

M.L. 2016, Chp. 186, Sec. 2, Subd. 03k Project Abstract

For the Period Ending June 30, 2019

PROJECT TITLE: Evaluate Temperature, Streamflow, and Hydrogeology Impact on Brook Trout Habitat

PROJECT MANAGER: Bob Tipping

AFFILIATION: Minnesota Department of Health

MAILING ADDRESS: 625 Robert Street North

CITY/STATE/ZIP: Saint Paul, MN 55164

PHONE: (651) 201-4649

E-MAIL: bob.tipping@state.mn.us

WEBSITE:

FUNDING SOURCE: Environment and Natural Resources Trust Fund

LEGAL CITATION: [M.L. 2016, Chp. 186, Sec. 2, Subd. 03k]

APPROPRIATION AMOUNT: \$ 115,000

AMOUNT SPENT: \$ 115,000

AMOUNT REMAINING: \$ 0

Sound bite of Project Outcomes and Results

Detailed stream temperature profiles combined with fish inventories show links between hydrogeologic setting and brook trout distribution and abundance. Results demonstrate how geologic maps of southeastern Minnesota, funded in large part by the ENRTF, can be used to manage trout populations dependent on base flow to streams.

Overall Project Outcome and Results

The recent discovery of resurgent brook trout populations in southeastern Minnesota streams has led to increased interest in documenting and improving critical habitat for this native species. Distributed Temperature Sensing (DTS) technology using fiber optic cables, 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. Continuous stream temperature measurements along one meter segments over distances up to 1900 meters were taken in winter when air and groundwater temperatures are most different. Transition from mixed populations of brown and brook trout to predominantly brook trout corresponded specific stream reaches showing preferential base flow inputs from groundwater.

At the regional scale, artesian conditions were compared to bedrock geology and brook trout abundance to locate areas where brook trout, including remnant brook trout, may be most successfully established. Brook trout are found almost exclusively in streams where the Oneota Dolomite and underlying bedrock units are uppermost bedrock. Streams in these settings have springs characterized by relatively constant temperatures, and are supplied by groundwater in generally poor connection to the land surface compared to near-surface aquifers. As such, they have relatively low susceptibility to high turbidity and contaminant pulses resulting from extreme storm events. At both regional and local cases our work (see attached) demonstrates to natural resource managers the direct geologic control on hydraulic head conditions – particularly on vertical head gradients between bedrock layers and the role they play both in stream base flow and brook trout distribution and abundance.

Project Results Use and Dissemination

The attached report is currently being revised for release as an Open-File Report available publically via the University of Minnesota's Digital Conservancy (<https://conservancy.umn.edu/>), and for peer-reviewed journal submittal. As a project that includes a hybrid of disciplines, it is expected that results will be presented at meetings with both groundwater and natural resource management focus. To date, the results have been

presented to a group of local residents and landowners from East Indian Creek in Wabasha County, organized by Jen Wahls, Landuse Outreach Coordinator for Wabasha County SWCD and by Nick Budde, student scholarship recipient at the Minnesota Groundwater Association Spring 2018 Conference (also attached).



Environment and Natural Resources Trust Fund (ENRTF) M.L. 2016 Work Plan Final Report

Date of Report: September 26, 2019

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2019

Does this submission include an amendment request? No

PROJECT TITLE: Evaluate Temperature, Streamflow, and Hydrogeology Impact on Brook Trout Habitat

Project Manager: Bob Tipping

Organization: Minnesota Department of Health

Mailing Address: 625 Robert Street North

City/State/Zip Code: Saint Paul, MN 55164

Telephone Number: (651) 201-4649

Email Address: bob.tipping@state.mn.us [former: tippi001@umn.edu]

Web Address: <http://health.state.mn.us> [former: <http://www.mngs.umn.edu/>]

Location: Dakota, Goodhue, Wabasha, Olmsted, Winona, Houston, Fillmore

Total ENRTF Project Budget:

ENRTF Appropriation: \$115,000

Amount Spent: \$115,000

Balance: \$0

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03k

Appropriation Language:

\$115,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota for the Minnesota Geological Survey to evaluate links between southeastern Minnesota stream temperatures, trout habitat, and bedrock hydrogeology to improve trout stream management. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Protecting Native Brook Trout: Temperature, Streamflow and Hydrogeology

II. PROJECT STATEMENT:

The recent discovery of resurgent brook trout populations – brook trout present in 68% of southeastern Minnesota streams compared to only 3% in the early 1970s - has led to an increased interest in documenting and improving critical habitat for this native species - the most temperature-sensitive of southeastern Minnesota's trout population. Many of the brook trout analyzed were not associated with known hatchery sources, leading investigators at the Minnesota DNR and University of Minnesota to focus on potentially remnant lineages that have proven their ability to sustain themselves in this region (Hoxmeier, Dieterman and Miller, 2015). Brook trout often display distinct distributions along stream reaches, thought to be caused by stream temperature, discharge, competition with brown trout, or a combination of all three. Previous groundwater and geologic investigations, funded in part by the LCCMR, have shown that specific layers within the bedrock provide greater groundwater flow. Stream reaches that cross these layers are subject to greater groundwater inputs, increased base flow and lower temperature along and downstream from these reaches thus providing habitat conditions supportive to brook trout.

The goal of this project is develop a workable temperature sensing methodology and apply the methodology to candidate trout stream reaches to quantify the changes in temperature, flow, and trout distributions that occur along them. Advances in temperature measurements using fiber optic cables (distributed temperature sensing, DTS) allow temperature to be recorded through time at regularly spaced intervals, over distances of 1 to 2 kilometers. Stream reaches to be measured will be chosen based on geologic mapping by the Minnesota Geological Survey, focusing in areas where different geologic conditions exist and information on trout distribution and abundance are available.

The proposed work will deliver maps showing where significant reductions in temperature and increases in stream flow are expected to occur. Because these intervals are in large part controlled by subsurface geologic conditions and detailed geologic maps exist for the region, results can be readily extended to unmeasured reaches in southeastern Minnesota. Once developed, the DTS methodology may be applicable to trout streams in other regions of Minnesota and to other aquatic resources that are sensitive to stream temperature distribution such as state and federally listed rare and endangered species

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 1, 2017:

Suitable sites for streamflow and temperature measurements were identified in two distinct hydrogeologic settings. Sites have historic trout distribution data.

Project Status as of July 1, 2017:

N/A

Project Status as of January 1, 2018:

Stream flow and temperature measurements have been made at East Indian Creek, Wabasha County, MN – the first of two distinct hydrogeologic settings picked for the project. A fish count and inventory was conducted by DNR Fisheries – Lakeville office along the same stream reach.

Amendment Request (12/28/2017):

Amendment Approved by LCCMR 01/08/2018. Activity 1 – stream reach suitability assessment, has been completed at a lower cost than expected; Activity 2 – seasonal measurements of temperature, flow and trout distribution is costing more than expected. We propose to shift the remaining Activity 1 balance for personnel [\$19,135] and travel [\$542] to respective Activity 2 budgets. Activity 2 personnel budget changes from \$25,700 to \$44,835 and Activity 2 travel budget changes from \$2,400 to \$2,942.

Project Status as of July 1, 2018:

Amendment Request (06/29/2018):

Activity 2 - In the workplan budget, \$12,800 was set in the budget category *Professional/Technical/Service Contracts* to cover the cost of leasing distributed temperature sensing equipment from the Center for Transformative Environmental Monitoring Systems (CTEMPS). Because this work did not require setting up a service contract, these funds were placed in the general supplies account at the University. We propose to move \$12,800 from *Professional/Technical/Service Contracts* to the *Equipment/Tools/Supplies, overall budget* category to be consistent with University budget categories; Activity 2 - Seasonal measurements of temperature, flow and trout distribution are now planned to extend to winter of 2018/2019 rather than fall 2018. We propose to change Activity 2 outcome finish dates from January 1, 2019 to January 31, 2019 to accommodate this change; Activity 2 - Seasonal measurements of temperature, flow and trout distribution has required more staff time than expected. We propose to shift \$10,000 from Activity 3 personnel to Activity 2 personnel.

Amendment Approved: [08/01/2018]

Activity 1 is completed. Activity 3 is will begin January 1, 2019

Project Status as of January 1, 2019:

Temperature measurements have been made in Trout Brook, Dakota County, MN – the second of two distinct hydrogeologic settings picked for the project. A fish count and inventory is planned by DNR Fisheries – Lakeville office along the same stream reach. Twelve shallow piezometers were installed along the stream in order to measure vertical hydraulic head gradients. Seven of the piezometers were also equipped with temperature sensors to measure stream bed and stream water temperatures. One additional DTS installation at Brown’s Creek in Washington County Minnesota is under consideration, pending access and equipment availability.

Project Status as of April 15, 2019:

Amendment Request (04/15/2019):

Activity 3 data interpretation and final report requires more staff time than expected and Activity 2 Professional/Technical/Service Contracts, Activity 2 Equipment/Tools/Supplies, and Activity 2 and 3 travel are less than expected. To cover the additional personnel costs for Activity 3, we propose shifting \$1,800 from Activity 2 Service contracts, \$13, 928 from Equipment/Tools/supplies, \$867 from Activity 2 travel and \$633 from Activity 3 travel to Activity 3 personnel. Activity 2 and Activity 3 budget totals have been adjusted for this proposed transfer.

Amendment Approved by LCCMR 4/21/2019

Project Status as of September 26, 2019:

Amendment Request (09/26/2019):

All final account entries not available when August 16th report was submitted. As a result the following adjustments were made. Service Contract for \$272 not spent, budget amount changed to 0; Supplies total less than reported, budget amount for Activity 2 changed from \$17,900 to \$17,728; personnel more than reported, budgeted amount for Activity 3 changed from \$32,928 to \$33,038; travel more than reported, budgeted amount for Activity 3 changed to \$167 to \$501.

Amendment Approved by LCCMR 10/10/2019

Overall Project Outcomes and Results:

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. Distributed Temperature Sensing (DTS) technology using fiber optic cables, 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. Continuous stream temperature measurements along one meter segments over distances up to 1900 meters were taken in winter when air and groundwater temperatures are most different. Transition from mixed populations of brown and brook trout to predominantly brook trout corresponded specific stream reaches showing preferential base flow inputs from groundwater.

At the regional scale, artesian conditions were compared to bedrock geology and brook trout abundance to locate areas where brook trout, including remnant brook trout, may be most successfully established. Brook trout are found in almost exclusively in streams where the Oneota Dolomite and underlying bedrock units are uppermost bedrock. Streams in these settings have springs characterized by relatively constant temperatures, and are supplied by groundwater in generally poor connection to the land surface compared to near-surface aquifers. As such, they have relatively low susceptibility to high turbidity and contaminant pulses resulting from extreme storm events. At both regional and local cases our work (see attached) demonstrates to natural resource managers the direct geologic control on hydraulic head conditions – particularly on vertical head gradients between bedrock layers and the role they play both in stream base flow and brook trout distribution and abundance.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Stream reach suitability assessment

Description: To identify sites suitable for streamflow temperature measurement, we will use County Geologic Atlas maps from the Minnesota Geological Survey and previous trout distribution investigations to target potential reaches. Because the cable must remain submerged during measurement phases, factors such as stream depth, morphology, and bed characteristics will be considered. Ideally, we will identify reaches in several different geologic settings where contributions to streamflow will be primarily from groundwater (baseflow).

Summary Budget Information for Activity 1:

ENRTF Budget: \$ 6,823
Amount Spent: \$ 6,823
Balance: \$ 0

Outcome	Completion Date
1. Identification of potential stream reaches for measurement based on hydrogeologic setting and historic trout distribution data	December 1, 2016

Activity Status as of January 1, 2017:

Suitable sites for 2017 streamflow temperature and flow measurements in Wabasha and Dakota Counties were identified and confirmed with field visits. Field visits included reconnaissance streamflow measurements, originally scheduled as part of activity 2. Appropriate land owners and/or responsible parties have been contacted for stream access. Additional sites were also identified for 2018. Conducted a literature review on data collection and analysis using Distributed Temperature Sensing (DTS) equipment.

Activity Status as of July 1, 2017:

N/A

Activity Status as of January 1, 2018:

Activity 1 completed. Requesting remaining personnel and travel balances from Activity 1 [19,677] be transferred to Activity 2 personnel and travel budget.

Activity Status as of July 1, 2018:

N/A

Activity Status as of January 1, 2019:

N/A

Activity Status as of April 15, 2019:

N/A

Final Report Summary:

Through benefit of cooperation with landowners and Dakota County Parks, we were able to conduct this work in three distinct hydrogeologic settings. The number of potential sites scoped as part of this activity far exceed the number that we would be able to install at. This became apparent once we began the process of installation, data collection and removal (Activity 2)

ACTIVITY 2: Seasonal measurements of temperature, flow and trout distribution

Description: Temperature data will be collected in different seasons from Spring 2017 until Winter 2018/2019. Fish population assessments and streamflow measurements will be conducted seasonally during the same time period.

Summary Budget Information for Activity 2:

ENRTF Budget: \$ ~~75,082~~
\$ 74,638

Amount Spent: \$ 74,638
Balance: \$ 0

Outcome	Completion Date
1. Application for DTS equipment from Center for Transformative Environmental Monitoring Programs (CTEMPS)	December 31, 2016
2. Equipment acquired and training completed	May 1, 2017
3. Practical aspects and pitfalls of using DTS equipment to measure stream temperatures identified. Seasonal measurements of stream temperature, flow and trout distribution taken.	June 1, 2018
4. links between stream temperature, streamflow and bedrock geology analyzed	January 31, 2019
5. links between brook trout populations and bedrock geology analyzed	January 31, 2019

Activity Status as of January 1, 2017:

Staff from the Center for Transformative Environmental Monitoring Programs (CTEMPS) contacted and application for DTS equipment submitted. Installation dates subject to change depending on equipment and staff availability, and final decisions on first installation season (spring or late summer-fall, 2017). Portable flow-meter purchased and reconnaissance measurements made at target sites.

Activity Status as of July 1, 2017:

N/A

Activity Status as of January 1, 2018:

DTS measuring equipment and cable received from CTEMPS . Two-thousand meters of cable installed in East Indian Creek headwaters – Wabasha County, Minnesota, the first of two distinct hydrogeologic settings picked for the project. Stream temperature data was collected at 5 minute intervals from August 25th to September 28th, 2017. Data are currently being calibrated and analyzed. A winter DTS measurement at this site is planned

for the week of January 8th through January 12th, 2018. A fish count and inventory was conducted by DNR Fisheries – Lakeville office along this same stream reach. Fish species are primarily brook trout, with the proportion of brook trout to brown trout increasing upstream. Synoptic stream flow measurements made after the fish inventory confirms base flow increasing along the reach. Activity 2 has cost more than expected in the original budget. Requesting remaining personnel and travel balances from Activity 1 [19,677] be transferred to Activity 2 personnel and travel budget. It is expected this change will cover the cost of DTS measurements at the second site.

