OBSERVATIONS FROM BOREHOLE DILUTION LOGGING EXPERIMENTS IN FRACTURED CRYSTALLINE ROCK UNDER AMBIENT AND PUMP TEST CONDITIONS

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Abstract

Identifying hydraulically active fractures in low permeability, crystalline-bedrock aquifers requires a variety of geophysical and hydrogeophysical borehole tools and approaches. One such approach is Single Borehole Dilution Tests (SBDT), which in some low flow cases have been shown to provide greater resolution of borehole flow than other logging procedures, such as vertical differential Heat Pulse Flowmeter (HPFM) logging. Because the tools used in SBDT collect continuous profiles of water quality or dye changes, they can identify horizontal flow zones and vertical flow. We used SBDT with a food grade blue dye as a tracer and dual photometer-nephelometer measurements to identify low flow zones.

SBDT were conducted at seven wells with open boreholes (exceeding 300 ft). At most of the wells HPFM logs were also collected. The seven wells are set in low-permeability, fractured granite and gneiss rocks underlying a former tetrachloroeythylene (PCE) source area at the Savage Municipal Well Superfund site in Milford, NH. Time series SBDT logs were collected at each of the seven wells under three distinct hydraulic conditions: (1) ambient conditions prior to a pump test at an adjacent well, (2) mid test, after 2-3 days of the start of the pump test, and (3) at the end of the test, after 8-9 days of the pump test. None of the SBDT were conducted under pumping conditions in the logged well. For each condition, wells were initially passively spiked with blue dye once and subsequent time series measurements were made.

Measurement accuracy and precision of the photometer tool is important in SBDT when attempting to detect low rates of borehole flow. Tests indicate that under ambient conditions, none of the wells had detectable flow as measured with HPFM logging. With SBDT, 4 of the 7 showed the presence of some very low flow. None of 5 (2 of the 7 wells initially logged with HPFM under ambient conditions were not re-logged) wells logged with the HPFM during the pump test had detectable flow. However, 3 of the 5 wells showed the patterns of very low flow with SBDT during the pump test including pumping induced changes of inflow and outflow patterns at one well.

Introduction

Understanding the location of hydraulically active fractures and fracture connectivity in crystalline-rock aquifers is critical in the delineation of contaminant pathways and assessing risk to possible receptors. One of the standard suites of tools used to detect fractures and borehole flow in open boreholes is a Heat-Pulse Flowmeter (HPFM). HPFM measurements are made with the tool in a stationary position in the borehole at discrete intervals (non-continuous). Most HPFMs measure only the vertical movement of fluid in a borehole and require differences in inflows and outflows at any given depth (Keys, 1990). A HPFM with a diverter to channel flow through the tool can usually measure flow

of 0.01 to 1.5 gallons per minute (gal/min). HPFM logs are typically collected under ambient conditions (no pumping in logged well), and under low rates of pumping (less than 1 gal/min; called pumping HPFM) with the pump in the casing of the logged well. HPFM logging under low rate pumping identifies hydraulically active fractures for low-flow conditions. We arbitrarily define hydraulically active fractures as yielding a minimum of 0.01 gal/min (40 milliliters per minute (mL/min)).

Relatively long (> 300 ft) open boreholes are typically drilled in fractured crystalline-rock aquifers of the northeastern U.S. to intersect a sufficient number of water-bearing fractures to supply water to a well or intersect hydraulically active fractures for groundwater sampling. This criterion applies for residential-supply wells, large water-supply wells, or monitoring wells. By drilling long open boreholes, artificial conduits are created between fractures that would normally not be connected. As a result, induced transport of contaminants can occur if a single fracture contains contaminated groundwater.

Monitoring wells with open boreholes are sometimes left in place at contaminated sites if ambient flow is undetected with HPFM. However, a significant mass of contaminants can be transported regardless of whether flow is detected with HPFM. For example, vertical flow rates as little as 0.005 gal/min (below most tool detection levels) with a contaminant concentration of tetrachloroethyelene (PCE) difference of 10,000 micrograms per liter (µg/L) between fractures can promote transport of as much as 100,000,000 µg of PCE mass in an open borehole in a year. Regardless if vertical flow occurs in the borehole, contaminants can be redistributed by in-well mixing (Vroblesky and Peterson, 2004).

In low-permeability rocks or in cases where flow is primarily horizontal, ambient vertical flow may be undetectable with HPFM. The determination of ambient flow is often made with just a single HPFM log and uncertainty regarding accuracy and consistency of borehole flow (transient variations) exists. Borehole fluid logs that measure temperature or conductivity can be used to assist in the determination of horizontal flow (Williams and Paillet, 2002). However, fractures with similar horizontal inflowing water conductivity and temperature as that of the wellbore can go unnoticed.

Single Borehole Dilution Tests (SBDT) (Pitrak et al., 2007; Maurice et al., 2011) can potentially identify flow at one-order of magnitude (.0003 gal/min) lower than HPFM logs (.005 gal/min). SBDT measure essentially a continuous profile of the borehole, which facilitates identification of horizontal and vertical borehole flow. Successive logs identify changes in dye concentrations over time. Under ambient conditions, SBDT can be used to map patterns of borehole flow between fractures intersecting the well. Under pumping conditions (single well pumping) in the logged well, SBDT can be used to determine the transmissivity of fractures (Brainerd and Robbins, 2004).

