Evaluation of created thermal refugia in streams as a climate adaptation strategy for fish populations experiencing thermal stress

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Background

Stream ecology is heavily influenced by thermal regimes: water temperature dynamics affect the development of aquatic organisms, species distribution, microbial metabolic rates, along with their ecosystem processes and services (Kløve et al. 2014). Cold-water adapted aquatic organisms have evolved to be dependent on shading and groundwater discharge in streams as a protective buffer against variable annual temperatures (Ebersole et al. 2003). These thermal refugia are discrete cooler water patches created by groundwater seepage, emergent hyporheic exchange, tributary confluence, or riparian shading, and are often found in discontinuous patches within the stream reach (Kurylyk et al. 2015). As air temperatures rise and short duration droughts increase due to climate change (Isaak et al. 2015, Huntington et al. 2009), cold-water adapted species will need to rely more heavily on natural thermal refugia to survive, especially during periods where peak temperatures exceed their metabolic thresholds. However, natural thermal refugia are often not well distributed along stream corridors (Petty et al. 2012), and their effectiveness may decrease as shallow groundwater also warms (Briggs et al. 2008).

Cold-water adapted fish species are highly adept at seeking out cooler temperatures within their habitat and using these areas to thermoregulate. Studies performed on salmon and trout with thermal tracking telemetry found them able to maintain body temperatures significantly lower than that of the main stream reach, which was at temperatures greater than their survival threshold (Baird and Krueger, 2003, Mathews and Berg, 1997). The fish accomplished this by congregating in areas with groundwater seeps or springs, suggesting that their survival in areas with high surface temperatures is dependent on their access to cold-water discharges (Petty et al. 2012, Snook et al. 2016). Trout and other cold-water adapted fish species have been observed to use microhabitats within their watershed based on groundwater discharge zones and separate out their habitats based on fish size and their ideal temperature range (Torgersen et al. 2012). Additionally, studies of salmon indicate fish alter their migration activity in pursuit of spawning grounds and in order to behaviorally thermoregulate in cool tributaries while surface waters remain at peak and stressful temperatures (Goniea et al. 2006).

In marginal thermal habitat, cold-water fish behavioral strategies rely heavily on natural thermal refugia, which sources range from groundwater seeps and springs, deeper hyporheic exchange, riparian shading or deep points within the stream bathymetry, and tributary confluence (Kurylyk et al. 2015). While all of these mechanisms can potentially be utilized by cold-water adapted species for thermoregulation, it is difficult for some species to access them due to the uneven distribution of groundwater seeps throughout watersheds, resulting in species isolation and fragmentation. Many natural cold pockets may be exposed to aerial predators, particularly stream confluence zones, and are therefore not suitable to serve as refugia. Also, due to human alterations to streams, riparian shading and hyporheic exchange may become disrupted, further limiting natural thermal refugia and decreasing cold thermal input (Goniea et al. 2006). Rising surface water temperatures and droughts due to climate change also decrease the input of groundwater into systems, and groundwater flowing shallowly beneath the surface (up to ~5 m) is at risk to temperature fluctuations and warming trends (Kurylyk et al. 2014, Briggs et al. 2018). Along with the limited availability of natural refugia, feeding opportunities can become sparse for cold-water adapted species in these crowded, cool areas (Baird and Krueger, 2003). Migrating species experience higher prespawn mortality in areas with too much exposure to high surface temperatures (Goniea et al. 2006). These factors put fish species at risk as they face warmer temperatures and less refugia available to them to alleviate thermal stress.

Due to inherent challenges presented by natural thermal refugia, human ‘engineered’ cold water pockets may be a viable addition to help cold-water species survive hot periods (Kurylyk et al. 2015) . In general, physical stream restoration projects are seeking to better incorporate ecological services, and are focusing on altering thermal regimes through riparian cover, hyporheic exchange remediation (Doll et al. 2003, Hare et al. 2017), and augmenting natural thermal refugia with artificial refugia, by mimicking groundwater seeps (Kurylyk et al. 2015). In the summer season when cold-water adapted species are faced with peak temperatures for short periods of time, a cold-water refugia created by pumping nearby aquifer groundwater directly into a point within the stream reach could provide protection from lethal temperatures. While these pumped point-scale inputs may not serve to lower the overall temperature of the surface water, it would create a thermal refuge by creating a spatially focused cold pocket under the 'right' hydrodynamic conditions (Briggs et al. 2018).