Activity Status as of July 1, 2018:

A winter DTS measurements were made between January 8th and January 29th 2018 in the East Indian Creek headwaters – Wabasha County. Data from the Fall 2017 and Winter 2018 installations were calibrated and analyzed. Outcrop mapping, borehole geophysics and passive seismic transects were conducted at Trout Brook in southeastern Dakota County in preparation for the second DTS installation, scheduled to take place in late fall/early winter of 2018, possibly stretching into January of 2019 depending on conditions and equipment availability. Installation in Dakota County has moved from fall 2018 to winter 2018/2019 in order to take advantage the greater temperature differential between groundwater and surface water at that time.

Activity Status as of January 1, 2019:

A total of 1800 meters of cable was installed in Trout Brook – Dakota County Minnesota, the second of two distinct hydrogeology settings picked for the project. Stream temperature data were collected at 5 minute intervals along 1300 meters of cable from December 11th to December 19th 2018. An additional 500 meters of cable was installed on December 19th. Stream temperature data were collected on both cables at 8 minute intervals from December 19th until December 25th. Twelve shallow piezometers were installed along the stream in order to measure vertical hydraulic head gradients. Seven of the piezometers were also equipped with temperature sensors to measure stream bed and stream water temperatures. Prior to cable installation, re-splicing of cable ends were required due to a break in the original 2000 meter cable used at East Indian Creek.

One additional DTS installation at Brown’s Creek in Washington County Minnesota is under consideration, pending access and equipment availability.

Activity Status as of April 15, 2019:

A total of 1600 meters of cable was installed at Valley Creek – Washington County Minnesota. This third site was added because of mapped faults along the measured stream reach – providing a third distinct hydrogeologic setting for the project. Shallow piezometers added to Trout Brook.

Final Report Summary:

Installation activities and data calibration ended up being the most labor intensive and time consuming parts of the project. By the third installation at Valley Creek in Washington County, methods for cable and equipment installation and removal had been work out and these tasks went far more smoothly than the first installation at East Indian Creek, Wabasha County. The additional work to install shallow piezometers with temperature transducers was not in the original work plan, but provided valuable data at low cost, and will be used in future investigations to supplement DTS profiles. DTS equipment has a steep learning curve, but the data provided could not be obtained in any other way. Perhaps the biggest benefit from this activity was to understand the pitfalls and the benefits of these methods. With this knowledge we can provide clear direction and advice for future DTS projects.

ACTIVITY 3: Critical reach mapping and report

Description: Report with interpretation of collected data will provide, for the first time, maps showing the extent of both measured and projected cold water reaches, their correlation with trout habitat, and their position relative to specific bedrock hydrogeologic conditions.

Summary Budget Information for Activity 3:

ENRTF Budget: \$ ~~33,095~~

\$33,028

Amount Spent: \$ 33,028

Balance: \$ 0

Outcome	Completion Date
1. Map capturing key reaches where significant reductions in temperature and increases in stream flow to occur. Map will also show areas where significant reductions in temperature and increases in flow are expected to occur based on investigation results.	June 1, 2019
2. Map identifying distribution of brook trout associated with colder reaches	June 1, 2019

Activity Status as of January 1, 2017:

no activity during the reporting period

Activity Status as of July 1, 2017:

N/A

Activity Status as of January 1, 2018:

no activity during the reporting period

Activity Status as of July 1, 2018:

no activity during the reporting period

Activity Status as of January 1, 2019:

no activity during the reporting period

Activity Status as of April 15, 2019:

Work has begun on data interpretation and analysis, figures, and report outline.

Activity Status as of June 29, 2019:

Work completed on data interpretation and analysis, figures, and report outline and final report text.

Final Report Summary:

Work completed and final report reviewed by co-authors. Maps included as attachment and as figures in final report.

V. DISSEMINATION:

Description: Report and maps will be disseminated as Minnesota Geological Survey Open File Report, stored at the University of Minnesota's Digital Conservancy (<http://conservancy.umn.edu/>) and accessible via the Minnesota Geological Survey's web site (<http://www.mngs.umn.edu/>). Results will be presented in talks at Minnesota Ground Water Association and MN Water conferences. Publication in peer-reviewed journals will also be pursued.

Status as of January 1, 2017:

no activity during the reporting period

Status as of July 1, 2017:

N/A

Status as of January 1, 2018:

no activity during the reporting period

Status as of July 1, 2018:

Status as of January 1, 2019:

no activity during the reporting period

Status as of April 15, 2019:

no activity during the reporting period

Status as of August 16, 2019:

Report in review for distribution as MGS open-file report.

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Final Report Summary:

The attached report is currently being revised for release as an Open-File Report available publically via the University of Minnesota's Digital Conservancy (<https://conservancy.umn.edu/>), and for peer-reviewed journal submittal. As a project that includes a hybrid of disciplines, it is expected that results will be presented at meetings with both groundwater and natural resource management focus. This is the time where trout investigations in southeastern Minnesota have been conducted within the context of detailed geologic and hydraulic head mapping. The results demonstrate the value of this approach to assess focused groundwater inputs on trout distribution and abundance at both local and regional scales. As such, project results benefit natural resource, landuse, and water use managers. To date, the results have been presented to a group of local residents and landowners from East Indian Creek in Wabasha County, organized by Jen Wahls, Landuse Outreach Coordinator for Wabasha County SWCD and by Nick Budde, student scholarship recipient at the Minnesota Groundwater Association Spring 2018 Conference.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	\$ Amount	Overview Explanation
Personnel:	\$ 94,438	1 project manager and hydrogeologist at 14.8% FTE each year for 3 years (\$41,890); 1 lead geologist at 6.6% FTE each year for 3 years (\$20,156); 1 geologist at 5.5% FTE each year for 3 years (\$11,818); 1 geologist at 7.1% FTE each year for 3 years (\$12,969); field tech support (\$5,967); geophysicist (\$1,638)
Professional/Technical/Service Contracts:	\$ 0	Fiber optic cable repair (\$0) [not billed]
Equipment/Tools/Supplies:	\$ 17,728	leasing Distributed Temperature Sensing (DTS) equipment during the project and technical support from Center for Transformative Environmental Monitoring Programs (CTEMPS), administered jointly by Oregon State University, University of Nevada-Reno, and National

		Science Foundation (\$6716.69); Portable Velocity Meter with 20' Cable for stream gauging (\$4,982.47); Supplies to submerge and protect data collection equipment (\$1751.54); Final shipping costs for DTS equipment – 3 shipping events (\$1967.33); 2000 meters of armored fiber optic cable (\$2,000); DTS cable collectors (\$0); DTS water-tight splice boxes (\$310)
Travel Expenses in MN:	\$ 2,834	Final Travel expenses between potential and established field sites
TOTAL ENRTF BUDGET: \$ 115,000		

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than \$5,000:

A Portable Velocity Meter with 20 feet of cable for stream gauging is expected to cost \$4,903. This purchase will cost less than contracting out for professional services, provide more scheduling flexibility, and allow us to conduct flow surveys at more than one site. After the project has ended, the equipment will continue to be used by the Minnesota Geological Survey and Earth Sciences Department at the University of Minnesota for research and educational purposes.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 0.85

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 0.06

B. Other Funds:

Source of Funds	\$ Amount Proposed	\$ Amount Spent	Use of Other Funds
Non-state			
	\$	\$	
State			
DNR Fisheries (In-kind Support)	\$ 15,200	\$	One month salary equivalent, in each of two project years for John Hoxmeier, MNDNR Fisheries to lead the fish population assessment and assist with DTS equipment installation and monitoring
MPCA (In-kind Support)	\$ 16,000		One month salary equivalent in each of two project years for MPCA staff person to assist with siting, DTS equipment installation and monitoring
University of Minnesota (In-kind Support)	\$ 46,362		The University of Minnesota's Facilities and Administrative rate is 52% of modified total direct costs (total direct less graduate student fringe, capital equipment, subawards over \$25,000 and on-site facilities rental). The amount, if F&A expenses would have

			been allowed on this project, would be \$46,362
Minnesota Geological Survey (MGS)	\$ 922	\$ 922	MGS provided travel support to workshop on use of DTS equipment
TOTAL OTHER FUNDS:	\$ 78,484	\$ 922	

Additional funding provided by MGS to support attending DTS workshop, December 10-11, 2016

VII. PROJECT STRATEGY:

A. Project Partners:

Project Partners Not Receiving Funds:

- Minnesota Department of Natural Resources – Fisheries Division: John Hoxmeier providing in-kind support to lead fish population assessment and to assist with Distributed Temperature Sensing (DTS) equipment installation and monitoring.
- Minnesota Pollution control Agency: Staff providing in-kind assistance with DTS equipment installation and monitoring.
- University of Minnesota Department of Earth Sciences: Technical support for equipment field testing.

Project Partners Receiving Funds:

- Center for Transformative Environmental Monitoring Systems (CTEMPS), jointly operated by Oregon State University, Corvallis and the University of Nevada, Reno, and funded by the National Science Foundation: \$12,800 to lease DTS equipment used during the investigation.

B. Project Impact and Long-term Strategy:

The proposed work will deliver maps showing where significant reductions in temperature and increases in stream flow are expected to occur. Because these intervals are in large part controlled by subsurface geologic conditions and detailed geologic maps exist for the region, results can be readily extended to unmeasured reaches in southeastern Minnesota. Once developed, the DTS methodology may be applicable to trout streams in other regions of Minnesota and to other aquatic resources that are sensitive to stream temperature distribution such as state and federally listed rare and endangered species.

The study will benefit the MN DNR in developing better management strategies for conserving recently discovered remnant brook trout populations in Minnesota. Given that brook trout rely heavily on cold groundwater inputs, information on these inputs is crucial toward understanding limits to their distribution. With a predicted increase in air temperatures over the next half century, identifying coldwater springs and stream reaches will become even more valuable in terms of providing coldwater fish refuge.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	\$ Amount
Proposed project builds on County Geologic Atlas mapping program, with the first southeastern Minnesota Geologic Atlas map completed in 1982. Since 2007, Statewide ENRTF 2007-2014 \$3,952,199; CWF 2010-2014 \$674,000; DNR 2007-2014 \$2,155,694; Fed cost-sharing 2008-2013 \$663,791. ENRTF 2015-2018 \$2,040,000	2007 - 2018	\$9,485,684
Clean Water Fund - County Geologic Atlases for Houston and Winona Counties	7/1/2010 – 12/31/2014	\$305,000
ENRTF funded a 2010 project "Investigation of the hydrologic properties of the St. Lawrence Formation" (M.L. 2010, Chp. 362, Sec. 2, Subd. 3a). The results of that investigation have led to findings that we will apply to this proposed project	7/1/2010 – 6/30/2013	\$307,000

Investigation of bedrock controls on nitrate distribution in southeastern Minnesota streams, funded by the Minnesota Pollution Control Agency - 319/Clean Water Partnership/TMDL project	1/3/2011 – 6/30/2013	\$73,563
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VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

A. Parcel List: N/A

B. Acquisition/Restoration Information: N/A

IX. VISUAL COMPONENT or MAP(S):

A.

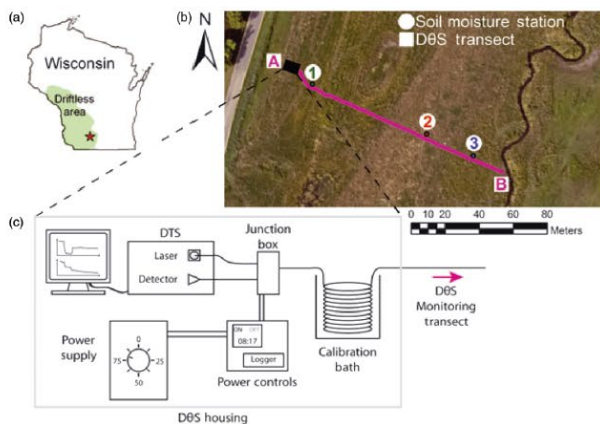


B.



Southeastern Minnesota brook trout average less than 10 inches, although brook trout up to 17 inches are occasionally caught. Because brookies can tolerate only the cleanest and clearest water, fishing for this species invariably takes anglers to the most pristine and scenic areas of the southeast.

C.



Distributed Temperature Sensing installation in southwestern Wisconsin. (Striegl and Loheide, 2012)

D.



Brook trout, streams and temperature, southeastern Minnesota. **A.** Brook trout require cold, clean water to thrive. **B.** Photo of brook trout from MnDNR news release, April 16, 2015. **C.** Distributed Temperature Sensing (DTS) installation to look at soil moisture profiles, southwestern Wisconsin. **D.** Photo of trout stream from MnDNR news release, April 16, 2015.

- A. http://www.dnr.state.mn.us/fishing/trout_streams/trout_species.html
- B. <http://news.dnr.state.mn.us/2015/04/16/for-trout-fishing-in-southeastern-minnesota-these-are-the-good-old-days/>
- C. Striegl, A. and Loheide, S., 2012, Heated distributed temperature sensing for field scale moisture monitoring, Groundwater, v. 50 no. 3, p. 340-347.

<http://news.dnr.state.mn.us/2015/04/16/for-trout-fishing-in-southeastern-minnesota-these-are-the-good-old-days/>

X. RESEARCH ADDENDUM: N/A

XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted not later than January 1, 2017; July 1, 2017; January 1, 2018; July 1, 2018, and January 1, 2019. A final report and associated products will be submitted between June 30 and August 15, 2019.

