# EVALUATION OF TEMPERATURE, STREAMFLOW, AND HYDROGEOLOGY IMPACT ON BROOK TROUT HABITAT

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**Executive Summary**

Distributed Temperature Sensing (DTS) technology, combined with detailed mapping of geologic conditions and hydraulic head were used to identify areas of preferential base flow at three southeastern Minnesota trout streams— East Indian Creek in Wabasha County, Trout Brook in Dakota County, and Valley Creek in Washington County. Results were compared to fish inventories conducted by the Minnesota Department of Natural Resources to evaluate influence of focused groundwater input on brook trout distribution and abundance. In addition, regional geologic conditions and hydraulic head distribution between aquifers were compared to previous southeastern Minnesota brook trout investigations to evaluate regional hydrogeologic controls on base flow and brook trout abundance. This project was funded by the Minnesota Environment and Natural Resources Trust Fund (ENRTF).

Distributed Temperature Sensing (DTS) methods use fiber optic cable to provide high resolution temporal and spatial temperature profiles. With measurements taken at 2 meter resolution over 5 minute intervals, these methods allowed for up to 2000 meters of stream temperature to be monitored as temperatures changed on diurnal cycles. Winter installations, where air temperature is significantly colder than groundwater temperature, provided the most detailed measurements of groundwater input. Warmer stream temperatures, close to overlapping profiles between time intervals and little to no change in temperature with distance, were interpreted as stream reaches with preferential groundwater input. Conversely, downward trending temperature profiles with distance and greater separation of temperature profiles between time intervals were interpreted as reaches with less groundwater input.

At East Indian Creek in Wabasha County, changes in groundwater input identified using this method corresponded to a transition from mixed brown and brook trout populations to predominantly brook trout. At Trout Brook in Dakota County, DTS combined with piezometer measurements showed that the measured stream section was predominantly continuous groundwater input. Trout distribution in this section showed brook trout are the predominant species, although brown trout are prevalent further

downstream. At the time of this report, fish inventories have not been conducted on Valley Creek in Washington County.

At the regional scale, maps showing the distribution of bedrock units together with hydraulic head data can be used as a first-pass to locate areas where brook trout, including remnant brook trout, may be most successfully established. At site-specific scale, our methods can be used to verify preferential conditions, and identify potentially ideal areas along individual stream reaches. Piezometer data (hydraulic head and temperature) and stream flow measurements collected at Trout Brook are a cost-effective, quick way to determine where preferential groundwater input from the older, deeper aquifers may occur. DTS methods provide better groundwater input resolution, albeit with more time intensive data collection, on a pool-by-pool and temporal basis.

At both regional and local cases our work demonstrates geologic control on hydraulic head conditions – particularly on vertical head gradients between bedrock layers and the role they play in stream base flow. At East Indian Creek, gravity-drainage of groundwater within the Jordan Sandstone is the source for stream headwaters. Additional groundwater input where the stream runs adjacent to the north valley wall corresponds to a marked increase in brook trout population from conditions further downstream. Reduced groundwater input is identified where the stream runs closer to the bedrock valley axis and as depth-to-bedrock increases.

At Trout Brook, preferential groundwater input is found where the stream is in close proximity to the Shakopee Formation – Oneota Dolomite contact within the Prairie du Chien Group. This section of markedly high porosity and permeability receives water via gravity drainage from both the overlying Shakopee Formation and the underlying Jordan Sandstone – where artesian conditions exist at this site. As with East Indian Creek, the largest groundwater inputs occur under shallow-to-bedrock conditions where the stream flows close to valley walls.

At Valley Creek, springs are produced from artesian conditions in several underlying bedrock layers combined with fractures associated with faulting. The Shakopee-Oneota contact may also be a source of these springs, with water contributed via fractures from underlying bedrock aquifers and/or gravity drainage from the overlying Shakopee Formation.

Although the focus of this report is specifically on brook trout, the DTS methodology and conclusions reached as part of this investigation may be applicable to other aquatic resources that are sensitive to stream flow and temperature distribution.

## Introduction

Trout investigations in southeastern Minnesota have considered the impact of stream temperature and base flow conditions on trout health and abundance, focusing specifically on stream reaches dominated by groundwater input. Krider et al. (2013) investigated the relationship between air temperature and water temperature in groundwater-fed streams. Linear regression models were used to classify streams as predominantly groundwater fed, with low slopes and high intercepts in comparison to surface-water dominated streams. French et al. (2017) used these stream classifications to investigate brown trout winter growth in 24 southeastern Minnesota streams ranging from predominantly groundwater fed to surface-water dominated streams. Thermal regime positively influenced winter growth for both males and juveniles, likely mediated by moderation of winter stream water temperature by groundwater. Brown trout in southeastern Minnesota have been shown to have highest seasonal survival in winter, and exhibited positive growth in length during this season (Dieterman and Hoxmeier, 2011; Dieterman et al., 2012). Winter brown trout growth may benefit from winter emergence of invertebrates (French et al., 2014; Anderson et al., 2016), which also rely on stream temperatures moderated by groundwater input.

The recent discovery of resurgent brook trout populations in southeastern Minnesota streams has led to an increased interest in documenting and improving critical habitat for this native species. Brook trout are the most temperature-sensitive of southeastern Minnesota's trout population; however, they have increased their distribution from 3% in the early 1970s to 68% today. The expansion of brook trout is coincident with increasing stream baseflows in Minnesota. Many of the brook trout analyzed were not associated with known hatchery sources, leading investigators at the Minnesota Department of Natural Resources (MnDNR) to focus on potentially remnant lineages that have proven their ability to sustain themselves in this region (Hoxmeier et al., 2015). Brook trout often display distinct distributions along stream reaches, thought to be controlled by stream temperature, discharge, competition with brown trout, or a combination of all three. Previous groundwater and geologic investigations in southeastern Minnesota, funded in part by the Minnesota Environment and Natural Resources Trust Fund (ENRTF), have shown that specific layers within the bedrock contribute greater groundwater flow than others (Runkel et al, 2003, 2006, 2013, 2016, 2018; Tipping et al. 2006). Stream reaches that cross these layers are subject to greater groundwater inputs, increased base flow and lower summer temperatures along and downstream from these reaches – thus, providing habitat conditions supportive to brook trout.

The goal of this project, as funded by the ENRTF, was to develop a workable temperature-sensing methodology and apply the methodology to candidate trout stream reaches to quantify changes in temperature, flow, and trout distributions that occur along them. Advances in temperature measurements using fiber optic cables, collectively referred to as distributed temperature sensing (or DTS), allowed temperature to be recorded through time at two meter-spaced intervals over distances of 1 to 2 kilometers along three southeastern Minnesota streams. In addition, detailed geologic mapping, hydraulic head, and flow measurements were conducted at these sites, along with inventories of regional hydraulic head data. Measured stream reaches were chosen based on regional geologic mapping by the Minnesota Geological Survey, focusing in areas where different geologic and hydrologic conditions exist and data on trout distribution and abundance are available.

This project delivers maps and cross sections showing where significant changes in temperature and stream flow are expected to occur at three hydrogeologically distinct sites in southeastern Minnesota. As time permitted, fish inventories were conducted by MnDNR staff to compare brook trout populations with hydrogeologic settings and stream temperature. Because these intervals are in large part controlled by subsurface geologic and hydraulic head conditions, results were extended to unmeasured reaches in southeastern Minnesota where detailed geologic mapping and trout data exist. Although the focus of this report is specifically on brook trout, the DTS methodology and conclusions reached as part of this investigation may be applicable to other aquatic resources that are sensitive to stream temperature distribution.

## Methods

The project goals were investigated both at local and regional scales. At the local scale, three distinct hydrogeologic settings with brook trout populations within southeastern Minnesota were identified and DTS equipment was installed (Figure 1). All sites are located where Cambrian and Ordovician bedrock is exposed or under a thin (<50ft) cover of alluvium. Winter months were chosen for data collection to maximize differences between groundwater temperature (warm) and air temperature (cold). Over distances of up to 1900 meters, DTS methods provided temperature measurements at 1 meter spacing, taken every 5 minutes, over the period of several days. At all sites, fallen trees prevented continuous submergence of the cable along monitored stream reaches. At these obstructions, approximately 10 meters of cable were coiled and placed on the stream bank. For winter installation, the streambank coils provided excellent markers in the DTS profiles because of large differences between groundwater and air temperature. Additional coils were submerged with RBR temperature transducers (RBR Limited, http://www.rbr-global.com) attached to assist with calibration.

In addition to stream temperature profiles collected using DTS equipment, detailed geologic mapping was conducted and hydraulic data were collected at each site. Geologic data collection included passive seismic profiles to estimate depth to bedrock, outcrop investigations, and structural mapping. Rasters of bedrock lithostratigraphic unit elevations were created and used to construct cross sections showing unit thicknesses and secondary porosity (fracture and conduit) distributions relevant to groundwater flow. Hydraulic data collection included synoptic streamflow measurements along the DTS-installed stream section, shallow piezometer installation to measure vertical hydraulic gradients along with streambed and stream temperature, and - depending on availability - water level measurements in wells nested in different aquifers (e.g., MnDNR Cooperative Groundwater Monitoring (CGM) Program).

As time permitted, fish inventories were conducted by DNR Fisheries. Electrofishing methods were used to count and inventory trout species by pool. These results were compared with stream temperature profiles in an attempt to recognize relationships between brook trout distribution and abundance and preferential groundwater input.

At the regional scale, brook trout abundance data from previous investigations were reviewed in the context of bedrock hydrostratigraphic setting and regional hydraulic head data. The goal of this part of the project was to see what regional inferences could be made, both by extrapolation of local-scale results and identifying possible regional patterns not recognized in site-specific investigations.

## Results

### *Hydrogeologic setting – site investigations*

The three sites chosen for DTS installation are distinct from one another both in local bedrock lithostratigraphy and hydraulic head distribution. At site 1, East Indian Creek in Wabasha County (Figure 1), the DTS cable was installed where the streambed extends over the lower two-thirds of the Jordan Sandstone (upstream) and the upper one-half of the St. Lawrence Formation (downstream) (Figure 2). Numerous springs are located in the stream headwaters. Alluvium thickness based on passive seismic measurements ranges from 10 to 50 feet. (Figure 3). Headwater springs are gravity-fed as groundwater within the partially-saturated Jordan Sandstone drains into the stream valley (Figure 3). Regional potentiometric surface mapping (Blum, 2018) shows artesian conditions within the Tunnel City Group midway through the measured reach (Figure 3).

At site 2, Trout Brook in Dakota County (see Fig. 1), the DTS cables were installed where the streambed extends over the lowest part of the Shakopee Formation (upstream) and the upper part of the Oneota Dolomite (downstream) of the Prairie du Chien Group (Figure 4). Alluvium thickness estimated from passive seismic profiles ranges from 30 to 50 feet (Figure 5). Hydraulic head measurements from upstream shallow piezometers show a distinct upward vertical hydraulic head gradient of 0.1 throughout the measured section, corresponding to warmer and less variable winter streambed temperatures from these piezometers compared to downstream piezometer measurements.

Continuous water level measurements from a nearby DNR observation well nest show that the Jordan and Tunnel City aquifers have hydraulic heads above the stream elevation across the entire monitored stream reach, which is likely responsible for the upward vertical hydraulic head gradient measured in the piezometers (Fig. 6A). The lowest hydraulic head is at or near the Shakopee-Oneota contact.

At site 3, Valley Creek in Washington County (see Fig. 1), DTS cables were installed where the stream bed extends over the Shakopee Formation of the Prairie du Chien Group (upstream) to the St. Lawrence Formation (downstream) (Figure 7). The stream crosses a fault with estimated vertical bedrock offsets of over 100 feet (Figure 8, Steenberg and Retzler, 2016). Numerous sand boil springs are located in the ponds near the stream headwaters.

Limited hydraulic head data from wells and numerous sand boil springs in the stream headwaters indicate the Jordan Sandstone likely responsible for strong artesian conditions, providing the majority of streamflow at the site. The spring cluster is interpreted to be fault-related (Mossler, 2005; Steenberg and Retzler, 2016). In addition to the Jordan, artesian conditions inTunnel City Group, and Wonewoc Sandstone are potentially additional sources for artesian conditions water moving upward through fractures associated with faulting, although there are no nearby water level measurements to confirm this.

*Temperature Profiles – East Indian Creek*

Figure 9 shows the location of the 1900 m of DTS cable, coils and RBR temperature transducers installed along East Indian Creek and accompanies East Indian Creek temperature profiles (Figures 10 ) Calibrated January 9th, 2018 DTS data for East Indian Creek were plotted for Coordinated Universal Times (UTC) 08:00 (2 am Central Standard Time [CST]), 12:00 (6 am CST), 14:00 (8 am CST), 16:00 (10 am CST), 18:00 (12 pm CST) and 20:00 (2 pm CST) (Figure 10). Subaerial coil locations, calibration baths and end-of-reel cable are labeled and readily identified as large deviations from stream temperature.

Smaller deviations are also visible as specific locations along the cable. Air temperatures measured at the Rochester Airport for January 9th ranged from -5.0 to 4.4 degrees centigrade. A second set of calibrated plots (Figure 11) is for January 12th, 2018 which was colder, with air temperatures measured at the Rochester Airport ranging from -22.8 to -16.1 degrees centigrade. Because of the cold temperature, the DTS system shut down and a repeat of January 9th profile times was not possible. Plotted UTC times 1:00 (January 11, 7 pm CST), 3:00 (January 11, 9 pm CST) and 17:00 (11 am CST)

The January 9 and January 12 datasets have generally similar profile characteristics, but with greater resolution in the latter due to the greater difference between air and groundwater temperature. Both show stream temperature warms during the day. Interpretation of relative contributions of groundwater along the monitored stream reach used several characteristics of the plotted temperature data (Figures 10, 11). With air temperature colder than groundwater temperature, greater groundwater input is recognized by warmer temperatures, close to overlapping profiles between time intervals, and little or no change in temperature with distance. Upward trending profiles are associated with focused groundwater input. Reduced groundwater input corresponds to downward trending temperatures with distance, and more separation between time intervals.

Preferential groundwater input is interpreted along three intervals of the monitored stream reach. The headwaters (approximately 1850 to 1750 meters) is the uppermost reach with significant input, with the warmest water, little or no change with distance, and having close to overlapping temperature profiles. Temperatures decline from approximately 1500 to 1300 meters. Slight warming present from 830 to 700 meters, where groundwater input increases. This interval also shows an increase in temperature with distance and is interpreted as focused groundwater input.

*Temperature Profiles – Trout Brook*

Figure 13 shows the location of the DTS cable and related instrumentation, as well as locations of stream flow measurements for Trout Brook. Trout Brook temperature profiles are shown in Figures 14 and 15. Calibrated December 12th, 2018 DTS data were plotted for Coordinated Universal Times (UTC)

08:00 (2 am CST), 12:00 (6 am CST), 14:00 (8 am CST) 16:00 (10 am CST), 18:00 (12 pm CST) and 20:00 (2 pm CST). The data plotted in Figure 14 are for a 1200 meter cable running upstream of the DTS station, and the data plotted in Figure 15 are for a 600 meter cable extended downstream from the station. Air temperature as measured at Rochester Airport ranged from -2.8 and -5.6 degrees centigrade. A notable spike in temperature is labeled as coil 2 (Fig 14). At this location, 10 meters of fiber optic cable were coiled and submerged at a sand boil spring. Downstream temperatures show a gradual decline from this focused input. Relatively flat temperature along all profile lines indicate consistent groundwater contributions along this section of the stream, extending to about 400 meters downstream from the DTS station (Fig 15) From 400 meters to the end of the cable, temperature profiles start moving in a slightly downward trend, associated with less groundwater input. This trend is supported by piezometer hydraulic head and temperature measurements, showing a drop in upward gradient and cooling of streambed temperatures as Trout Brook turns southward downstream from piezometer 3 (Figure 16). The cause for warm spikes in the temperature profile is unclear and may be focused groundwater input and/or related to pool depth where the cable is insulated from the air temperature by deeper water.