Goals and Objectives

The goal of this project was to assess the effectiveness of potential engineered thermal refugia as a climate-change adaption strategy by pumping nearby alluvial aquifer groundwater at a controlled rate into the stream channel during a peak temperature period. We assessed the extent of the thermal anomaly created using a combination of temperature sensing, visual dye, and hydrodynamic methods. The objectives of this study were to

1) Characterize effective created cold water plume volume by exploring the relationships between ambient warm surface water flow and facilitated discharge by pumping in controlled volumes of shallow floodplain groundwater across a natural gradient of in-channel flow rates.
2) Assess the effectiveness of an engineered baffle to limit local mixing of surface water with groundwater, potentially enhancing the size of the created cold water pocket.

Field Site

The field site where the cold groundwater discharge plume was installed was in the Fenton River located in Tolland County, CT. The site was selected based on proximity to UCONN's monitoring and production well field, providing easy access to shallow groundwater for pumping. Additionally, the upstream USGS stream gage 01121330 provides a sub-daily record of river discharge. The location within the Fenton River for the initial pumping experiments was chosen in the middle of the stream channel instead of along the banks due to its relative depth in order to prevent the location from drying up during the low flow periods of the summer, and due to its lessened tree cover in order to maximize sunlight for images of the dye tracer in the surface water.

Groundwater injection

Before pumping groundwater to the stream reach, the well (MW4S-99) was assessed for its ability to be pumped at a sustained, consistent rate, and also its ability to produce minimally turbid water at a relatively cooler temperature than the surface water

(Vokoun et al. 2016). After a series of well tests, the water was determined to be averaging around 10 °C in the well, and 11-12 °C after being pumped through the hose line to the discharge point in the stream reach which was 43 feet away. Its depth to water was 6.8 feet and recharge rate was 32 seconds after filling 10 gallons. It had a 12'' outer diameter casing and 21.5' screen length. The pump used in conjunction with the well was a Grundfos pump which pumped at a maximum rate of 7 gal/min at 400 Hz. A realized rate pump test was performed using a 10 L bucket with six trials, averaging a rate of 0.41 L/s. The well water was pumped through 50 feet of reinforced PVC braided tubing and flowed through a distributed release slotted pipe placed on the streambed to mimic a groundwater seep. Large stakes held up the hosing to prevent it from trailing in the water and warming prematurely. The discharge pipe was placed directly behind the baffle in the area where velocity was assumed to be lowest. The baffle was created with 1 meter long wood boards cut to the same size and stacked two on top of each other vertically and held in place by rebar in order to form a v-shape obstruction pointed upstream. This was designed to disrupt the flow and prevent the surface water from mixing immediately with groundwater since the groundwater was being pumped to a discrete point instead of seeping in a uniform front like in natural thermal refugia (Kurylyk et al. 2015).

The time of year for the experiment (August, 2018) was chosen based on the mean discharge over the past 7 years as recorded by the USGS Fenton River gage, which showed March to be the peak flow month of the year with 67 ft^3/s, July to be the driest with 9.5 ft^3/s, and the medium flow rate 35 ft^3/s in May. The two experiments performed were on a high flow day (65 ft^3/s) after a rainfall event and a medium flow day (35 ft^3/s).

Approach and Results by Objective

Objective One

The bathymetry of the streambed field site and the surrounding topography were surveyed using a total station (Nikon Nivo) (Figure 1). This also included spatial characterization of the baffle, rebar, pump hose line, well, and other landmarks. A total of 342 points were taken to characterize the area.