This paper presents findings from SBDT done in fractured granite and gneiss underlying a former PCE source area at the Savage Municipal Well Superfund site in Milford, NH. Time series logs from SBDT were collected at each of the seven wells under three distinct hydraulic conditions: (1) ambient conditions prior to a pump test at an adjacent well, (2) mid test, after 2-3 days of the start of the pump test, and (3) at the end of the test, after 8-9 days of the pump test. None of the SBDT were conducted under pumping conditions in the logged well. The primary objective of this work is to identify borehole flow conditions and fracture connectivity under ambient and pump-test conditions from a 2013 pump test. The boreholes intersect fractures at different depths with various concentrations of PCE. The results of the SBDT will be used to improve monitoring strategies at the site including long-term groundwater sampling of hydraulically active fractures. Further, findings will be used to assist in the development of remedial plans to mitigate PCE contamination.

A comparison of SBDT with HPFM logs collected under ambient conditions and during the pump test (called pump test HPFM) is included as a frame of reference and to provide insight into potential differences as it relates to borehole flow. Comparative measurements between SBDT and

HPFM were not done under rigorously controlled conditions and readers should consult other studies for a quantitative comparison (Paillet et al., 2010).

Overview of Ambient Water Flow in Open Boreholes in Crystalline Rock

Movement of water through crystalline-rock aquifers of the northeastern U.S. is dependent on the presence of secondary porosity such as fractures and joints. A schematic of ambient borehole flow in an open borehole is shown in Figure 1. Similar patterns can occur in wells undergoing low rates of pumping as long as the pumping rate does not exceed potential fracture inflows. Vertical flow occurs as a result of the differences in hydraulic head and transmissivity of fractures that intersect the open borehole. Vertical flow is induced only when fracture inflows do not equal fracture outflows (net change in flow) at a given depth. For the example provided, a net change in flow occurs at fractures F1, F2, F4, and F5 (Figure 1). Under cross flow conditions where inflow equals outflow (zero net change in flow) at a fracture (F3; Figure 1), no detectable change in flow can be observed with conventional vertical differential HPFM logging. In contrast, SBDT can detect a zero net cross flow (inflow = outflow) (F3; Figure 1) by a decrease in dye concentration or an inflection point in the logged profile.
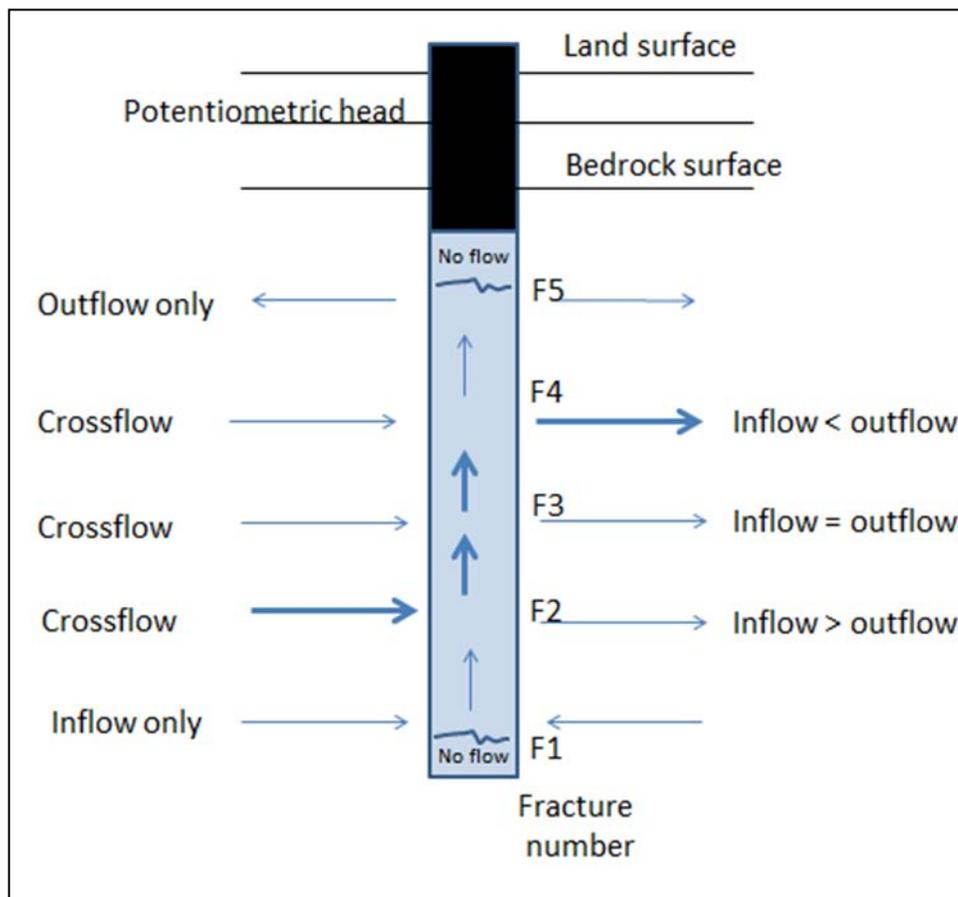

Figure 1: Schematic of borehole flow patterns, under ambient conditions or where the pump rate is less than the well yield, in an open borehole intersected by multiple fractures (modified from Maurice et al., 2011) [Arrow width shows relative vertical flow rates]