In addition to DTS cable, shallow piezometers were installed upstream, within, and downstream from the DTS measured section (Fig. 16). Piezometers were used to measure hydraulic head within the stream bed compared to the stream surface, with piezometer water levels above stream level indicating upward vertical hydraulic head gradient. In addition, several of the piezometers were instrumented with temperature transducers both inside the piezometer (below the stream bed) and outside in the stream water. Upward hydraulic gradients of 0.1 to 0.2 were measured in piezometers 1, 2, and 3; upward gradients were an order of magnitude less in in piezometers 4 and 5. Temperature patterns are consistent with measured vertical gradients: steady, consistently warmer streambed temperature measured inside piezometers 1, 2 and 3, and slowly declining streambed temperatures in piezometers 4 and 5. Piezometer 6 temperatures, measured at the downstream end of the park, show less groundwater influence, with streambed temperatures following stream temperatures. Located at a sand boil spring, piezometer 2 has notably different temperature profiles than the other piezometers, with stream temperature elevated locally and close to streambed temperature.

*Temperature Profiles – Valley Creek*

Figure 17 shows the location of the DTS cable and associated instrumentation for Valley Creek and accompanies temperature profiles in Figures 18 and 19. Uncalibrated February 19$^{th}$, 2019 DTS data for Valley Creek 600m cable were plotted for Coordinated Universal Times (UTC) 08:00 (2 am CST), 12:00 (6 am CST), 14:00 (8 am CST), 16:00 (10 am CST), 18:00 (12 pm CST) and 20:00 (2 pm CST) (Figure 18). Air temperature as measured at Minneapolis/St. Paul Airport ranged from –5.6 and -19.4 degrees centigrade. Data were not successfully calibrated, due in part to temperature transducer malfunctions. The data, however, provide a reasonable match to measured stream temperatures. As with East Indian Creek and Trout Brook profiles, interpreted groundwater inputs are based on relative changes in profile temperature, slope and separation between time profiles. Headwaters are markedly warmer than the rest of the stream. Higher stream temperature indicates the predominance of groundwater entering the stream under artesian conditions. A slight warming of stream water temperature between coils 11 and 10 indicate focused groundwater input along this reach; a similar increase is present midway between coils 10 and 09.

Uncalibrated February 19th, 2019 DTS data for Valley Creek 1200m cable were plotted for the same UTC time intervals as the 600m cable (Figure 19). A temperature profile drop occurs just downstream from the main spring pond inlet. From this point to the first bend downstream from the DTS station, stream temperature is constant and elevated relative to downstream, indicative of possible groundwater input along this reach. Profiles downstream from this point remain relatively constant; without functioning RBR transducers, conclusions drawn from minor changes in uncalibrated data are speculative. Cable loop marks location were the cable doubles back on itself, resulting in relative symmetry between 700 and 900 meter cable distances.

## Discussion

*Hydrogeologic setting and temperature profiles – site investigations*

While trout investigations in southeastern Minnesota have attributed fish abundance and health to groundwater inputs, none of these investigations looked specifically at geologic and hydraulic head controls on preferential base flow to streams. In this investigation, detailed stream temperature profiles along with streamflow and vertical hydraulic head gradient measurements combined with geologic mapping provide an improved understanding of focused groundwater inputs at each stream site.

Stream site cross sections (Figures 3, 5 and 8) show horizontal bedding parallel partings (BPPs) typically found at specific stratigraphic horizons within bedrock units. Also depicted on the cross section are systematic, regularly-spaced vertical fractures resulting from regional tectonic stresses. These features exist in all southeast Minnesota bedrock; their termination points typically occur at predictable, and therefore mappable, lithologic changes and are represented in cross sections as spaces between vertical lines. Combined, BPPs and vertical fractures provide for rapid groundwater transport with preferential bedding parallel (horizontal) flow supplied from above and below by systematic vertical fractures. Collectively, these secondary porosity and permeability features provide the bulk of water movement in sedimentary bedrock, whereas most water storage occurs in the rock matrix.

At East Indian Creek, stream water is provided primarily by gravity drainage as a partially saturated Jordan Sandstone drains into the stream valley. Stream headwaters have numerous springs located near the valley walls. No sand boil (artesian) springs were observed and groundwater is uniformly at or near the ground surface. Under winter conditions, groundwater is warmer than air temperature; stream profiles in this section have relatively warmer water than downstream, with close to overlapping profiles between time intervals for a single day (Figure 10). These conditions persist downstream to approximately the 1550 meter mark (as measured from downstream), where profiles show stream temperature cooling from 1550 to 1300 meters and greater separation between time intervals. This cooling section of the stream corresponds to an increase in depth-to-bedrock as the stream moves towards the valley axis. Cooling is associated with diminished groundwater input as the effect of air temperature is not buffered by warmer base flow. From 1300 to 1000 meters, stream profiles show relatively constant temperature where the stream is positioned closer to the southern side of the valley, before dropping again from 1000 to 830 meters.

East Indian Creek approaches the north valley wall at 730 meters, marked by an increase in stream temperature and reduced temperature separation between profiles (Figure 12). Warmer stream temperature is attributed to the stream's proximity to the valley wall, with possible focused groundwater input from BPPs within the lower Jordan Sandstone and upper St. Lawrence Formation. The contact between the Jordan Sandstone and St. Lawrence Formation is transitional, with relative proportion of siltstone beds to fine to very fine-grained sandstone of the lower Jordan increasing with depth (Mossler, 2008). Regionally, this stratigraphic position has both vertical fracture terminations and hydraulically active BPPs, resulting in greater groundwater flow through the bedrock (Runkel et al., 2016). A common expression of these conditions is the preferential clustering of springs at this stratigraphic position in southeastern Minnesota (Green et al., 2012) Source water from gravity drainage through the Jordan Sandstone at this site may be augmented by upward flow from artesian conditions below the St. Lawrence Formation within the Tunnel City Group (Fig. 3).

The increase in East Indian Creek stream temperature along the north valley wall along with other profile trends discussed are more pronounced in DTS data collected during colder air temperature conditions on January 12, 2018. When compared with fish inventory results, there is a marked increase in percent brook trout population corresponding to stream reaches with focused groundwater input (Figure 11). The north wall valley section between cable distance 730 and 700 meters shows a sharp transition from mixed brook and brown trout populations downstream to predominantly brook trout; brook and brown trout are both present upstream where descending temperature profiles and greater separation between profiles indicate reduced groundwater input; brook trout again are the dominant species by pool in the headwaters, where warmer temperatures and less separation between profiles indicate greater groundwater input.

At Trout Brook, BPPs and large conduits, as depicted on the cross section, occur along the contact between the Shakopee Formation and the Oneota Dolomite of the Prairie du Chien Group. These features are located at or just below the streambed in the upstream portion of the park where DTS stream profiles were measured. Upward hydraulic head measurements from streambed piezometers, increased stream flow, consistently warm winter stream temperature profiles and surrounding observation well data are indicators of preferential base flow occurring along the Shakopee-Oneota contact along this section of the stream.

Source water from gravity drainage through the Shakopee Formation at this site is likely augmented by upward flow from artesian conditions in the underlying Jordan Sandstone. Hydraulic head in the underlying Jordan Sandstone is higher than stream level, both along the measured stream section and downstream to the Cannon River. The upward spike in stream temperature at coil 2 is the result of groundwater input from a series of sand boil springs at that location – indicating artesian conditions below the stream bed. Higher hydraulic head can be transmitted to the stream valley via BPPs and conduits along the Shakopee-Oneota contact. In similar hydrogeologic settings along the Cannon River, borehole flowmeter measurements in wells with open-hole intervals across the Shakopee-Oneota contact have shown higher heads in the overlying Shakopee Formation (gravity drainage) and underlying Jordan Sandstone (artesian) with flow converging and exiting the borehole near the contact to discharge into the Cannon River or one of its tributaries (Tipping el al., 2006). This hydraulic head configuration with lowest values near the Shakopee-Oneota contact is confirmed by nested water level measurements from DNR observation wells at the north end of the park.

Trout Brook stream temperature profiles were measured where the stream is in relatively close proximity to the valley wall – south valley wall for the 1200m cable and east valley wall for the upper portion of the 600m cable. Warmer temperatures, close to overlapping temperature profiles with time, and minor change in temperature with distance all indicate groundwater input along this reach. There is a marked increase in stream flow where the stream turns southward, close to the east valley wall (Figure 13, piezometer 3), duplicating streamflow measurement results from Groten et al. (2015). The ubiquitous presence of horsetails (*Equisetum hyenmale*) on the terrace west and south of this bend also indicate relatively greater groundwater inputs in this area, contributing to hyporheic flow as streamflow direction shifts from east to south. Downstream from this site, a slight decrease in stream temperature at the 400 meter mark and slightly greater separation between time intervals (Figure 15), is interpreted as decreased groundwater input. Similarly, the warm spike on the 1200m cable at the sand boil spring and warm spikes at approximately the 160, 220 and 390 meter marks on the 600m cable may also be focused groundwater input through the streambed, although no sand boil springs were identified along this section.

A fish inventory along the DTS-measured section of Trout Brook was conducted by DNR staff on January 15th, 2019. Pools were inventoried starting upstream from the DTS station (Figure 13, coil 1). Proportion of brook trout was similar among pools and averaged 67% throughout the first 500 m of the DTS reach. The entire DTS reach was not able to be sampled due to the unusually high numbers of trout. Inventory results are similar to earlier investigations on Trout Brook, showing a predominance of brook trout along the northern section of the stream (Hoxmeier, 2017). As with East Indian Creek, these data indicate greater percent brook trout populations associated with zones of preferential groundwater input to streams. Furthermore, these groundwater inputs are spatially coincident with geologic conditions conducive to preferential groundwater flow in southeastern Minnesota (Runkel et al., 2003, 2006, 2013, 2016, 2018; Tipping et al. 2006).

The headwaters of Valley Creek are characterized by a high number of sand boil springs in both natural and constructed ponds, hereafter referred to as spring ponds, accounting for the majority of water in the stream (Figures 7 and 17). In the absence of local nested hydraulic head measurements in lower aquifers, the source or sources of artesian head conditions producing the springs is speculative. In the stream itself, headwaters are considerably warmer compared to either East Indian Creek or Trout Brook, with temperatures greater than 10 degrees centigrade. These warmer waters support the hypothesis that sand boil source waters are from deeper aquifers.

In Valley Creek, warmest waters are in the uppermost headwaters from 380 to 360 meters on the 600m cable (Figure 18). Declining temperatures and greater separation between profiles from 350 to 300 meters indicate reduced groundwater input, whereas an increase in temperature from 260 to 230 meters shows greater groundwater input. This latter section runs southeast of a spring pond separated from the stream by a berm, and may be receiving increased base flow via interflow from the pond. A similar increase in stream temperature occurs from approximately 175 to 160 meters. A slow decline in stream temperature with slightly greater separation between profiles from 160 to 40 meters indicates reduced groundwater input. This section of the stream is a greater distance from the spring ponds (Figure 17).

Downstream from the Valley Creek DTS station, warmest waters on the 1200m cable occur just upstream from a small footbridge in a section receiving input from a spring pond just south of the stream. A slight increase in stream temperature from 80 to 100 meters on the 1200m cable is downstream from the inlet from the largest of the spring ponds to the northwest of the stream. This pond also receives water from the second upstream spring pond near the 600m cable discussed earlier. Malfunctioning RBR temperature transducers (locations on Figure 19), did not allow for calibration, so interpretation of minor fluctuations downstream from 100 meters is speculative, although overall constant temperature with little or no change in separation between profiles along this section of the stream suggests relatively uniform groundwater input.

At the time of this report, a recent fish inventory of Valley Creek headwaters has not been conducted. Earlier investigations showed a transition from brown to brook trout occurring downstream from the measured section, on the north side of Valley Creek Trail (Weigel, 1994). Even though air temperatures during DTS installation were similar to both East Indian Creek and Trout Brook, Valley Creek temperatures are considerably warmer, and likely reflect greater groundwater input from deeper artesian aquifers. As with Trout Brook, focused groundwater flow to the headwaters area likely occurs along BPPs and conduits at or near the Shakopee-Oneota contact within the Prairie du Chien Group. The Jordan Sandstone, Tunnel City Group and Wonewoc Sandstone are all potential local artesian sources for water moving upward to this contact through vertical fractures associated with faulting.

*Hydrogeologic setting - regional Investigation*

As mapping and related hydrostratigraphic research across southeastern Minnesota has progressed over the past 20 years, our ability to evaluate the hydrologic controls on ecologic conditions has improved. For example, Runkel et al. (2013) showed that hydrogeologic setting has a significant impact on nitrate concentrations in base flow of coldwater streams. A comparison of the hydrogeologic conditions to the distribution, population, and genetic makeup of brook trout at regional scale similarly reveals some potentially key relationships. Hoxmeier et al. (2015) noted that the spatial distribution of brook trout across southeastern Minnesota indicate a preference for low-order (small, upper-reach) tributary streams that receive groundwater input from bedrock units relatively low in the aquifer system. Figure 20 illustrates that phenomenon, showing that brook trout have been documented almost exclusively from streams where the Oneota Dolomite and underlying bedrock units are uppermost bedrock. Groundwater input from these units is known to include a significant component of relatively old, regionally-sourced water (Runkel et al., 2013). Individual springs in this setting are characterized by relatively constant temperatures (Luhmann et al. 2011). In addition, the generally poor connection of the groundwater to land surface conditions also results in relatively low levels of anthropogenic contaminants (Runkel et al., 2013), and a relatively low susceptibility to extreme events that can include high turbidity and contaminant levels. In contrast, coldwater streams that cross stratigraphically higher bedrock units to the west, such as the Galena Group, receive groundwater input from springs and disseminated base flow with a greater susceptibility to contaminants, temperature changes, and extreme events. This reflects well-developed karstic properties and dominance of locally-sourced water.

At a more local scale the distribution, population, and genetics of brook trout may also in part be controlled by local variability in hydraulic head conditions. Under otherwise similar hydrogeologic settings, such as the transmissivity of the bedrock and unconsolidated materials along a stream reach, the hydraulic head of the aquifers may be the most significant factor that determines the volume and steadiness of groundwater inputs. Figure 20 illustrates where hydraulic head is sufficiently high that artesian conditions are possible. These areas would be more likely to have greater flux and potentially steadier groundwater inputs to streams than areas where hydraulic head is estimated to be below the land surface. A local example linked to brook trout data is illustrated in Figure 21A. Potential artesian conditions are much more prevalent across the upper tributary reaches of Rush Creek in comparison to tributaries to nearby Money Creek. These artesian conditions may account for the greater abundance of brook trout in the Rush Creek tributaries than those in Money Creek. The Rush Creek populations also include those with remnant genetics, which have not been recorded in the upper Money Creek tributaries.

Although our results show an apparent link between hydrogeologic setting and brook trout populations, many other factors are known to play a role (e.g. Hoxmeier et al., 2015). This appears to be reflected locally in southeastern Minnesota, such as across southern Wabasha and northwestern Winona Counties (Figure 21B). Several tributaries to the Zumbro River and along East Indian Creek (one of our research sites), have relatively high brook trout populations, including remnant brook trout. These apparently healthy populations are present on stream reaches across lower bedrock units with possible artesian groundwater, which is consistent with the hypothesis that such conditions play a role in creating a suitable habitat. However, other tributaries to the Zumbro River, as well as most sampled tributaries to the Whitewater River in nearby Winona County, have apparently similar hydrogeologic conditions but notably lower brook trout abundance. This demonstrates the importance of local factors along individual tributaries that include land use, accessibility for brook trout re-establishment, and stocking practices. Furthermore our regional scale depiction of artesian conditions is not likely to be representative across all individual stream reaches. Verification at site-specific scale can be accomplished with the collection of additional hydraulic head and temperature information along individual stream reaches. Piezometer data (hydraulic head and temperature) and stream flow measurements collected at Trout Brook are a cost-effective, quick way to determine artesian conditions where preferential groundwater input from the older, deeper aquifers may occur.

## Conclusions and Recommendations

The value of distributed temperature profiles provided by DTS systems is the high resolution of stream temperature measurements, in terms of both distance and time. With measurements taken at within 2 meter resolution and over 5 minute intervals, these methods allowed for up to 1900 meters of stream temperature to be monitored as temperatures change on diurnal cycles. Winter installations provided the most detailed measurements of groundwater input; with air temperature significantly colder than groundwater temperature - warmer stream temperatures, close to overlapping profiles between time intervals, and little to no change in temperature with distance all indicate reaches with preferential groundwater input. Conversely, downward trending temperature profiles with distance and greater separation between time interval profiles suggests less groundwater input.