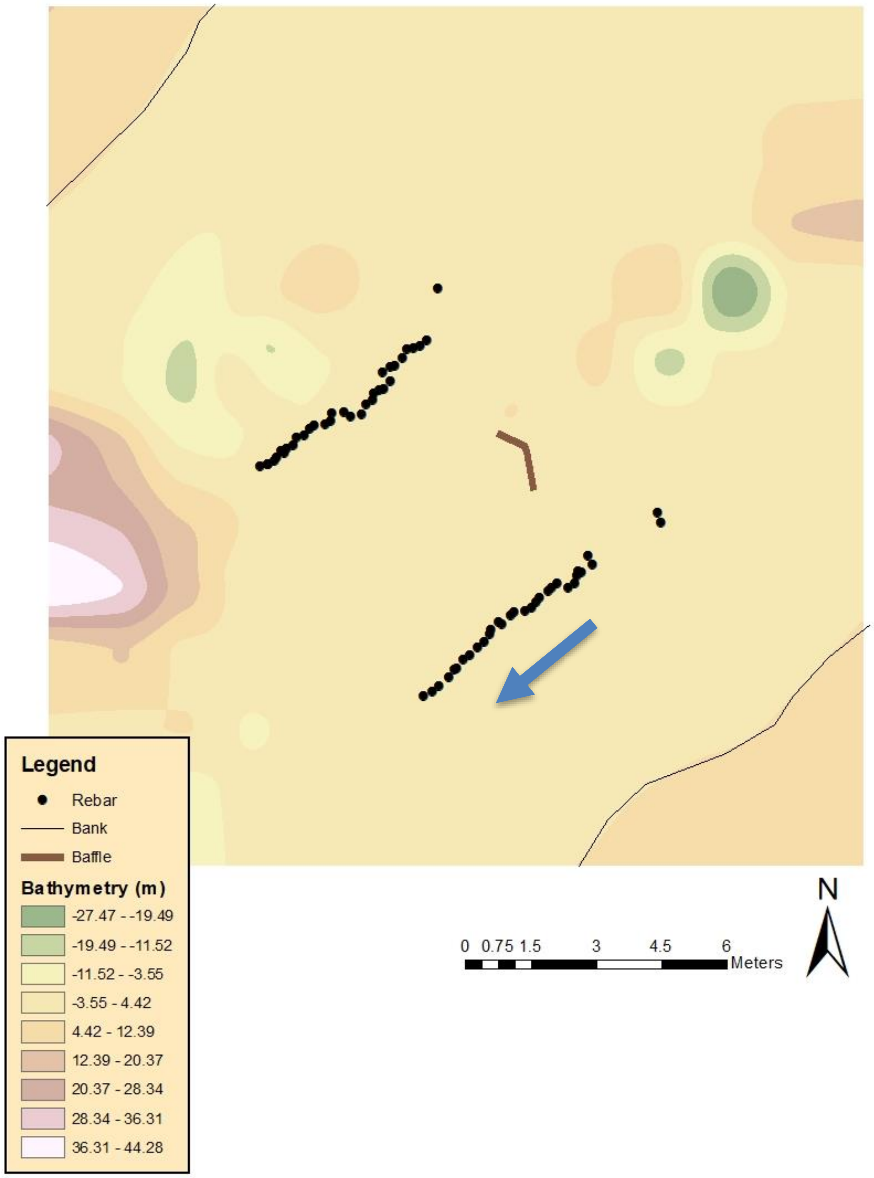
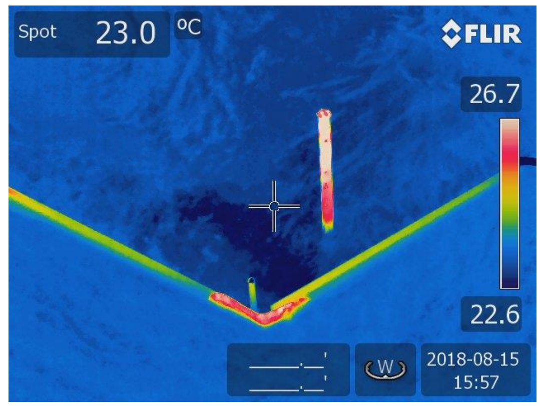


Figure 1. Field site bathymetry. Blue arrow indicates flow direction.

In order to assess the extent of the cold groundwater plume created, a variety of thermal imaging technologies were used to detect the movement of the colder groundwater (9-11°C) in the surface water (23°C). Thermal infrared images were used to distinguish any thermal anomalies at the surface (Handcock et al. 2012), while a fiber optic distributed temperature sensing cable (FO-DTS) was used to detect any cold-water plumes along the bottom of the water column. (Rosenberry et al. 2016, Briggs et al. 2012). Brilliant Blue Dye injected into the pump line was used as a tracer to visualize where the groundwater was moving within the water column and how rapidly it was mixing with the surface water, and natural light photos were taken of this progression.