**Environment and Natural Resources Trust Fund
FINAL M.L. 2016 Project Budget**



Project Title: Evaluate Temperature, Streamflow, and Hydrogeology Impact on Brook Trout Habitat

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03k

Project Manager: Bob Tipping

Organization: Minnesota Geological Survey

M.L. 2016 ENRTF Appropriation: \$ 115,000

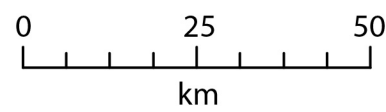
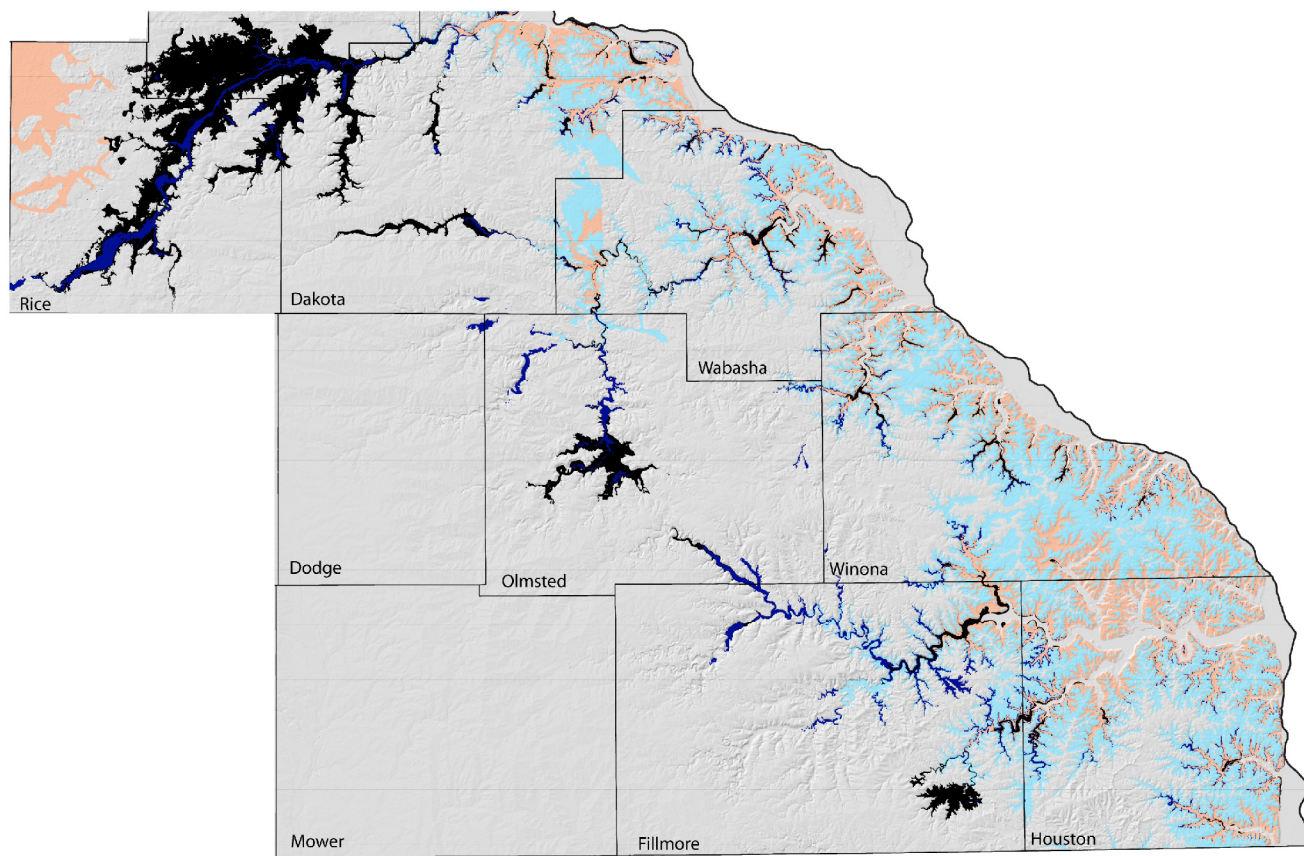
Project Length and Completion Date: 3 Years, June 30, 2019

Date of Report: September 25, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 12/18/2017	Amount Spent	Activity 1 Balance	Revised Activity 2 Budget 09/25/2019	Amount Spent	Activity 2 Balance	Revised Activity 3 Budget 09/25/2019	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	Stream reach suitability assessment										
Personnel (Wages and Benefits), overall budget	\$6,565	6,565.00	\$0	\$54,835	\$54,835	\$0	\$33,038	\$33,038	\$0	\$94,438	\$0
Bob Tipping, Project Manager, Geologist: [73.6 % salary, 26.4 % benefits]; 9.5% FTE each year for 3 year: \$27,000]											
Tony Runkel, Geologist: [73.6 % salary, 26.4 % benefits];8.5% FTE each year for 3 years: \$25,800]											
Julia Steenberg, Geologist: [73.6 % salary, 26.4 % benefits]; 6.0% FTE each year for 3 years: \$13,300]											
Andrew Retzler, Geologist: [73.6 % salary, 26.4 % benefits]; 6.0% FTE each year for 3 years: \$11,000]											
Professional/Technical/Service Contracts											
CTEMPS Technical support in the field (2 people, 4 days). Airfare: \$1,200; lodging \$118/day; food: \$50/person per day											
Equipment/Tools/Supplies, overall budget				\$17,728	\$17,728	\$0				\$17,728	\$0
Center for Transformative Environmental Monitoring Systems (CTEMPS), jointly operated by Oregon State University, Corvallis and the University of Nevada, Reno, and funded by the National Science Foundation. Leasing of Distributed Temperature Sensing (DTS) equipment used during the project											
Portable Velocity Meter with 20' Cable for stream gauging [\$4,903]											
Supplies to submerge and protect data collection equipment, and fiber optic cable in the stream bed [\$1,055]											
Estimated shipping for DTS equipment, [4 shipping events at \$1,500 per event: \$6,000]											
2000 meters of armored fiber optic cable used as part of the DTS installation [\$2.50/meter: \$5000]											
Cable connectors used as part of the DTS installation [18 at \$50 each: \$900]											
Water tight splice boxes [18 at \$65 each: \$1170]											
Travel expenses in Minnesota											
Travel between potential and established field sites – 2000 miles - 0.17/mile- and vehicle rental - \$239/week for 4 weeks – (\$1,300); lodging – 10 days at \$118/day (\$1,180); meals – 30 days at \$48/day (\$1440)	\$258	\$258	\$0	\$2,075	\$2,075	\$0	\$501	\$501	\$0	\$2,834	\$0
COLUMN TOTAL	\$6,823	\$6,823	\$0	\$74,638	\$74,638	\$0	\$33,539	\$33,539	\$0	\$115,000	\$0

SE MINNESOTA BROOK TROUT DISTRIBUTION COMPARED TO BEDROCK GEOLOGY AND ARTESIAN CONDITIONS

Map A



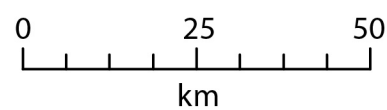
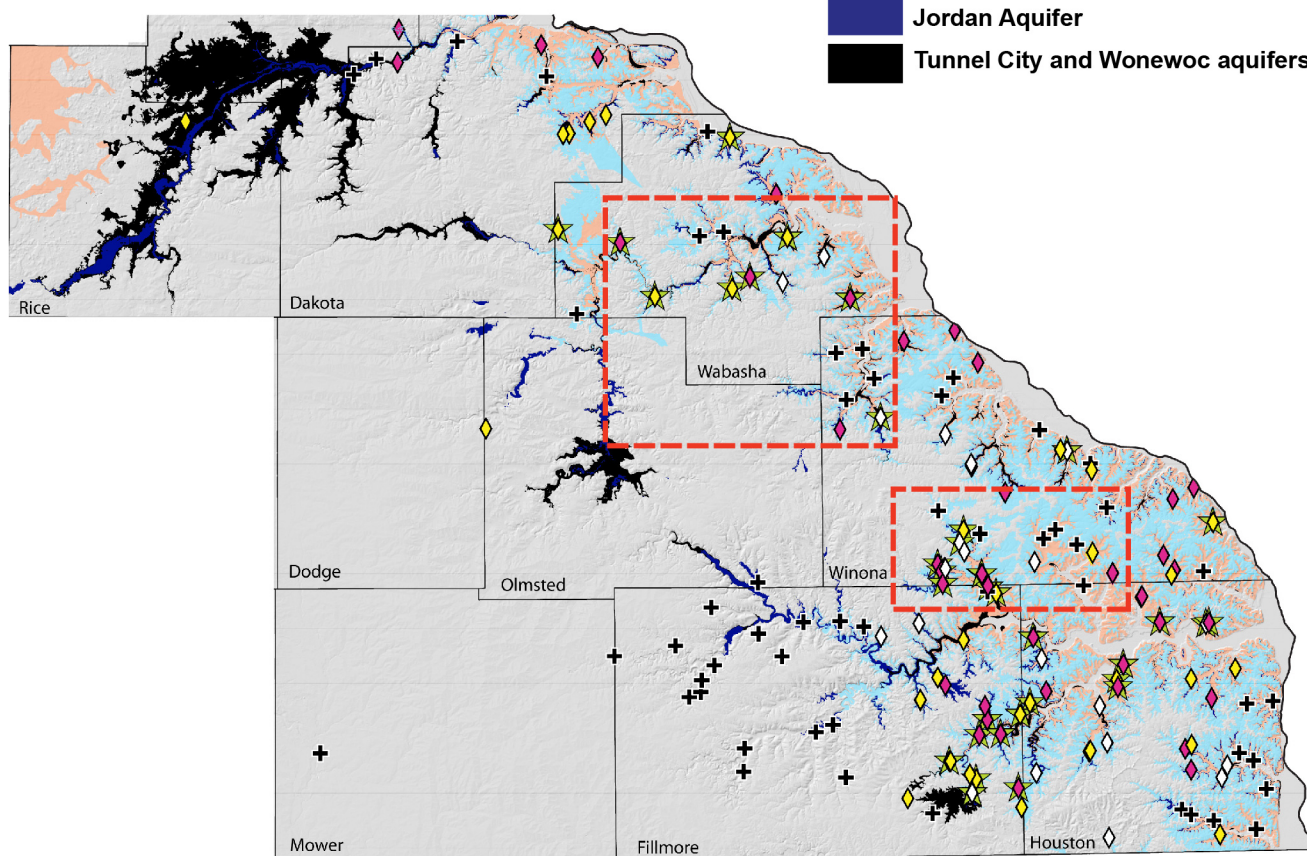
Bedrock units

- Oneota Dolomite
- Jordan Sandstone, St Lawrence Fm., Tunnel City Gp.

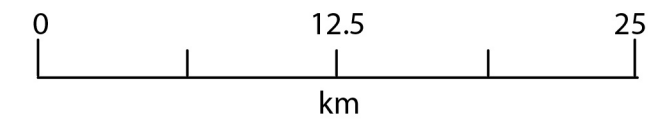
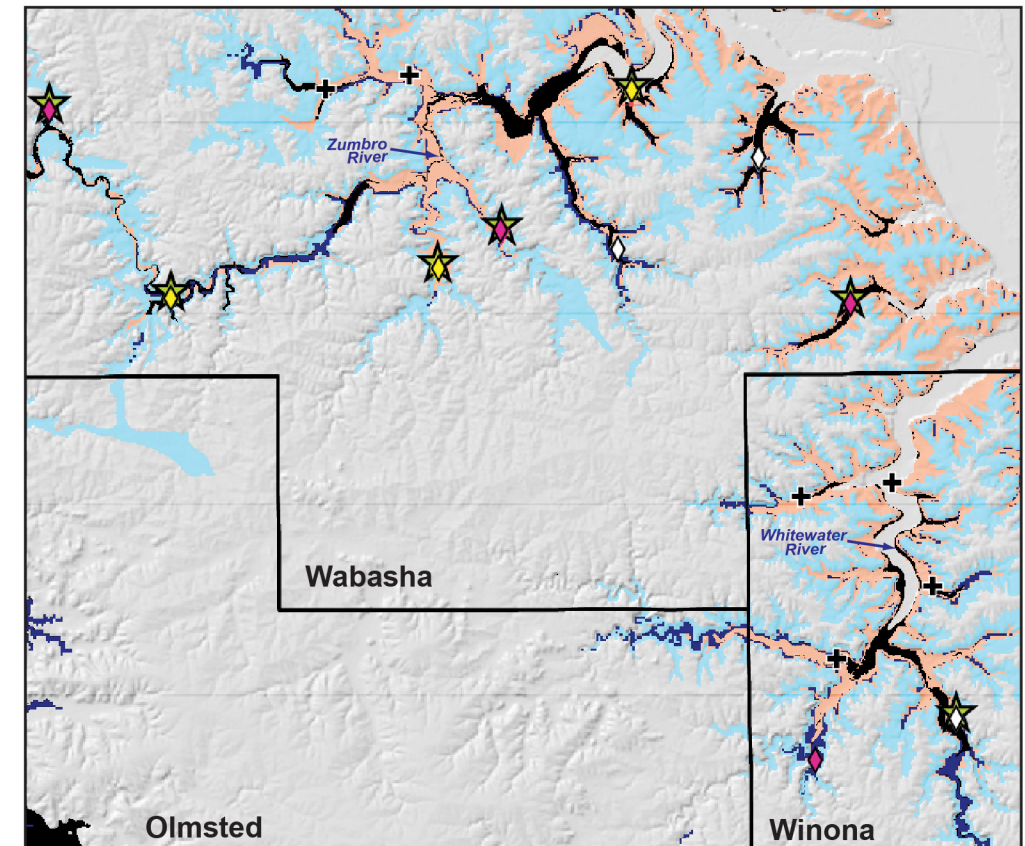
Artesian Conditions

- Jordan Aquifer
- Tunnel City and Wonewoc aquifers

Map B



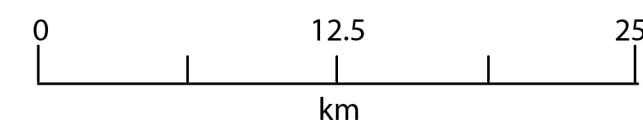
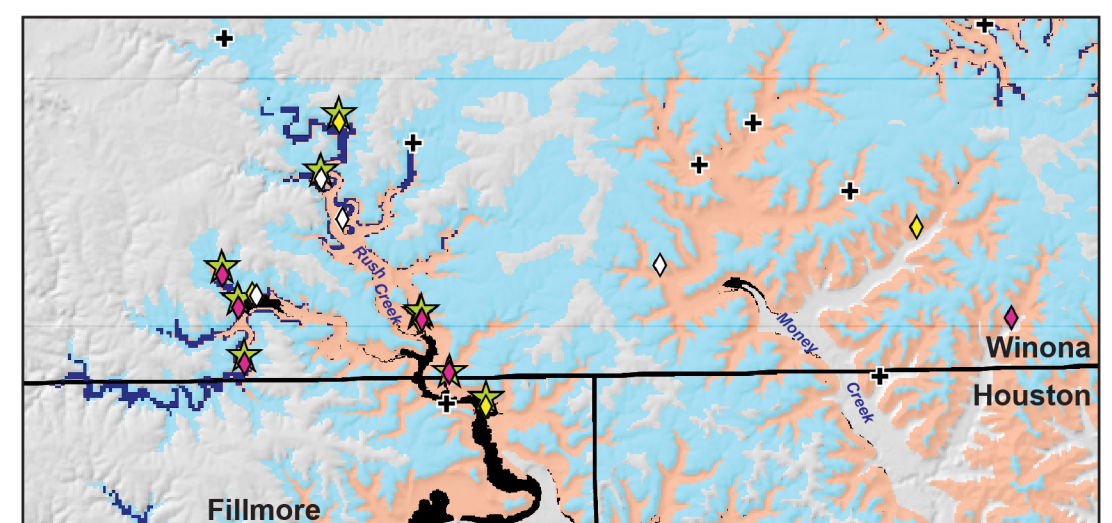
Inset 1



Brook Trout

- Abundant
- Common
- Rare
- None
- Remnant genetics

Inset 2



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).

Local examples comparing hydrogeologic conditions to brook trout distribution. **1)** 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; **2)** 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.



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Map produced by as part of project funded by the Minnesota Environment and Natural Resources Trust Fund, "Evaluation of Temperature, Streamflow and Hydrogeology impact on Brook Trout Habitat" Project M.L. 2016, Chp. 186, Sec. 2, Subd. 03k



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

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August, 2019



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Funded through the Environment and Natural Resource Trust Fund as recommended by the Legislative and Citizen's Commission on Minnesota Resources (LCCMR).