In the case of East Indian Creek, changes in groundwater input identified using this method corresponded to a transition from mixed brown and brook trout populations to predominantly brook trout. In Trout Brook, DTS combined with piezometer measurements showed that the stream section measured was predominantly continuous groundwater input. Fish inventory along this section showed brook trout are the predominant species; the transition from brown to brook trout may be further downstream. At the time of this report, fish inventories have not been conducted on Valley Creek.

At the regional scale, maps showing the distribution of bedrock units together with hydraulic head data can be used as a first-pass to locate areas where brook trout, including remnant brook trout, may be most successfully established. At site-specific scale, our methods can be used to verify preferential conditions and identify potentially ideal areas along individual stream reaches. Piezometer data (hydraulic head and temperature) and stream flow measurements collected at Trout Brook are a cost-effective, quick way to determine where preferential groundwater input from the older, deeper aquifers may occur.   DTS methods provide better groundwater input resolution, albeit with more time-intensive data collection, on a pool-by-pool and temporal basis.

At both regional and local cases our work demonstrates geologic control on hydraulic head conditions – particularly on vertical head gradients between bedrock layers and the role they play in stream base flow.  Although the focus of this report is specifically on brook trout, the DTS methodology and conclusions reached as part of this investigation may be applicable to other aquatic resources that are sensitive to stream flow and temperature distribution.

**Acknowledgements**

Field-based investigations such as this project would not have been possible without the cooperation of landowners and park, county, and state agency staff. The authors gratefully acknowledge the assistance provided by DNR staff Doug Dieterman, Randy Binder, Nick Evans, Vanessa Barrata, Wes Rutelionis , Samantha Putlak, John Barry, and Scot Johnson; MGS staff Jarrod Cicha, Jordan Mayer and Shawn Scott, MGS field techs Sonia Ellison Alex Lutze and Anik Regan; the Dittrich family, Larry Gates, Dakota County Parks, Dakota County SWCD, the Berggren family, and the Daley family. Special thanks to John Hoxmeier of The DNR – Lake City office for organizing and conducting fish inventories along with guidance on project design and report review, and to Nick Budde for his work on East Indian Creek data as part of his senior thesis project at St. Cloud State. The authors also gratefully acknowledge DTS equipment and technical support provided by the Center for Transformative Monitoring Programs (CTEMPs), an NSF-funded program, administered jointly by Oregon State University and the University of Nevada-Reno. Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund (ENRTF).

**List of Figures**

**Figure 11**. East Indian Creek stream temperature profiles - from January 12th, 2018 with interpretation of relative groundwater inputs along the stream reach based on profile characteristics. Upstream to downstream is plotted left to right. Times recorded for each profile are in Coordinated Universal Time (UTC). Percent brook trout shown per sampled pool distance from the downstream DTS station. Note marked increase in percent brook trout where stream runs close to north wall and receives focused groundwater input.

**Figure 12**. Map view of the DTS-measured reach of East Indian Creek showing percent brook trout by pool. A marked increase in percent brook trout occurs where the stream runs along the north wall of the valley (Figure 11).

**Figure 13**. DTS installation, Trout Brook, showing locations of fiber optic cable, coils, RBR temperature transducers, DTS collection station, and stream flow measurements. A 1200 meter (red) and 600 meter (light red) cable was used, with collection station between the two. Streamflow measurements made October 28, 2018.

**Figure 14**. Trout Brook DTS stream temperature profiles - 1200 meter cable - from December 12, 2018. with interpretation of relative groundwater inputs along the stream reach based on profile characteristics Upstream to downstream is plotted left to right. Times recorded for each profile are in Coordinated Universal Time (UTC).

**Figure 15**. Trout Brook DTS stream temperature profiles - 600 meter cable - from December 12, 2018 with interpretation of relative groundwater inputs along the stream reach based on profile characteristics. Upstream to downstream is plotted left to right. Times recorded for each profile are in Coordinated Universal Time (UTC).

**Figure 16.** Piezometer installation - Trout Brook. Upward hydraulic gradients were measured in piezometers 1, 2, and 3; minor to no upward gradients were measured in piezometers 4 and 5. Graphs below show streambed temperatures (groundwater) over a period of 6 days (measured inside the piezometer) compared to stream (surface water) temperatures (measured outside the piezometer). Downstream piezometers show less groundwater influence.

**Figure 17**. DTS installation, Valley Creek showing locations of fiber optic cable, coil locations, RBR temperature transducers, and DTS collection station. A 1200 meter (red) and 600 meter (light red) cable was used. DTS station for both cables is located where the two cables meet. Unlike East Indian Creek and Trout Brook, numerous obstructions in the stream required more subaerial cable exposure; subaerial coils provide markers readily identified on profiles as large deviations in temperature.

**Figure 18.** Valley Creek DTS stream temperature profiles - 600 meter cable - from February 19, 2019 with interpretation of relative groundwater inputs along the stream reach based on profile characteristics. Upstream to downstream is plotted left to right. Times recorded for each profile are in Coordinated Universal Time (UTC).

**Figure 19.** Valley Creek DTS stream temperature profiles - 1200 meter cable - from February 19, 2019 with interpretation of relative groundwater inputs along the stream reach based on profile characteristics. Upstream to downstream is plotted left to right. Times recorded for each profile are in Coordinated Universal Time (UTC). Data are uncalibrated but provide a reasonable match to measured stream temperatures.

**Figure 20.** Maps highlighting the uppermost bedrock units (Oneota Dolomite downward through the Tunnel City Group) and potential artesian hydraulic head conditions that appear to be linked to preferential habitat for brook trout. **A)** Highlights the key bedrock units and greatest potential for artesian hydraulic head conditions. **B)** Map shown in A), with overlay illustrating brook trout distribution, population and genetic results. The latter shows where brook trout with remnant genetics have been identified. Bedrock map is based on compilation mapping provided in Runkel et al. (2013), which is largely derived from the County Geologic Atlas Program by the Minnesota Geological Survey and Minnesota Department of Natural Resources. Possible artesian conditions were mapped as part of this project by subtracting the elevation of the land surface from the elevation of groundwater potentiometric contours from Blum (2018). Brook trout population and genetic data are from the Minnesota Department of Natural Resources and described by Hoxmeier et al. (2015).

**Figure 21.** Local examples comparing hydrogeologic conditions to brook trout distribution. **A)** The more widespread potential artesian conditions in Rush Creek tributaries compared to Money Creek may account for the greater abundance and presence of remnant brook trout in the former; **B)** The stream reaches in this area show local inconsistency in a comparison of hydrogeologic conditions to brook trout distribution. Although higher populations and presence of remnant brook trout correspond to low bedrock units and possible artesian conditions, several other stream reaches with those same conditions have no brook trout. See Figure 20 for location of A) and B), and for sources of information.

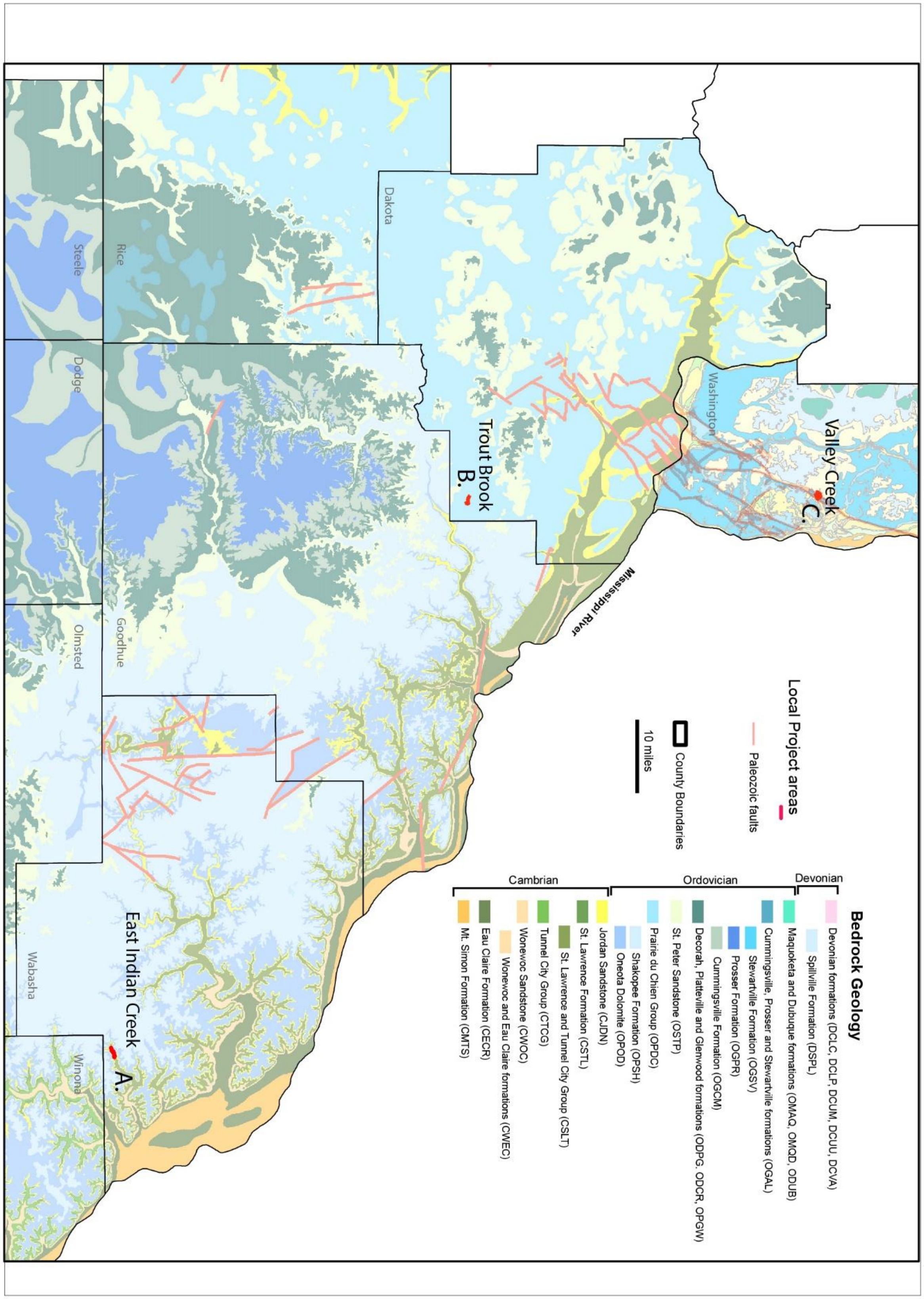

Bedrock Geology
Devonian
Devonian formations (DCLC, DCLP, DCUM, DCUU, DCVA)
Spillville Formation (DSPL)
Ordovician
Maquoketa and Dubuque formations (OMAQ, OMQD, ODUB)
Cummingsville, Prosser and Stewartville formations (OGAL)
Stewartville Formation (OGSV)
Prosser Formation (OGPR)
Cummingsville Formation (OGCM)
Decorah, Platteville and Glenwood formations (ODPG, ODCR, OPGW)
St. Peter Sandstone (OSTP)
Prairie du Chien Group (OPDC)
Shakopee Formation (OPSH)
Oneota Dolomite (OPOD)
Cambrian
Jordan Sandstone (CJDN)
St. Lawrence Formation (CSTL)
St. Lawrence and Tunnel City Group (CSLT)
Tunnel City Group (CTCG)
Wonewoc Sandstone (CWOC)
Wonewoc and Eau Claire formations (CWEC)
Eau Claire Formation (CECR)
Mt. Simon Formation (CMTS)
Local Project areas
Paleozoic faults
County Boundaries
10 miles
Valley Creek
C.
Trout Brook
B.
East Indian Creek
A.
Mississippi River
Dakota
Washington
Rice
Steele
Dodge
Goodhue
Olmsted
Wabasha
Winona

Figure 1

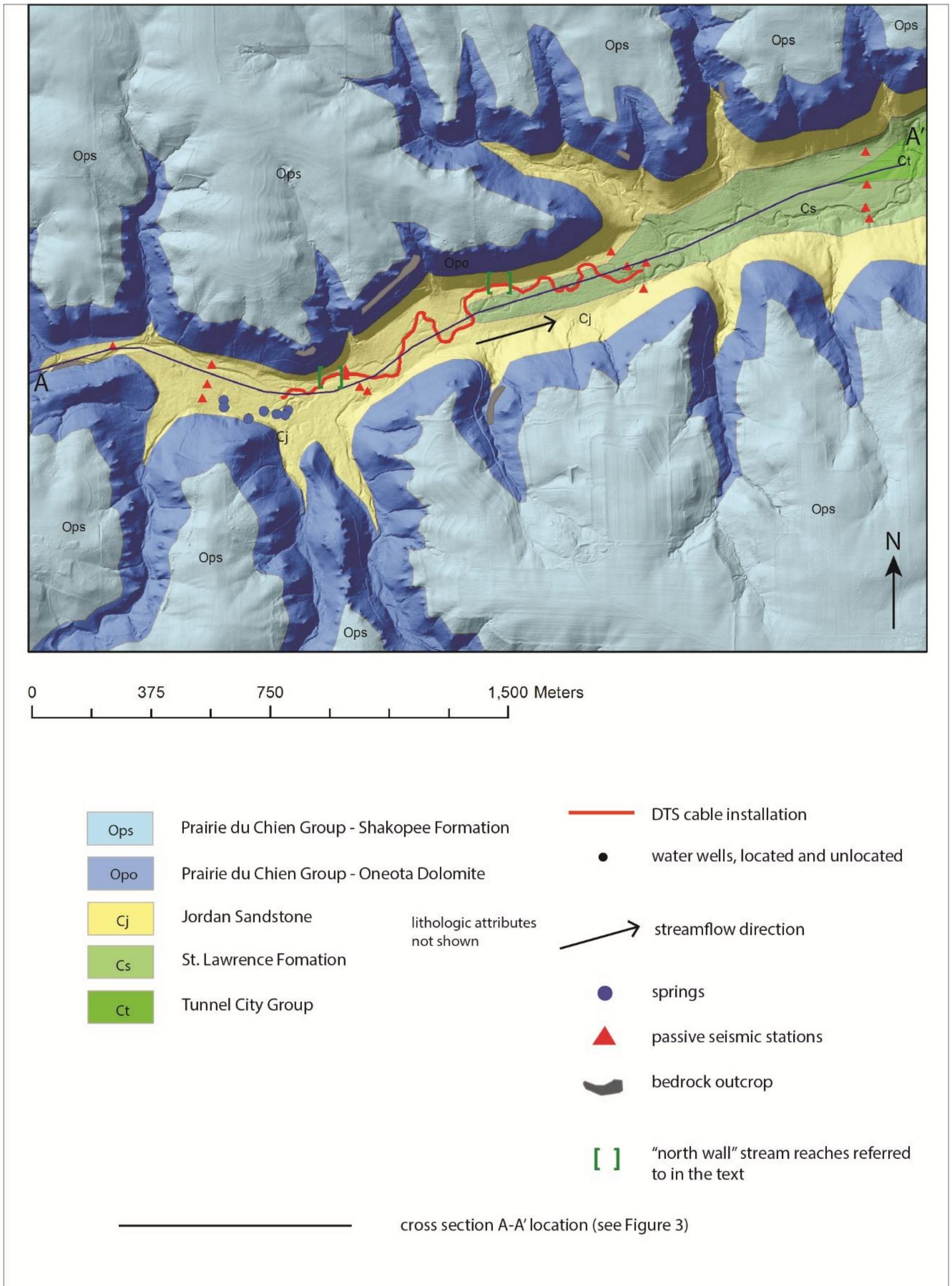

Ops
Opo
Cj
Cs
Ct
A
A'
N
0
375
750
1,500 Meters
Ops Prairie du Chien Group - Shakopee Formation
Opo Prairie du Chien Group - Oneota Dolomite
Cj Jordan Sandstone
Cs St. Lawrence Fomation
Ct Tunnel City Group
lithologic attributes not shown
DTS cable installation
water wells, located and unlocated
streamflow direction
springs
passive seismic stations
bedrock outcrop
"north wall" stream reaches referred to in the text
cross section A-A' location (see Figure 3)