A FLIR T-640 infrared camera was used to image the surface of the stream reach around the baffle where the groundwater was injected (Figures 2 and 3). Images were taken from the top of a ladder positioned directly above the baffle in order to minimize glare. 28 photos were collected between both days. The imaging was used to detect thermal anomalies at the surface on two different discharge days:



Figures 2 (left) and 3 (right). Infrared images of baffle and surface water. The cold groundwater was injected directly behind the baffle. Figure 2 is from the medium discharge day, 35 ft^3/s, and Figure 3 is from the high discharge day, 65 ft^3/s.

The FO-DTS cable was positioned 11.6 cm above the streambed (on average), and wrapped around pulley wheels connected to rebar stakes in the streambed in order to prevent bending or damage to the cable. This setup created a grid downstream of the baffle, as depicted in Figure 4, using 213 meters of the cable. The middle, left, and right-side portions of the cable attached to the rebar were spatially identified using the total station. This configuration was used for both experiments, in the same position each day.

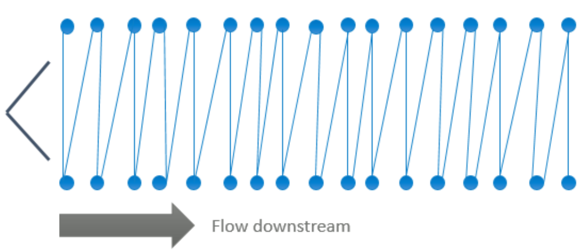


Figure 4. Conceptual FO-DTS grid setup with rebar (blue dots) and baffle (grey line)

The fiber optic cable detected temperature data points through time at each of the points depicted in Figures 5 and 6 below. The cable collected data on both discharge days, at 65 ft^3/s, and at 35 ft^3/s.