Description of Study Site and Pump Test

The bedrock system (designated as operable unit #3 (OU3)) underlying the Savage Municipal Well Superfund site offers an excellent case study of borehole flow in relatively long open boreholes set in fractured crystalline rocks of the northeastern U.S. The underlying rocks are predominantly granite and gneiss with a preferred northeast strike and westerly dip (Burton and Harte, 2013). A network of approximately sixteen long open borehole wells has been installed at the site. Tetrachloroethylene (PCE) has been detected in groundwater from deep (>300 feet below land surface) fractures in monitoring wells to the south and north side of the Souhegan River (Weston Solutions, Inc., 2010) (Figure 2). The source of the PCE is an overlying unconsolidated sediment aquifer. For remedial purposes, the overlying aquifer is divided into 2 operable units (OU1 and OU2). OU1 contains a low permeability slurry "barrier" wall that encircles known source areas (Figure 2). Both OU1 and OU2 contain injection and extraction wells for hydraulic control of the dissolved plume. Ambient flow has been measured with HPFM logging in only 1 of the 11 wells logged (Weston Solutions, Inc., 2012). Discrete fracture groundwater samples (7-23 ft packer intervals) were collected with a straddle packer assembly during hydraulic testing at the 16 wells and sometimes showed large (100,000 µg/L) concentration differences in PCE.
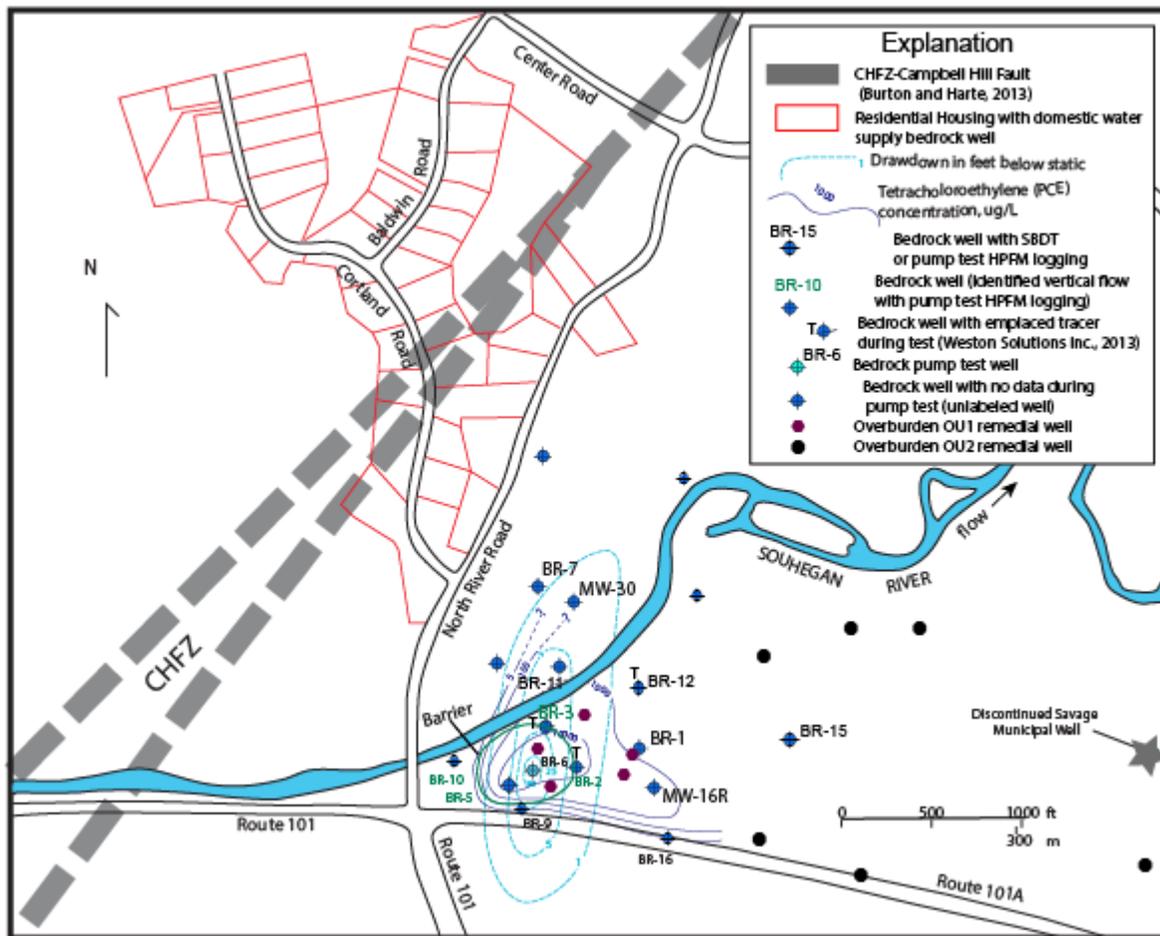

Figure 2: Site map with well locations (information on pump test drawdowns and tetracholoroethylene (PCE) concentrations from Weston Solutions, Inc. 2012).

A previous pump test in December 2010 and in 2013 (this study) identified a preferred north-northeast hydraulic connection at most wells, which trends near (to the east) some residential, bedrock water supply wells (Figure 2). Two bedrock monitoring wells on the north side of the River have PCE concentrations above 10 µg/L, although, wells closest to the residential wells have no detectable PCE concentrations. Given the proximity of the residential wells to contamination, it is important to identify potential pathways of contaminant transport, or hydraulic connection, under current and potential future conditions.