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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 in Tunnel 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 19th, 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 where 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 et 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 hyemale*) 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 1. Regional bedrock geologic map of southeastern Minnesota with DTS cable installation sites: **A.** East Indian Creek, Wabasha County; **B.** Trout Brook, Dakota County; **C.** Valley Creek, Washington County. All sites are located where Cambrian and Ordovician strata are uppermost bedrock and are overlain by a thin (<50ft) cover of unconsolidated sediment.

Figure 2. Hydrogeologic setting in map view for East Indian Creek, Wabasha County showing measured stream reach in context of distribution of uppermost bedrock units and springs. Also shown are passive seismic stations used for estimating thickness of alluvial cover in Fig 3.

Figure 3. Hydrogeologic setting and measured stream reach in cross-section view for East Indian Creek. Tunnel City Group hydraulic head (dashed green line) based on regional mapping (Blum, 2018).

Figure 4. Hydrogeologic setting in map view for Trout Brook, Dakota County showing measured stream reach in context of distribution of uppermost bedrock units and springs. DNR well nests provided information on elevation of unit contacts and hydraulic head shown on Fig. 3. Passive seismic stations used for estimating thickness of alluvial cover. Piezometers used to measure hydraulic head gradients and water temperatures in stream bed.

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Figure 7. Hydrogeologic setting in map view for Valley Creek, Washington County showing measured stream reach in context of distribution of uppermost bedrock units and springs

Figure 8. Hydrogeologic setting in cross-section view for Valley Creek, Washington County. Note monitored section of stream crosses underlying bedrock fault that may be associated with increased groundwater input.

Figure 9. DTS installation, East Indian Creek, showing locations of fiber optic cable (1900m), coils, RBR temperature transducers, DTS collection station, and stream flow measurements. Streamflow measurements made October 12, 2017.

Figure 10. East Indian Creek stream temperature profiles - from January 9th, 2018, with interpretation of relative groundwater inputs along the stream reach based on profile characteristics. Upstream to downstream is plotted left to right. Subaerial coils are readily identified as large deviations in temperature. Smaller deviations are also visible at specific locations along the cable. Times recorded for each profile are in Coordinated Universal Time (UTC).

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.

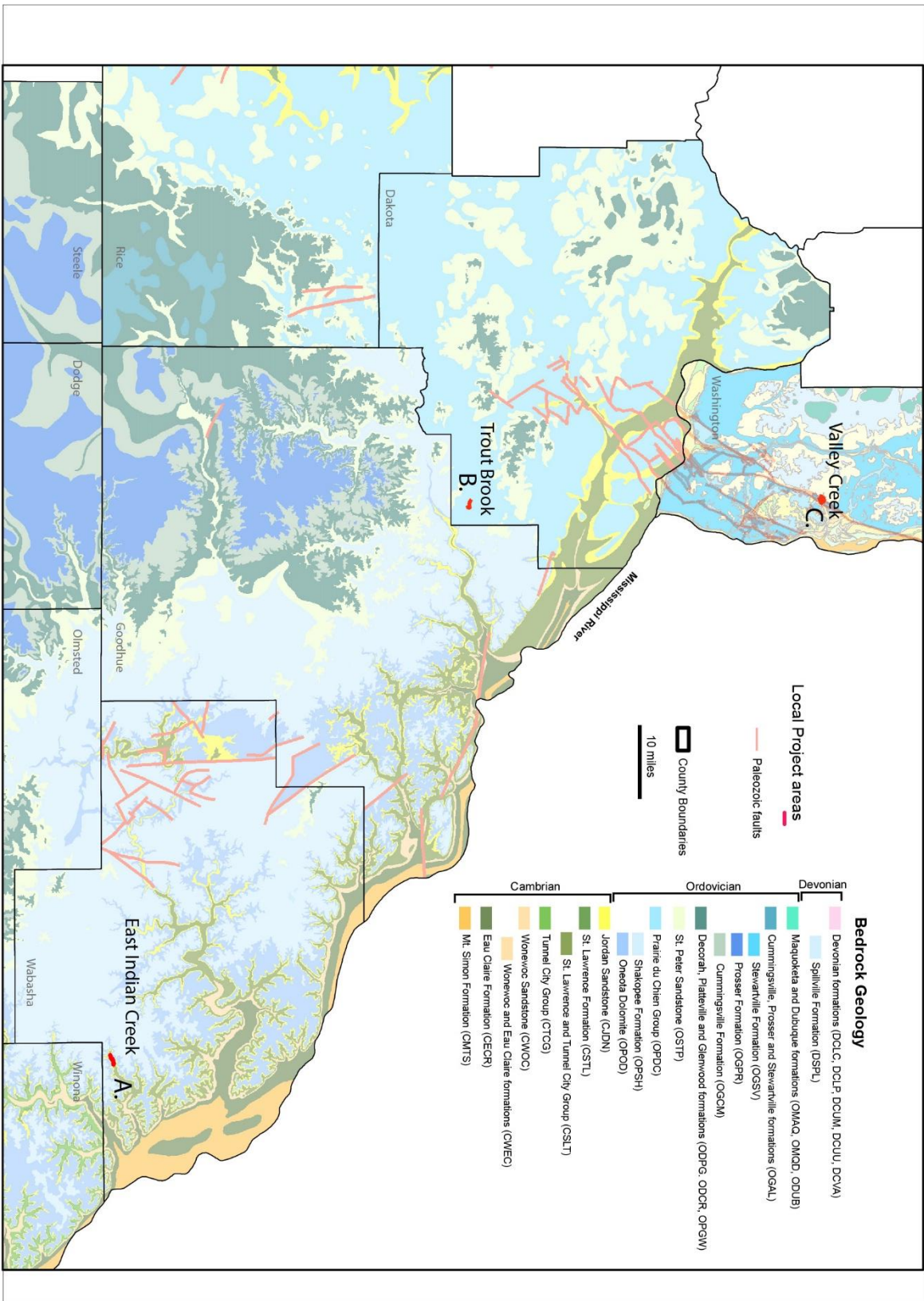
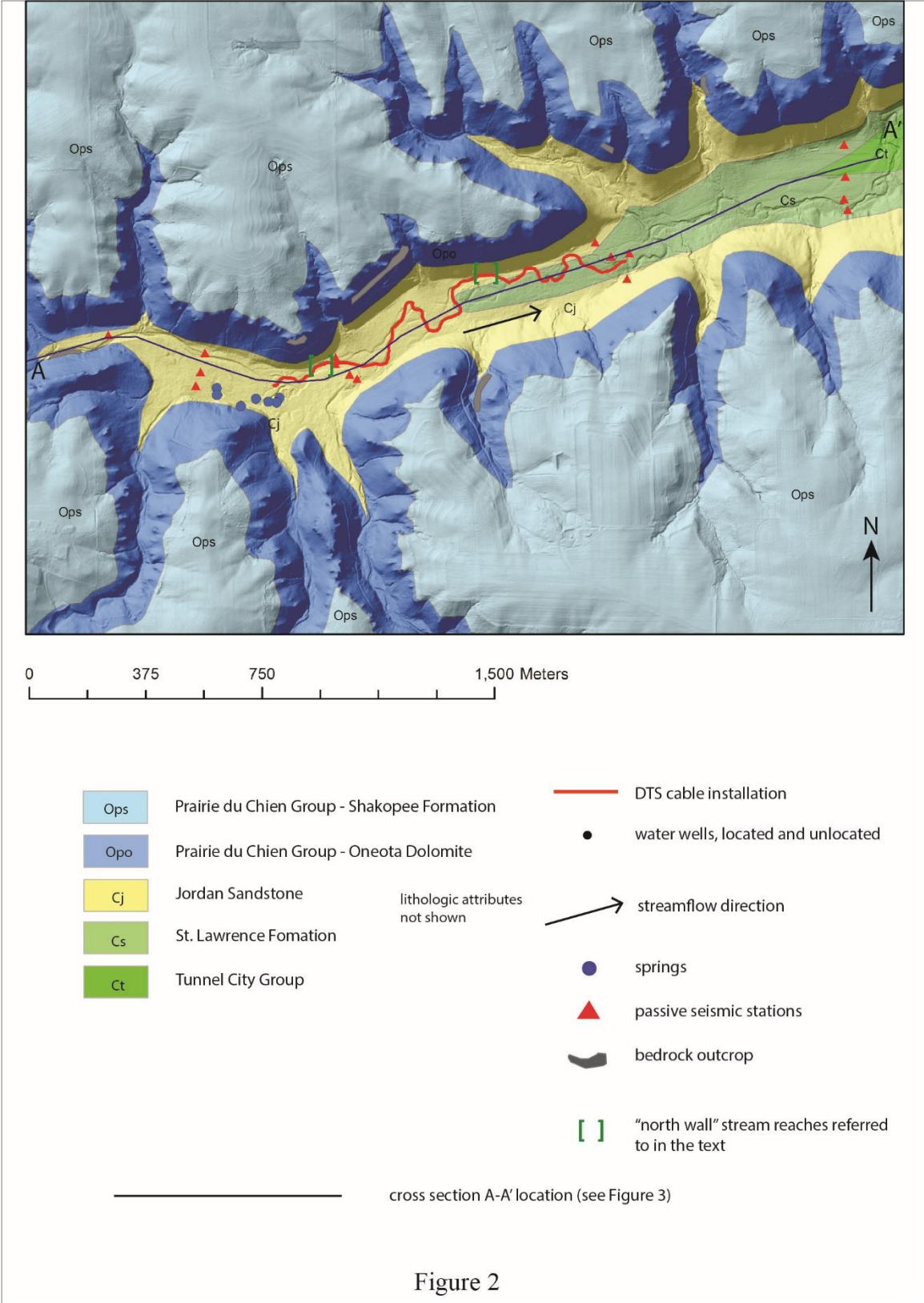


Figure 1



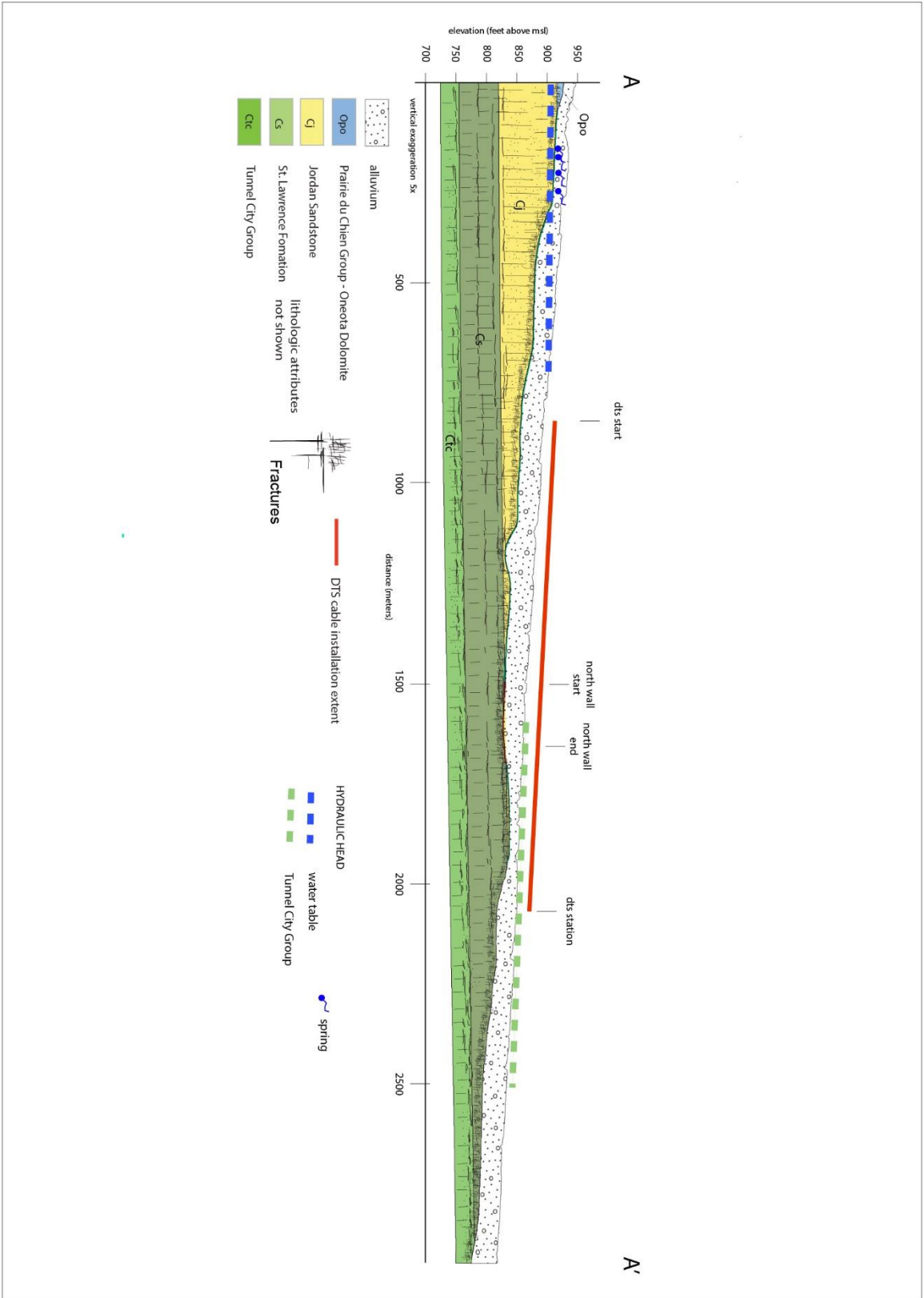


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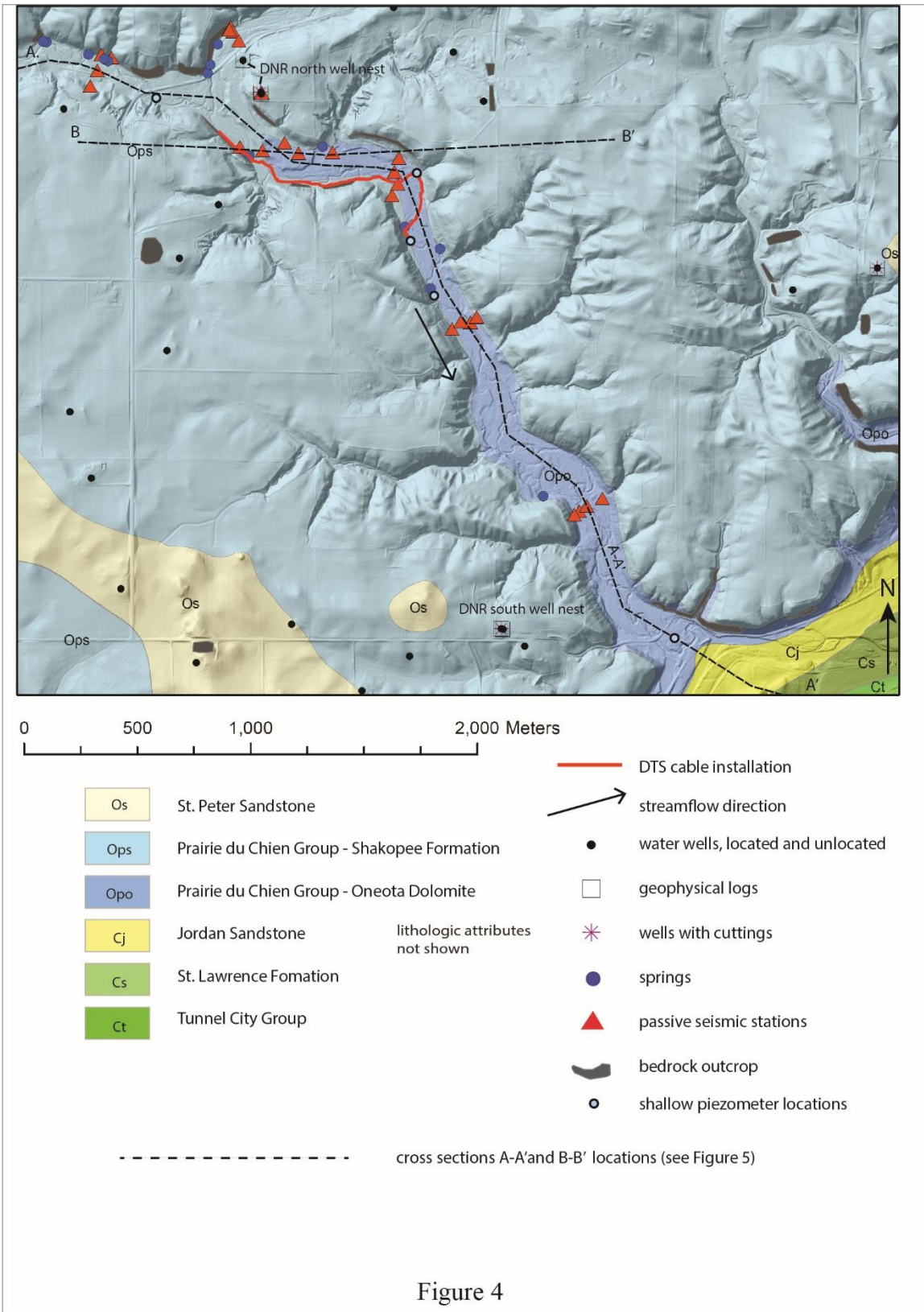