Figure 2

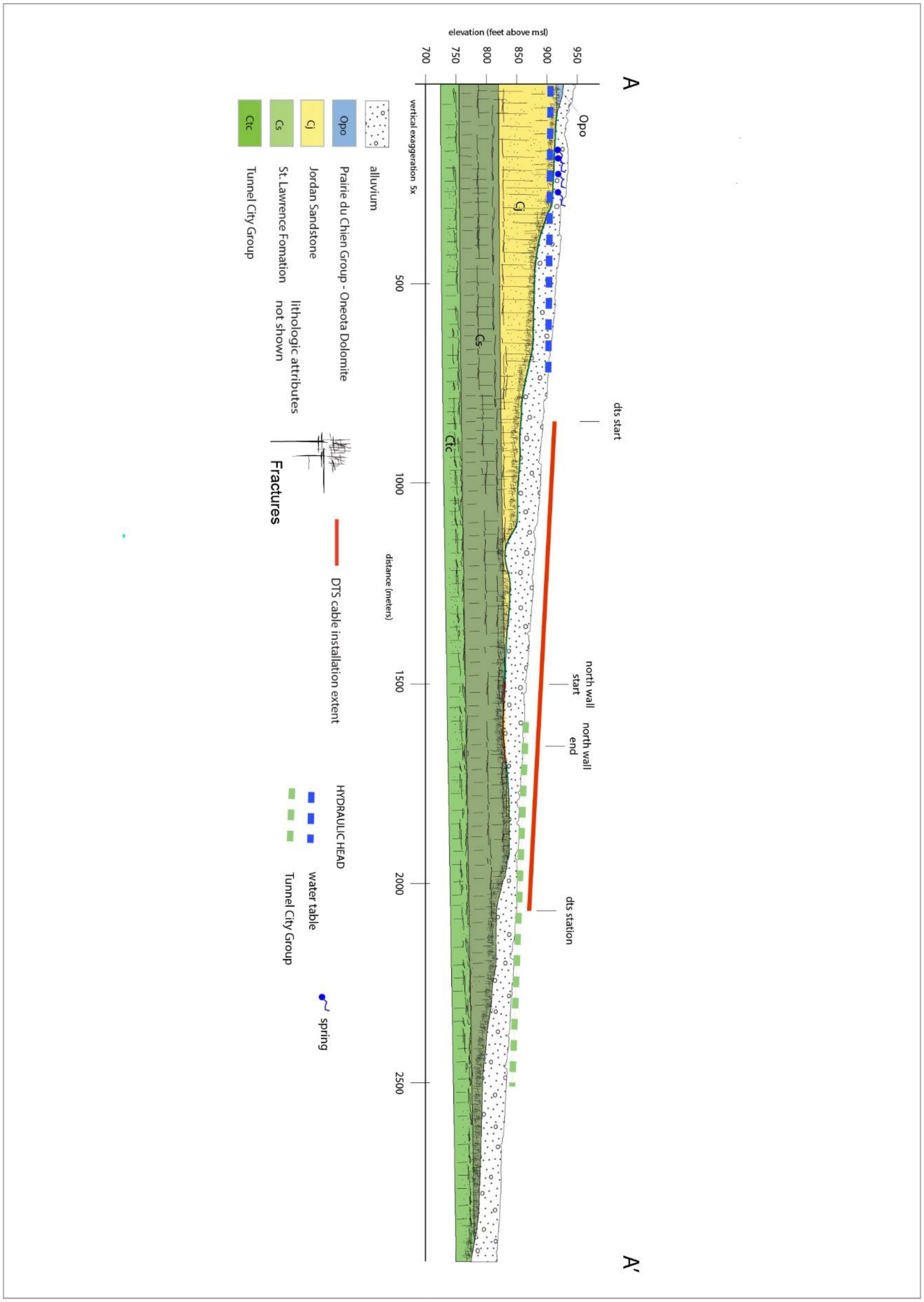

A
A'
elevation (feet above msl)
950
900
850
800
750
700
Opo
Cj
Cs
Ctc
vertical exaggeration 5x
distance (meters)
500
1000
1500
2000
2500
dts start
north wall start
north wall end
dts station
alluvium
Opo Prairie du Chien Group - Oneota Dolomite
Cj Jordan Sandstone
Cs St. Lawrence Fomation
Ctc Tunnel City Group
lithologic attributes not shown
Fractures
DTS cable installation extent
HYDRAULIC HEAD
water table
Tunnel City Group
spring

Figure 3

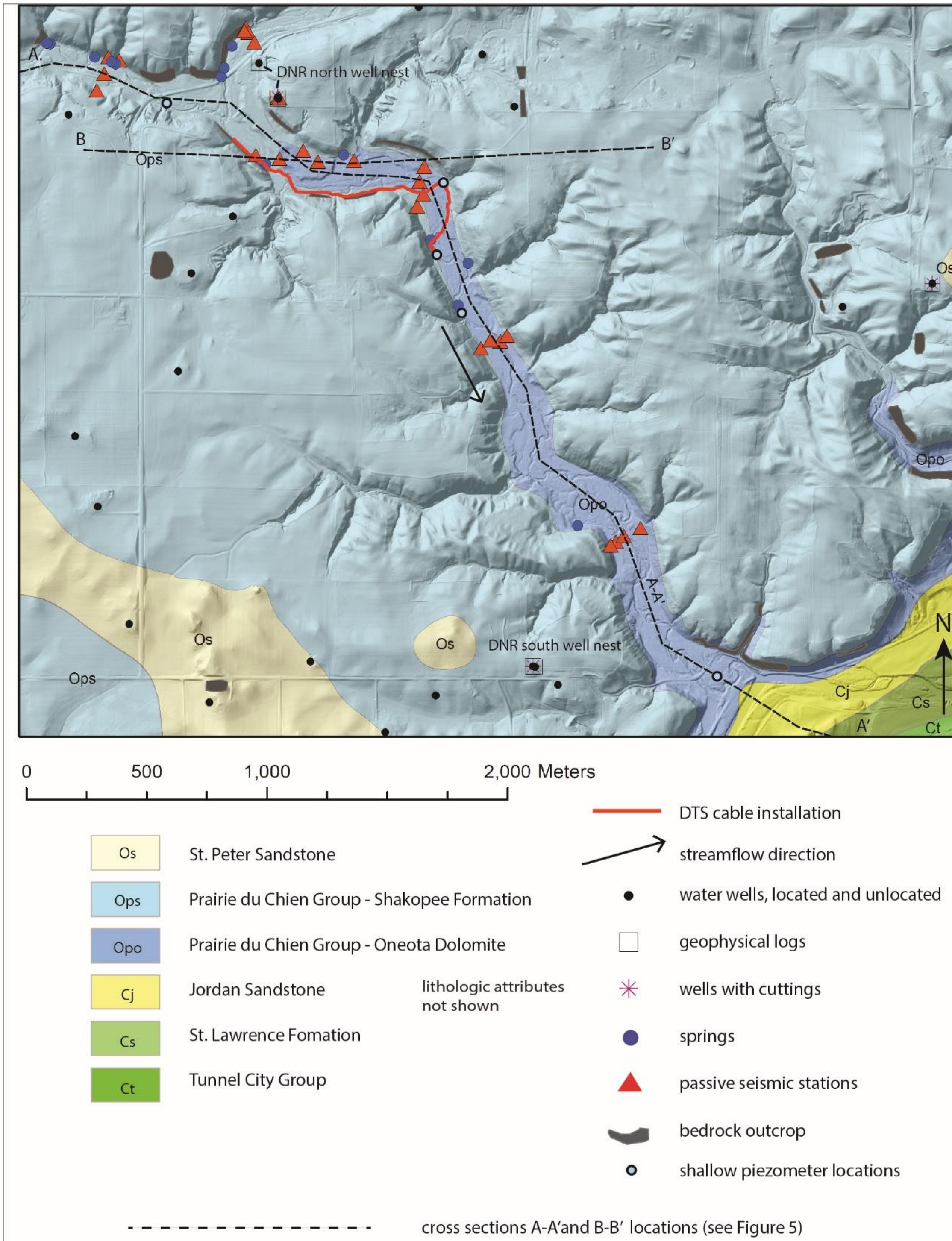

A
A'
B
B'
A-A'
DNR north well nest
DNR south well nest
Os
Ops
Opo
Cj
Cs
Ct
N
0
500
1,000
2,000 Meters
Os St. Peter Sandstone
Ops Prairie du Chien Group - Shakopee Formation
Opo Prairie du Chien Group - Oneota Dolomite
Cj Jordan Sandstone
Cs St. Lawrence Fomation
Ct Tunnel City Group
lithologic attributes not shown
DTS cable installation
streamflow direction
water wells, located and unlocated
geophysical logs
wells with cuttings
springs
passive seismic stations
bedrock outcrop
shallow piezometer locations
cross sections A-A'and B-B' locations (see Figure 5)

Figure 4

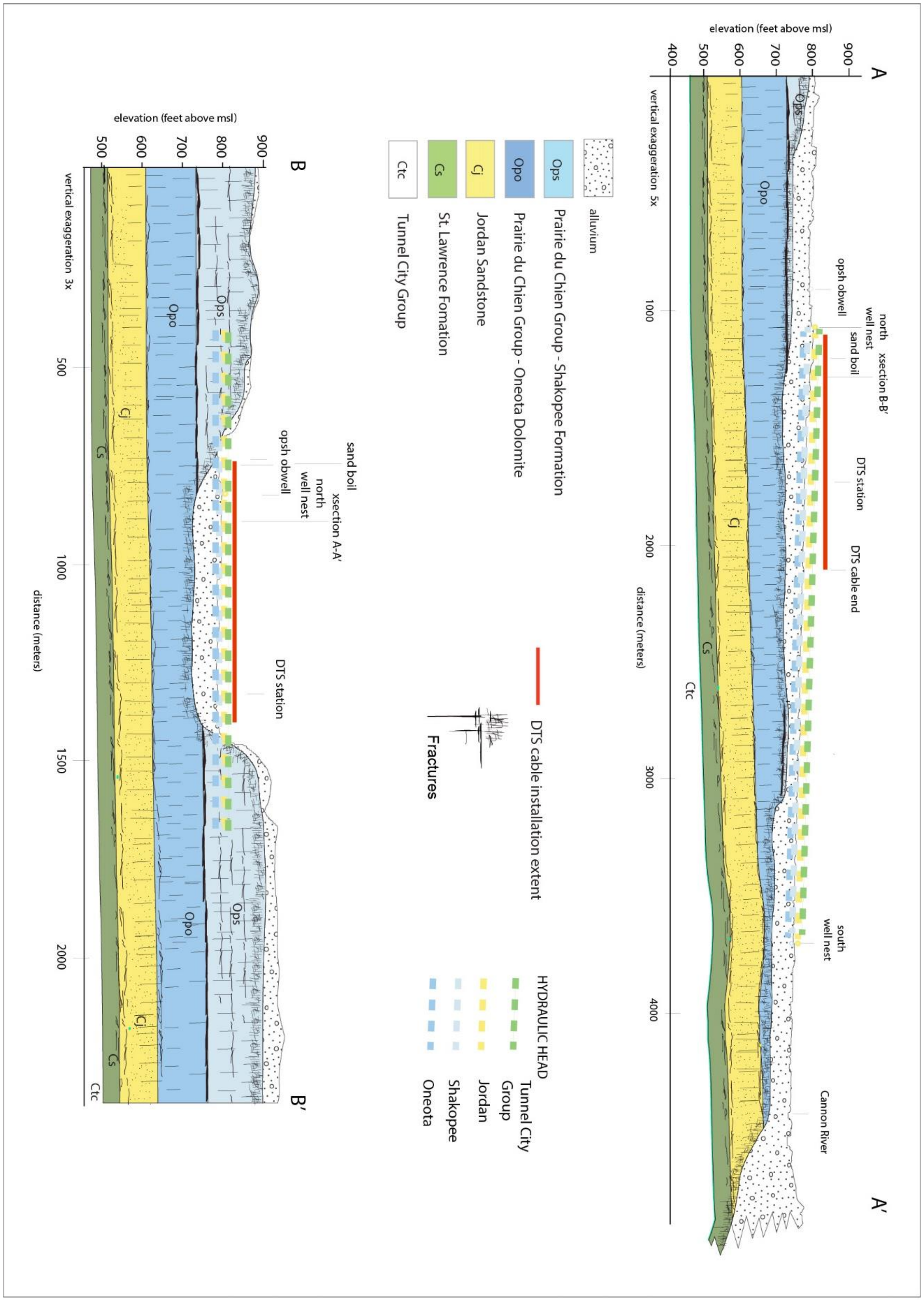
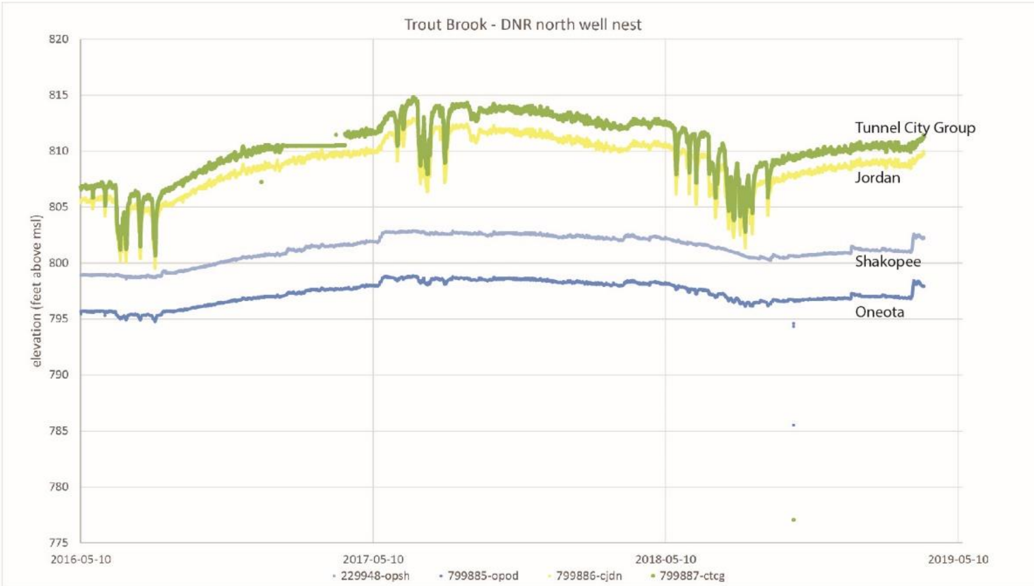
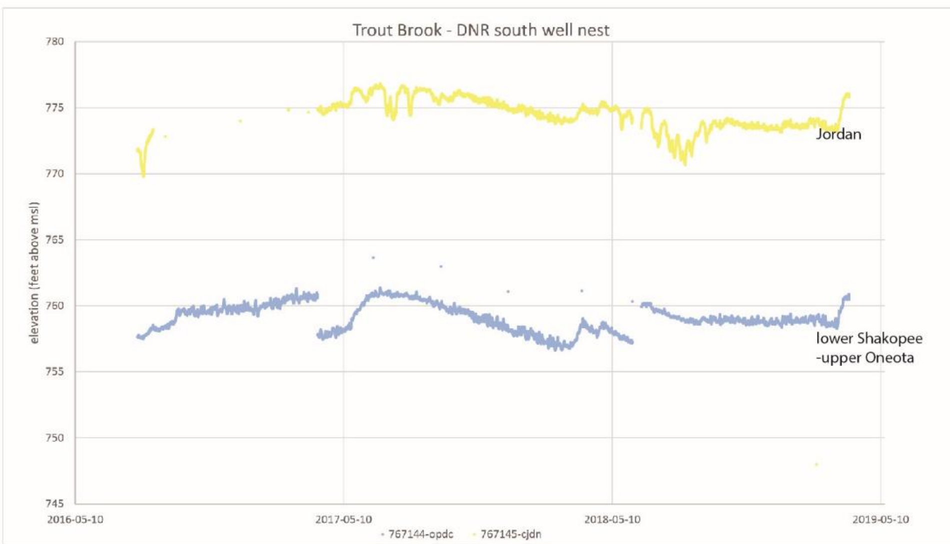

A
A′
elevation (feet above msl)
400
500
600
700
800
900
vertical exaggeration 5x
distance (meters)
1000
2000
3000
4000
Ops
Opo
Cj
Cs
Ctc
opsh obwell
north well nest
sand boil
xsection B-B′
DTS station
DTS cable end
south well nest
Cannon River
B
B′
vertical exaggeration 3x
500
1000
1500
2000
sand boil
opsh obwell
north well nest
xsection A-A′
alluvium
Ops
Prairie du Chien Group - Shakopee Formation
Opo
Prairie du Chien Group - Oneota Dolomite
Cj
Jordan Sandstone
Cs
St. Lawrence Formation
Ctc
Tunnel City Group
DTS cable installation extent
Fractures
HYDRAULIC HEAD
Tunnel City Group
Jordan
Shakopee
Oneota

Figure 5

A.


