Borehole flow characterization using DTS to monitor discrete in-well heat tracer tests

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Introduction

What we did:
Conduct in-well heat tracer tests to identify aquifer characteristics. Results shown for two wells (A and B).

Motivation:
Heterogeneities, including bedding plane partings, in siliciclastic bedrock aquifers can significantly influence flow.

Innovation:
Use of an electrical heater to induce heat pulses and use of DTS to monitor heat pulse evolution and transport.

Study Location

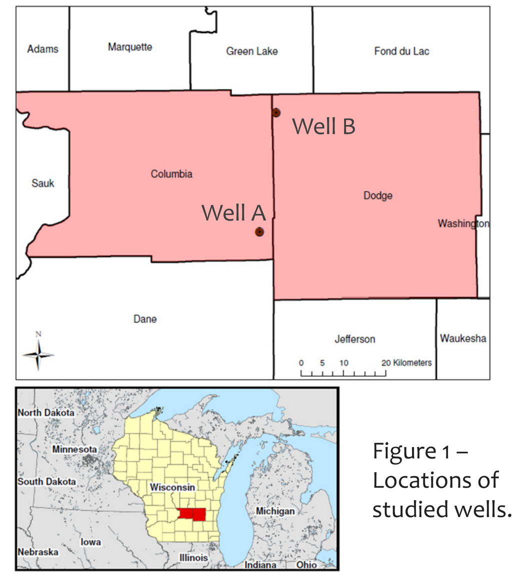


Figure 1 – Locations of studied wells.

Abstract

Heat tracer tests in open wells or boreholes provide valuable information about the adjacent formations, including the presence of permeable features such as fractures, the presence of aquitards, and whether flow is upward or downward. Heat tracer tests in wells are complicated due to the challenges of adding heat to the well and then measuring the movement of heat in the well while minimizing disturbance of the water column.

Distributed Temperature Sensing (DTS) technology makes use of the physical behavior of light in optical fiber to measure temperatures along a fiber optic cable. DTS systems have been deployed in a wide variety of hydrological settings and recently have been used in downhole environments to measure ambient temperature profiles and responses to induced temperature perturbations. DTS monitoring of borehole temperatures allows rapid collection of temperature data along the full borehole length while causing no disturbance to the water column during measurement.

We have developed a simple electric heater that can be used to induce heat pulses into the water column at discrete intervals. The heater consists of a 2,000 watt cartridge heater, shrouded in a perforated steel housing, and attached to electrical cable. The heater can be raised or lowered in the well to target specific zones of interest. The heating element is approximately 0.25 meter in length allowing for heat pulses to be induced at discrete intervals. The combination of discrete heat pulses induced via electric heater with DTS measurement of temperature response in the well allows for detailed characterization of the flow regime within the well.

We used DTS monitoring and the downhole electrical heater to profile the open portion of several bedrock wells. Using this system we were able to identify important flow characteristics in the wells, including borehole flow direction, velocity, and locations of inflows and outflows. The results indicate that DTS monitoring of induced heat pulses is an effective method for detailed borehole flow regime characterization.

Methods

Method of heat induction:

- 2,000 watt cartridge heater element
- Stainless steel perforated shroud
- 10 gauge (30 amp) grounded, wet environment electrical cord
- Powered by standard 120 volt generator

Figure 2 – Photo of heater showing shroud and electrical cord on a spool.

Method of temperature measurement:

- Distributed Temperature Sensing (DTS) system
- Fiber optic cable deployed over full length of well
- Spatial sampling: 1 m (spatial resolution of ~2 m)
- Integration time: 30 seconds
- Temperature resolution: 0.1 °C
- Single-ended measurements collected to reduce sampling time
- Two calibration baths were used, an ice bath and an ambient temperature bath
- Cable was deployed in duplexed configuration to allow for calibration baths at both ends of the cable

