ground water

Active Thermal Tracer Tests for Improved Hydrostratigraphic Characterization

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Abstract

Subsurface heterogeneity in hydraulic properties and processes is a fundamental challenge in hydrogeology. We have developed an improved method of borehole dilution testing for hydrostratigraphic characterization, in which distributed temperature sensing (DTS) is used to monitor advective heat movement. DTS offers many advantages over conventional technologies including response times in the order of seconds rather than minutes, the ability to profile temperature synoptically in a well without disturbing the fluid column, sensitivity to a wider range of flow rates than conventional spinner and heat pulse flow meters, and the ease of interpretation. Open-well thermal dilution tests in two multiaquifer wells near Madison, Wisconsin, provided detailed information on the borehole flow regimes, including flow rates and the locations of inflows from both fractures and porous media. The results led to an enhanced understanding of flow in a hydrostratigraphic unit previously conceptualized as homogenous and isotropic.

Introduction

Subsurface heterogeneity in hydraulic properties and processes is a fundamental challenge in hydrogeology. Most hydrogeologic problems are complicated by uncertainties resulting from spatial variations in permeability, which are the result of complex and nonrandom geologic depositional processes and are, therefore, difficult or impossible to fully characterize. In deeper wells with long open intervals, investigation of vertical aquifer heterogeneity is often conducted by wireline geophysical logging (natural gamma, caliper, normal resistivity, etc.), or by closed-interval packer testing. Borehole dilution tests are a promising, but less frequently applied technique. Unlike methods that only measure physical rock properties, dilution tests, which measure flow, can delineate hydraulically active intervals. By utilizing controlled tracers, they also have less potential to produce ambiguous results than methods that rely solely on ambient fluid properties. In comparison to downhole flow meters (e.g., heat pulse, electromagnetic, and impeller flow meters), dilution tests have the advantage of a larger sensitivity range at a lower cost. This paper describes an improved method of borehole dilution testing, in which distributed temperature sensing (DTS) is used to monitor advective heat movement at an unprecedented level of detail.

Previous Borehole Dilution Studies

Numerous studies have developed methodologies for borehole dilution testing and analysis. In the simplest case, strictly horizontal flow through a well produces a log-linear decrease in the concentration of an introduced tracer, which can be used to calculate specific discharge (Ogilvi 1958; Pitrak et al. 2007). Oftentimes, however, especially in heterogeneous and fractured-rock settings, the use of this technique in open wells is precluded by ambient vertical flows between permeable horizons

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Received August 2011, accepted January 2012.

doi: 10.1111/j.1745-6584.2012.00913.x

(Michalski and Klepp 1990; Elci et al. 2001; Runkel et al. 2006; Meyer et al. 2008; Hart and Luczaj 2010; Pehme et al. 2010; Maurice et al. 2011). Closed-interval dilution testing in these settings can be extremely labor intensive.

Alternatively, tracer migration in an open, flowing well can be monitored to obtain flow rates and locate zones of inflow and outflow. The earliest of these experiments coincided with the development of fluid conductivity logging equipment, and involved the point-injection of a brine slug and observation of a minimum resistivity breakthrough at some downstream location. Although effective for measuring low flow velocities, equipment limitations initially made this technique cumbersome (Patten and Bennett 1962). Subsequent experiments turned to radioactive tracers (such as iodine-131), which could be easily monitored with wireline gamma tools (Marine 1980). Use of this technique was ultimately limited by negative perceptions toward the release of radioactive substances into the environment (Keys 1997).

Improvements in fluid conductivity logging equipment led to a resurgence in borehole dilution studies after 1990. Michalski and Klepp (1990) utilized point injections of a brine solution and continuous conductivity profiling to measure borehole flow velocities and locate hydraulically active fractures. Tsang et al. (1990) developed the flowing fluid electric conductivity (FFEC) logging technique, where the borehole is first replaced with water of a different, uniform conductivity, and then pumped to draw native water from factures or other high permeability zones. Continuous profiling of conductivity during pumping provides information on both the locations of producing zones and their individual dissolved solid concentrations. Numerical modeling of the evolving borehole concentration profiles can yield estimates of fracture flow rates (Tsang et al. 1990; Löw et al. 1994; Evans 1995; Doughty and Tsang 2005; Doughty 2008). Multiple pumping rates can be used to produce robust estimates of fracture transmissivities and far-field heads (Tsang and Doughty 2003; Doughty et al. 2005). Despite extensive success in low-permeability settings, the FFEC technique may be difficult or impossible to implement in situations where high permeabilities and/or significant ambient inflows preclude the creation of a uniform fluid conductivity condition in the borehole. In addition, it does not provide any information on ambient flows. West and Odling (2007) employed open-well dilution of a saline tracer to measure cross-well flows in a monitoring well adjacent to a pumping well. Although analysis of the observed tracer profiles with an analytical model yielded fracture hydraulic properties, the method requires both cross-well pumping and an aquifer system of discrete permeable layers separated by impermeable intervals. A recent study by Maurice et al. (2011) utilized both point and uniform injections of a saline tracer solution under ambient flow conditions. Forward modeling of borehole concentrations allowed for the interpretation of more complex profiles (as opposed to the simple migration of a tracer peak between two fractures), to obtain inflow and outflow locations and flow rates. Despite significant measurement advantages over other tracers such as dyes (Brainerd and Robbins 2004), fluid conductivity remains limited by instrumentation that can only record measurements at a single point, which must be moved up and down a well to create high-resolution profiles.