Trout Brook - DNR north well nest
elevation (feet above msl)
Tunnel City Group
Jordan
Shakopee
Oneota
2016-05-10
2017-05-10
2018-05-10
2019-05-10
229948-opsh
799885-opod
799886-cjdn
799887-ctcg

B.


Trout Brook - DNR south well nest
elevation (feet above msl)
Jordan
lower Shakopee
-upper Oneota
2016-05-10
2017-05-10
2018-05-10
2019-05-10
767144-opdc
767145-cjdn

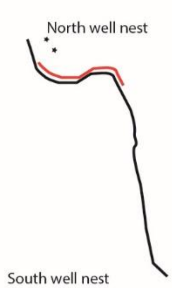

North well nest
South well nest

Figure 6

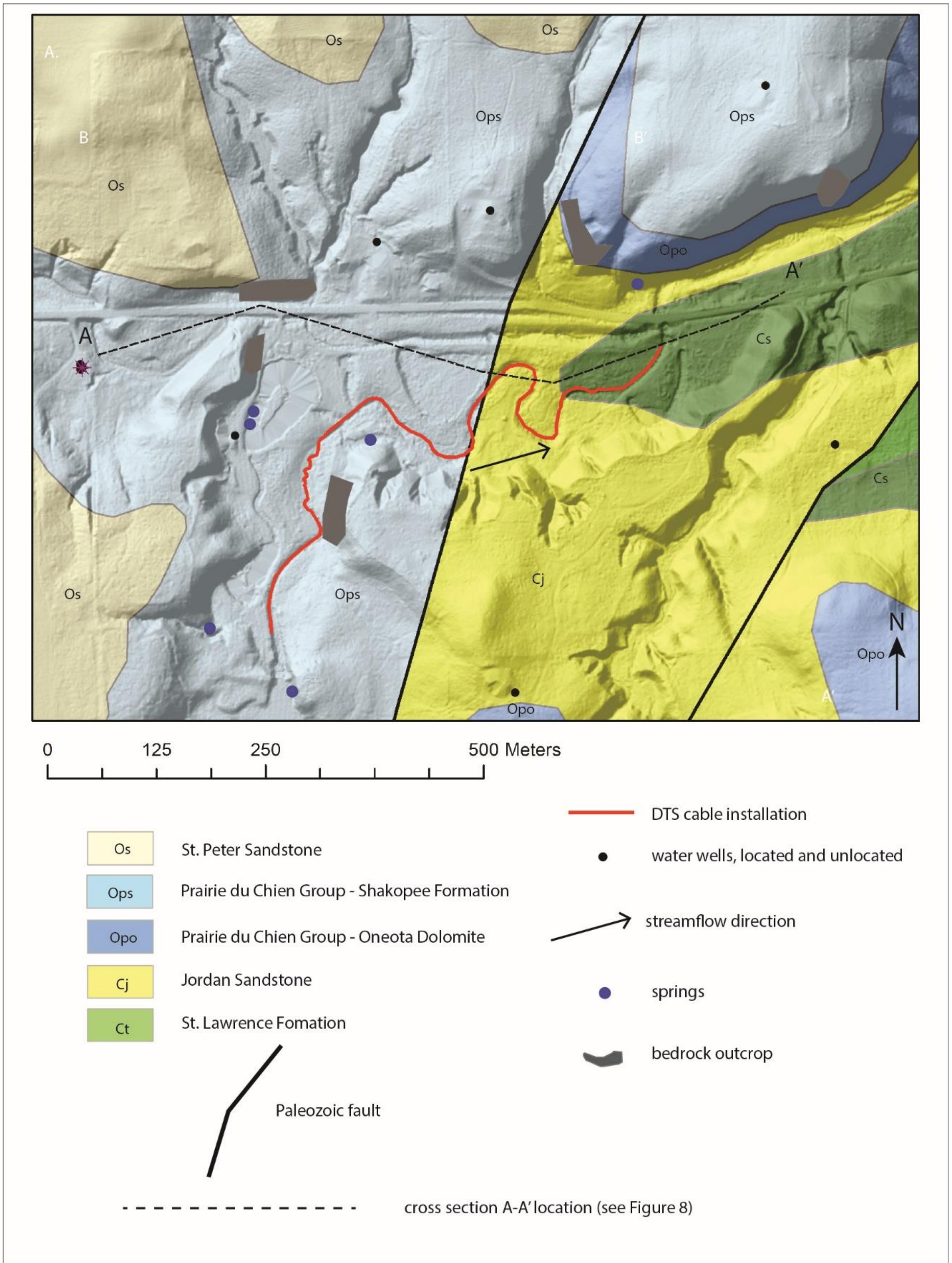

A.
Os
Os
B
Os
Ops
Ops
B'
Opo
A'
A
Cs
Cs
Cj
Ops
Os
N
Opo
Opo
A'
0
125
250
500 Meters
DTS cable installation
water wells, located and unlocated
Os
St. Peter Sandstone
Ops
Prairie du Chien Group - Shakopee Formation
streamflow direction
Opo
Prairie du Chien Group - Oneota Dolomite
Cj
Jordan Sandstone
springs
Ct
St. Lawrence Fomation
bedrock outcrop
Paleozoic fault
cross section A-A' location (see Figure 8)

Figure 7

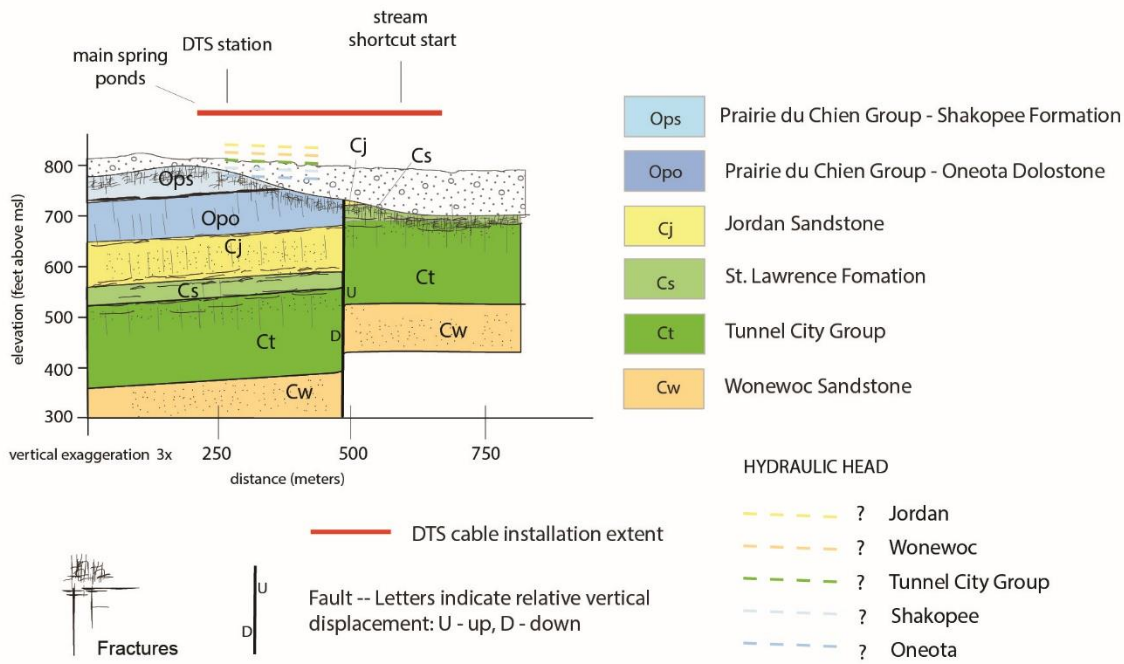

stream
shortcut start
main spring
ponds
DTS station
Cj
Cs
Ops
Opo
Cj
Cs
Ct
Cw
Ct
Cw
U
D
800
700
600
500
400
300
elevation (feet above msl)
vertical exaggeration 3x
250
500
750
distance (meters)
Ops Prairie du Chien Group - Shakopee Formation
Opo Prairie du Chien Group - Oneota Dolostone
Cj Jordan Sandstone
Cs St. Lawrence Fomation
Ct Tunnel City Group
Cw Wonewoc Sandstone
HYDRAULIC HEAD
? Jordan
? Wonewoc
? Tunnel City Group
? Shakopee
? Oneota
DTS cable installation extent
Fractures
Fault -- Letters indicate relative vertical displacement: U - up, D - down

Figure 8

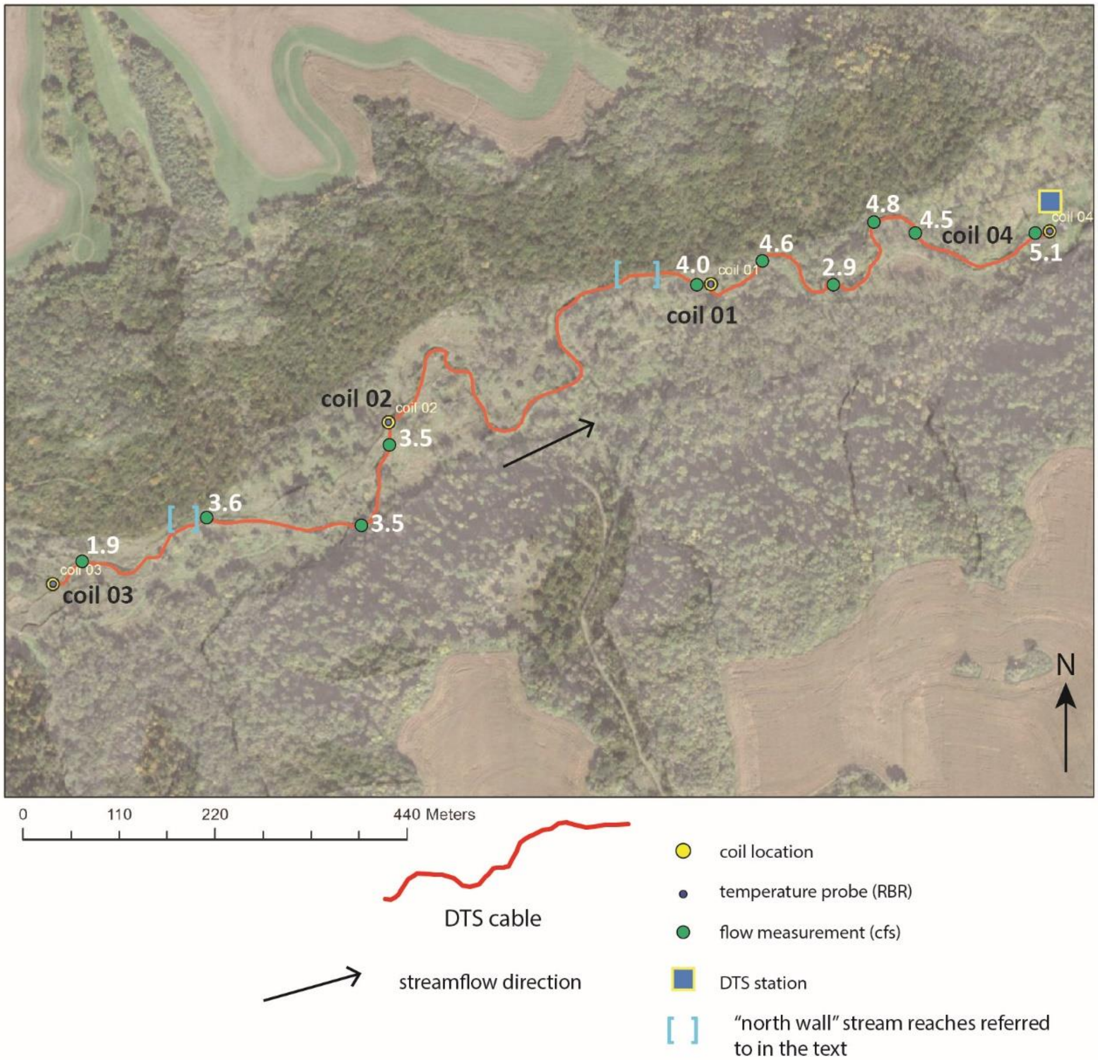

coil 03
1.9
3.6
3.5
coil 02
3.5
4.0
coil 01
4.6
2.9
4.8
4.5
coil 04
5.1
N
0
110
220
440 Meters
DTS cable
streamflow direction
coil location
temperature probe (RBR)
flow measurement (cfs)
DTS station
"north wall" stream reaches referred to in the text

Figure 9

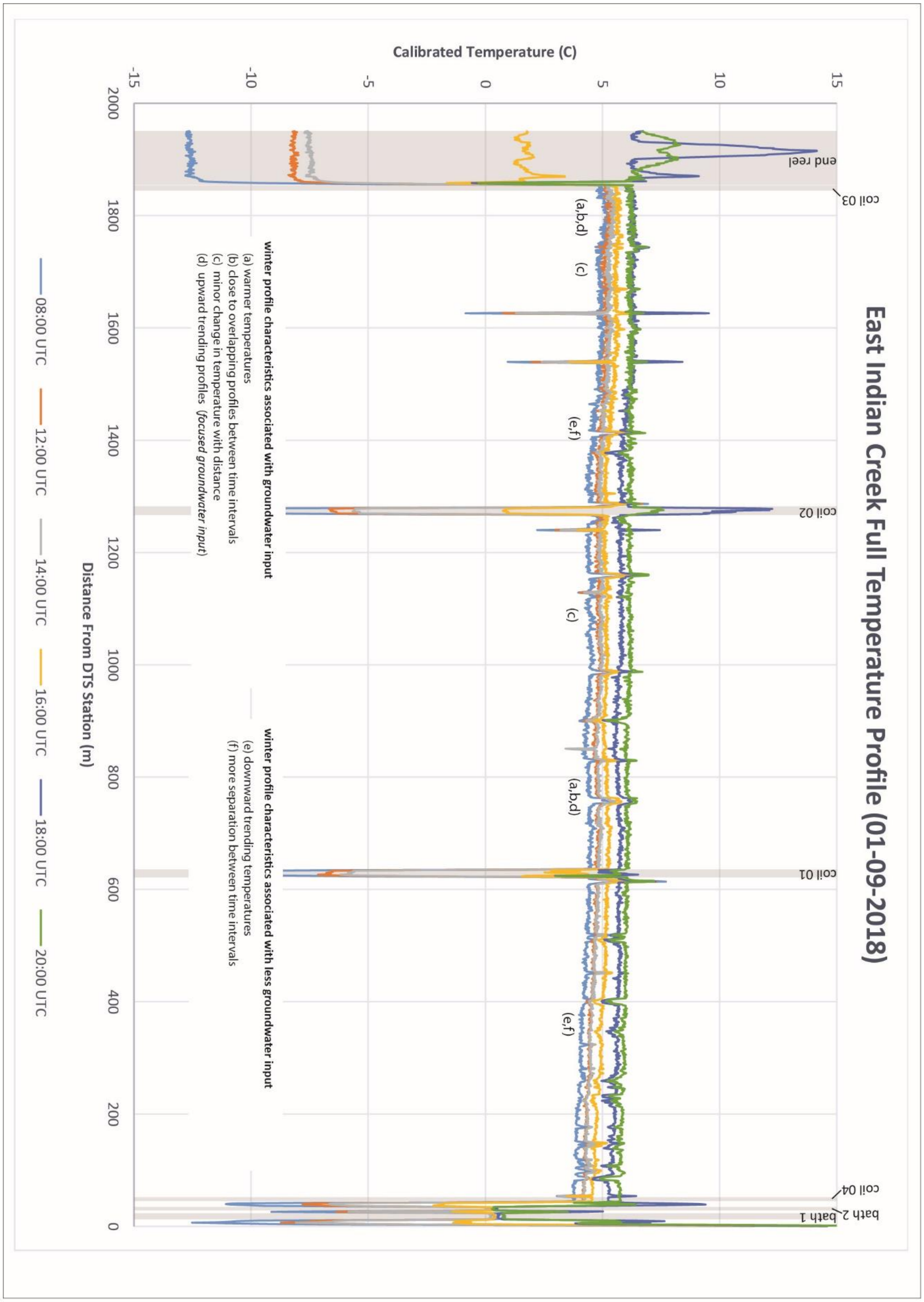

East Indian Creek Full Temperature Profile (01-09-2018)
Calibrated Temperature (C)
Distance From DTS Station (m)
end reel
coil 03
coil 02
coil 01
coil 04
bath 2
bath 1
(a,b,d)
(c)
(e,f)
winter profile characteristics associated with groundwater input
(a) warmer temperatures
(b) close to overlapping profiles between time intervals
(c) minor change in temperature with distance
(d) upward trending profiles (focused groundwater input)
winter profile characteristics associated with less groundwater input
(e) downward trending temperatures
(f) more separation between time intervals
08:00 UTC
12:00 UTC
14:00 UTC
16:00 UTC
18:00 UTC
20:00 UTC