Flow has generally not been observed during ambient HPFM logging, but during single well pumping at low rates (typically less than 1 gal/min), pumped HPFM logging has generally identified several fractures contributing to flow in the borehole. For the pump test in December of 2010, where extraction was approximately 9 gal/min from an adjacent well (BR-6), pump test HPFM logging at 6 nearby monitoring wells observed borehole flow in 3 wells that previously had no detectable ambient flow. The three wells with measured borehole flow were aligned north-northeast of the pumping well indicating an anisotropic hydraulic connection in the rock.

In April of 2013 (this study), the pump test was performed for 9 days at the same well (BR-6), which is located inside the barrier wall in OU1 (Figure 2). During this test, SBDT logs, HPFM logs, and independent tracers were used to identify intrawell and interwell connectivity (Weston Solutions, Inc., 2013). Well BR-6 was pumped at a rate of 9 gal/min (same as the April 2010 test) and drawdowns exceeded 100 ft. The well has an open borehole from 110 to 500 ft below top of casing.

Method Application

A dual photometer and nephelometer probe (model HFN-381, W&R Instruments [1], Inc.) was used for SBDT. The probe connects to a standard borehole drawworks and associated instruments. Photometer and nephelometer values are initially recorded in counts per second of scatter. The photometer measures direct light penetration whereas the nephelometer measures side scatter and is essentially a downhole turbidity meter. Both are converted to units of g/10L using factory calibrations. One g/10L is equivalent to 100 mg/L. Data from turbidity meters are typically recorded in NTU (nephelometic turbidity units). Twenty nine NTU units is approximately equivalent to 1 g/10L.

A food-grade blue dye was dispersed passively with soaked sponges secured to the top of the downhole dye probe. Dye concentrations were pre-mixed based on volumetric dilution methods from an initial 13.4 % dye concentration. Two different dosage applications of dye were evaluated to assess borehole fluid disbursement for SBDT. A 2 cubic centimeter per liter (cc/L) dosage from the initial dye or 0.03 % dye concentration was compared to a 4 cc/L from the initial dye or 0.06 % dye concentration.

SBDT logging was done under ambient conditions (pre-test) over a span of six days in early April 2013 at seven wells. Logging was also done during the pump test (April 17-26, 2013), near the early part of the 9 day pump test at three wells (called 76-hour logs or mid-test). Another set of logs was collected near the culmination of the 9 day test (called end of test or 8 or 9 day logs) at seven wells (repeat of ambient logs). For each condition, wells were initially passively spiked with blue dye once (one sweep of the well), the sponges removed, and subsequent time series measurements were made for each grouping of conditions. Time series measurements were typically done 10 minutes after spiking (recorded from beginning of spiking), 30 minutes after spiking, 1 hour after spiking, 3-4 hours after

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[1] Any use of trade, firm, or product names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

spiking, and for ambient conditions 6 days after spiking. Passive spiking often provided a non-uniform dye distribution. In some cases, this is advantage to map vertical flow from the movement of non-uniform dye fronts.

Instrument response was near instantaneous and data were collected at a rate of 28 ft/min during downhole logging. For the deepest well, approximately 500 ft deep, logging took approximately 18 minutes. No time corrections were applied. Due to the configuration of the probe and position of the sensors, logging is performed going downhole only.

The photometer tool was checked against known dye standards (deionized water with no dye) and different dye standards. Values at the start of the day and end of the day were compared. Typically, drift was small within the day (photometer values > .03 g/10L). However, between days, values differed by larger amounts (photometer values > .2 g/10L). Photometer values for the same day and between days were adjusted for instrument drift when discrepancies were noted. The light sensors require cleaning after each use. Coating on the light sensor was noted during initial testing of the tool and subsequent logging included systematic cleaning.

Borehole flows measured under ambient conditions with SBDT was compared to borehole flows during the pump test with SBDT to identify differences in borehole flow from aquifer pumping and to assess fracture connectivity of the logged well to the pumped well (BR-6; Figure 2). SBDT were compared to HPFM logs collected for the site (Weston Solutions, Inc., 2010, 2012, 2013). Ambient HPFM logs were collected within the first year of well construction and data sets are not contemporaneous with ambient SBDT. Pumping HPFM logs (low rate pumping in logged well) were collected after ambient HPFM logs. Pump test SBDT and pump test HPFM were generally collected within three days of each other during the April 17-26, 2013 pump test.

Results

In general, SBDT are an effective tool in the identification of borehole flow for very low flow particularly under ambient conditions. However, several factors complicate or potentially obscure SBDT results. The photometer values were found to be affected by the turbidity of the borehole water, the presence of the dye, and background material (casing vs. rock surfaces). Large changes in the color of the borehole wall as evident by differences in photometer values within and outside the steel casing suggest a sensitivity of the photometer measurements to background material. Redistribution of the dye from cased to uncased parts of the well can affect identification of dilution near the top of the open borehole. The dye has a density of 0.8 grams per cubic centimeter (g/cm^3) so it should not sink under uniform pressure head in the borehole. Therefore, dye movement from the cased to uncased parts of the well maybe related to small changes in pressure in the borehole from fluctuations in potentiometric head of fractures. All these factors can obscure dye distributional circulation patterns over time.

Results from the dosage experiments (0.03% and 0.06%) showed that photometer values varied to a depth of approximately 330 ft below top of casing. Therefore, we concluded that adequate disbursement of dye occurred to a depth of approximately 330 ft. Below that depth, the turbidity of the water obscured differences in photometer values. Most flow is observed in boreholes above 330 ft as determined from single well, low-rate pumping, HPFM logging (pump in casing of logged well).