Distributed Temperature Sensing

Temperature measurements, which have been extensively employed in other types of hydrogeologic tracer studies (Anderson 2005), offer another means of characterizing borehole flow. As a tracer, heat is inexpensive and environmentally benign. Until recently, however, available temperature logging equipment offered no resolution, cost, or efficiency advantages over fluid conductivity sensors. Raman-based DTS is an optical time-domain reflectometry technique that allows for the rapid profiling of temperature using fiber-optic cables. A thorough treatment of DTS theory can be found in Tyler et al. (2009), Selker et al. (2006a), and Hurtig et al. (1994). In short, laser light is pulsed down an optical fiber, and the backscattered signal is monitored. The intensity ratio of the anti-Stokes and Stokes components of the returning light, which are produced by inelastic photon collisions, is a function of fiber temperature. The locations of measurements are determined by two-way travel times. The result is a stationary, synoptic reading of temperature along the entire length of the sensor cable, at spatial intervals as fine as 1 m or less, which can be repeated at time intervals of less than 1 min.

The fine spatial and temporal monitoring ability of DTS is creating new and unprecedented opportunities to study hydraulic heterogeneity at a wide range of scales. Following recent improvements in instrument cost and design (Selker et al. 2006a), the last several years have seen an explosion of DTS applications in hydrologic investigations. Most of these have been in surface water (Selker et al. 2006a; Westhoff et al. 2007; Moffett et al. 2008; Tyler et al. 2009) and surface water/groundwater interactions (Selker et al. 2006b; Lowry et al. 2007; Henderson et al. 2009; Vogt et al. 2010). Although DTS is now widely used by the oil and gas industry for downhole production monitoring (Simonits and Franzen 2007), downhole uses in hydrogeology have been limited.

In the first widely cited Earth-science application of DTS, Hurtig et al. (1994) used DTS to monitor the injection of hot and cold water under closed-packer conditions into two 40-m deep inclined boreholes in fractured crystalline rock at the Grimsel Test Site (Wettingen, Switzerland). By profiling temperatures during injection, they were able to detect a fracture in one of the boreholes by a sharp decrease in temperature. Macfarlane et al. (2002) conducted a two-well, forced-gradient thermal tracer test in the Dakota aquifer of western Kansas, with the goal of obtaining bulk aquifer properties. Although they observed some thermal breakthrough, a short screen interval and pumping-induced mixing in the production well water column precluded the collection of detailed information on vertical aquifer heterogeneity. Büttner and

Huenges (2003) used DTS to monitor transient thermal effects associated with the drilling of a 3000-m deep borehole (HSDP-2) on the big island of Hawaii. Changes in temperature following the periodic injection and removal of drilling fluid revealed multiple aquifers, which corresponded to other geophysical and lithological data. Henninges et al. (2005) located fractures by using DTS to monitor the injection of cool water into an enhanced geothermal well near Berlin, Germany, while Yamano and Goto (2005) located the loss of cool injection water to a casing rupture in a deep borehole intersecting the Nojima Fault zone in Japan.

Although these studies demonstrated the utility of DTS for repeated synoptic temperature profiling, and the ability of DTS to locate hydraulically important features, none of them investigated borehole flow in as much detail as the above-mentioned saline tracer studies. This paper shows how the expanded resolution capabilities of DTS can be used for the detailed visualization of complex borehole flow patterns in a heterogeneous, clastic bedrock aquifer. We present results from three field experiments conducted near Madison, Wisconsin, in which conventional logging and DTS were used to trace the migration of minimally heated (<10 °C above ambient) water in flowing boreholes.

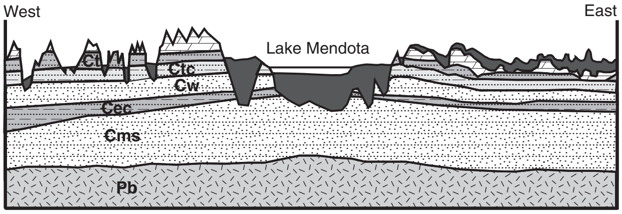
Methods

Regional Hydrogeologic Setting

South-central Wisconsin is underlain by a sequence of relatively flat-lying and undeformed lower-Paleozoic clastic and carbonate bedrock units, which collectively make up the Cambrian-Ordovician aquifer system (also known in Wisconsin as the Sandstone Aquifer). Within this sequence, vertical transitions between sandstones, siltstones/shales, and dolomites form a hydrostratigraphy of multiple aquifers separated by leaky aquitards.

The significance of hydraulic heterogeneity within the sandstones of the Cambrian-Ordovician aquifer system is being increasingly recognized. Several recent investigations have found laterally continuous bedding plane-parallel fractures to have a dominating effect on flow in the Tunnel City Group (Runkel et al. 2006; Swanson et al. 2006; Swanson 2007). This finding may also extend to other units. In the initial characterization study of well DN-1440 (also used in this study), Anderson (2002) noted significant borehole flow from fractures in the Wonewoc Formation. Similar investigations by Hart and Luczaj (2010) have observed fracture-dominated borehole flow in other sandstones. Some question remains as to the lateral continuity, and therefore regional significance of these features.

