibration was achieved in 15 min for each measurement.

Flow into and out of the second borehole was calculated from the transmissivity and head information for the open borehole (Figure 10). The flow into the borehole is above the 20 m depth and associated with the higher head difference at 12 m and the very transmissive interval from 16 to 17 m. Figure 10 also shows the transmissivity profile for the second borehole.

A synthetic open borehole flow log was also calculated from the flow into the borehole (Figure 10). The peak downward flow rate was 0.2 L/min. This information is very useful to assessments of potential cross connection effects while the borehole is open as described by Sterling et al. 2005 especially if associated with knowledge of the contaminant distribution.

Discussion

The RHP is performed quickly with an expected halt at the top of each measurement interval to last for approximately 15 min for sufficient equilibration of the head beneath the liner. If an equilibration has not been achieved in that time, the final asymptote may be calculated from the measured head data based on the assumption that the convergence to an asymptote is an exponential. Therefore, the time needed to perform a profile of the entire borehole is dependent on the number of intervals measured. A reasonable resolution may be 8 to 10 intervals in 2.5 h. Less transmissive boreholes (e.g., $<0.4\,\text{cm}^2/\text{s}$) will require a longer wait. Since equilibrium is never reached mathematically, the calculation of the asymptote, as was carried out for
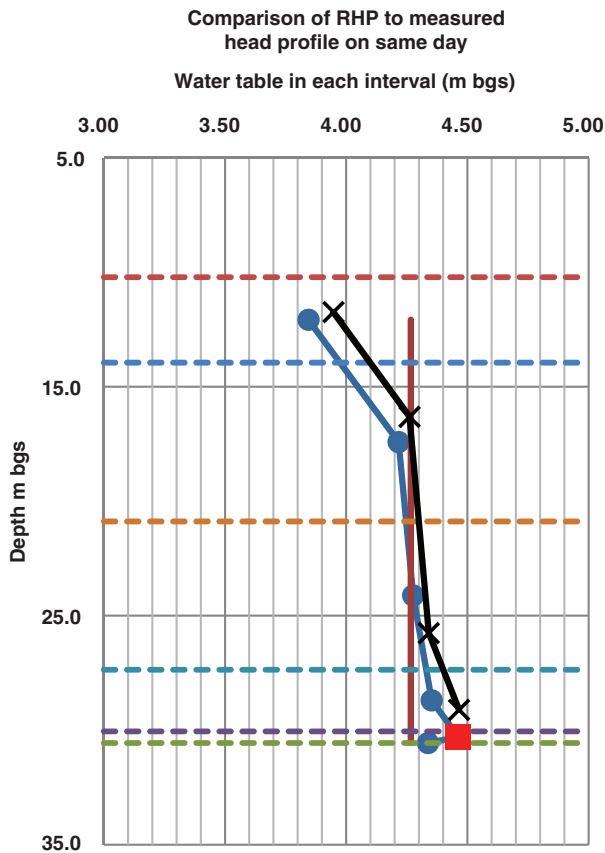
**Comparison of RHP to measured
head profile on same day**

Water table in each interval (m bgs)

Figure 9. RHP head (blue curve) calculated from equilibrium heads and transmissivity (T) values measured in a 150 mm borehole in NJ. The black line is the head measured on the same day in a Water FLUTe^TM MLS system in the same borehole. The red data point of the RHP plot has a low transmissivity value in the interval and is therefore less reliable. The horizontal dashed lines are where the liner was stopped to record the equilibrium head as the liner was inverted from the borehole.

Figure 9, is recommended. A high storativity such as for an unconfined aquifer may require a very long time to equilibrate. A series of 20 or more intervals is possible in 1 d. The continuous transmissivity profile allows many intervals for measurement and also shows the relative importance of each such zone as a proportion of the total borehole transmissivity.