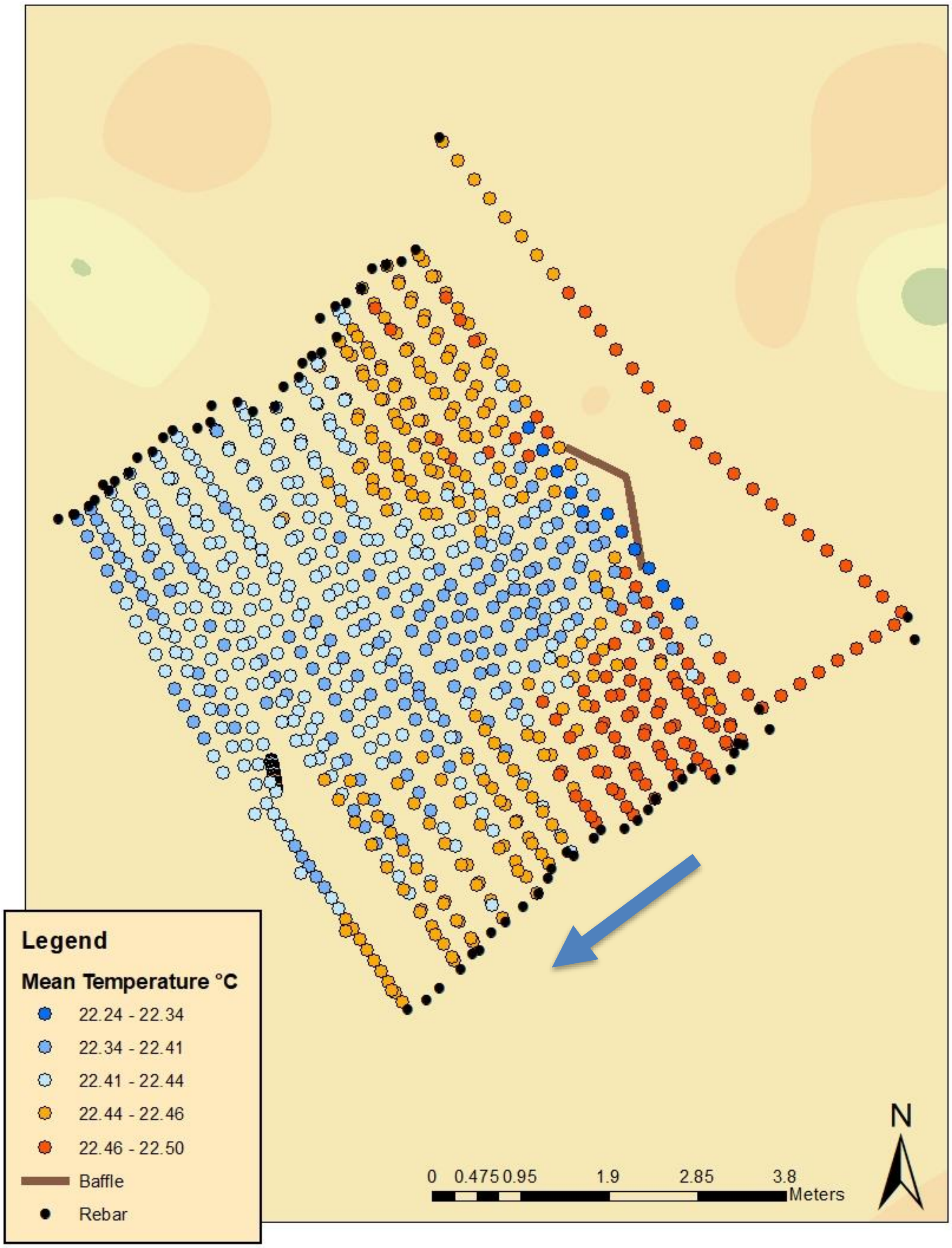


Figure 5. FO-DTS cable collected data from 35 ft^3/s discharge day. Each colored dot represents the average temperature data points collected by the cable at that point, and the black dots represent rebar. The brown line is the baffle, and the temperature data is overlaid on the streambed bathymetry. The large blue arrow shows the direction of flow.