Near Madison, Wisconsin, the bedrock hydrostratigraphy can be broadly lumped into an upper and lower aquifer separated by the Eau Claire aquitard. In some places (e.g., under the Madison lakes; Figure 1) the absence of the Eau Claire allows for increased connection between the units (Bradbury et al. 1999). Municipal pumping has lowered water levels in both bedrock aquifers. This has substantially altered the natural flow system, creating vertical hydraulic gradients between the upper and lower aquifers that are complex in both space and time. The Madison lakes, which previously received regional groundwater discharge, now lose water to the lower aquifer over much of their area (Bradbury et al. 1999). Although this has buffered drawdowns, it presents a potential long-term threat to water quality in the lower aquifer. An exception to this gradient reversal is the northern end of Lake Mendota, which lies near the margin of the regional cone of depression. In this area (which includes well DN-1440), vertical gradients are sufficiently small to allow for periodic flow reversals in response to municipal pumping cycles (Bradbury et al. 1999; Anderson 2002).



P	Pleistocene Deposits	Undifferentiated, unlithified deposits	■	Surficial aquifer
Os	Sinnipee Group	Dolomite and shale	▨	Undifferentiated fractured rock and porous-media aquifers
Oa	Ancell Group	Sandstone and shale	▨	
Opdc	Prairie du Chien Group	Dolomite and dolomitic sandstone	▨	
Ꞓt	Trempaleau Group	Sandstone, dolomite, and siltstone	▨	
Ꞓtc	Tunnel City Group	Sandstone	▨	Upper bedrock Aquifer
Ꞓw	Wonewoc Formation	Sandstone	▨	
Ꞓec	Eau Claire Formation	Sandstone, siltstone, and shale	▨	Eau Claire Aquitard
Ꞓms	Mt Simon Formation	Sandstone	▨	Lower bedrock Aquifer
Pb	Precambrian basement	Undifferentiated igneous and metamorphic rocks	▨	Lower no-flow boundary

Figure 1. Stratigraphic cross section of Dane County (modified from Massie-Ferch et al. 1997).

The physiographic setting of the Driftless Area, located immediately west of Madison, is also conducive to vertical hydraulic gradients in the Cambrian-Ordovician aquifer system. The landscape is characterized by the absence of glacial deposits and a well-developed dendritic drainage system that deeply dissects the Paleozoic bedrock, which is often exposed or covered only by thin soils. This results in high rates of recharge (Hart et al. 2009), which can occur in different hydrostratigraphic units at different elevations, leading to vertical variations in head at downgradient locations.

Two multiaquifer research wells near Madison (Wisconsin Geological and Natural History Survey nos. DN-1440 and IW-512) were chosen for the thermal dilution experiments. These wells have been characterized in previous studies, so an abundance of information exists for comparison with DTS data. Preferential flow in the sandstone units intersected by these wells remains an ongoing area of research interest, with implications for water supply, contaminant transport, and ecosystem protection

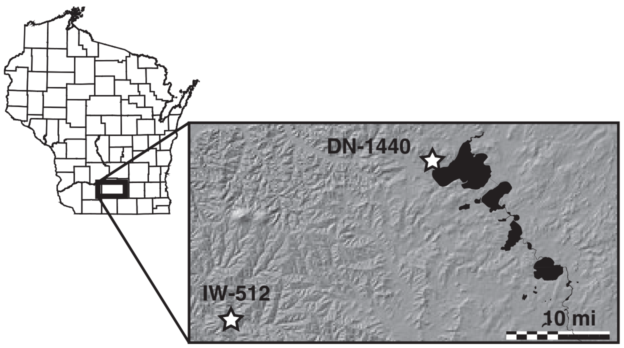


Figure 2. Locations of research wells IW-512 and DN-1440.

(Swanson and Bahr 2004; Swanson et al. 2006; Borchardt et al. 2007; Meyer et al. 2008). An additional goal of this study was therefore to use DTS to refine existing conceptual models of the Cambrian-Ordovician aquifer system.

DN-1440 Site Description

Well DN-1440 is situated in the Pheasant Branch Conservancy, which is located north of Middleton, Wisconsin near Lake Mendota (Figure 2). The conservancy is known for a complex of springs that collectively provide a steady flow of approximately 57 L/s (2 cfs) to a wetland complex and small stream. Large geochemical differences between individual boils spaced only tens of meters apart suggest that the complex receives focused regional discharge from a relatively large (10 s of km^2) catchment area (Hunt and Steuer 2000).

Hydrostratigraphically, the springs are thought to emanate from preferential flow zones in the upper bedrock aquifer, in particular the Tunnel City Group. This was evidenced by relatively steady heads in the upper aquifer in comparison to the lower aquifer, which is influenced by municipal pumping schedules (Anderson 2002). In addition, numerous secondary porosity features were detected in the Tunnel City and Wonewoc during the drilling of DN-1440, some of which correlate to anomalies in the geophysical logs (e.g., changes in resistivity, temperature and flow) that are consistent with hydraulically active bedding plane fractures. The locations of these features are denoted by the gray bands in Figure 3 (from Anderson 2002).

Well DN-1440 is 0.15 m (0.50 feet) in diameter, cased from 0 to 24 m (80 feet) bgs, and open from 24 to 87 m (285 feet) bgs. As shown in Figure 3, the open interval intersects both the upper and lower aquifers, allowing for borehole flow between the units in the presence of vertical hydraulic gradients. Packer head testing by Anderson (2002) showed a periodic reversal in the vertical gradient between the two aquifers that correlated with pumping schedules for Middleton, Wisconsin municipal Wells 4 and 5, which are located approximately 1.5 and 3 km from DN-1440, respectively. Figure 3 suggests that flow in the upper aquifer interval of DN-1440 is significantly influenced by fractures. Specifically, the fractures at depths of 58.5 and 69.5 m bgs appear to be important, as evidenced by abrupt transitions in temperature and fluid conductivity, and high values of hydraulic conductivity obtained through closed-interval packer testing (Anderson 2002). Smoother profiles in the geophysical logs below the base of the Eau Claire, and a smoother borehole wall texture observed in a downhole video log suggest that flow in the Mt. Simon may be more intergranular.