The head in each interval is calculated from an equation with the transmissivity of that interval as a denominator. Therefore, the error of the head calculated is directly dependent on the error inherent in the measured transmissivity of that interval. Relatively low transmissivity intervals are not well measured by the FLUTe transmissivity profiling method (Keller et al. 2014) and therefore those intervals have higher uncertainty. To identify those intervals, the ΔT_i of each interval is compared to both the total transmissivity below that interval and also a defined test value considered to be the limit of resolution of the transmissivity profile. Relatively low ΔT intervals are identified and plotted as red points on the graph (e.g., Figure 6). Those calculated head values should be considered uncertain. For those intervals of low ΔT, one can

expect the actual head to lie between the head above and the head below the low ΔT zone. It is recommended that a caliper log be used in the calculation of transmissivity to obtain the best result.

Fortunately, the head at each interval is also calculated from the sum of the ΔT and head products for each interval (Equation 4). Therefore, intervals with low transmissivity contribute less to the sum and are therefore less important to the error in the high transmissivity intervals. The transducer measurement of the equilibrium head at each elevation where the liner is halted is of relatively high resolution ($\sim$0.05% of full scale) and provides a useful measurement of the blended head of the interval below the liner station.

Because the transmissivity profile calculated from the liner measurement is dependent on the actual formation head distribution (Keller et al. 2014) and not the water level in the open hole as assumed in the initial transmissivity profile calculation, it is useful to use the RHP measured to refine the head used in the transmissivity profile calculation. For that reason, it is also useful to perform the initial transmissivity profile with a driving head well above the open borehole head and therefore probably well above the formation head variations so that all flow is out of the borehole. If the RHP head profile result is very different (e.g., >1 m) from the open borehole head, it is recommended that the transmissivity calculation be redone using the RHP result as the formation head profile. If the resulting transmissivity profile does not change the RHP values significantly, no further iterations are needed. Neither the liner velocity for the transmissivity measurement nor the equilibrium measurements of the RHP procedure are changed by the iterations.

It is reasonable that low ΔT intervals of uncertain head be combined with adjacent intervals for more well-behaved results. However, it is also useful to apply hydrologic judgment to correction of the head in the low transmissivity intervals. Significant excursions in low ΔT intervals departing from the hydraulic head distribution in adjacent intervals associated with larger transmissivity values may not be meaningful. When such excursions are considered unreliable, the zone in question might be assumed to have a head value lying between heads of the more transmissive intervals immediately above and below. If an iteration of the transmissivity profile is performed, the head values in the low ΔT intervals should be adjusted accordingly.

The location of the stopping points for the head profile is best selected so that each interval straddles a high flow zone as seen on the transmissivity profile. The reason is that the high flow zones are often the determining factors of the head in an interval. Low flow zones may or may not be aquitards. Including two aquifers or flow zones of different head in one measurement interval only reduces the resolution of the profile, so it is better to err on the side of too many zones rather than too few.

As described above, it is very useful to use the transmissivity profile (Figure 4) as a guide for selection of
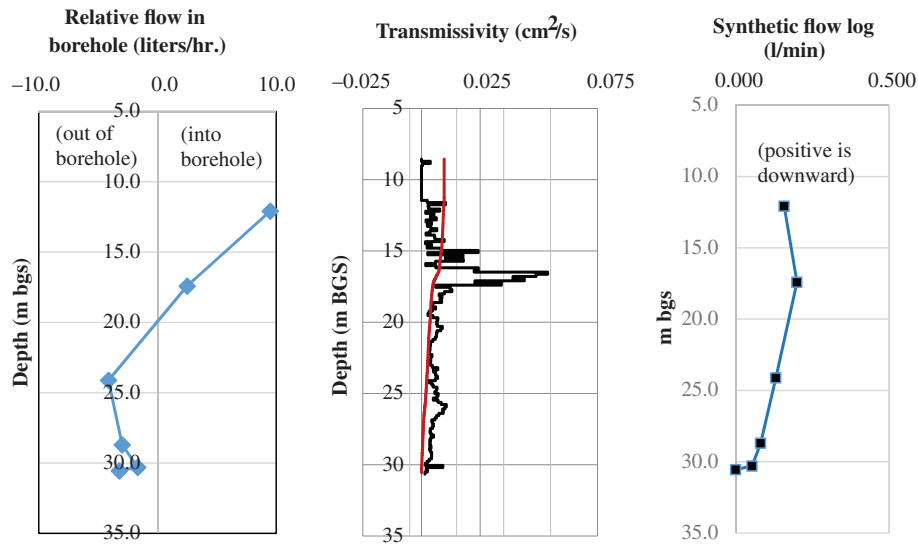
Figure 10. Flow into and out of 150 mm borehole calculated from the formation head, interval transmissivity values, and the water table in the open borehole. The vertical flow plot is a synthetic flowmeter log from the relative flow plot.