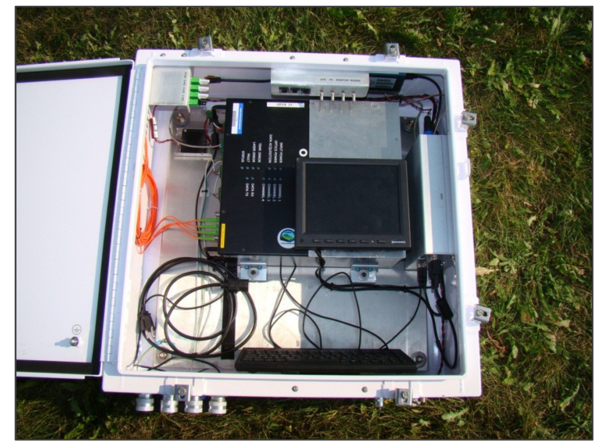
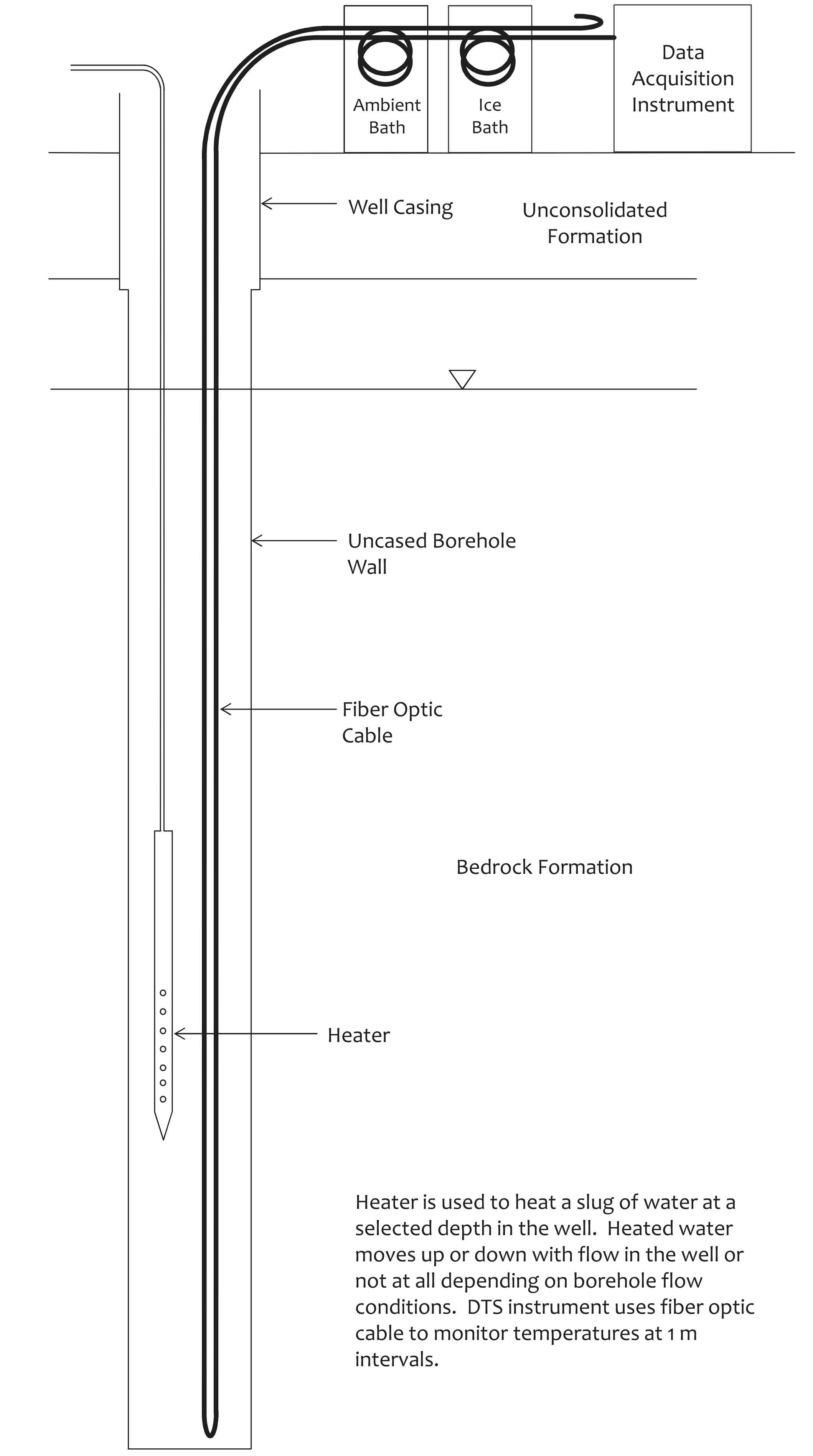


Figure 3 – Photo of the DTS unit. The instrument used for this work was a Sensornet Oryx rented from the Center for Transformative Environmental Monitoring Programs (CTEMPs).