IW-512 Site Description

Well IW-512 is situated in a quarry off Iowa County Highway A, in a valley near Hollandale, Wisconsin (Figure 2). The well is 0.15 m (0.50 feet) in diameter, cased from 0 to 24 m (80 feet) bgs, and open from 24 to 200 m (650 feet) bgs. The open interval of IW-512 intersects at least three aquifers: the Mt. Simon, the Wonewoc/Tunnel City, and an upper aquifer consisting of a thin layer of sandstone (possibly the Jordan) and the fractured dolomite of the Prairie du Chien Group. As in DN-1440, there is significant hydrostratigraphic and hydraulic heterogeneity in portions of this well. Previous geophysical investigations by Hart and Luczaj (2010) have documented numerous fractures in the upper 100 m and diverging flow in the Wonewoc Formation. Gradual changes in the temperature, fluid conductivity, and impeller flow logs suggest that there is also substantial intergranular flow occurring in the Wonewoc and Mt. Simon intervals (Figure 4).

Heads in the Wonewoc/Tunnel City aquifer at this location are sufficiently high to create a composite head for the well that is approximately 1 to 2 m above the land surface. In the absence of a valve or standpipe, steady-state flow out of the top of casing can reach 180 L/min (48 gpm), as shown on the gold impeller flowmeter curve (Flowing 8/6/09) in Figure 4. The DTS experiment described below was conducted under this flowing condition. Alternatively, when a cap or riser pipe prevents the flow of water out of the casing, upward flow in the well exits into the sandstone unit at about 45 m bgs, as shown by the dark blue impeller flowmeter curve (Not Flowing 8/10/09) in Figure 4.

Heating System

A system was developed to heat groundwater with minimal disturbance (Figure 5). The heating system consists of a coil of 1.27 cm (0.5 inch) diameter copper pipe immersed in a cauldron of water heated by a high-pressure propane burner. Well water is delivered to the system at adjustable rates of approximately 4 to 13 L/min (1 to 3.5 gpm) via a submersible Grundfos pump situated in the cased portion of the borehole. The heated water is returned to the well via heavy-duty rubber garden hose. A short segment of pipe attached to the outlet of the garden hose keeps the hose taut in the well. A movable, high capacity hose reel allows for the outlet to be easily raised and lowered in the well, up to depths of more than 150 m (500 feet) bgs.

Flow is measured using an Omega piston-type, variable-area inline flowmeter. This device is not ideal for water with high concentrations of suspended solids, which

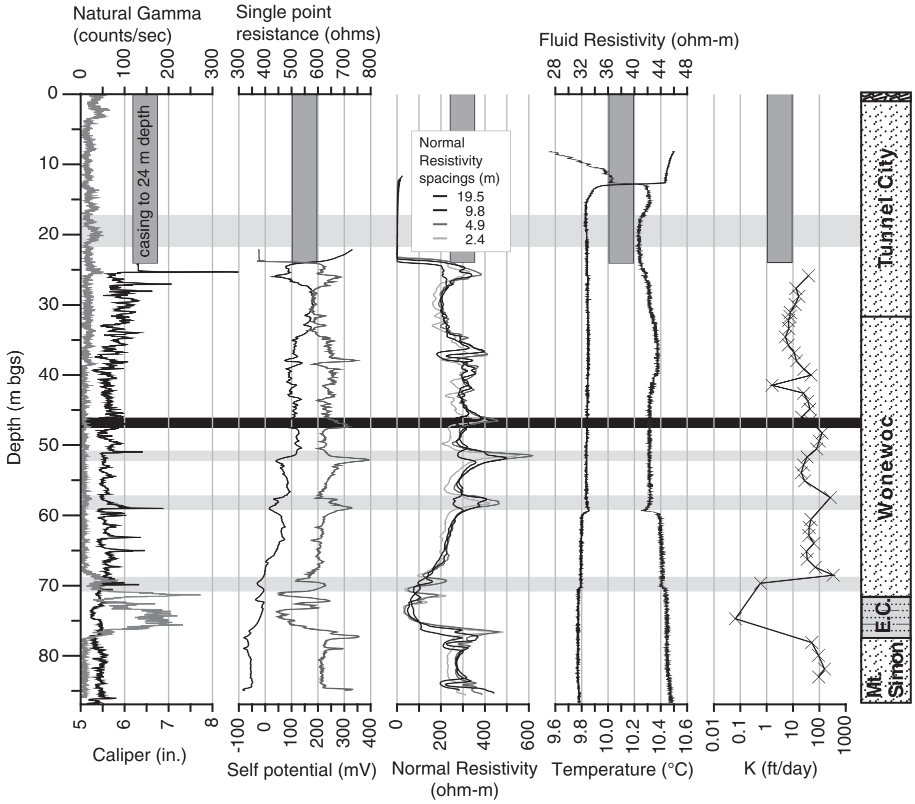


Figure 3. Geophysical logs of DN-1440 (modified from Anderson 2002).