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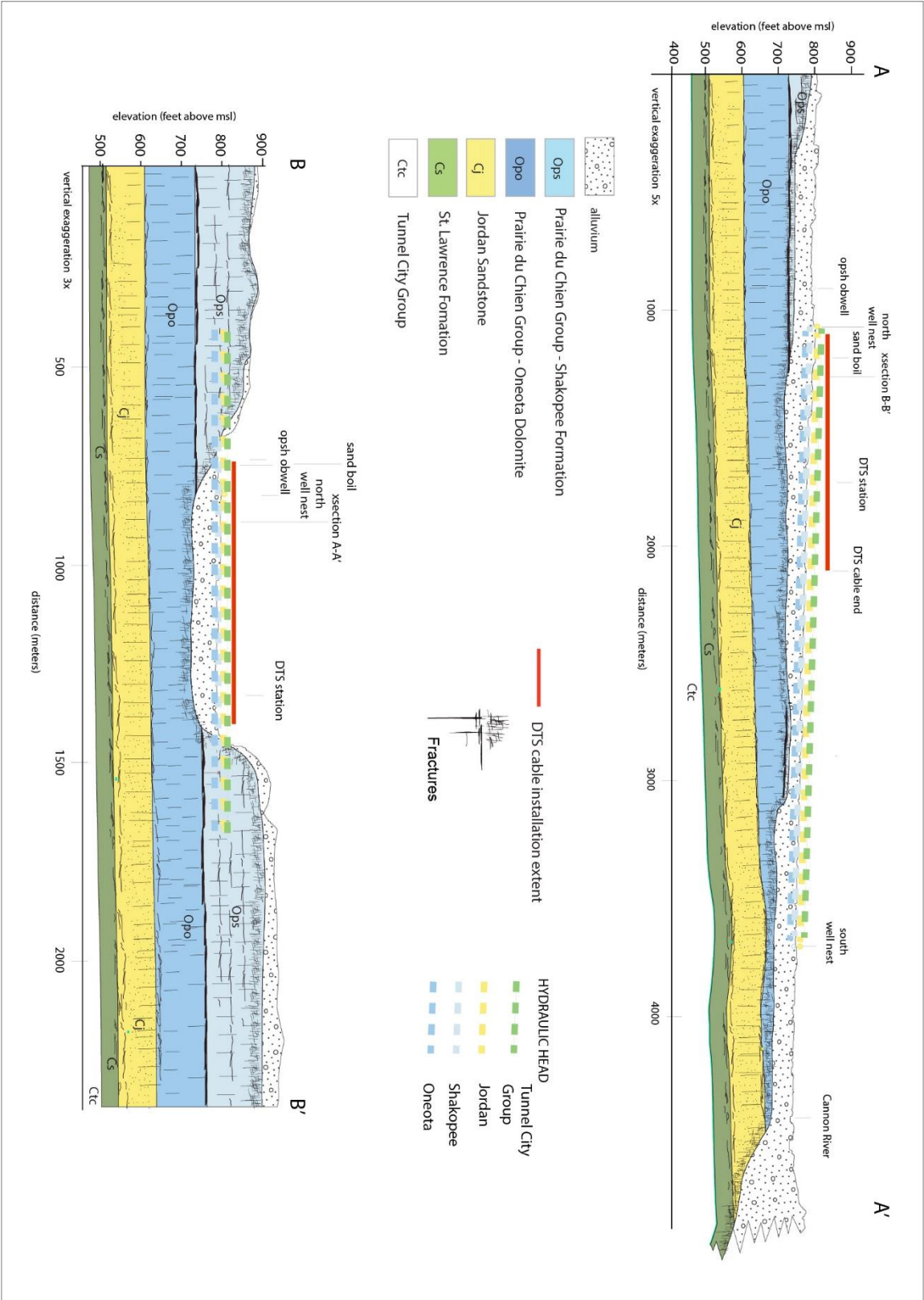
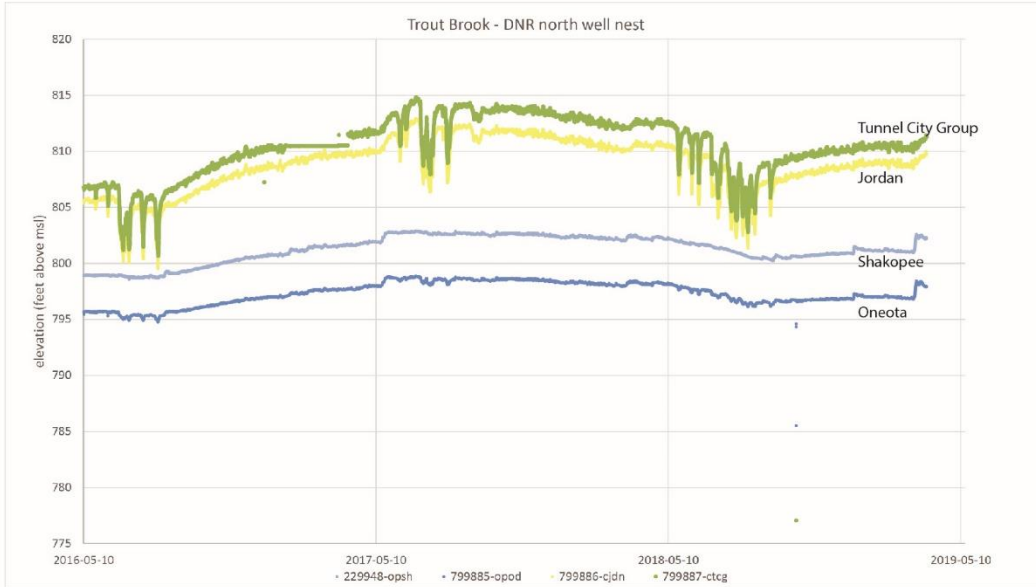


Figure 5

A.



B.

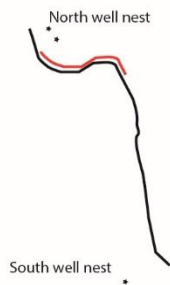
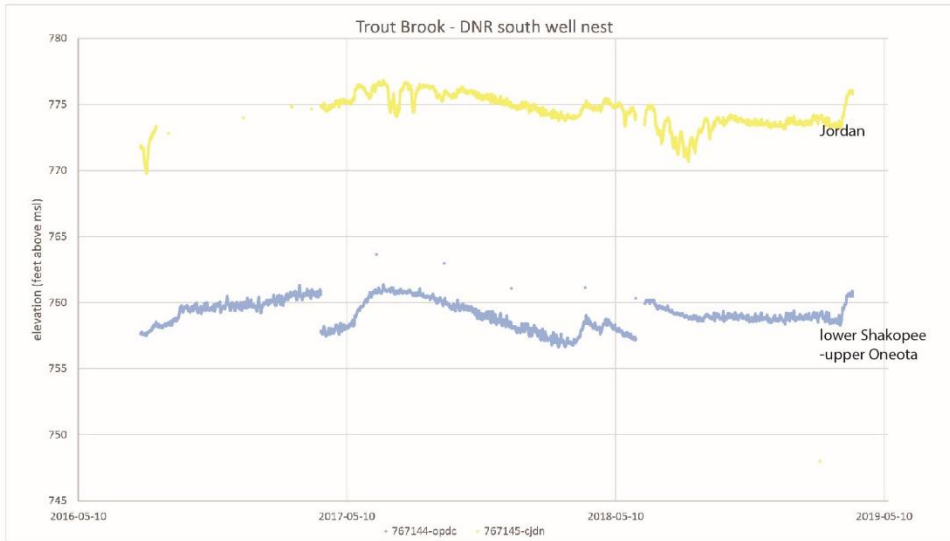


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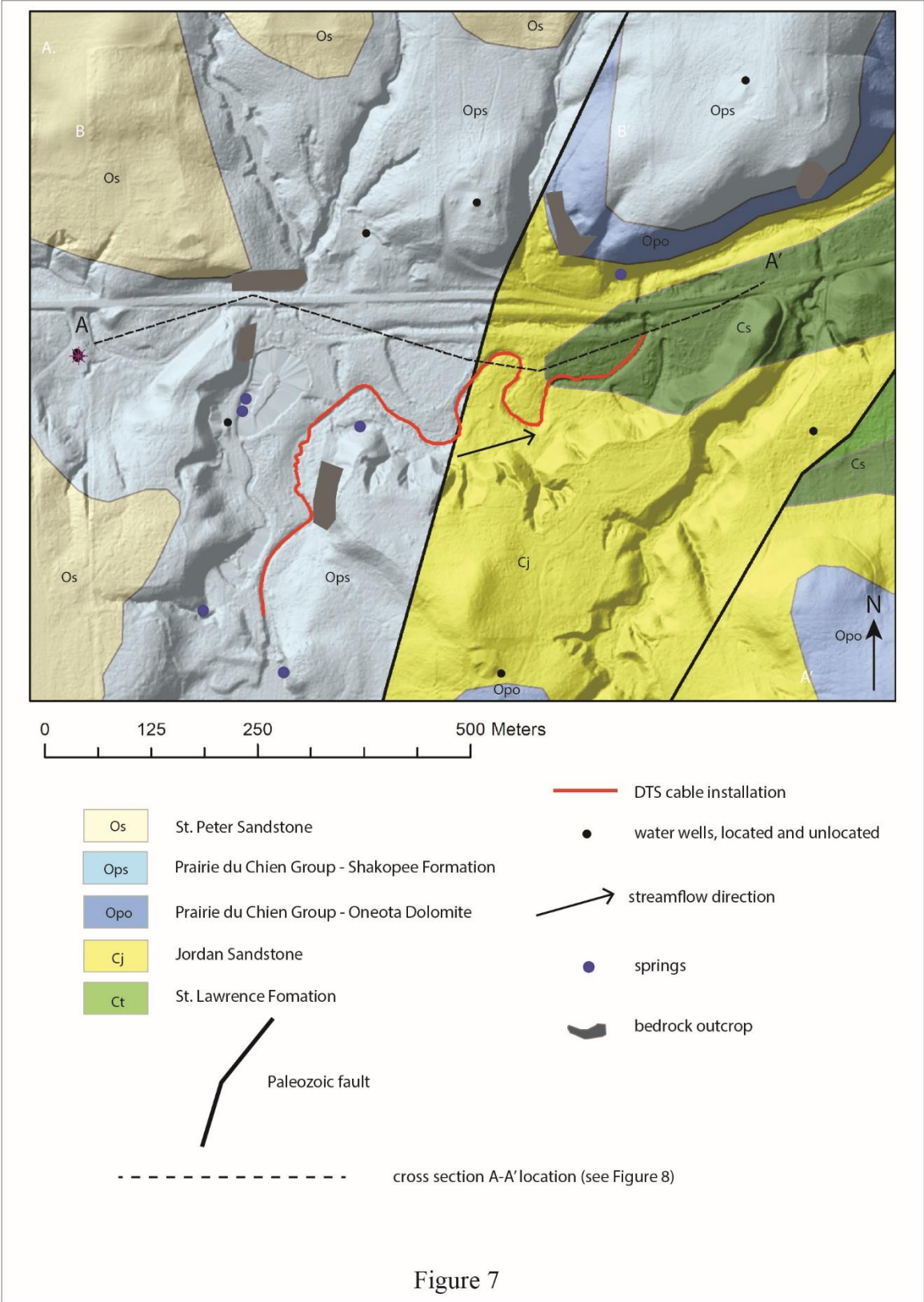