Experiment Design



Heater is used to heat a slug of water at a selected depth in the well. Heated water moves up or down with flow in the well or not at all depending on borehole flow conditions. DTS instrument uses fiber optic cable to monitor temperatures at 1 m intervals.

Figure 4 – Schematic showing the experimental setup with the heater and fiber optic cable down-hole.

Note: Not to scale

Results

Geology

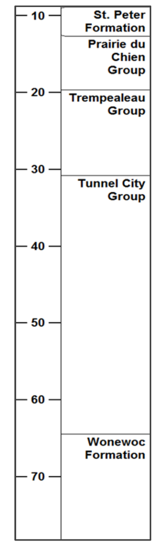


Figure 5 – Generalized stratigraphic column for Well A.

Identifying Flow Features

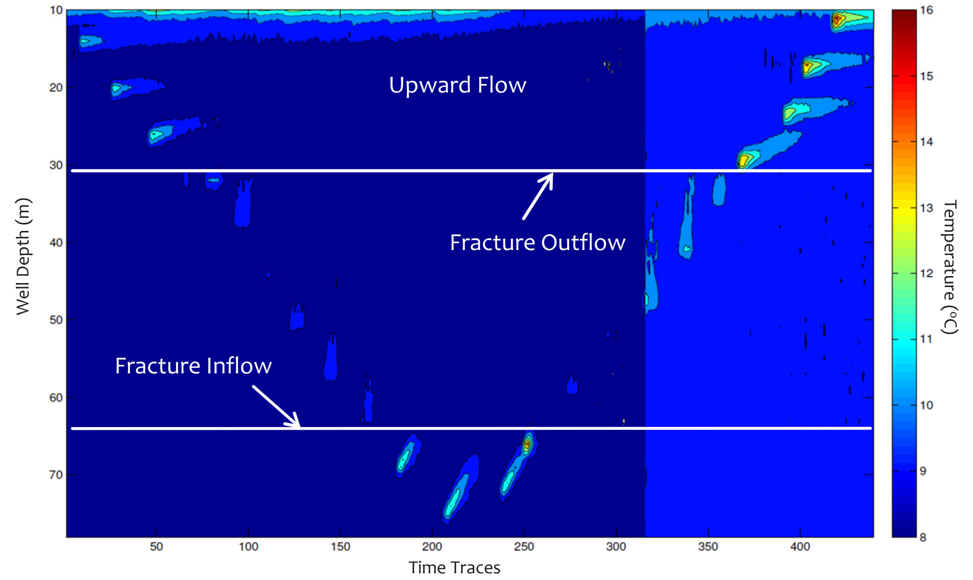


Figure 6 – DTS plot for Well A. Plot shows contoured temperature responses for discrete heat pulses with depth and time. Note color change at time trace 315 is due to an unexplained change in the ice bath temperature measurement, which impacts the instrument calibration.