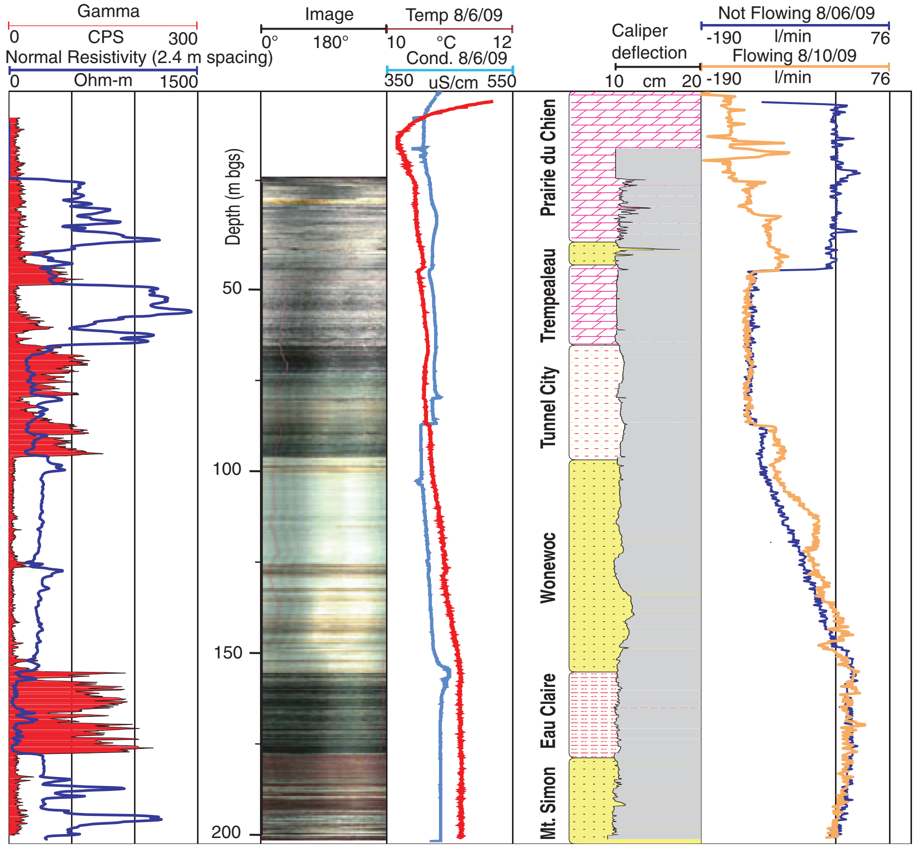


Figure 4. Geophysical logs of IW-512.

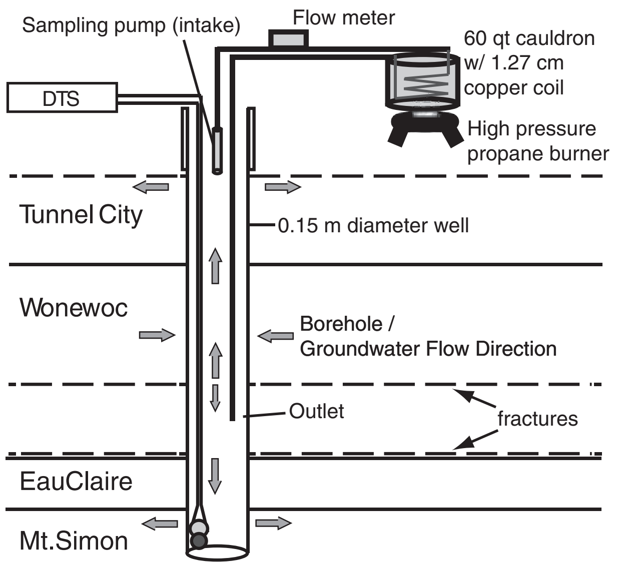


Figure 5. Schematic of the heating system setup in DN-1440.

inhibit the motion of the piston. Problems encountered during operation at DN-1440 suggest that the reported heating system flow rates may be underestimated.

High flow rates in the well remove more heat from the outlet hose. Therefore, the overall output of the system ranges from approximately 1 to 4 kW. For a pumping rate of 8 L/min (2.1 gpm), this corresponds to a temperature increase of approximately 2 to 7 °C at the outlet.

Setup and takedown of the heating system and DTS equipment can be accomplished in a few hours or less. Each of the experiments reported in this study was accomplished in a day of fieldwork.

Tracer Tests

Three open-well thermal tracer dilution experiments utilized DTS to monitor several tracer release techniques. A test conducted in DN-1440 on May 19, 2010 utilized a continuous release of heated water tracer from a fixed location. The heating system was run for 2 h and 40 min at approximately 10 L/min (2.7 gpm), with the outlet briefly at 73 m (240 feet) bgs for the first 10 min and then lowered to just above the bottom of the well (87 m, 285 feet bgs) for the remainder of the experiment.

A second experiment in DN-1440, conducted on May 28, 2010, released pulses of heat at various depths, by activating the heating system for 10 to 15 min. with the outlet set at the different target depths.

An experiment in IW-512, conducted on May 27, 2010, utilized a continuous tracer release at multiple locations. The heating system was run mostly continuously from 11:30 to 14:30 at approximately 13 L/min (3.4 gpm), with the outlet lowered in approximately 12 m increments. When the outlet reached 158 m (below the location of the divergence in flow), it was left stationary until 15:50, when the system was shut-off. The heating system was then pulsed in two 15-min increments at approximately 130 m bgs and approximately 95 m bgs, before being permanently shut-off.