the stopping elevations of the inverting liner. The transmissivity profile has extraordinary spatial resolution as compared to most transmissivity measurement methods. The transmissivity profile data can be reduced quickly to allow immediate selection of stopping elevations.

A reasonable concern is whether the flexible liner is a sufficient seal of the borehole to avoid communication with flow zones above the bottom end of the liner while the equilibrium state is developing below the liner. Since the recommended practice is to have each measurement interval straddle a flow zone, the measurement interval often includes the enlarged sections of the borehole due to higher fracture frequency. The less permeable intervals above the more permeable intervals are therefore well sealed by the liner. The elevations for stopping of the liner should be selected to be relatively low transmissivity zones. The borehole photo of a liner in place (Figure 11) shows how well the thin, strong liner melds with the borehole wall. The liner is also of a somewhat larger diameter than the nominal borehole to allow the liner to meld the better with the borehole wall, sealing the borehole against vertical flow.

Another reasonable concern is the small, but finite, flow adjacent to the transducer cable and its effect on the equilibrium pressures. While generally not significant, the transducer can be suspended on an extremely slender steel cable. The transducer data are then recovered after the RHP is completed and both the refined transmissivity and RHP can be calculated using the transducer data. The initial transmissivity profile for selection of the stopping elevations can be performed, as was originally done with the transmissivity profile method, using the measured liner tension and the water level inside the liner to estimate the head beneath the liner (Keller et al. 2014).

It is noteworthy that a convenient time for any geophysical measurements in a borehole is when the liner has been removed during the RHP and the borehole

Figure 11. A borehole video snapshot of the interior of a 150 mm blank liner. The liner melds very well with the dolomite borehole wall, even over a ledge in a breakout in the upper left corner of the photo. Individual vugs are visible behind the liner (top of photo). Packers cannot conform so easily to the borehole wall.

is open. After the geophysical measurements, the blank liner can be reinstalled to seal the borehole. The ability to calculate a synthetic open borehole flow distribution allows useful confirmation of the head and transmissivity profiles by comparison with a flowmeter log of the hole without pumping. Comparison of expected flow zones with features in televiewer images is another reassurance of the transmissivity and RHP profile results. If the flow into or out of the borehole does not match a visible flow feature of a high quality televiewer log, one should be suspicious of the result.

The results of the transmissivity profile, head profile, and borehole flow calculations are entirely self-consistent and easily compared to open borehole water levels and other common measurements.

To date, the transmissivity and RHP measurements have been performed by experienced FLUTe crews. The RHP procedure could be performed by most field personnel after FLUTe completes the transmissivity profile, but with FLUTe at the wellhead, the RHP would normally be performed by FLUTe personnel. FLUTe provides the conversion of the RHP data to a head profile. The downhole transducer is recovered after the RHP.

Conclusion

Both the transmissivity profile with high resolution and the head profile in a borehole (often performed in a single day) provide very useful hydrologic information in site characterization and monitoring. That information can be used in the design of any additional diagnostics, and can be used in calculational assessments of groundwater transport in the subsurface. The identification and characterization of artesian intervals, aquitards and discrete aquifers is a significant aid to the design of multilevel systems for water quality and head histories. Coupled with site models and numerical calculations, one can gain important insight into the potential contaminant migration paths or the groundwater flows to be expected near mining facilities and other subsurface installations such as municipal water wells.