Measuring Flow

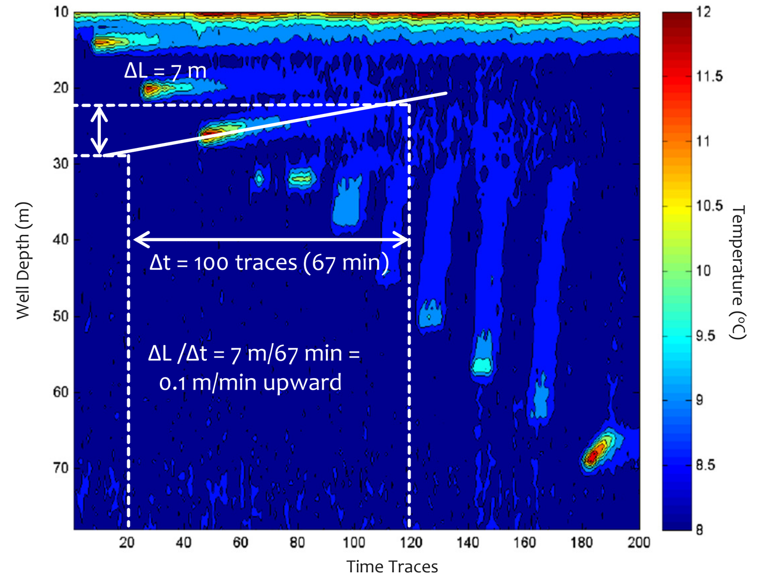


Figure 7 – Blow up of a portion of the DTS plot for Well A showing heat pulse slope used to calculate flow velocity. The graphical slope of a given heat pulse trace provides the velocity at which that pulse moved up or down in the well.

Flow Logs

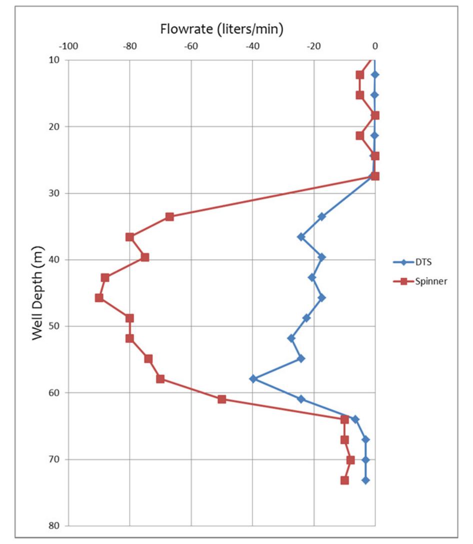


Figure 8 – Plot of DTS flowrate with depth for Well A. Plot also includes spinner flow meter results obtained from Well A on a different date.

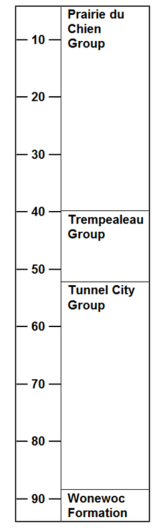


Figure 9 – Generalized stratigraphic column for Well B.

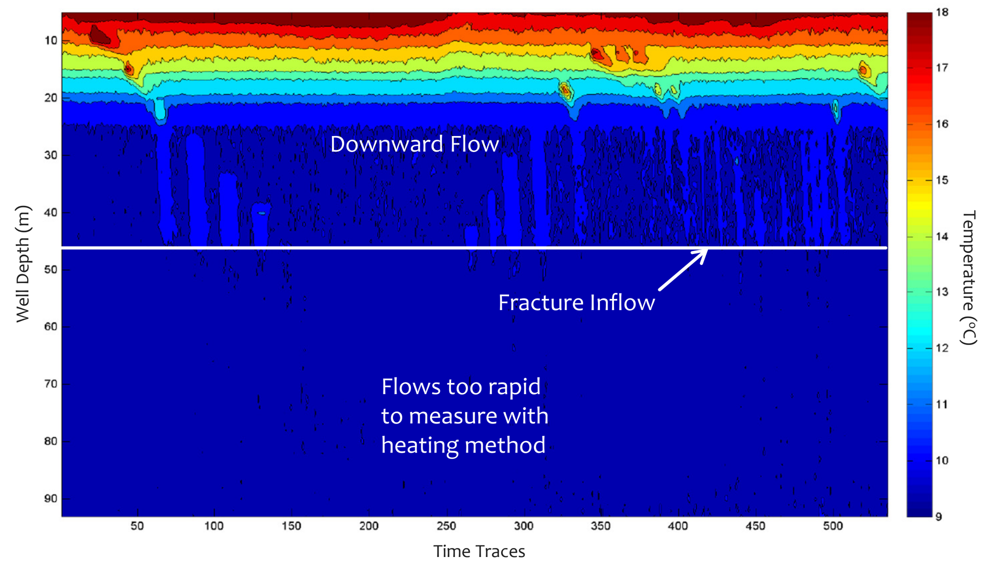


Figure 10 – DTS plot for Well B. Note that below 25 m only small increases in temperature could be achieved, and that below 47 m, flow was too fast to warm the water with a 2 kilowatt heater.