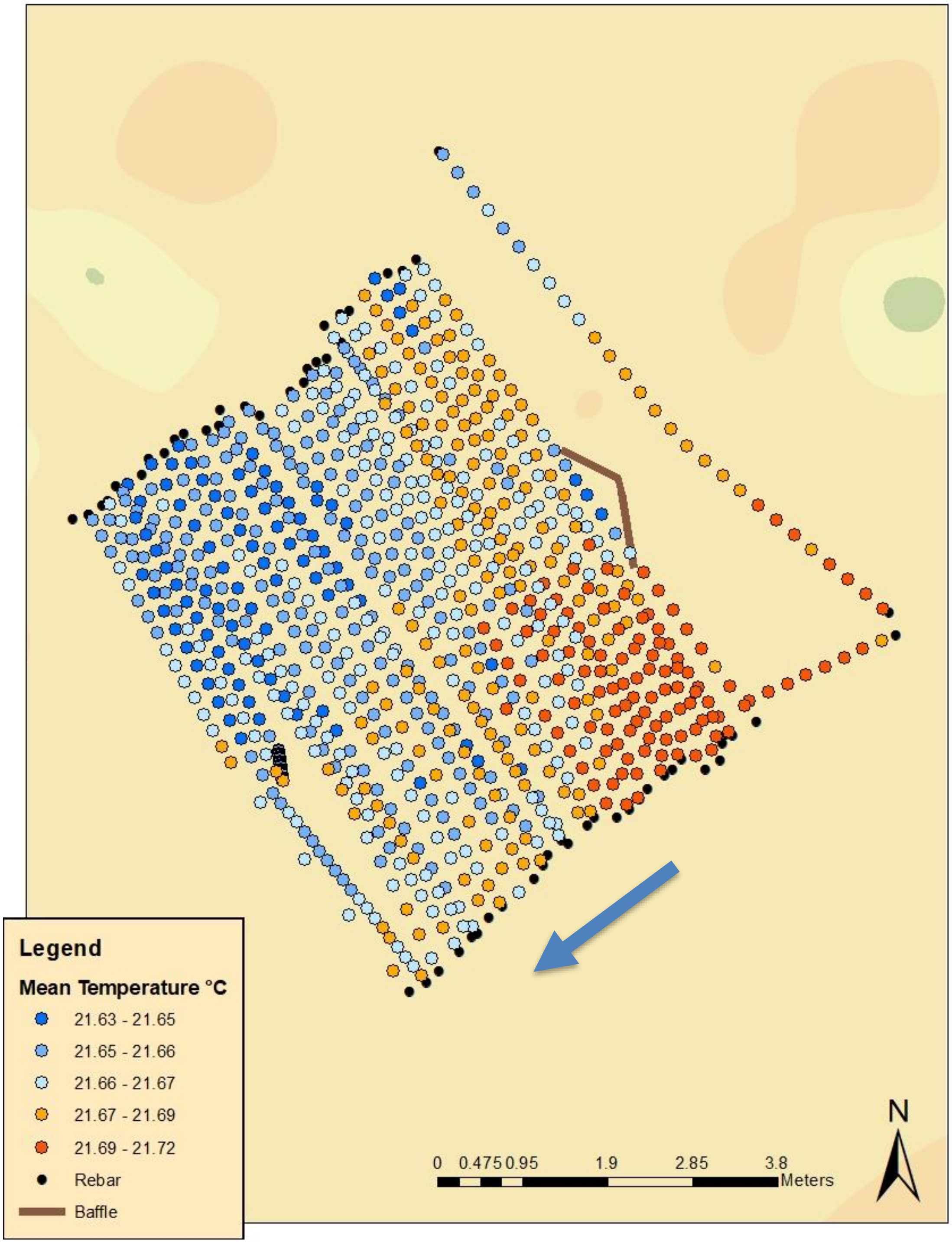


Figure 6. FO-DTS cable collected data from 65 ft^3/s discharge day.

Brilliant Blue dye was mixed from a powder to a concentration of 4 g/L and injected into the pump hose-line in order to produce a blue plume as shown in Figures 7 and 8.

Figure 7. Brilliant blue dye used as a tracer in groundwater, added to hose line.

Figure 8. Brilliant Blue dye injected into the groundwater as a tracer showing the development of a groundwater plume over several minutes of pumping.

Objective Two

In order to determine how effective the baffle was at disrupting flow and preventing the surface water from immediately mixing with groundwater, the flow-field of the stream site was assessed using a Flowtracker Handheld-ADV in conjunction with the total station device (Table 1). The flow field for the stream site with the baffle and without the baffle is depicted in Figure 9 below, including assessments for both days with different discharge.