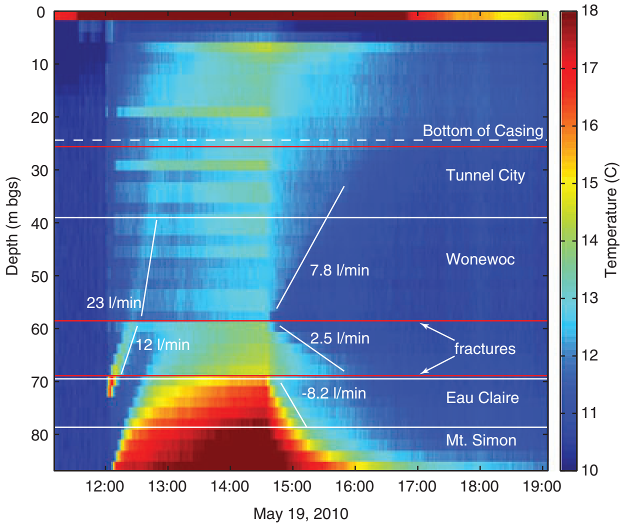


Figure 6. Image plot of DTS data from the continuous release experiment at DN-1440. The diagonal lines illustrate heat advection visible in the DTS data. The corresponding flow rates were estimated from the slopes of the lines in the distance vs. time plane.

In all experiments, DTS measurements were taken every minute, at a spatial resolution of 2 m. The DTS measurements were calibrated or verified by external reference thermometers, which were co-located with reference coils of the sensor cable in water baths of two different temperatures. The DTS data were then aggregated and plotted as color-coded depth/time temperature images in MATLAB (MathWorks).

Results and Discussion

DTS Experiments in DN-1440

Figure 6 shows a color-coded image of the results from the May 19 experiment in DN-1440, which used DTS to monitor the continuous operation of the heating system with the outlet fixed at the bottom of the well. Each pixel represents an individual measurement of temperature that is integrated over 2 m of cable and 1 min in time. The initial 50 min represent ambient temperatures, which are uniform due to vertical borehole flow. Activation of the heating system at 11:55, with the outlet stationed briefly at 73 m (240 feet) bgs, can be seen in the transition from blue to red pixels at this depth. Similar increases and subsequent decreases in temperature occurring at successively shallower depths in the well with time indicate upward movement of this initial pulse of heated water. Immediate warming throughout the upper portion of the borehole water column due to heat loss through the heating system outlet hosing can also be seen.

The transport of heat in the borehole is affected by advection, dispersion, free-convection (buoyancy effects), and the transfer of heat between the borehole and surrounding rock. In the absence of significant heat transfer to the surrounding rock, the velocity of the peak temperature (measured at each time interval) in a migrating heated water pulse should be indicative of the average advective velocity in the borehole, as dispersion would be expected to occur symmetrically about the peak temperature, and free-convection will dominate flow only when the buoyancy effects are large enough. The temperatures used in these tests were not high enough to induce significant convection in the tested wells of diameter 0.15 m (0.5 feet). Significant transfer of heat between the heat pulse and the borehole should produce a hysteretic effect, where the onset of peak temperature and the return to ambient temperature is delayed due to heat transfer to the surrounding rock, when temperature differences between the borehole and rock are greatest.

Visual inspection of the heated water pulse initiated at 73-m depth suggests that its displacement on the image is primarily the result of advection (Figure 6). This interpretation is consistent with velocities for the leading and trailing edges of the pulse that are very similar to the velocity of the peak temperatures. The velocity of the heat pulse is illustrated by the slope of the white annotation line drawn beneath it on the temperature image (Figure 6). The slopes of the lines were obtained within the MATLAB plotting interface, and converted to a velocity (Δdepth/Δtime) value using the dimensions of the image. The velocity value (m/min) was then multiplied by the cross sectional area (0.018 m^2) of the borehole to obtain the flow rate of 0.012 m^3/min or 12 L/min (Figure 6). This procedure was used to produce all other estimates of flow shown on Figures 6 through 8.

As the initial heat pulse passes the fracture at 58 m bgs, peak temperatures decrease substantially, making it difficult to see against the heating produced by the outlet hosing (Figure 6). The slope of the pulse on the image also appears to steepen, indicating an increase in borehole flow rate due to inflow from the fracture (Figure 6). The temperature decrease and advective velocity increase are consistent with the addition of cooler water entering the borehole at that depth. This depth is the same as that identified by Anderson (2002) as a fracture with inflow.

Following the relocation of the heating system outlet to the bottom of the well, the upward propagation of the outlet temperature in the interval below 70 m is delayed, presumably due to the transfer of heat from the borehole to the surrounding rock. The logarithmic shapes of the temperature isotherms in this interval shown in Figure 6 are interpreted to indicate a reduction in heat loss as temperatures in the outermost annulus of rock surrounding the borehole equilibrate with the water. Abrupt decreases in temperature at 69 and 58 m bgs indicate the inflow of cooler water from the two active fractures. In contrast to the outlet temperature, the velocity of the leading edge of the heated water released from the bottom of the well appears to indicate advection, as evidenced by a slope in the distance vs. time plane that is similar to that of the initial heat pulse released at 73 m bgs (Figure 6).