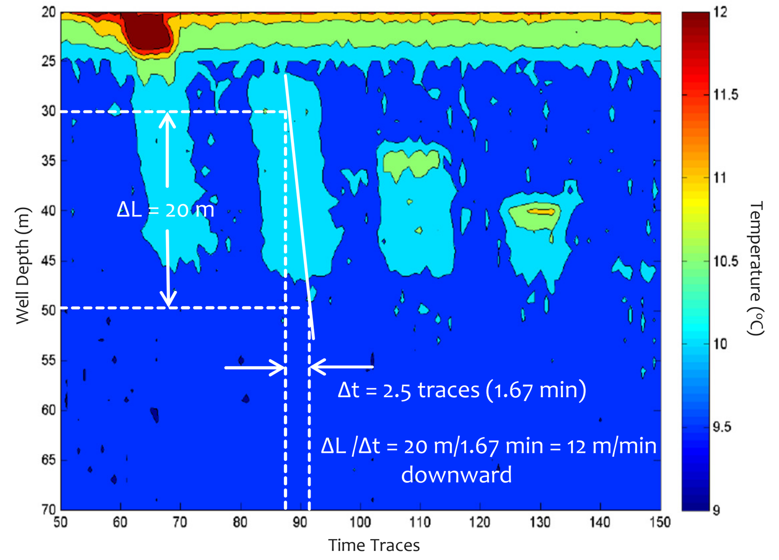


Figure 11 – Blow up of a portion of the DTS plot for Well B showing heat pulse slope used to calculate flow velocity.

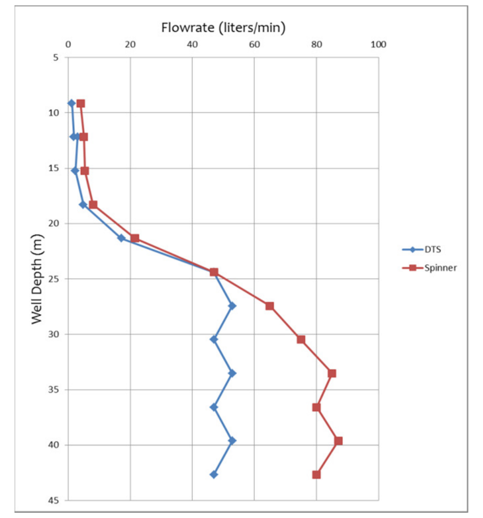


Figure 12 – Plot of DTS flowrate with depth for Well B. Plot also includes spinner flow meter results obtained from Well A on a different date.

Findings

Well A:

- Upward flows were measured for the studied length of this borehole
- Abrupt changes in upward flowrate occur at depths of 31 m and 64 m and indicate fractures are present at those depths
- Fracture at 64 m is contributing water to the borehole
- Fracture at 31 m is removing water from the borehole
- Apparent step changes in flow indicate fracture flow is more significant that porous-medium flow for most of the borehole
- DTS flow log matches general pattern of spinner flow log, and indicates step changes in flow
- Near-horizontal pulses demonstrate that buoyancy of warmed water does not cause significant upward transport of heat

Well B:

- Downward flows measured for the studied length of this borehole
- An abrupt increase in downward flowrate occurs at a depth of 47 m and indicates the presence of a fracture at this depth
- Fracture 47 m is contributing water to the borehole
- Outflows are occurring below the studied portion of this borehole
- Above 47 m, flow appears to come from porous medium contribution as successively deeper heat pulses have steeper slopes
- Below 47 m flows are too high to measure with this method
- DTS flow log matches general pattern of spinner flow log

Conclusions

- DTS is an excellent method of monitoring in-well heat tracer tests, providing real-time temperature data for the length of the borehole without disturbing the water column
- Method successfully measured upward and downward flows at a variety of flow rates, however, the method appears to underpredict the magnitude of flowrate as flowrates increase
- Method allowed for identification of discrete locations where changes in flow occur, indicating heterogeneity within the aquifer
- Results can be used to identify aquifer characteristics, including the presence of high flow zones or fractures
- Future research will evaluate the range of flow rates for which this method is applicable and causes of the apparent underprediction of flow rate

Acknowledgements

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- The DTS instrument and instrument support were provided by the Center for Transformative Environmental Monitoring Programs (CTEMPs)