Additional measurements of contaminant distribution and geophysical measurements such as the several televiewer methods, caliper logs, and borehole flow logs provide valuable complementary information and confirmation of the measurements of the combined transmissivity and head profiles described here.

In the examples provided, the ability to calculate the flow rates into the borehole is very useful for evaluation of potential cross connection effects on other measurements such as the FLUTe FACT or packer testing, if done. While the best confirmation of the method is an MLS measurement immediately after the RHP is performed, the results of a RHP are most useful in the early stages of a site investigation. The MLS systems provide long-term histories of head and contaminant levels, but are most effective when continuous profiles of hydraulic parameters have been done to guide the design of the MLS equipment installation.

Acknowledgments

References

Black, W.H., H.R. Smith, and F.D. Patton. 1986. Multiple-level ground-water monitoring with the MP system. In *Proceedings of the Conference on Surface and Borehole Geophysical Methods and Ground Water Instrumentation*. Dublin, Ohio: National Water Well Association.

Cherry, J.A., B.L. Parker, and C. Keller. 2007. A new depth-discrete multilevel monitoring approach for fractured rock. *Ground Water Monitoring and Remediation* 27, no. 2: 57–70.

Day-Lewis, F.D., C.D. Johnson, F.L. Paillet, and K.J. Halford. 2011. A computer program for flow-log analysis of single holes (FLASH). *Groundwater* 49, no. 6: 926–931.

Flach G.P., F.C. Sappington, W.P. Johnson, and R.A. Hiergesell. 2000. Electromagnetic borehole flowmeter (EBF) testing in R-area. WSRC-TR-2000-00170. Aiken, South Carolina: Westinghouse Savannah River Company Savannah River Site.

Goode, D.J., T.E. Imbrigiotta, and P.J. Lacombe. 2014. High-resolution delineation of chlorinated volatile organic compounds in a dipping fractured mudstone: Depth-and strata-dependent spatial variability from rock-core sampling. *Journal of Contaminant Hydrology* 171: 1–11.

Keller, C.E., J.A. Cherry, and B.L. Parker. 2014. New method for continuous transmissivity profiling in fractured Rock. *Groundwater* 52, no. 3: 352–367.

Meyer, J.R., B.L. Parker, E. Arnaud, and A.C. Runkel. 2016. Combining high resolution vertical gradients and sequence stratigraphy to delineate hydrogeologic units for a contaminated sedimentary rock aquifer system. *Journal of Hydrology* 534: 505–523.

Paillet, F.L. 1998. Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations. *Water Resources Research* 34: 997–1010.

Paillet, F.L., A.E. Hess, and J.H. Williams. 1998. Design, operation, and data analysis for a wireline packer system in open boreholes, with field-test results from Belvidere, Illinois. U.S. Geological Survey Open-File Report 98–413, 23. Reston, Virginia: USGS.

Quinn, P., J.A. Cherry, and B.L. Parker. 2015. Combined use of straddle packer testing and FLUTe profiling for hydraulic testing in fractured rock boreholes. *Journal of Hydrology* 524: 439–454.

Quinn, P., B.L. Parker, and J.A. Cherry. 2016. Blended head analyses to reduce uncertainty in packer testing in fractured-rock boreholes. *Hydrogeology Journal* 24, no. 1: 59–77.

Shapiro, A.M. 2002. Cautions and suggestons for geochemical sampling in fractured rock. *Groundwater Monitoring & Remediaiton* 22, no. 3: 151–164.

Sterling, S.N., B.L. Parker, J.A. Cherry, J.H. Williams, J.W. Lane Jr., and F.P. Haeni. 2005. Vertical cross contamination of trichloroethylene in a borehole in fractured sandstone. *Groundwater* 43, no. 4: 557–573.