Figure 10

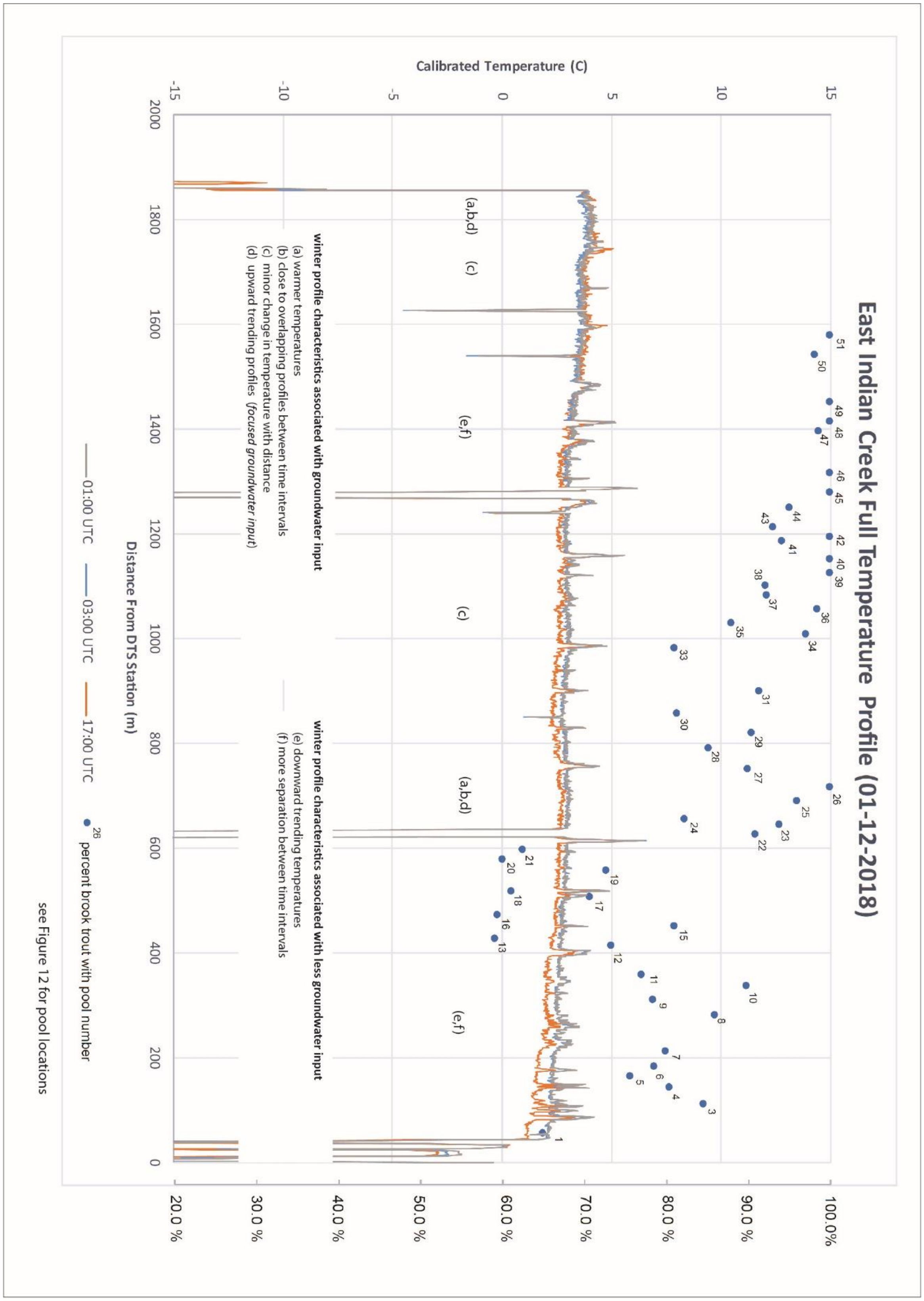

East Indian Creek Full Temperature Profile (01-12-2018)
Calibrated Temperature (C)
Distance From DTS Station (m)
winter profile characteristics associated with groundwater input
(a) warmer temperatures
(b) close to overlapping profiles between time intervals
(c) minor change in temperature with distance
(d) upward trending profiles (focused groundwater input)
winter profile characteristics associated with less groundwater input
(e) downward trending temperatures
(f) more separation between time intervals
01:00 UTC
03:00 UTC
17:00 UTC
percent brook trout with pool number
see Figure 12 for pool locations

Figure 11

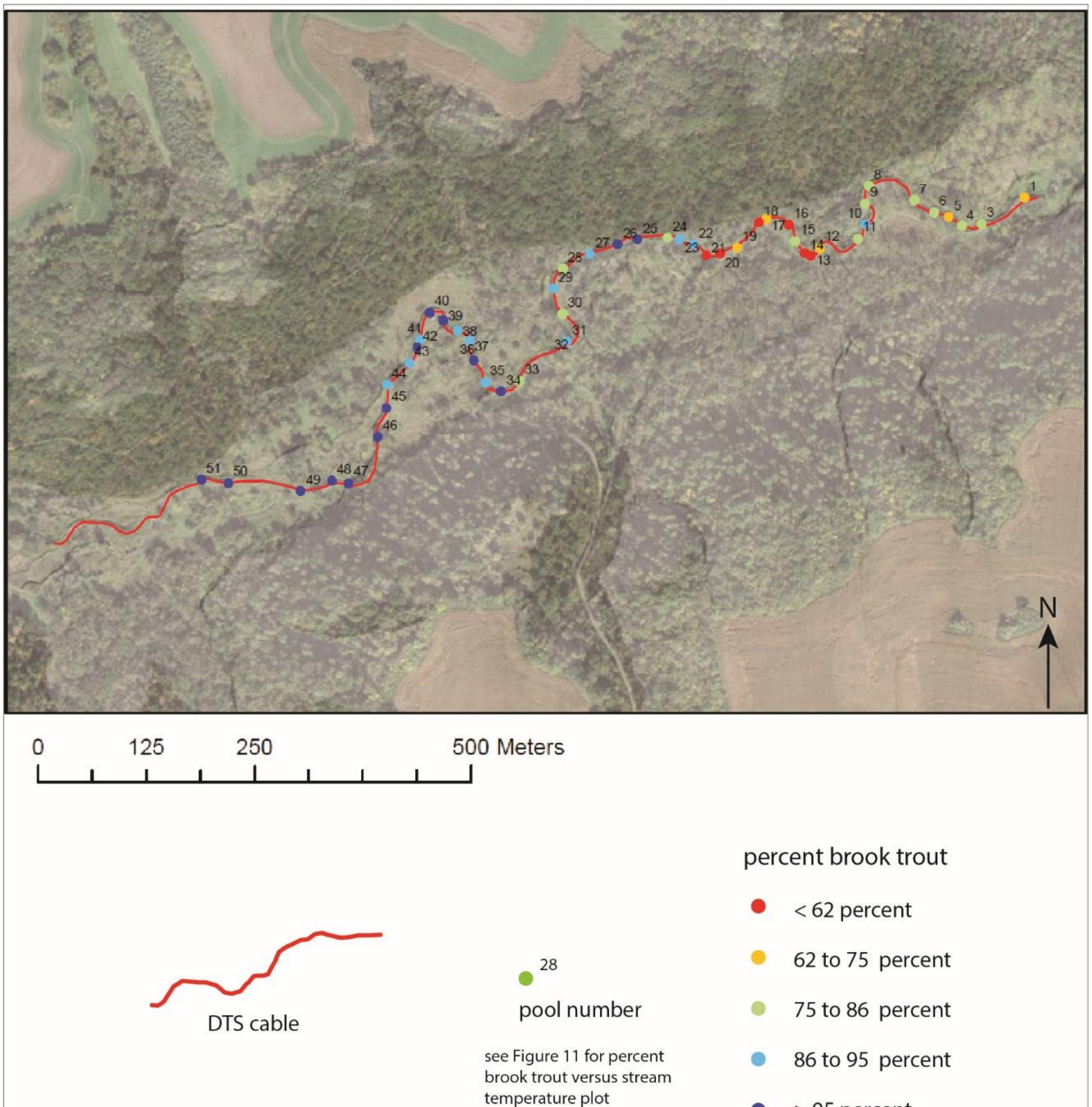
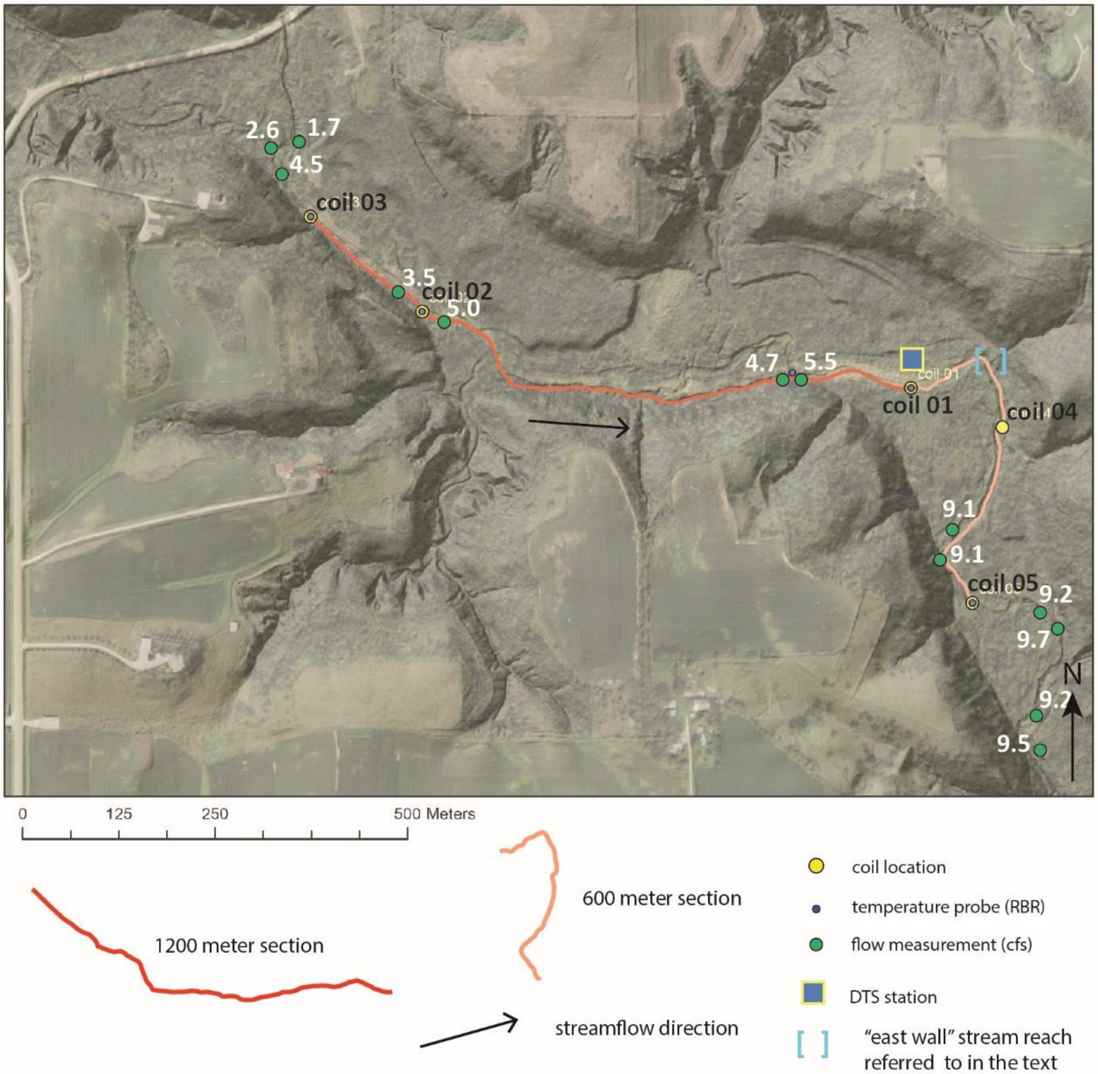
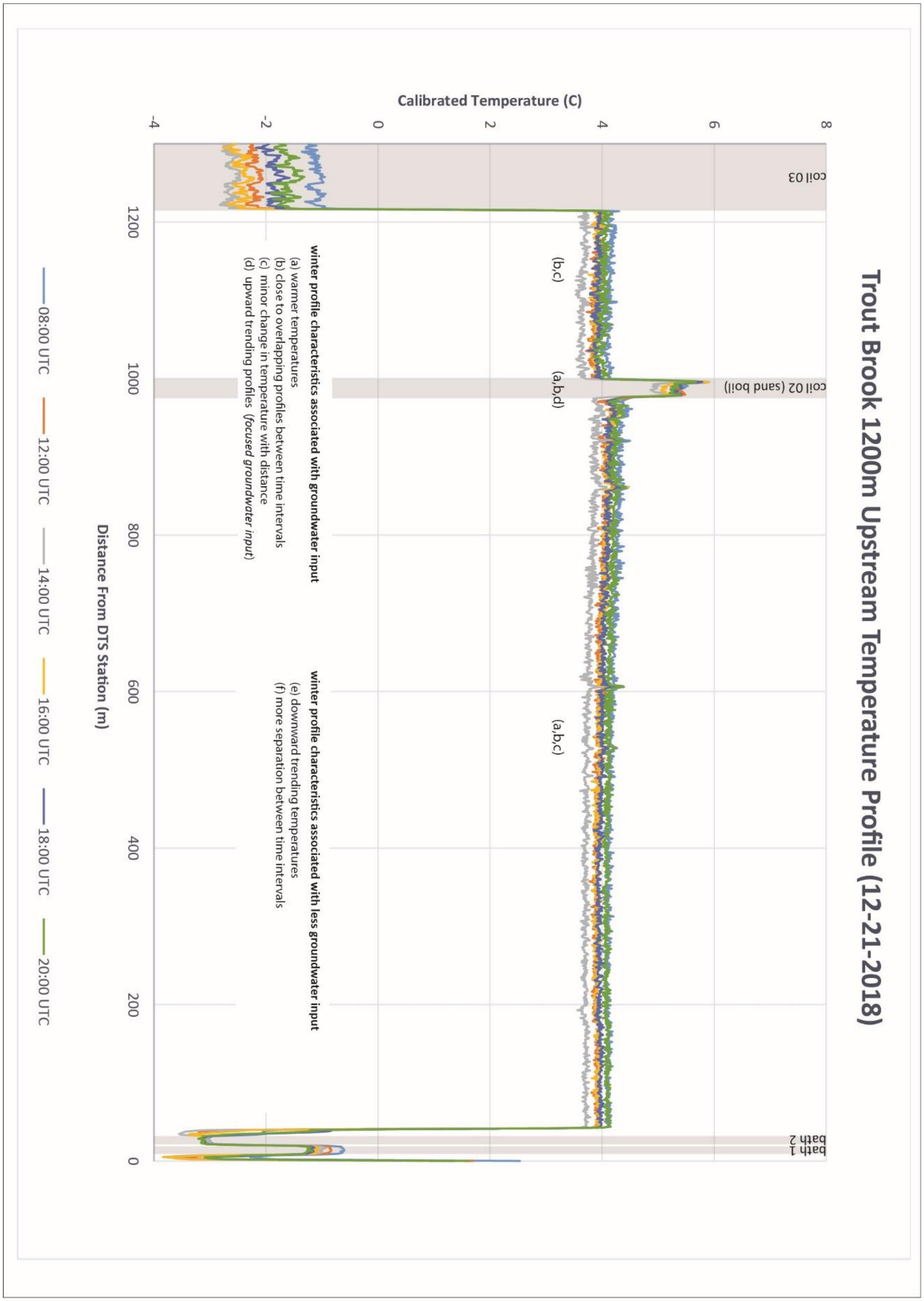

N
0
125
250
500 Meters
DTS cable
28
pool number
see Figure 11 for percent brook trout versus stream temperature plot
percent brook trout
< 62 percent
62 to 75 percent
75 to 86 percent
86 to 95 percent
> 95 percent