Table 1. Summary identifying the detection of borehole flow from multiple methods. [SBDT-Single Borehole Dilution Tests; NT-not tested; all depths below TOC (top of casing); Yes-flow detected; No-flow not detected; HPFM and tracer data from Weston Solutions, Inc., 2010, 2012, 2013; Columns 4-5 are for ambient conditions although not contemporaneous; Columns 6, and 7, 8, and 9 were collected during pump test in April 2013; Column 3 is included to show if active flow zones were identified in well]

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Well	Open borehole depths below top of casing in feet	Flow detected with HPFM logging using single well low rate pumping in well (Pumped HPFM)	Ambient flow detected with HPFM logging (Ambient HPFM), (Year logged)	SBDT-ambient low flow observed, April 4-9, 2013	Flow detected with HPFM logging during BR-6 pump test (Pump test HPFM)	SBDT-Mid-test (BR-6 pump test) flow observed	SBDT-End of test (Br-6 pump test) flow observed	Tracer transport identified from this well to BR-6 during BR-6 pump test (Pump transport)
MW-16R	100-390	Yes	No (2009)	Potential flow	No	No	No	NT
BR-12	116-422	Yes	No (2012)	Yes	No	NT	Yes	Yes
BR-15	103-394	Yes	No (2012)	Yes	NT	NT	Potential flow	NT
BR-1	107-400	Yes	No (2009)	No	No	No	No	NT
**BR-11	131-441	Yes	No (2012)	No	No	NT	Yes	NT
BR-7	110-500	No	No (2010)	No	NT	NT	No	NT
MW-30	161-440 (blocked at 287 ft)	Yes	No (2009,2012)	Possible diffuse horizontal dilution	No	No	Possible diffuse horizontal dilution	NT

** Large drawdown (approximately 26 ft) measured during pump test.

Under ambient conditions (pre-test logging), none of the wells had detectable flow as measured with heat-pulse flowmeter (HPFM) tools prior to our testing with SBDT (Table 1). With SBDT, 4 of the 7 wells showed the presence of some very low rates of borehole flow (Table 1). Transient borehole flow may account for the differences between SBDT and HPFM for ambient conditions given they were collected several years apart. For the mid-test logging, none of the three wells tested with SBDT showed detectable flow. During the end of the pump test logging (8th or 9th day of test), of the 5 wells relogged with the HPFM, none had detectable flow. With SBDT, 3 of the 5 wells showed the presence of some very low borehole flow. For the SBDT and HPFM collected during the pump test, logs were collected within a span of a few days after water-level drawdowns in the aquifer approached quasi-equilibrium. At one of the wells with detectable flow under both ambient conditions and during the pump test as

measured by SBDT, the photometer logs were different indicating changes in inflow and outflow patterns of active fractures (BR-12).

Wells BR-12 and BR-11 had the greatest evidence of borehole flow (Table 1, Figures 3 and 4). At wells BR-15, MW-30 and MW-16R, flow is qualified as potential meaning additional testing should be done to confirm results. Diffuse horizontal flow may be occurring at MW-30 based on a uniform decrease in photometer values as measured by successive logs.

Dilution occurred at the top of the open borehole in BR-12 under ambient conditions at about 115 to 135 ft below top of the well casing (TOC) (Figure 3). Photometer values show a consistent decrease over time at this interval. In contrast during the pump test, dilution is not noted at that interval. Water levels decreased at this well during the pump test indicating inflow to the borehole decreased and a net outflow occurred from the borehole. Open boreholes likely supply water storage to the aquifer during the pump test. A decrease in photometer values from approximately 140 ft to 240 ft below TOC during the pump test and inflection point at approximately 250 ft below TOC indicates outflow is occurring at the fracture at 253 ft. The fracture at 253 ft is noted in optical televiewer (OTV) and acoustic televiewer (ATV) logs and pumped HPFM logging (Weston Solutions, Inc., 2012). The OTV and ATV logs are reproduced in Figure 3 from Weston Solutions, Inc. (2012). Outflow from BR-12 was confirmed with an independent tracer during the pump test (Table 1) (Weston Solutions, Inc., 2013). The tracer emplaced into BR-12 prior to the pump test was detected in the pumped water from BR-6 located 700 ft away (Weston Solutions, Inc., 2013).

BR-11 shows no noticeable borehole flow under ambient conditions (Figure 4). The photometer values are consistent in the open borehole for the pre-test logs. Photometer values show a decrease from 140 to approximately 240 ft during the pump test. An inflection change in the photometer values at approximately 250 ft aligns with a mapped fracture at 253 ft as noted in OTV and ATV logs and pumped HPFM logging (Weston Solutions, Inc., 2012).