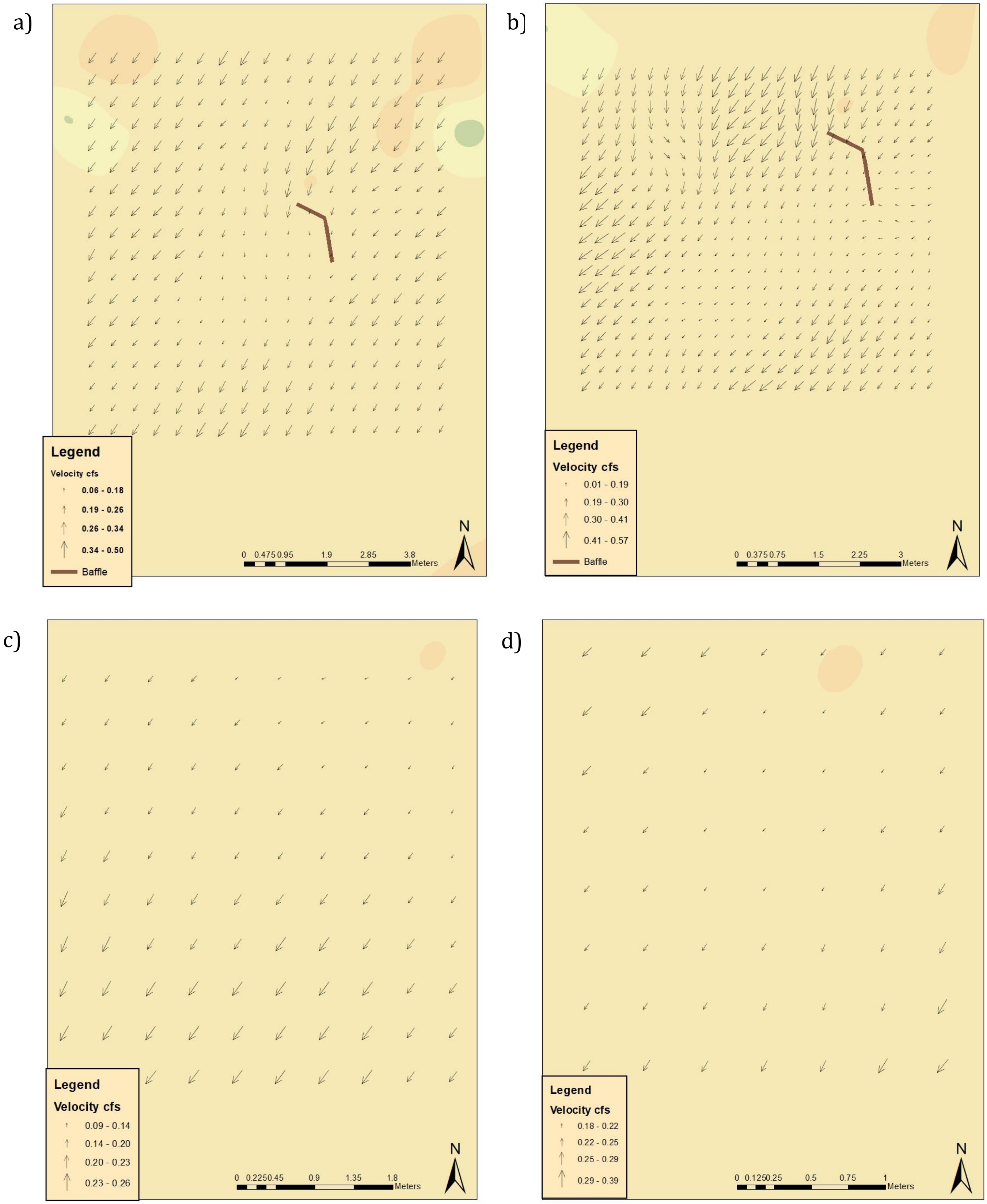

a)
Legend
Velocity cfs
0.06 - 0.18
0.19 - 0.26
0.26 - 0.34
0.34 - 0.50
Baffle
0 0.475 0.95 1.9 2.85 3.8
Meters
N
b)
Legend
Velocity cfs
0.01 - 0.19
0.19 - 0.30
0.30 - 0.41
0.41 - 0.57
Baffle
0 0.375 0.75 1.5 2.25 3
Meters
N
c)
Legend
Velocity cfs
0.09 - 0.14
0.14 - 0.20
0.20 - 0.23
0.23 - 0.26
0 0.225 0.45 0.9 1.35 1.8
Meters
N
d)
Legend
Velocity cfs
0.18 - 0.22
0.22 - 0.25
0.25 - 0.29
0.29 - 0.39
0 0.125 0.25 0.5 0.75 1
Meters
N

Figure 9. The flowfield of the stream around the baffle, depicted by velocity vectors from Flowtracker ADV data:

a) 35 ft^3/s discharge in Fenton river, with baffle
b) 65 ft^3/s discharge in Fenton river, with baffle
c) 35 ft^3/s discharge in Fenton river, without baffle
d) 65 ft^3/s discharge in Fenton river, without baffle

Conclusions and takeaways:

After assessing the extent of the cold water plume created while pumping at a rate of 0.41 L/s in the Fenton River, it was determined that a successful cold-water habitat would be best suited to low flow areas in a stream reach because at high flow (65 ft^3/s) there was not a viable cold-water plume detected by the FO-DTS or the thermal infrared imaging (Figures 6 and 3), and at medium flow there was a small thermal anomaly created and detected by the infrared and the fiber optic cable (Figures 5 and 2). The lack of a cold water pocket present at high flow and the limited amount present at medium flow could also be due to the absence of vertical movement of the cold water as it entered the stream reach. The dye revealed the cold water was not rapidly mixing with the surface water as it dissipated downstream, but as the temperature difference was not picked up by the fiber optic or the infrared images, the cold water must have been highly vertically constrained.

In conclusion, there was a trace of a thermal anomaly showing the potential for creating an effective cold water pocket under lower flow conditions. The recommendation for future studies would be to incorporate these thermal assessments on a plume injected in a slower flowing area of a stream, along the banks or out of the main channel flow path. This could result in a more significant temperature difference that would be able to be utilized by cold-water adapted fish species attempting to thermoregulate during extreme temperatures.

Future Work

Future work will include:

1) Experimenting with several methods of introducing the floodplain groundwater to

the stream channel, including different release configurations (e.g. focused vs distributed)

2) Different baffle configurations, including using natural restoration materials for the baffle components and setting up the baffle in the side channel flow near the banks
3) Performing the study on a low flow day (~10 ft^3/s) in order to assess how effective cold water plumes are at lowest discharge.

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