Figure 12



2.6
1.7
4.5
coil 03
3.5
coil 02
5.0
4.7
5.5
coil 01
coil 04
9.1
9.1
coil 05
9.2
9.7
N
9.2
9.5
0
125
250
500 Meters
1200 meter section
600 meter section
streamflow direction
coil location
temperature probe (RBR)
flow measurement (cfs)
DTS station
"east wall" stream reach referred to in the text


Figure 13



Trout Brook 1200m Upstream Temperature Profile (12-21-2018)
Calibrated Temperature (C)
Distance From DTS Station (m)
coil 03
coil 02 (sand boil)
bath 2
bath 1
(b,c)
(a,b,d)
(a,b,c)
winter profile characteristics associated with groundwater input
(a) warmer temperatures
(b) close to overlapping profiles between time intervals
(c) minor change in temperature with distance
(d) upward trending profiles (focused groundwater input)
winter profile characteristics associated with less groundwater input
(e) downward trending temperatures
(f) more separation between time intervals
08:00 UTC
12:00 UTC
14:00 UTC
16:00 UTC
18:00 UTC
20:00 UTC


Figure 14

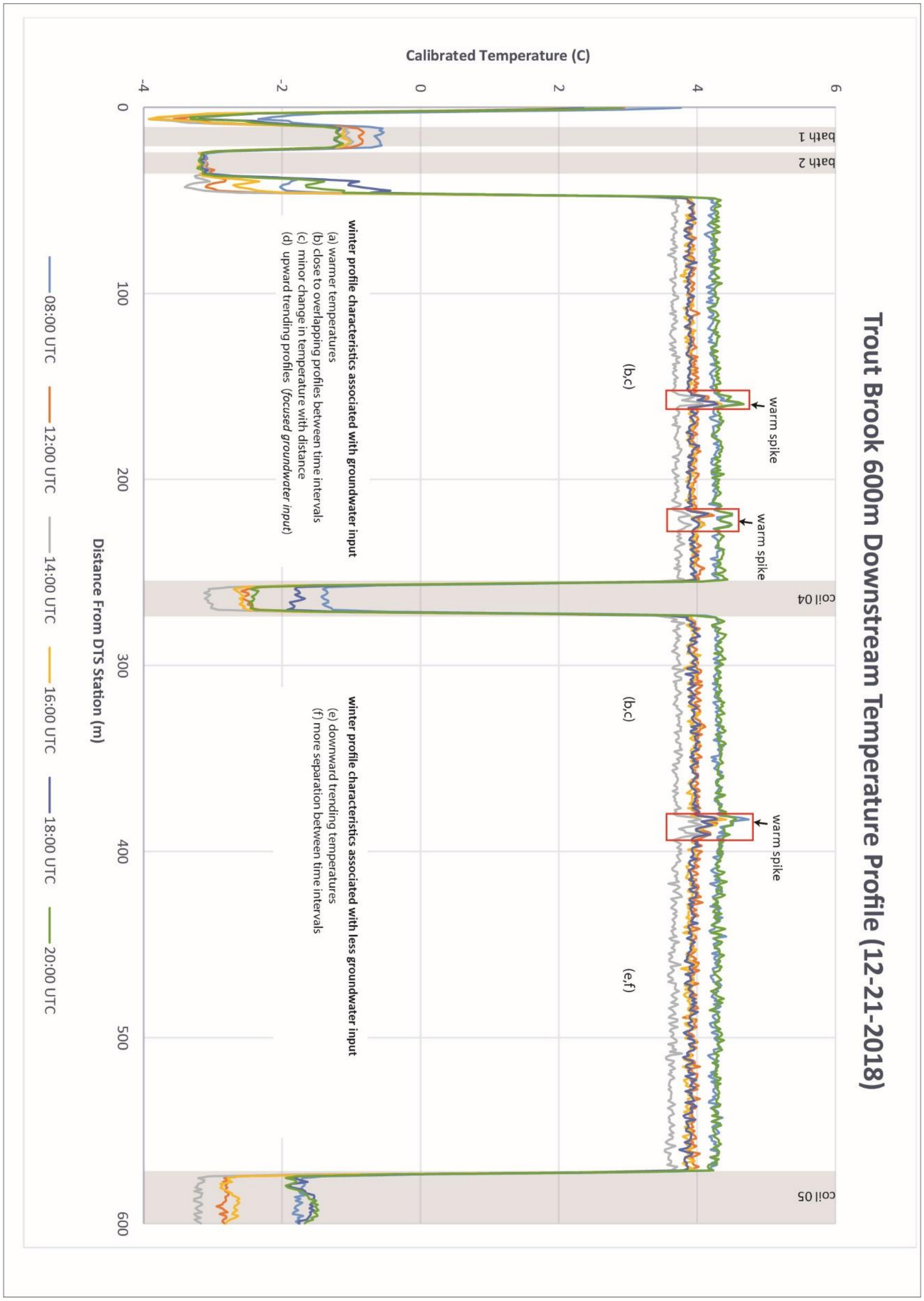

Trout Brook 600m Downstream Temperature Profile (12-21-2018)
Calibrated Temperature (C)
Distance From DTS Station (m)
bath 1
bath 2
coil 04
coil 05
warm spike
warm spike
warm spike
(b,c)
(b,c)
(e,f)
winter profile characteristics associated with groundwater input
(a) warmer temperatures
(b) close to overlapping profiles between time intervals
(c) minor change in temperature with distance
(d) upward trending profiles (focused groundwater input)
winter profile characteristics associated with less groundwater input
(e) downward trending temperatures
(f) more separation between time intervals
08:00 UTC
12:00 UTC
14:00 UTC
16:00 UTC
18:00 UTC
20:00 UTC

Figure 15

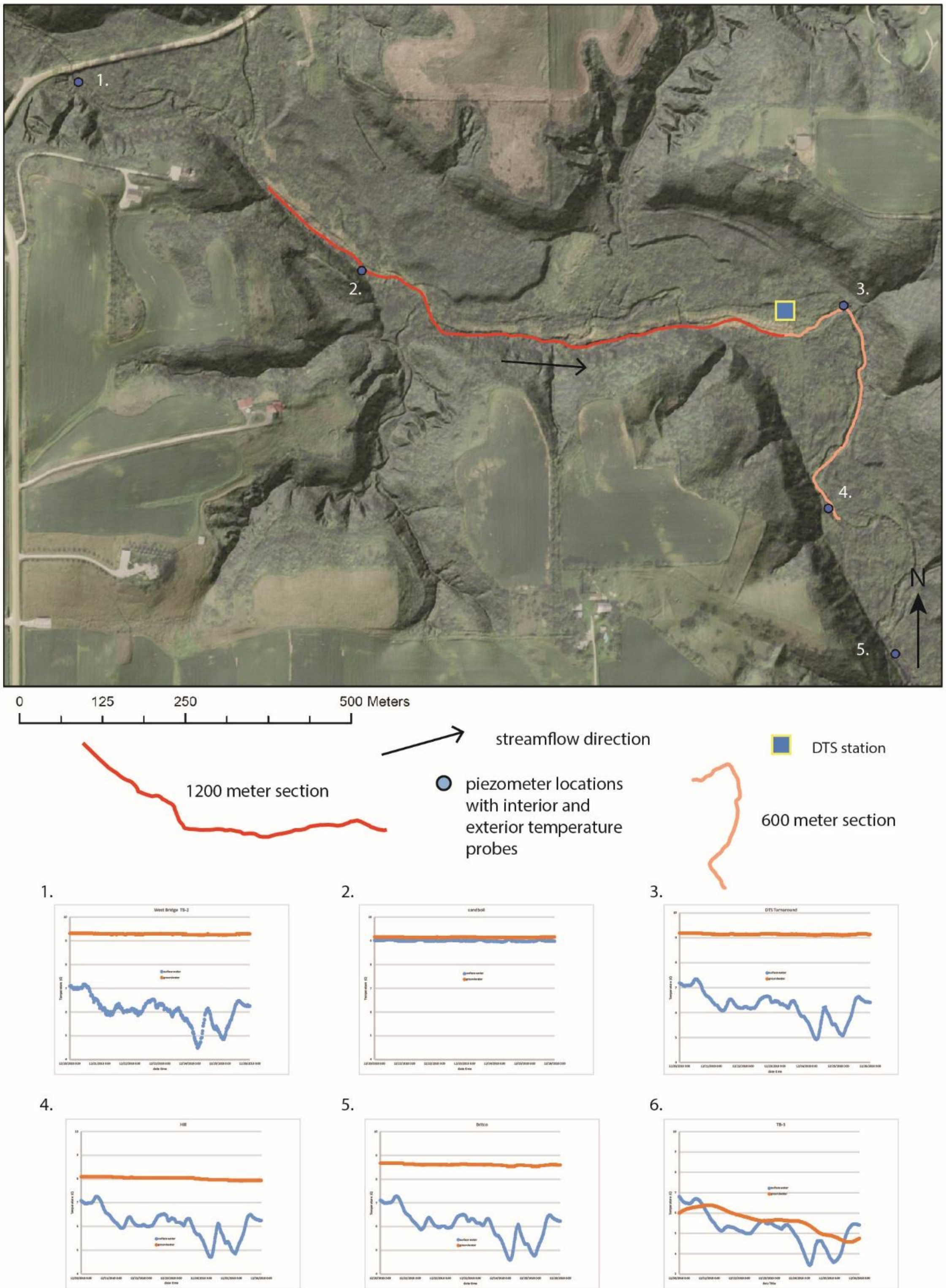

1.
2.
3.
4.
5.
N
0
125
250
500 Meters
streamflow direction
DTS station
1200 meter section
piezometer locations with interior and exterior temperature probes
600 meter section
1.
2.
3.
4.
5.
6.
not shown - at downstream end of park

Figure 16

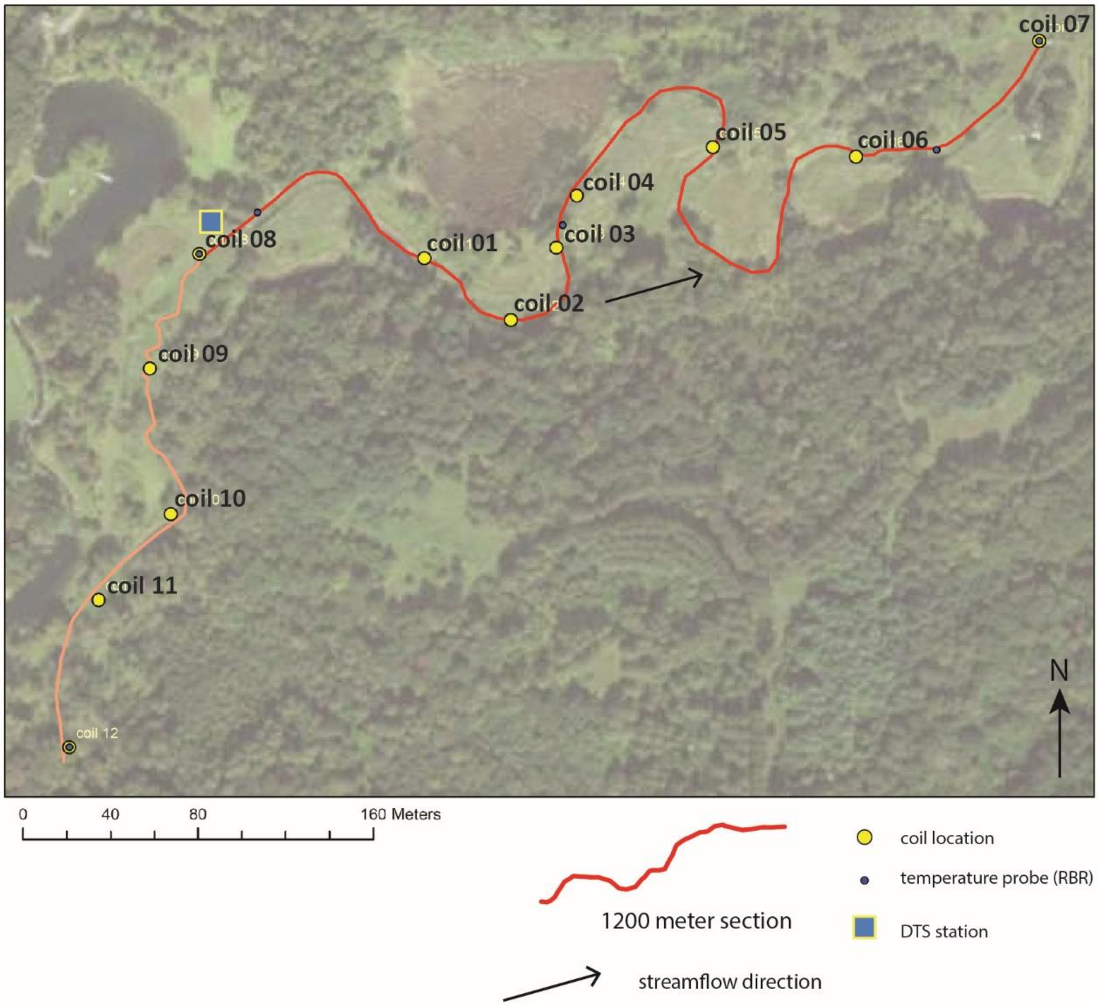

coil 07
coil 05
coil 06
coil 04
coil 08
coil 01
coil 03
coil 02
coil 09
coil 10
coil 11
coil 12
N
0
40
80
160 Meters
coil location
temperature probe (RBR)
1200 meter section
DTS station
streamflow direction