Wells BR-1 and BR-7 show no inflection points and consistent photometer values with minor changes for all hydraulic conditions logged (ambient, mid-test, near end of test). In this case, SBDT results confirmed HPFM logging results (Table 1). However, for wells BR-12 and BR-11, and potentially for wells MW-30 and MW-16R, SBDT detected very low flow whereas HPFM did not. Well BR-15 had no pump test HPFM logging performed so a comparison could not be made.
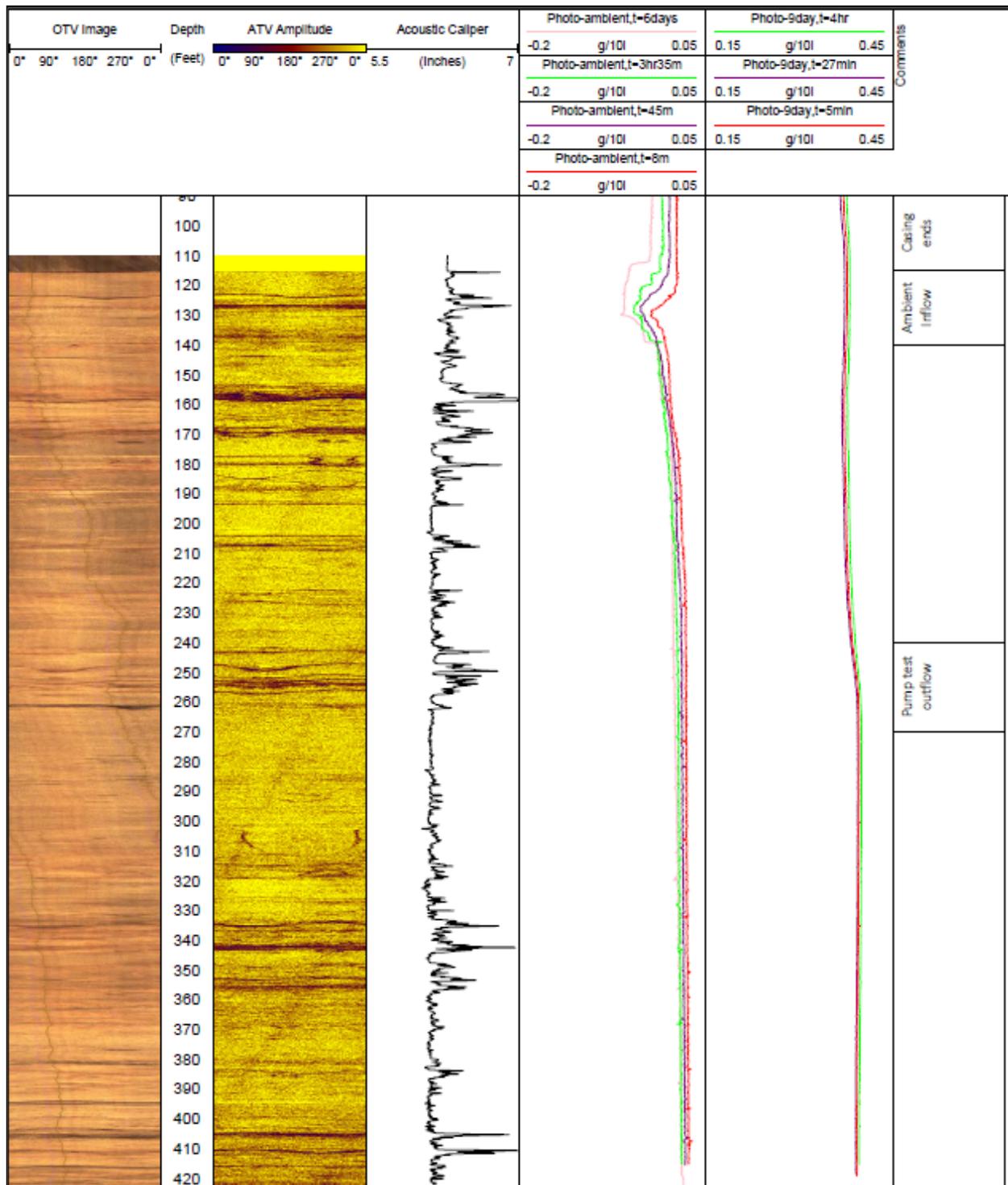
Figure 3: Borehole logs and SBDT logs for ambient and pump test conditions for BR-12, OU-3, Savage Municipal Supply Well Superfund site, Milford, New Hampshire. [Depth below casing; Information from OTV, ATV, and acoustic caliper from Hager-Richter Geoscience, Inc.]
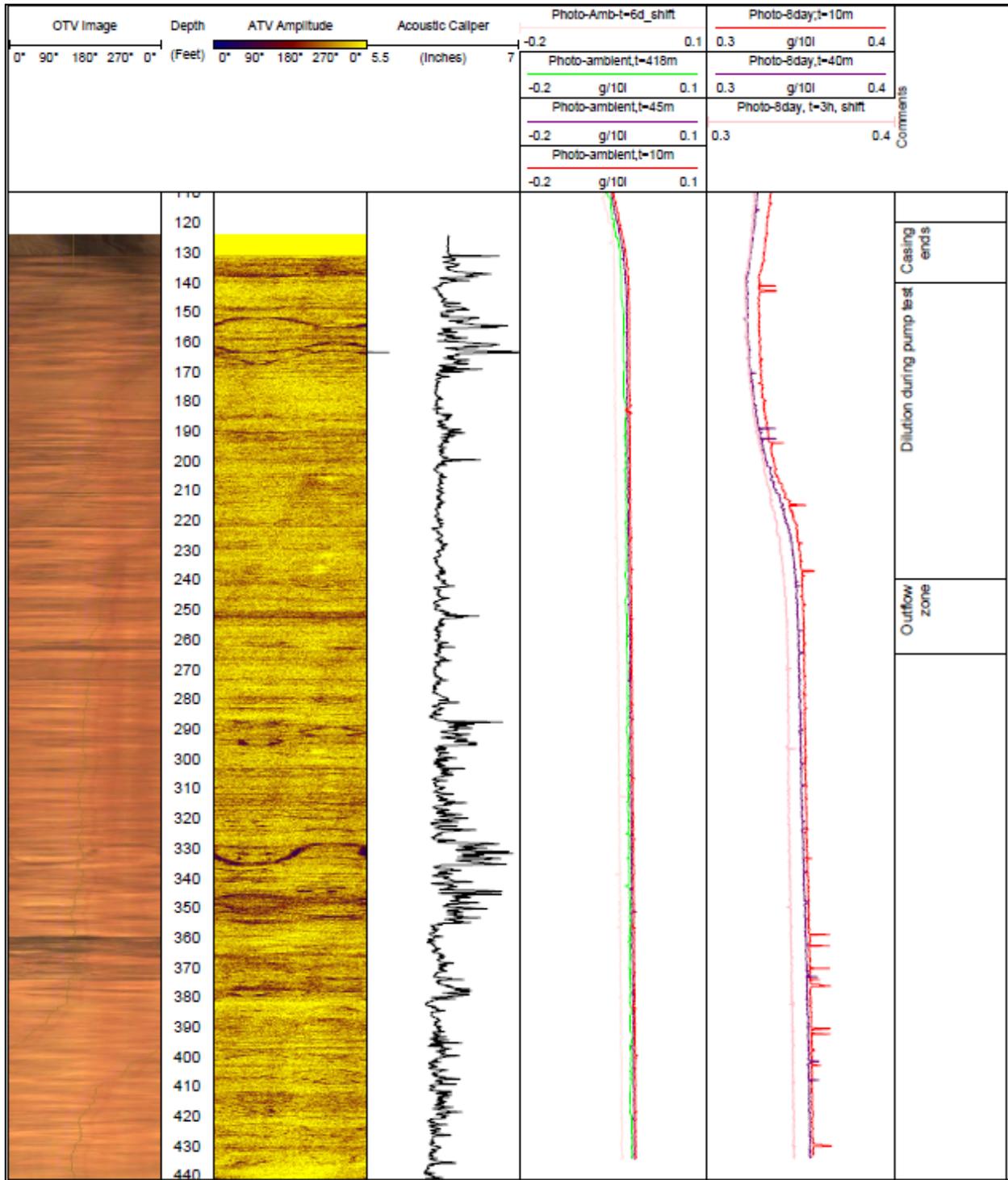
Figure 4: Borehole logs and SBDT logs for ambient and pump test conditions for BR-11, OU-3, Savage Municipal Supply Well Superfund site, Milford, New Hampshire. [Depth below casing; Information from OTV, ATV, and acoustic caliper from Hager-Richter Geoscience, Inc.].