The evolution of temperatures following the shut-off of the heating system (at 14:32) provides detailed information on the ambient flow regime in the well. Immediate cooling occurs at the locations of the two important fractures. Interestingly, the flow appears to diverge out of the fracture at 58 m bgs. Above this point, the leading edge of the upward migrating cool water appears to move at a constant rate, as indicated by the white line on Figure 6, which corresponds to a uniform flow rate of 7.8 L/min over this interval. The flow likely exits the well near the bottom of the casing, where a fracture is indicated in the geophysical logs (Figures 3 and 6). Below the fracture at 58 m, flow is downward at 2.5 L/min, as shown by the downward trending line. The temperature signal is lost from the influx of cooler water from the fracture at 69 m. Near the bottom of the well, a delay in cooling similar to the delay in heating discussed above is interpreted to indicate re-equilibration of the surrounding rock with the downward flowing cool water. Some of the curvature in the leading edge of the downward migrating cool water below the base of the Eau Claire may also indicate a gradual reduction in borehole flow rate due to the loss of water via intergranular flow into the Mt. Simon.

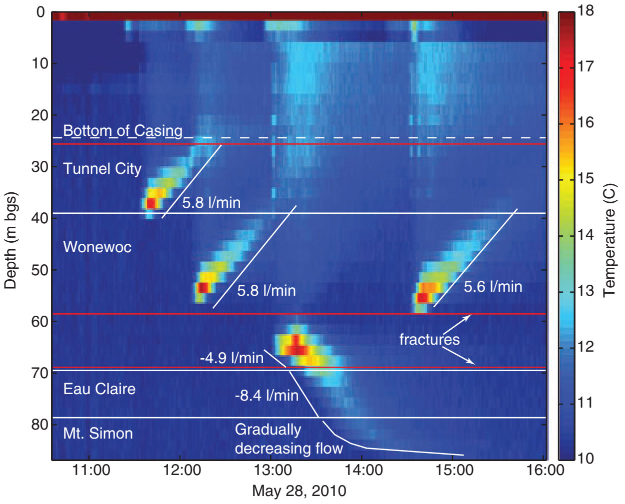


Figure 7. Image plot of DTS data from the discrete pulse experiment at DN-1440. The diagonal and curved lines illustrate heat advection visible in the DTS data. The corresponding flow rates were estimated from the slopes of the lines in the distance vs. time plane.

To further investigate these findings, a second DTS experiment conducted on May 28 monitored the migration of brief pulses of heat (Figure 7). Analysis of municipal pumping records and composite water levels in the well suggested that ambient flow conditions during this experiment were similar to those observed on May 19 (Anderson 2002; Leaf 2010). In comparison to a continuous release of heated water from a fixed location, discrete pulses have several advantages. By minimizing operation of the heating system and allowing specific depths to be targeted, they can provide greater temperature contrasts in the intervals of interest while maximizing the amount of time that ambient flow is being observed.

The three pulses released at 11:40, 12:10, and 14:40, above the fracture at 58 m bgs, indicate a constant rate of advection for most of the upper portion of the borehole, consistent with the results from the May 19 experiment

(Figure 7). For each pulse, the velocities of peak temperature were estimated by performing a linear regression analysis on the maximum temperatures measured at each time interval (Leaf 2010). For the heat pulses above 58 m bgs, the velocities obtained by regression compared favorably with those obtained by visually fitting a line to the trailing edge of the pulse, as described above. The leading edges of the upward migrating pulses, where cool water overlies heated water, appear to show faster velocities in early time, which may reflect the effects of free-convection (Figure 7).

At 69 m bgs, the slope of the downward migrating pulse becomes steeper, and temperatures in the pulse decrease, indicating additional inflow from the fracture at the base of the Wonewoc (Figure 7). An apparent gradual decrease in the pulse velocity below the base of the Eau Claire is consistent with the results of the May 19 experiment (Figure 6), and may indicate intergranular outflow into the Mt. Simon (as opposed to fracture flow). As discussed earlier, intergranular flow in the Mt. Simon is consistent with other borehole geophysical data (Figure 3).

DTS Experiment in IW-512

A third test conducted in well IW-512 monitored mostly continuous operation of the heating system with the outlet lowered to various depths (Figure 8). In the upper portion of the well, steep slopes in the leading and trailing edges of the heated water indicate flow rates in excess of 100 L/min, calculated as before from the slopes of the transported and heated water (Δdepth/Δtime). These flows are consistent with the spinner flow logs, Figure 4. The high flow rates limited the effectiveness of the heating system, by increasing both heat loss from the outlet hose and dilution at the outlet. This resulted in reduced contrast between the artificial and ambient temperatures and a lower signal-to-noise ratio. This problem was compounded by heating of the borehole from the outlet hose in the upper part of the well. The best data were obtained in the lower portion of the well where flow rates are lower.