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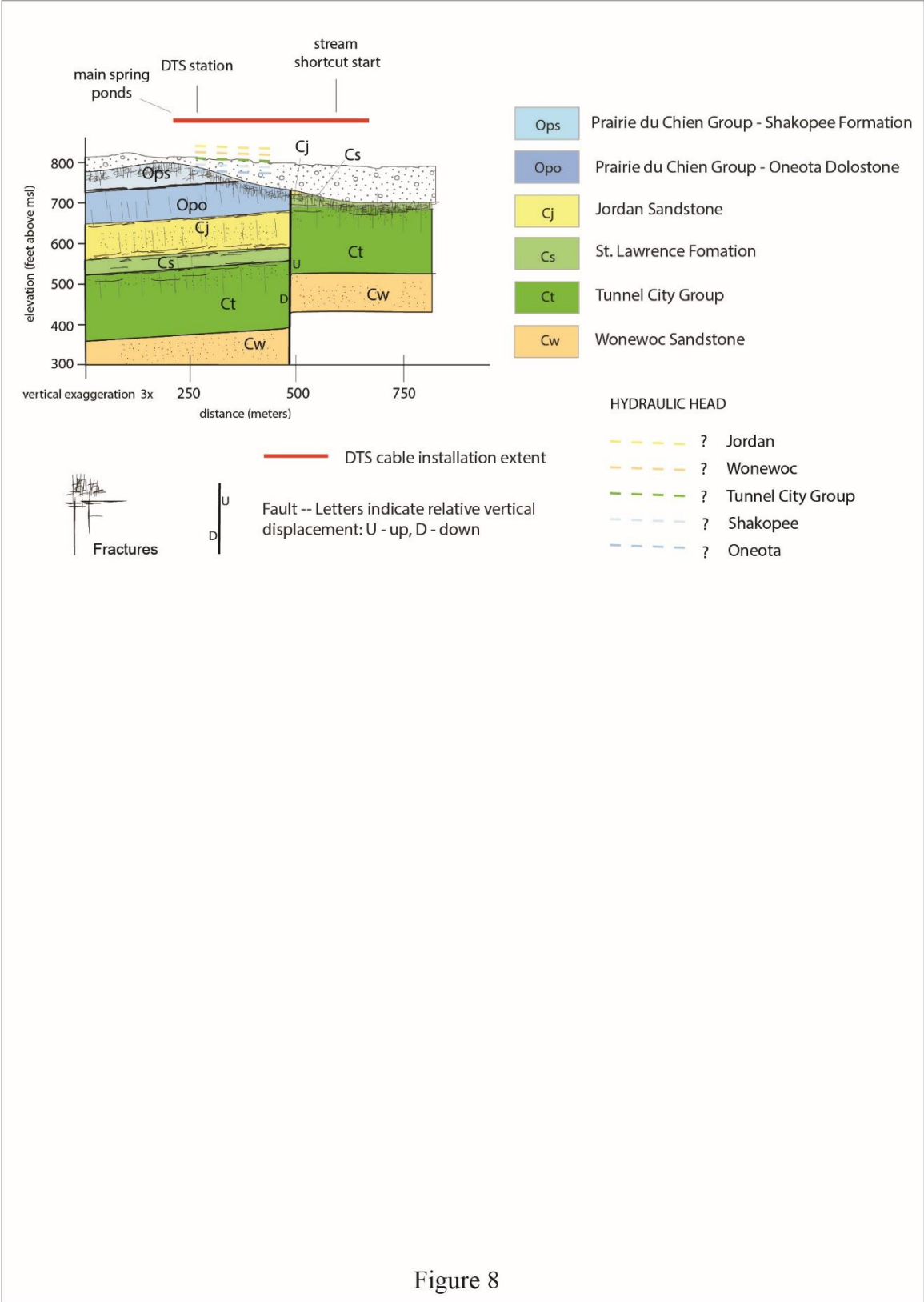


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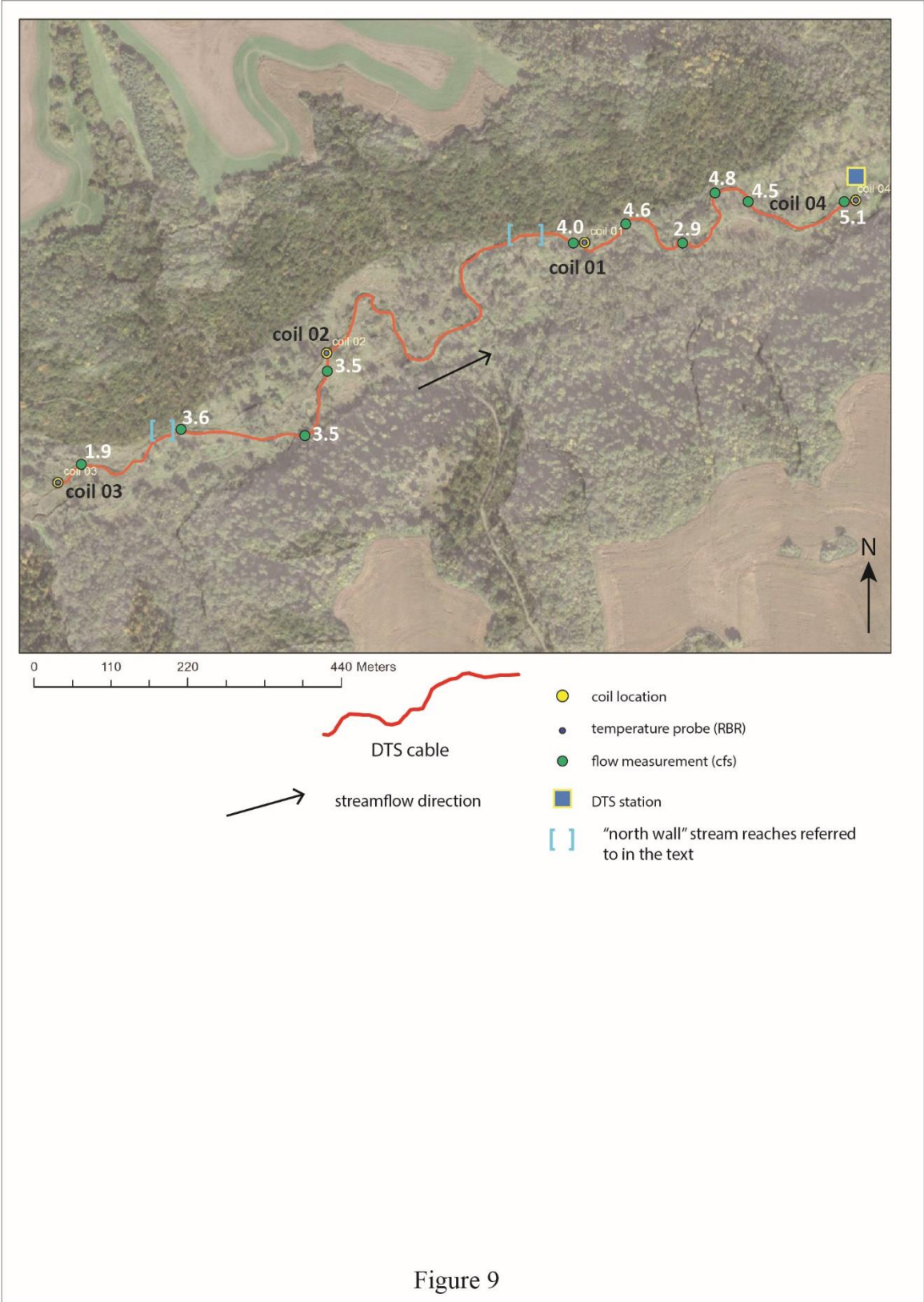


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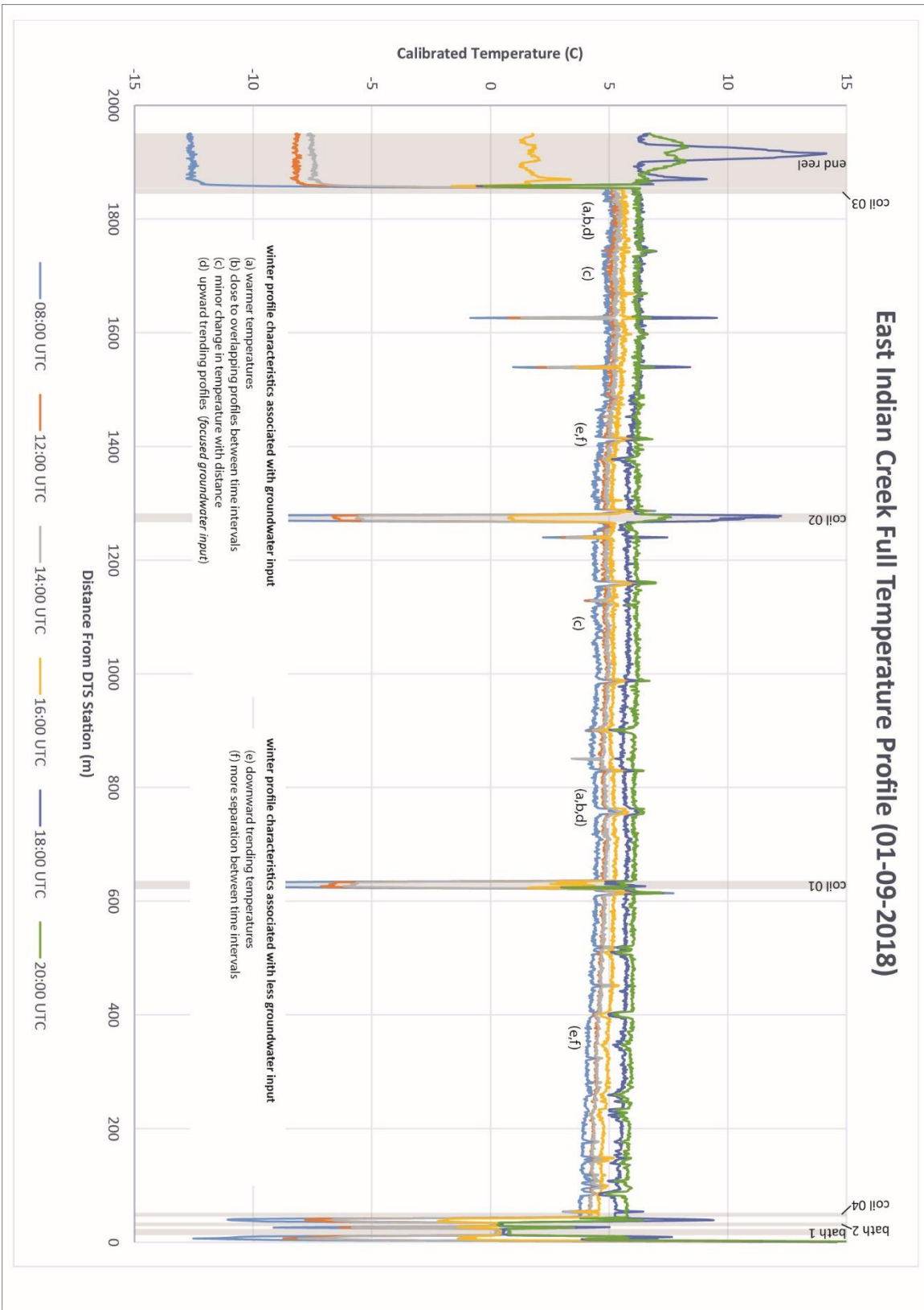


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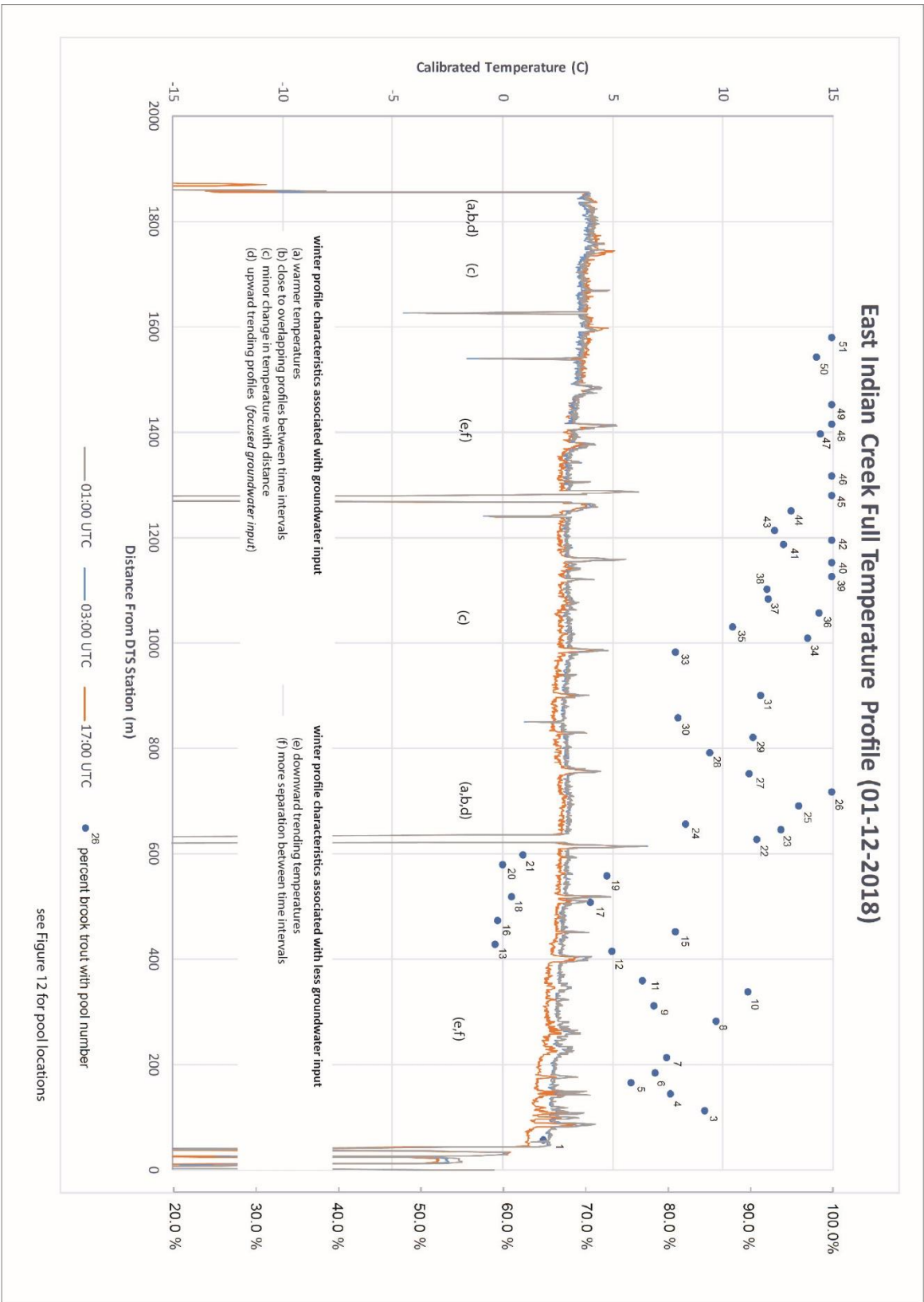
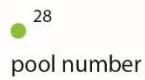
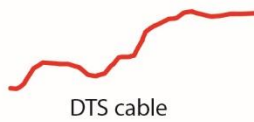
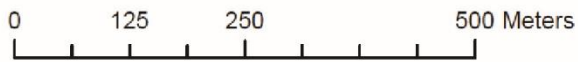
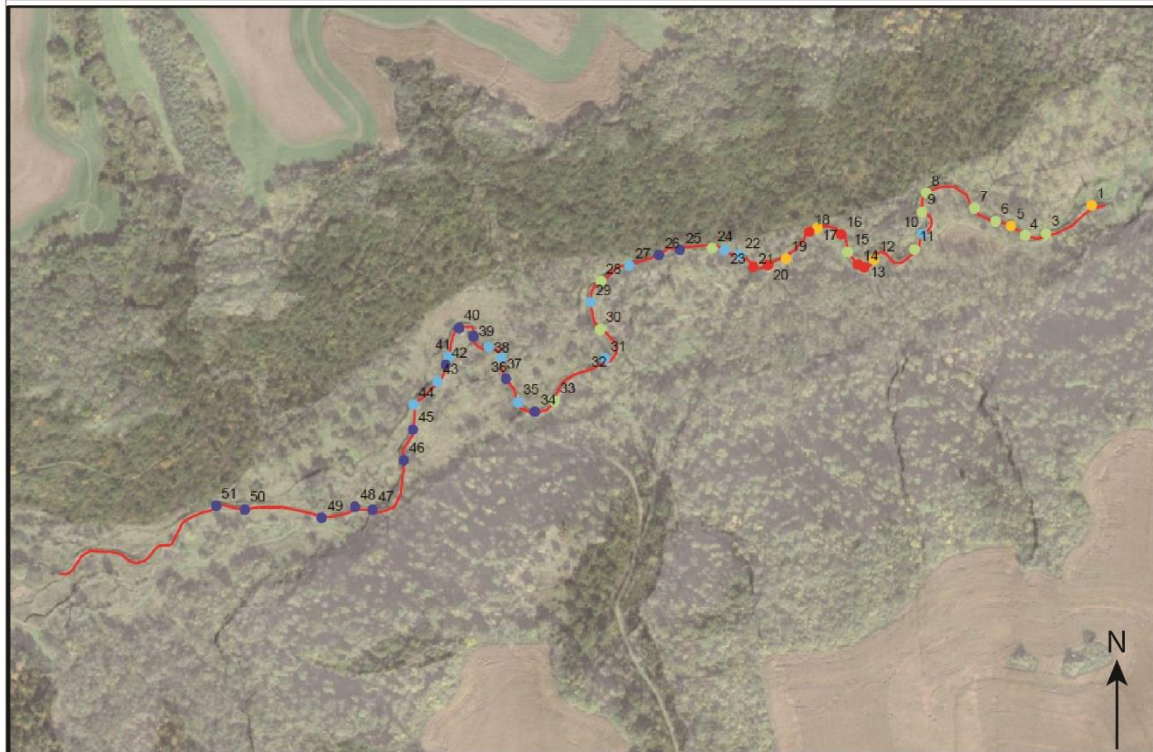