Cross plots of photometer and nephelometer values shows strong linear trends with the absence of borehole flow (Figure 5A). In general where no detectable flow was observed, three distinct depth-dependent slopes were visible: (1) a shallow slope with small photometer changes in the casing, (2) a steep slope in the upper open borehole with larger changes in photometer values, and (3) a shallow slope in the bottom open borehole with smaller photometer values.   While turbidity differences could be a factor inside and outside the casing, we conclude that background materials are affecting photometer values because of the change in slope between photometer and nephelometer values. Increased scatter in cross plots occur where flow zones are interpreted such as in the case of well BR-11 (Figure 5B).

Nephelometer values generally increased near the bottom of the well. At several wells, the inflection point where nephelometer values increased corresponded with known hydraulically active fractures as identified by pumped HPFM logging and latter sampled with straddle packers (Weston Solutions, Inc. 2012). Often samples from these fractures had high turbidity (>100 NTU). We conclude that high turbidity accumulates at the bottom of the well in inactive flow zones.
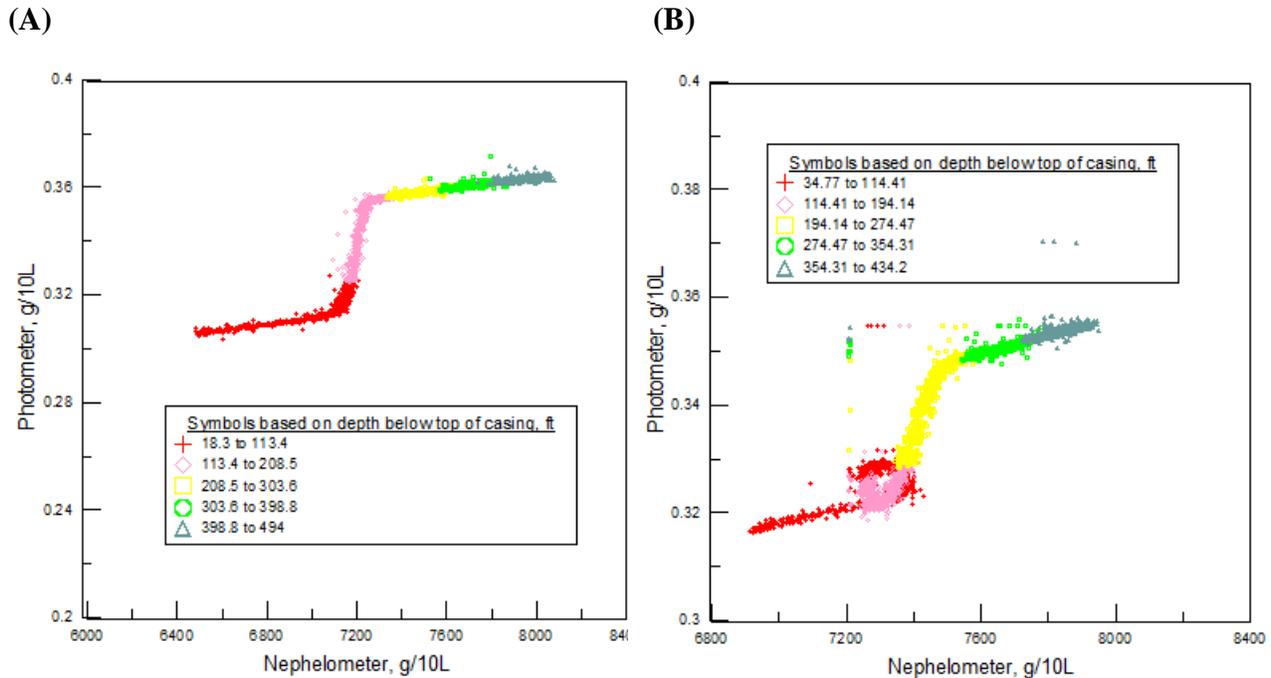