Figure 17

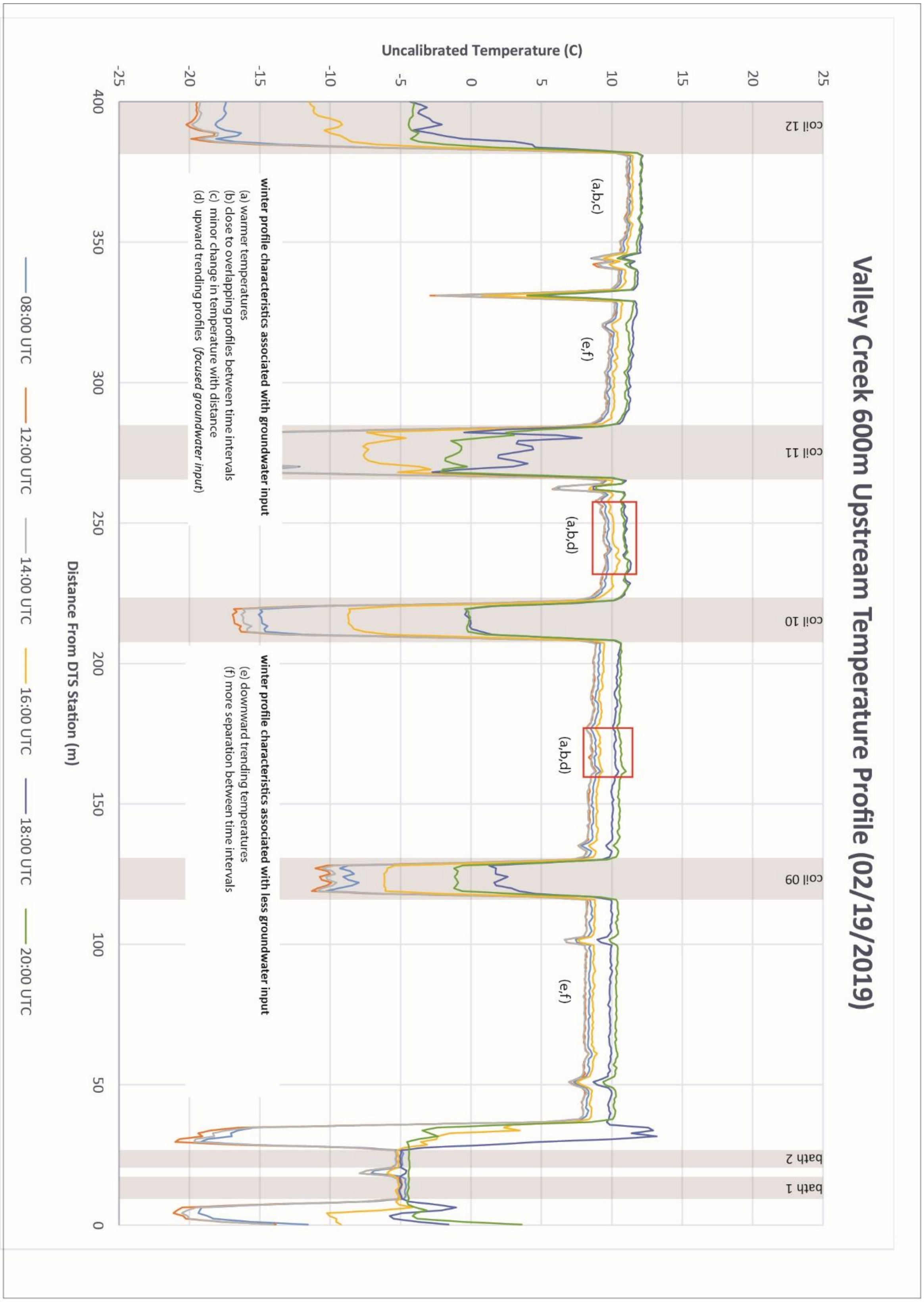
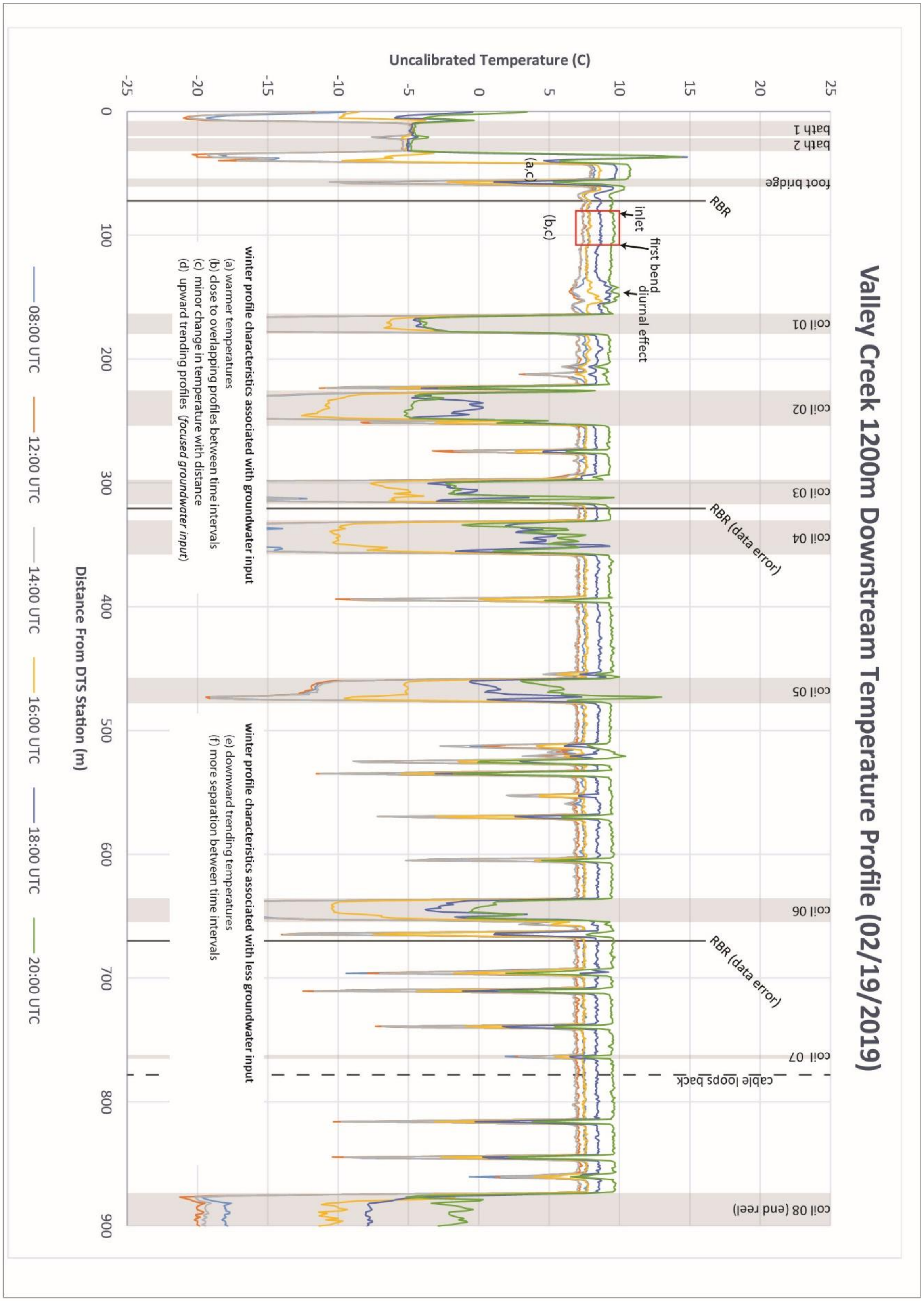
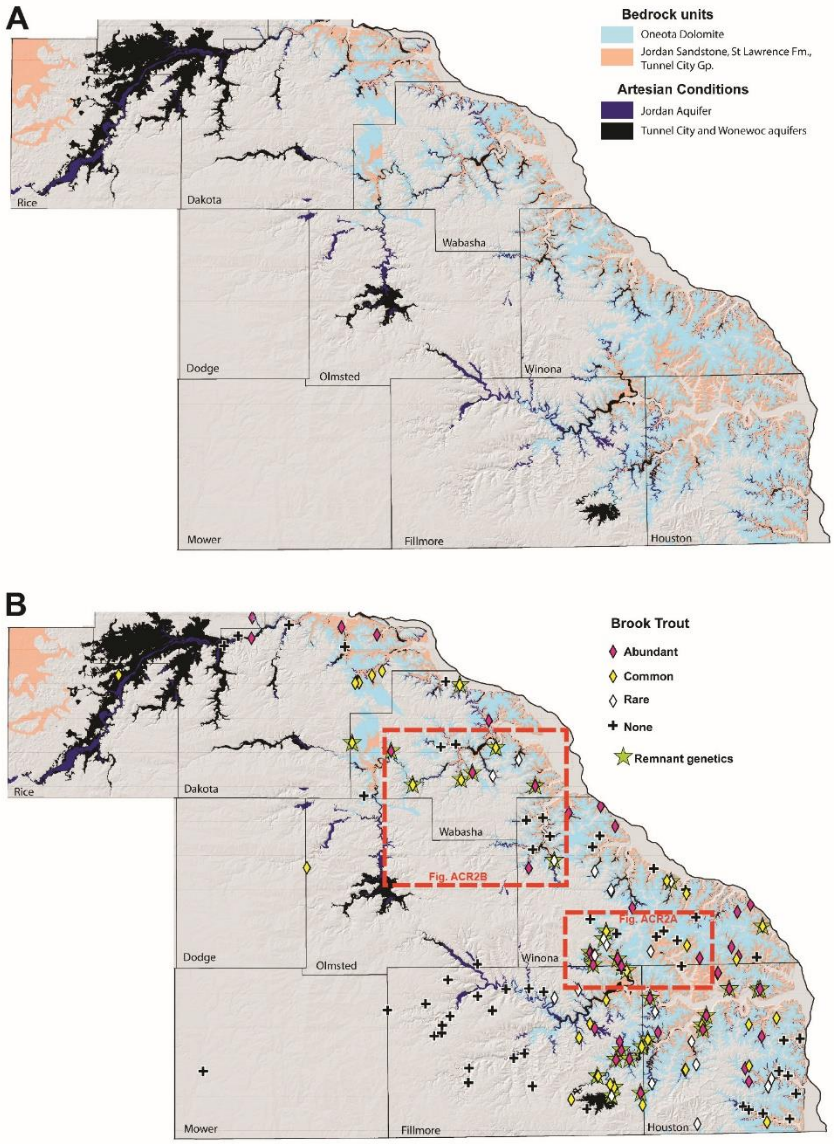

Valley Creek 600m Upstream Temperature Profile (02/19/2019)
Uncalibrated Temperature (C)
Distance From DTS Station (m)
coil 12
coil 11
coil 10
coil 09
bath 2
bath 1
(a,b,c)
(e,f)
(a,b,d)
(a,b,d)
(e,f)
winter profile characteristics associated with groundwater input
(a) warmer temperatures
(b) close to overlapping profiles between time intervals
(c) minor change in temperature with distance
(d) upward trending profiles (focused groundwater input)
winter profile characteristics associated with less groundwater input
(e) downward trending temperatures
(f) more separation between time intervals
08:00 UTC
12:00 UTC
14:00 UTC
16:00 UTC
18:00 UTC
20:00 UTC

Figure 18



Valley Creek 1200m Downstream Temperature Profile (02/19/2019)
Uncalibrated Temperature (C)
Distance From DTS Station (m)
bath 1
bath 2
foot bridge
RBR
inlet
first bend
diurnal effect
(a,c)
(b,c)
coil 01
coil 02
coil 03
RBR (data error)
coil 04
coil 05
coil 06
RBR (data error)
coil 07
cable loops back
coil 08 (end reel)
winter profile characteristics associated with groundwater input
(a) warmer temperatures
(b) close to overlapping profiles between time intervals
(c) minor change in temperature with distance
(d) upward trending profiles (focused groundwater input)
winter profile characteristics associated with less groundwater input
(e) downward trending temperatures
(f) more separation between time intervals
08:00 UTC
12:00 UTC
14:00 UTC
16:00 UTC
18:00 UTC
20:00 UTC


Figure 19



A
Bedrock units
Oneota Dolomite
Jordan Sandstone, St Lawrence Fm., Tunnel City Gp.
Artesian Conditions
Jordan Aquifer
Tunnel City and Wonewoc aquifers
Rice
Dakota
Wabasha
Dodge
Olmsted
Winona
Mower
Fillmore
Houston
B
Brook Trout
Abundant
Common
Rare
None
Remnant genetics
Fig. ACR2B
Fig. ACR2A
Rice
Dakota
Wabasha
Dodge
Olmsted
Winona
Mower
Fillmore
Houston


Figure 20

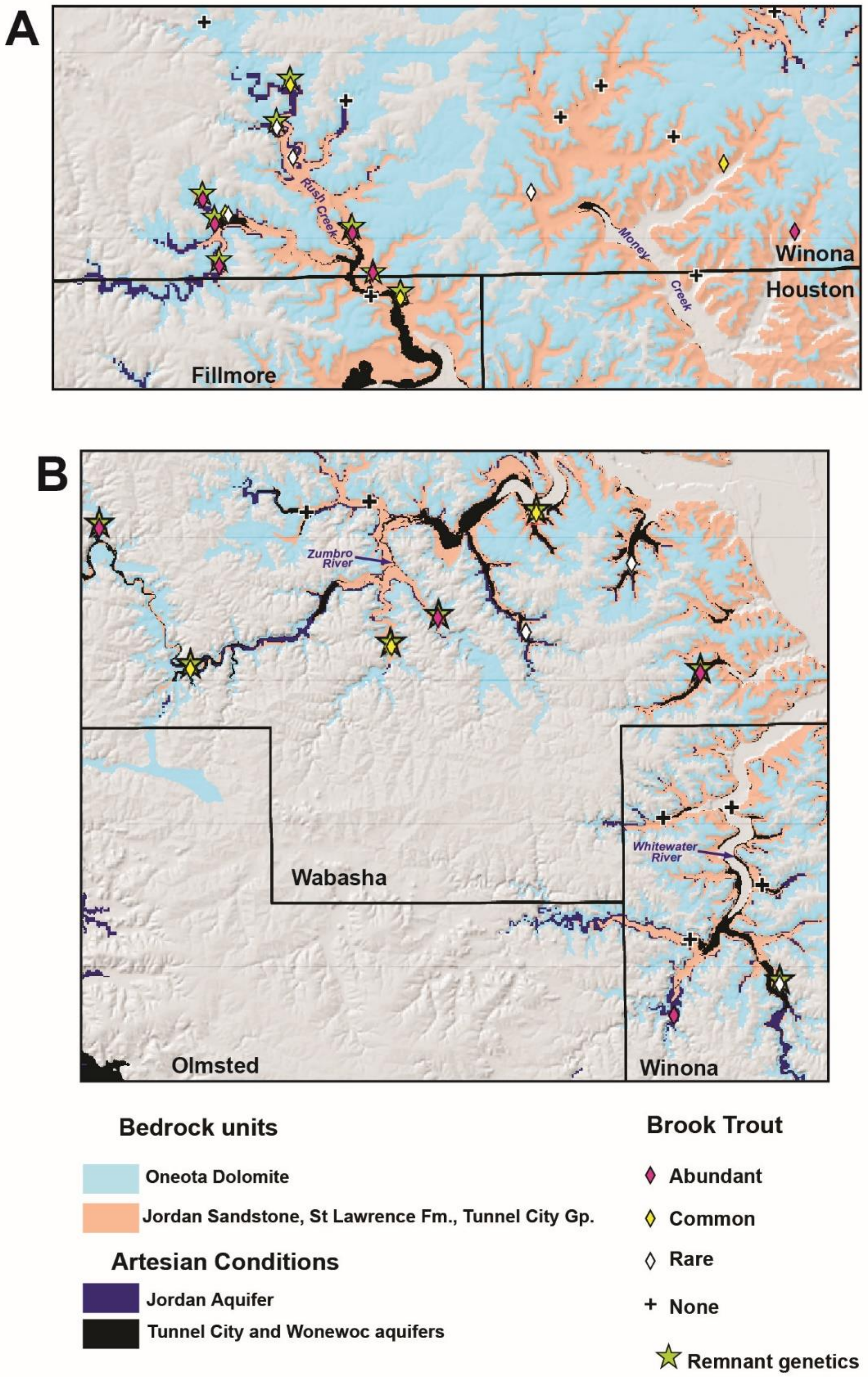

A
Rush Creek
Money Creek
Winona
Houston
Fillmore
B
Zumbro River
Whitewater River
Wabasha
Olmsted
Winona
Bedrock units
Oneota Dolomite
Jordan Sandstone, St Lawrence Fm., Tunnel City Gp.
Artesian Conditions
Jordan Aquifer
Tunnel City and Wonewoc aquifers
Brook Trout
Abundant
Common
Rare
None
Remnant genetics

Figure 21

**Appendicies**

*DTS temperature measurement and calibration*

DTS measurements were made using Oryx Distributed Temperature Sensing system (Sensornet Ltd) in combination with a duplex, unarmored flat cable. The DTS cable is not naturally buoyant. It was placed in the stream bed thalweg wherever possible, and secured with weights to prevent shifts due to increased streamflow. PT-100 temperature probes connected to the Oryx device monitored calibration bath temperatures. Coolers were used as calibration baths and contained 10 meters of coiled cable each, placed in brackets to keep the cable from being in contact with the cooler walls. Coolers were filled with propylene glycol antifreeze, with ice added to one of the baths to maintain a temperature difference between baths. Aquarium bubblers were placed in each bath to circulate the antifreeze. Additional temperature calibration points were monitored using RBR Solo and RBR Duet temperature transducers (RBR Ltd). Equipment and technical support was provided by the Center for Transformative Monitoring Programs (CTEMPs), an NSF-funded program, administered jointly by Oregon State University and the University of Nevada-Reno.

Calibration methods followed Hauser et al. (2011). Three independent points of known temperature and distance were used to solve for parameters accounting for: shift in photon energy at incident laser wavelength and scattered Raman (temperature sensitive) photon; laser and physical sensors; and differential attenuation. Calibration is dynamic, in that solved parameters apply to short time intervals where temperatures at calibration points – stream, calibration baths or streambank coils – remain constant. In our investigation, time periods were most often 15 minutes, using three consecutive 5 minute interval profiles. Calibration for selected days was processed using Python scripts to handle large amounts of raw data.

*Piezometer construction, installation and temperature measurement*

Piezometers were constructed from 5 foot, 1 ½ inch diameter electrical metal tube (EMT) conduit. Pipe was crimped at one end and slots cut from 0.4 to 1.0 feet from the crimped end to allow water to enter the pipe. Piezometers were driven into the stream bed, typically within 0.5 feet above the stream water level, resulting in the middle of piezometer slotted interval typically 3 to 3.5 feet below the stream bed. For temperature monitoring, Hobo Pro v2 (Onset Computer Corporation) temperature data loggers were placed both inside the piezometer at the middle of the slotted interval and outside the piezometer in the stream itself. Sponge was inserted over the logger on the inside of the piezometer to insulate the streambed portion of the piezometer from the stream, while allowing hydraulic head inside the piezometer to reach a steady-state level.

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