Figure 11



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

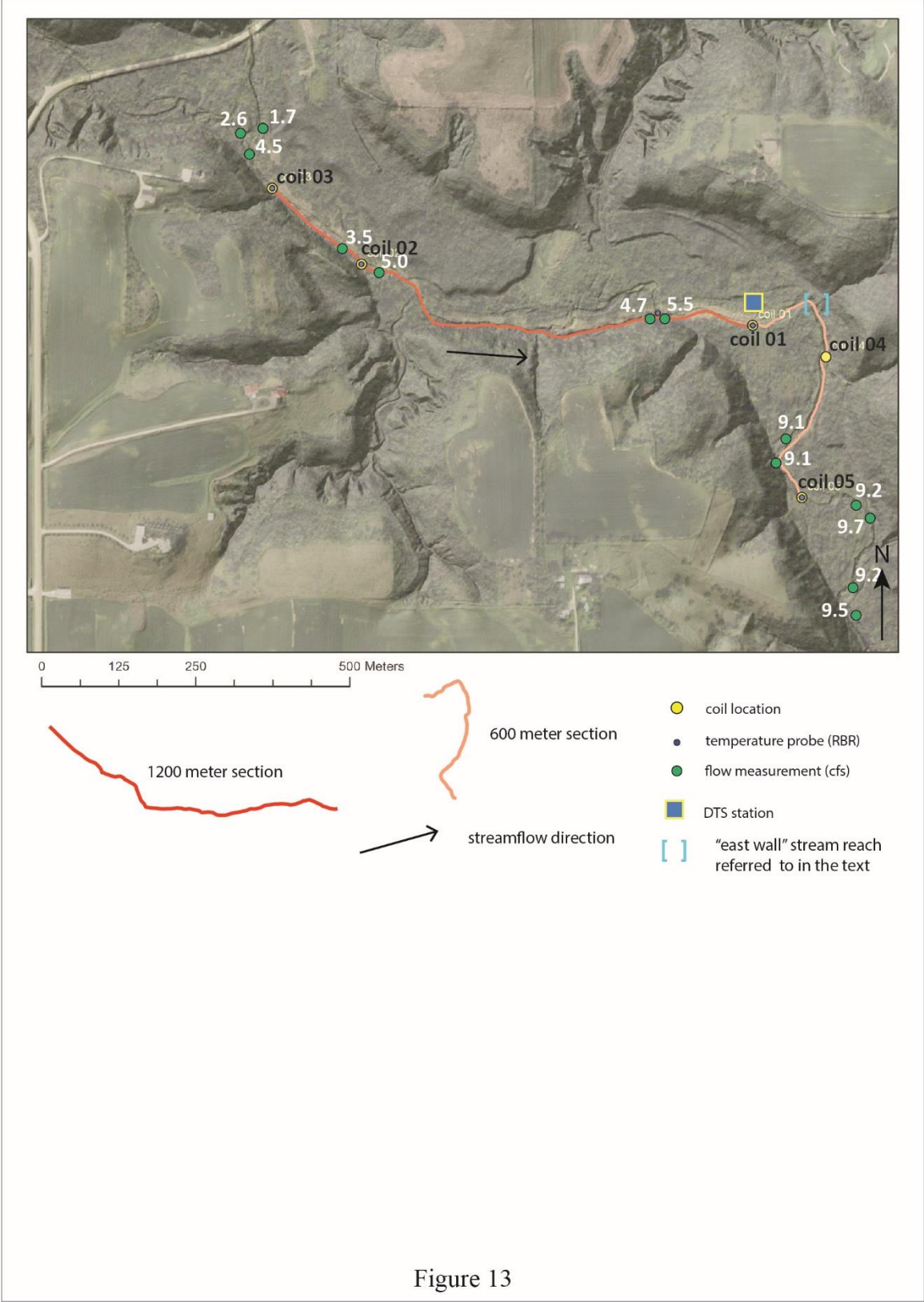


Figure 13

Trout Brook 1200m Upstream Temperature Profile (12-21-2018)



Figure 14

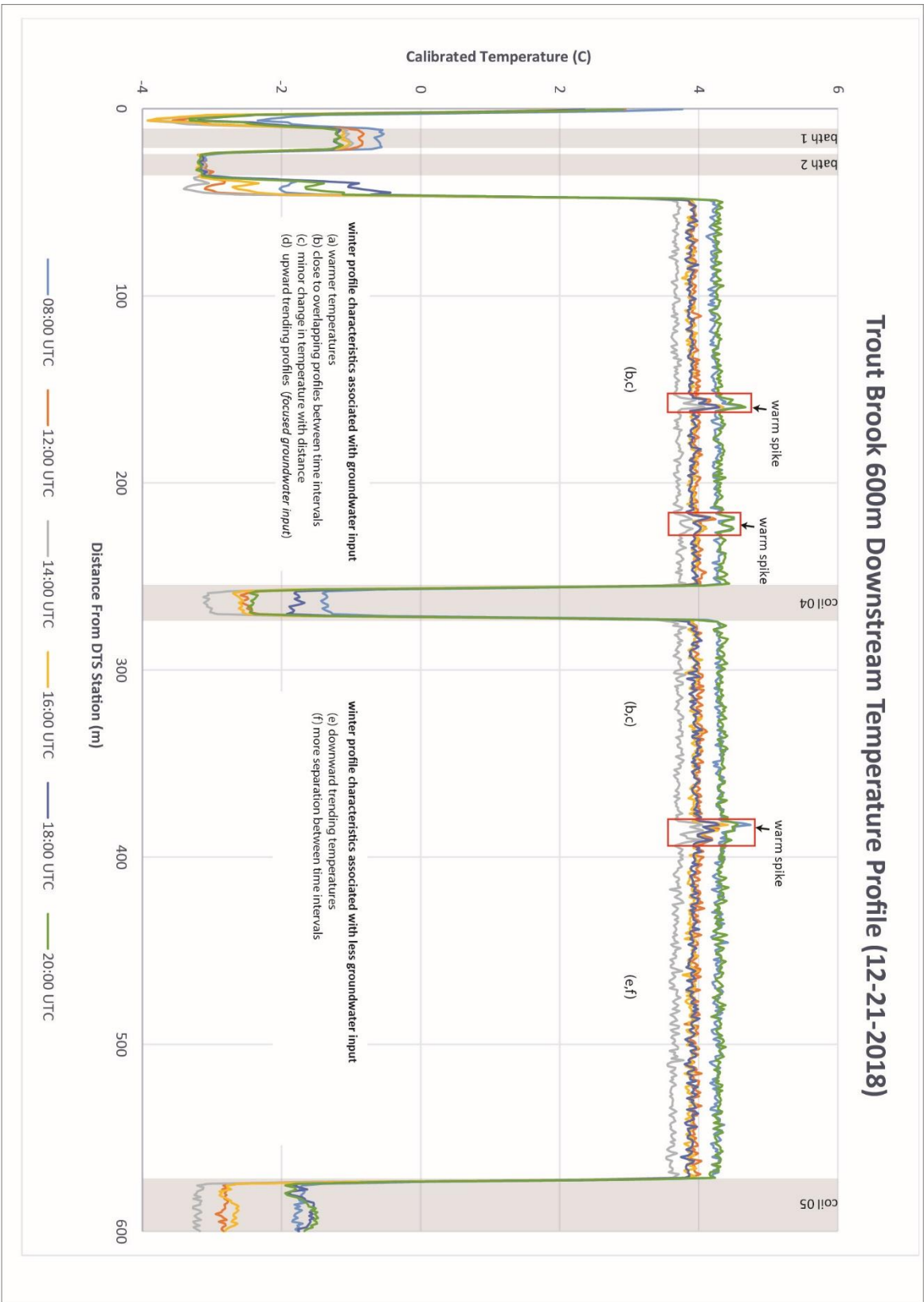
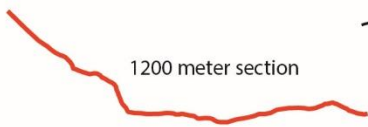


Figure 15



0 125 250 500 Meters



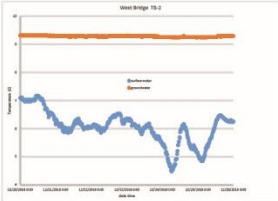
streamflow direction

piezometer locations with interior and exterior temperature probes

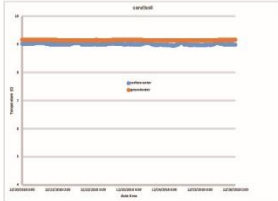
DTS station

600 meter section

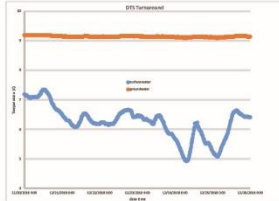
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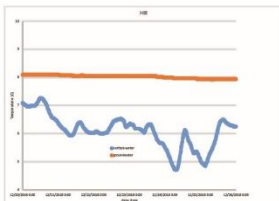
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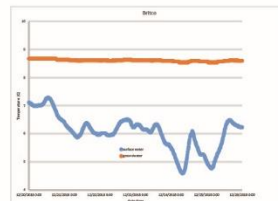
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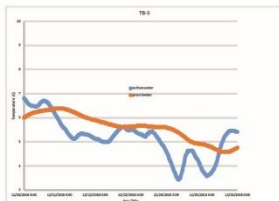
4.



5.



6.