Figure 5: Cross plots between photometer and nephelometer values for (A) BR-7 with no borehole flow and (B) BR-11 with borehole flow, OU-3, Savage Municipal Well Superfund site, Milford, New Hampshire.

Fracture Transmissivity of SBDT Detected Flow Zones

The estimated transmissivity of the fractures corresponding to flow zones detected with SBDT tend to be higher than the transmissivity of most hydraulically active fractures at the site. Transmissivity estimates from previously collected straddle packer hydraulic tests (Weston Solutions, Inc., 2013) were used to characterize hydraulic differences between all hydraulically active fractures at the site, and fractures coincident with non-detected and detected flow zones as determined by SBDT (Table 2). All hydraulically active fractures or fracture zones (90 zones; Table 2) from the 16 bedrock monitoring wells at the site have a median transmissivity of 0.053 ft2/d. All hydraulically active fractures from the seven wells logged with SBDT (32 zones including non-detect and detected flow zones; Table 2) have a similar median transmissivity (0.048 ft2/d; Table 2) as that of fractures from the entire monitoring network. The median transmissivity of fractures corresponding to the nine detected flow zones by SBDT is twice as much (0.130 ft2/d; Table 2). A SBDT detected flow zone corresponded with fracture transmissivity as low as 0.003 ft2/d (Table 2), but in general they tended to be more transmissive than non-detected SBDT flow zones. Independent estimates of transmissivity were not made with SBDT. Quantitative measurements of flow rates detected with SBDT logging require numerical modeling of photometer values (Maurice et al., 2011), which are beyond the scope of this study.

Table 2. Comparison of estimated transmissivity (ft^2/d) of packer interval data and observed dilution zones. [Identified hydraulically active fracture zones from pumped HPFM logs and subsequent packer testing (Weston Solutions, Inc., 2013; ft^2/d is square feet per day]

	Identified hydraulically active fractures zones from all wells	Identified hydraulically active fracture zones from wells logged with SBDT	SBDT observed flow zones
Number of zones	90	32	9
Standard deviation	2.545	0.189	0.234
Mean	0.621	0.119	0.197
Median	0.053	0.048	**0.130**
Minimum	0.000	0.000	**0.003**
Maximum	22.970	0.765	**0.765**
Sum	55.918	3.809	1.776

Conclusions

Several factors complicate or potentially obscure SBDT results. Turbidity and potential sensitivity to background material, such as casing and rock surfaces, may limit the detection of flow zones in low permeability aquifers. Calibration and regular cleaning of the downhole tools are critically important for data collection.

Given the limitations, SBDT were helpful in identifying several zones with very low flow or potential flow. Four wells had very low flow identified under ambient conditions. Four wells (not the same subset) also had very low flow identified during the pump test. Fractures at 253 ft from two wells were identified as outflowing during the pump test. One of the wells had a fracture at that depth that was steeply dipping; the other well had a fracture that was shallow dipping. Both wells are approximately 700 ft away from the pumping well and unlikely to have a direct fracture connection to the pump well

except through a series of cross connecting fractures. One of the two wells had an independent tracer confirm hydraulic connection to the pumped well during the test.

The detection of several flow zones with SBDT and corresponding non-detection of flow zones with vertical differential, Heat Pulse Flowmeters (HPFM) for ambient and pump test conditions could be related to differences in flow detection between the two tools. Fractures transporting contaminants are particularly important to identify. However, the possibility exists that several of the flow zones detected with SBDT were cross flowing fractures that had negligible net flow (inflow = outflow) and therefore unidentifiable with HPFM. Cross flowing fractures that transport contaminants can spread contaminants in the borehole by dispersion and diffusion processes. Transient borehole flow may also be a factor for the differences between SBDT and HPFM for ambient conditions given they were collected several years apart. For the SBDT and HPFM collected during the pump test, logs were collected within a span of a few days.

The concurrent measurements of photometer and nephelometer values provided insight into borehole flow patterns and the distribution of turbidity in wells. Examination of photometer and nephelometer values suggest photometer values are partly affected by turbidity and background materials. At wells with no detectable flow, a strong linear relation occurred between photometer and nephelometer. The interpreted presence of flow produced a poorer linear relation between photometer and nephelometer values. We think measurements of both parameters warrant further study.

For this study, SBDT were used in a qualitative manner and as a screening tool to identify potential flow zones for subsequent testing. Subsequent testing could include point dilution tests where identification of flow at specific fractures could be targeted.

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