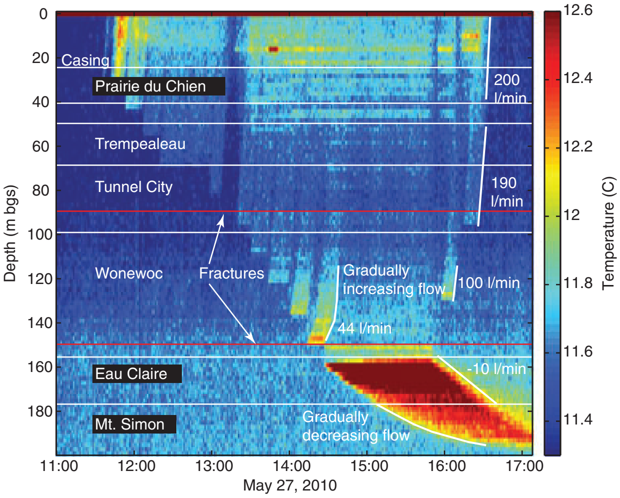


Figure 8. Image plot of DTS data from IW-512. The diagonal and curved lines illustrate heat advection visible in the DTS data. The corresponding flow rates were estimated from the slopes of the lines in the distance vs. time plane.

In the lower portion of the Wonewoc, some curvature may be visible in the trailing edges of the heated water, which would indicate a gradual upward increase in borehole flow from intergranular inflows, consistent with the geophysical logs. The fracture at 150 m bgs is clearly visible by an abrupt vertical transition in temperature at this depth between 14:30 and 15:50 (Figure 8). Diverging flow occurs just below this fracture, similar to DN-1440. Heated water released from the deepest outlet location (158 m bgs) flows downward. Curvature in the leading edge of the downward flowing heated water indicates a gradual decrease in borehole velocity. That gradual decrease suggests that outflow into the Mt. Simon is predominantly intergranular, similar to DN-1440 and is consistent with the spinner flow logs (Figure 4).

Implications for Conceptual Models of the Cambrian-Ordovician Aquifer System

DTS monitoring of the thermal dilution experiments in DN-1440 was able to delineate diverging ambient flow in the well. This phenomenon was not clearly observed in previous investigations, due to borehole flow rates that were between the sensitivity ranges for the heat pulse (3.8 L/min) and impeller flow meters (~25 L/min in a 0.15 m diameter well). The DN-1440 experiments were conducted during a period of increased effects from nearby municipal wells and below average composite water levels in the well (Leaf 2010). Downward flow across the Eau Claire aquitard during this condition is consistent with the findings of Anderson (2002). The observation of upward flow above 58 m bgs during this condition provides additional evidence for the upper aquifer being the source of the Pheasant Branch springs, which are characterized by steady flow rates.

The finding of significant fracture flow in the Wonewoc runs contrary to previous conceptual models that have characterized its flow as dominantly intergranular. The observation of diverging flow near bedding plane-parallel fractures at stratigraphically similar positions in both DN-1440 and IW-512 suggests that these features may be regionally significant, similar to the preferential flow zones in the Tunnel City Group noted by Swanson (2007), Swanson et al. (2006), Runkel et al. (2006), and Swanson and Bahr (2004).

Conclusions

In two bedrock wells open to the Cambrian-Ordovician aquifer system near Madison, Wisconsin, DTS monitoring of open-well thermal dilution tests provided detailed information on the borehole flow regimes, including flow rates and the locations of inflows from both fractures and porous media. The results led to an enhanced understanding of flow in a hydrostratigraphic unit previously conceptualized as homogenous and isotropic.

Although supporting characterization results (e.g., from borehole geophysics) are needed for the definitive interpretation of DTS data, DTS offers many advantages over conventional technologies. As a spatially synoptic method for monitoring tracer migration, DTS is sensitive to a wider range of flow rates than conventional heat pulse and spinner flow meter techniques, which were previously unable to adequately characterize the ambient flow regime in DN-1440. DTS measurements of heat advection are effectively integrated over the width of the borehole, in contrast to heat pulse and spinner flow techniques, which may respectively be biased by leakage around the diverter or turbulence near the edge of the borehole. In comparison to conventional wireline temperature loggers, DTS is superior in its response time, which is on the order of seconds rather than minutes, its ability to profile temperature in a well without disturbing the fluid column, and the ease of interpretation.

In this study, the synoptic nature of the DTS datasets (which can be visualized as images instead of profiles) and substantial supporting information allowed for the basic interpretation of tracer results without the use of models. Both constant source and discrete-pulse heating techniques produced useful complementary information, with the latter providing the most unambiguous results as a stand-alone technique. Future studies may utilize models of borehole heat transport during thermal dilution experiments to quantify the effects of free-convection and heat transfer to surrounding rock, or to estimate aquifer hydraulic properties.

The high flow rates in IW-512 represent the upper limit of the effective range for the heating system used in this study. An improved artificial heat source might not use heated water. For example, a submersible electric heater consisting of a resister element would eliminate any disturbance to the ambient flow regime and the problem of heat loss through the outlet hose. In addition, this would make it possible to quantify the amount of heat injected. It would also be more compact and easier to deploy in a wide variety of well constructions.

There is much potential for future DTS work in sedimentary aquifers. For example, in the Cambrian-Ordovician aquifer, DTS monitoring of open well thermal dilution tests in other locations in the Madison area may reveal important and correlatable hydrostratigraphic features that were previously unrecognized, enhancing our conceptual understanding of regional groundwater flow. As the cost of DTS continues to decrease, it could become a widely used downhole characterization technique.

Acknowledgments

Funding for this research was provided by the University of Wisconsin-Madison Water Resources Institute. The authors would also like to thank Scott Tyler and others at the Center for Transformative Environmental Monitoring Programs (CTEMPs) for their technical assistance, and for providing the DTS instrument used in this study. They are also grateful to the Wisconsin Geological and Natural History Survey for providing field equipment and assistance. Finally, the authors would like to thank three anonymous reviewers for their helpful comments.

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