not shown - at downstream end of park

Figure 16

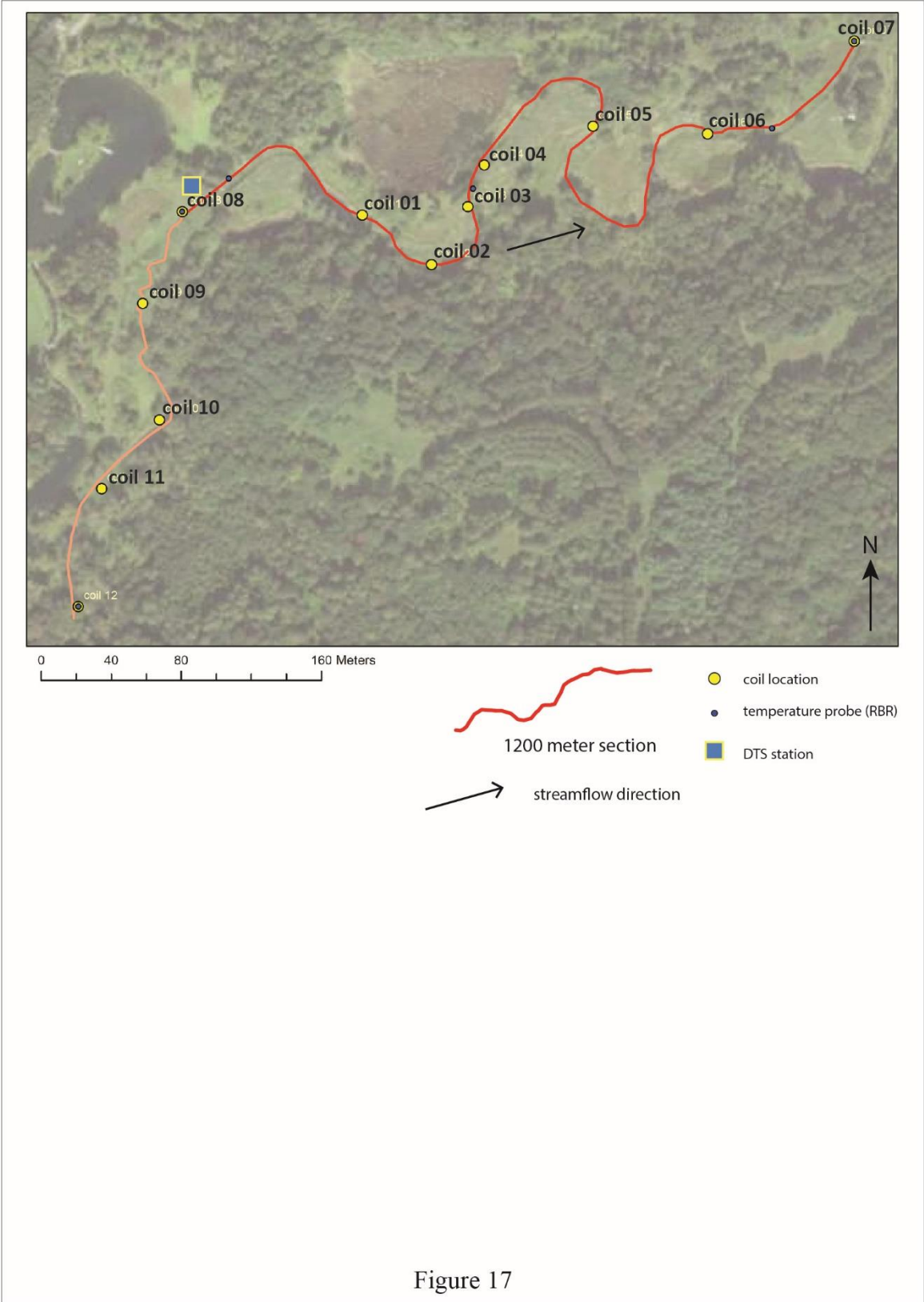


Figure 17

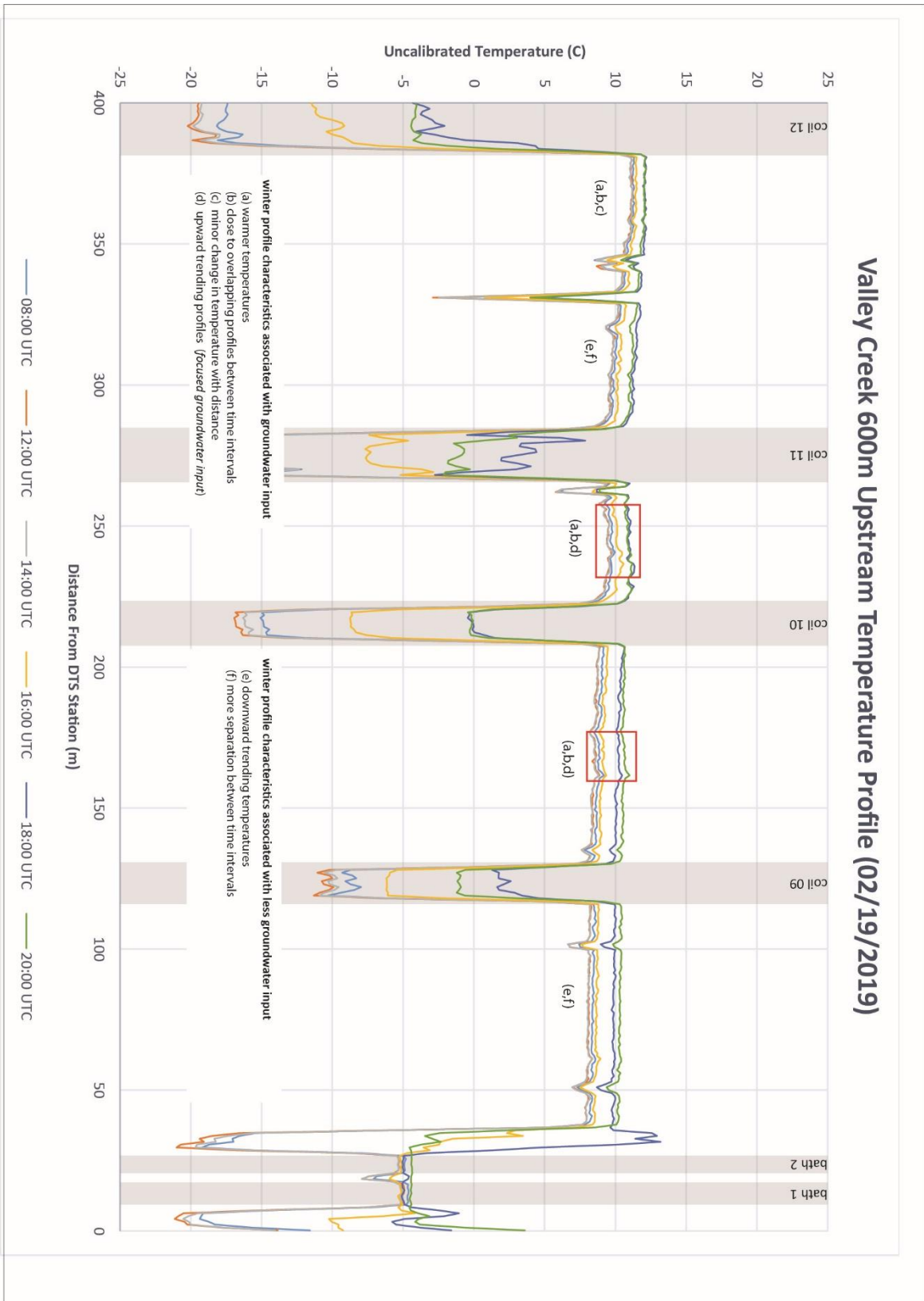


Figure 18

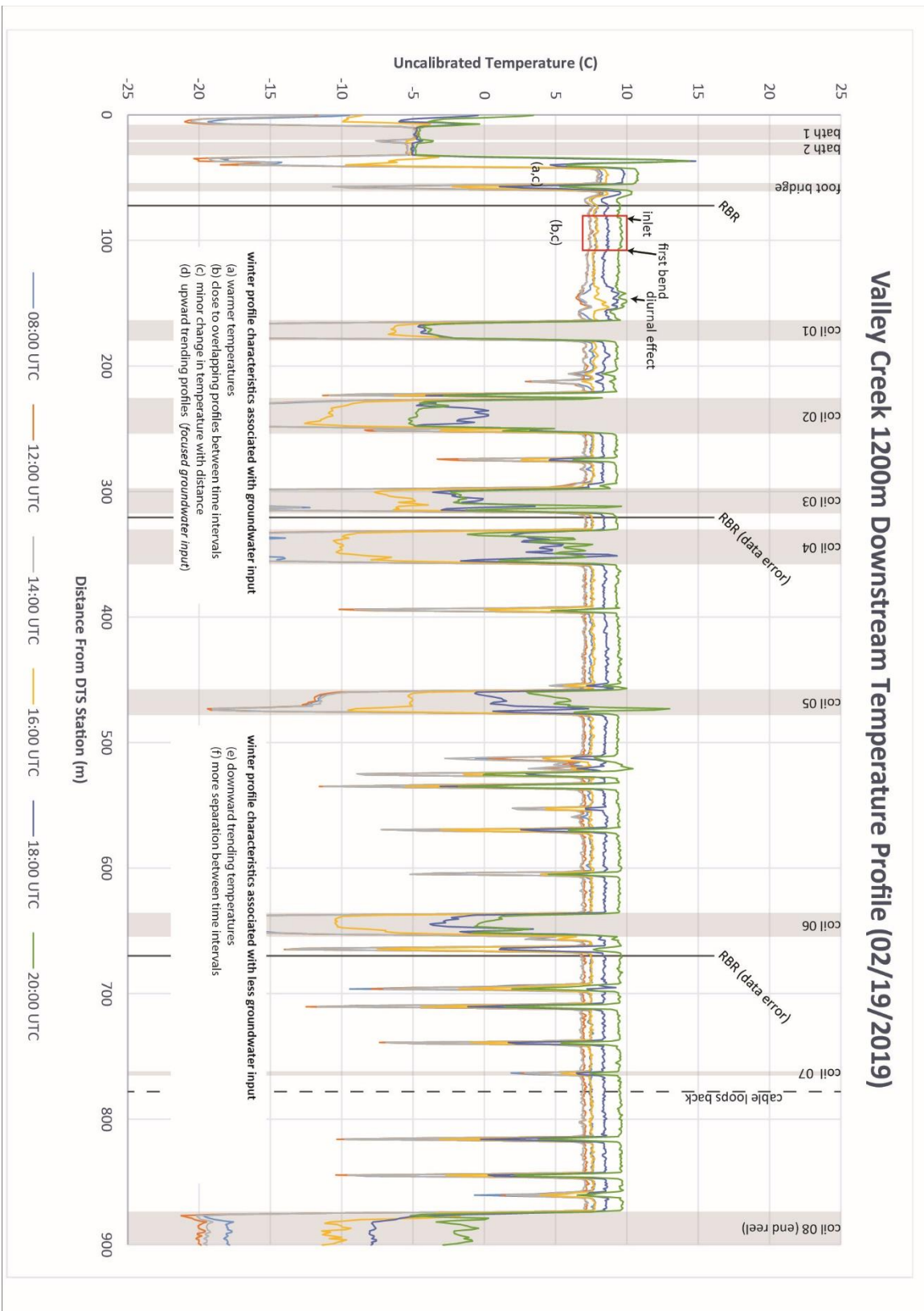


Figure 19

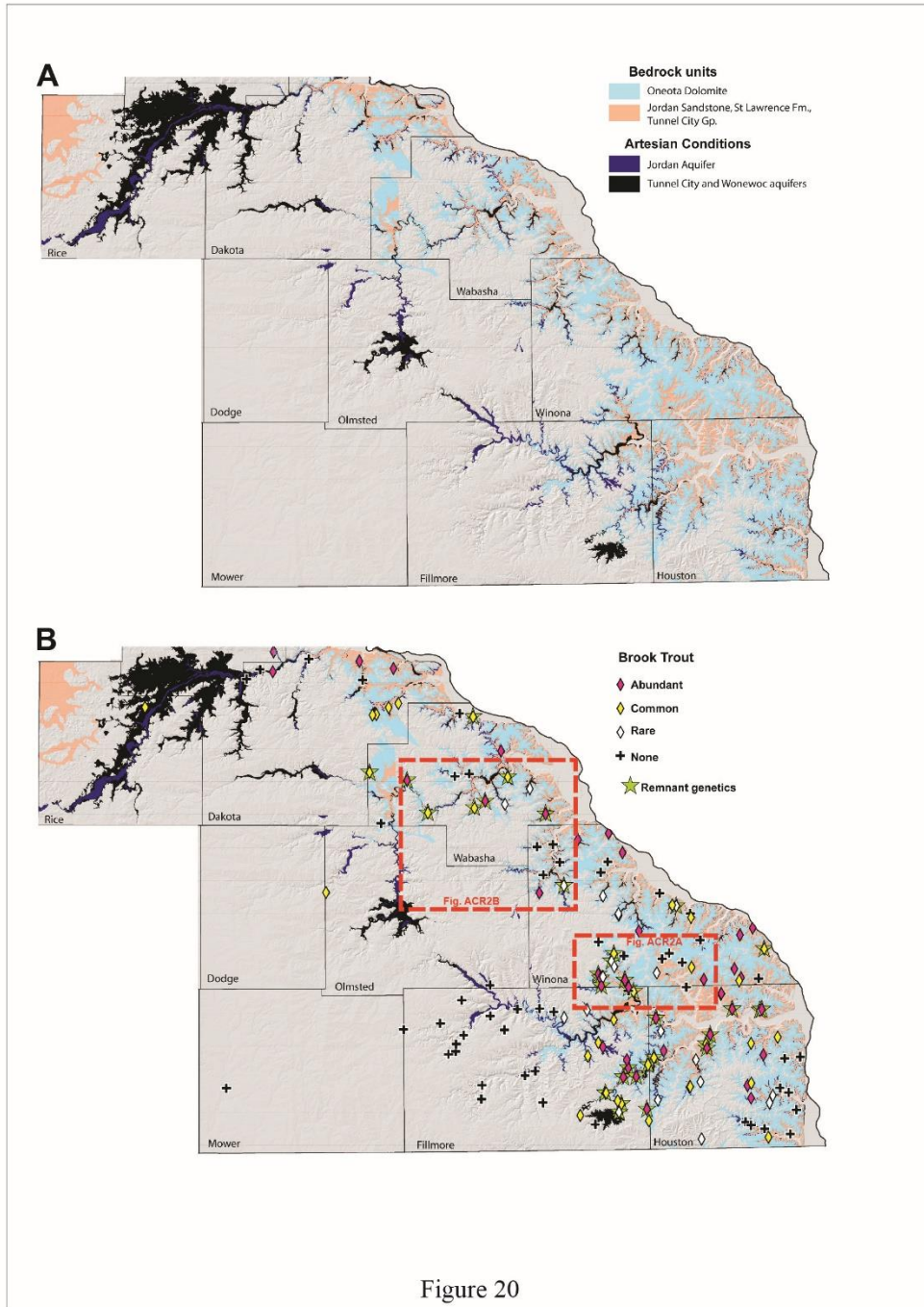


Figure 20

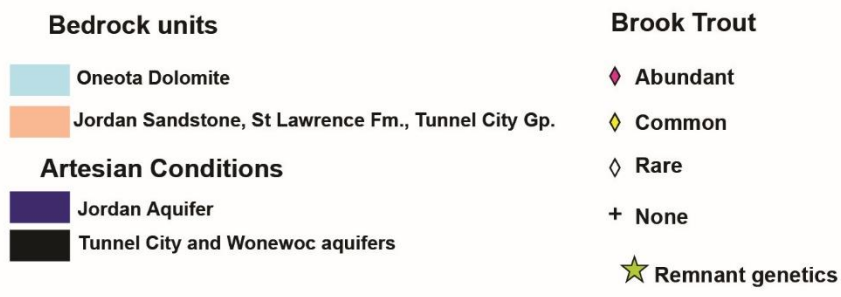
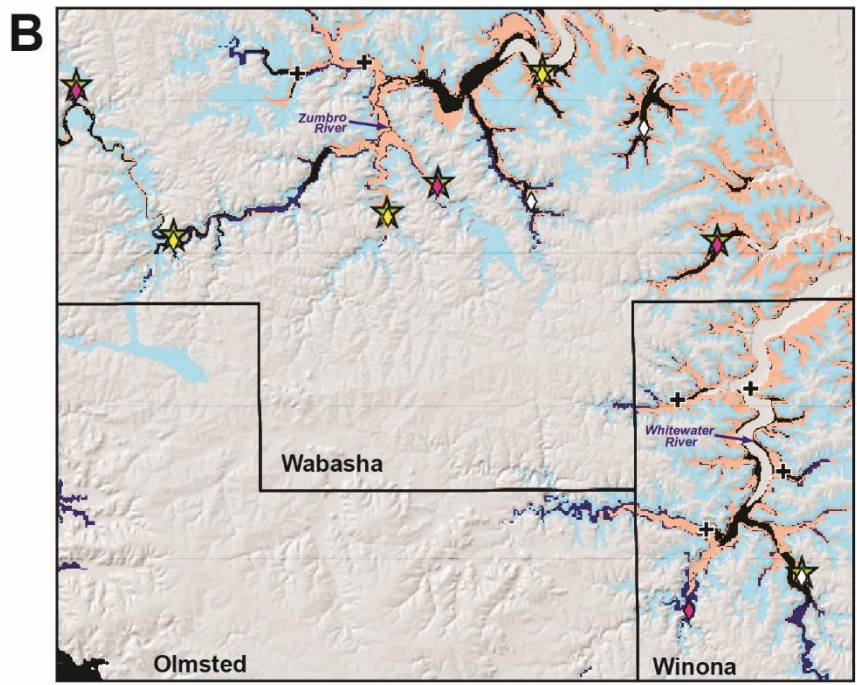
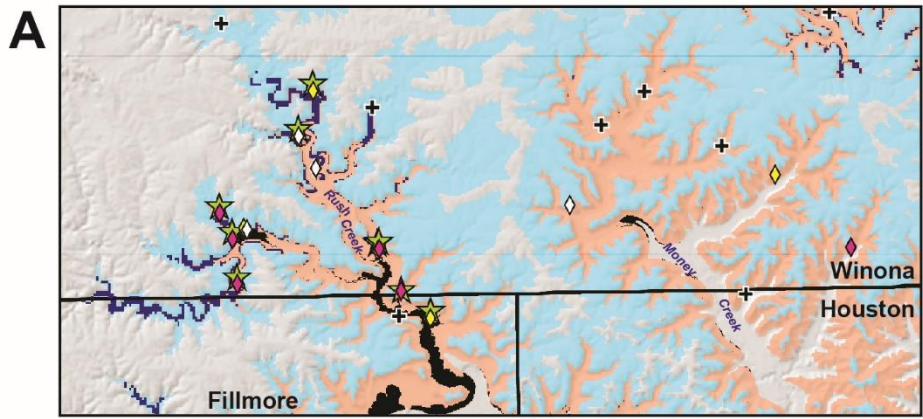


Figure 21

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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