Thermal Dynamics and Transient Storage in a Spring-fed Forested Headwater Stream, Southeastern PA, USA

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Introduction

Stream water temperature is a crucial controlling factor of stream ecosystem function. The mixing of surface water and groundwater underneath or next to the stream bed occurs in a process called hyporheic exchange and influences, or may regulate, stream temperature. Hyporheic exchange can cause ecologically and biogeochemically significant transfers of heat to the stream and may be enhanced by in-stream structures such as steps and log dams (Hester et al., 2009). Fiber-optic distributed temperature sensing (DTS) provides monitoring of water temperature at a high temporal and spatial scale and is useful for hydrologic applications. The DTS system uses a fiber-optic cable to pulse a laser, then measures the speed and dispersion of light, thus finding the average temperature along a 1-3 m length of cable (Tyler et al., 2009).

Salt tracers are also important for characterizing a stream and its processes. Chloride is often used as a conservative tracer to measure residence time and transient storage in a stream reach. These properties are influenced by hyporheic exchange and in-stream structures which add to the channel roughness and resulting flow resistance (Ensign & Doyle, 2005).

This study used both of these methods to determine thermal and transient storage dynamics of Spring Brook. The DTS system sought to identify points of warming and cooling in the stream, which may be attributed to hyporheic exchange. Through the salt release experiment, transient storage area relative to the open channel area (A_s/A), residence time, uptake length, and flow rate were calculated. The following hypotheses guided the experiments:

1. In-channel obstructions, such as large wood, increase hyporheic exchange, creating spatially associated cold thermal patches along the stream channel.

2. Reaches with more obstructions and more hyporheic exchange have greater transient storage capacity than unobstructed reaches.

Study System

Watershed description - Spring Brook in Southeastern Pennsylvania is a first-order spring-fed stream draining an 8 hectare 100% forested catchment located within the Laurels Preserve. Owned and managed by a local land trust, the Brandywine Conservancy, this site is the Christina River Basin (CRB) CZO's forested end member watershed. Although covered by 100% mature forest today, there are clear indications of past logging and charcoal production in the watershed, although no obvious signs of past grazing or row crop agriculture likely due to the steep hill slopes within the basin. The forested nature of the basin is unique in the region where most watersheds are fragmented mosaics of development, agriculture, pasture, and forest.

Reach selection - We selected two reaches within Spring Brook to test our hypotheses. Reach 1, located in the upper watershed, is a relatively debris-free reach characterized by plane-bed morphology and uniform substrate conditions (an unsorted mix ranging from cobble to sand-sized grains) (Figure 1). Reach 2, located downstream of Reach 1, contains several large wood pieces and is characterized by an irregular bed morphology with many pieces of large wood lying on and incorporated into the substrate, frequent changes in gradient, and some abrupt drops located downstream of select wood pieces (Figure 2). Grain size distributions in Reach 2 vary substantially at the sub-reach scale, with large packets of fine sediment wedges stored upstream of some wood pieces, and other sections resembling the uniform mix of Reach 1.

Figure 1. Reach 1 with cable spool on stream bank.

Figure 2. Large woody debris in Reach 2.

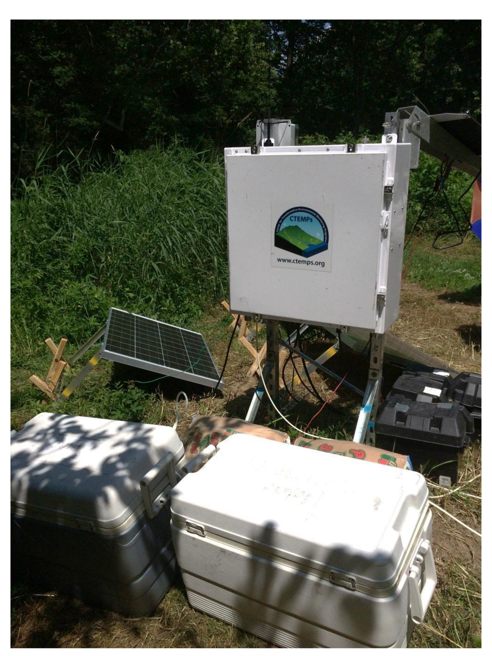

Figure 3. DTS system set-up.

Methods

Distributed temperature sensing:

- Single-ended DTS fiber-optic cable installed in Spring Brook on July 1, 2014 with two calibration water baths at the beginning of the cable each containing 20 m (Figure 3).
- Third calibration water bath added at the end of the cable on July 11 with 15 m.
- Independent temperature loggers, or HOBOs, were used in the baths, at three points in the stream, and in the air as temperature references.
- DTS programmed to collect data at 1.0 m increments every 5 minutes: 2 minutes for channel 1, 2 minutes for channel 2, and 1 minute of rest.
- Temperature data collected from July 1 to July 7 and from July 10 to July 24.

Chloride injections:

- Chloride was used as a conservative tracer at Reach 1 (51 m) and Reach 2 (79 m) on July 11.
- 25 g NaCl in 100 mL nanopure water was released above each reach, with an injection at Reach 2, then Reach 1.
- Specific conductivity was monitored below each injection point and at the end of the stream using YSI 600XLM sondes at intervals of 5 seconds.
- The USGS OTIS model was used to determine the hydrologic transient storage parameters.

Results

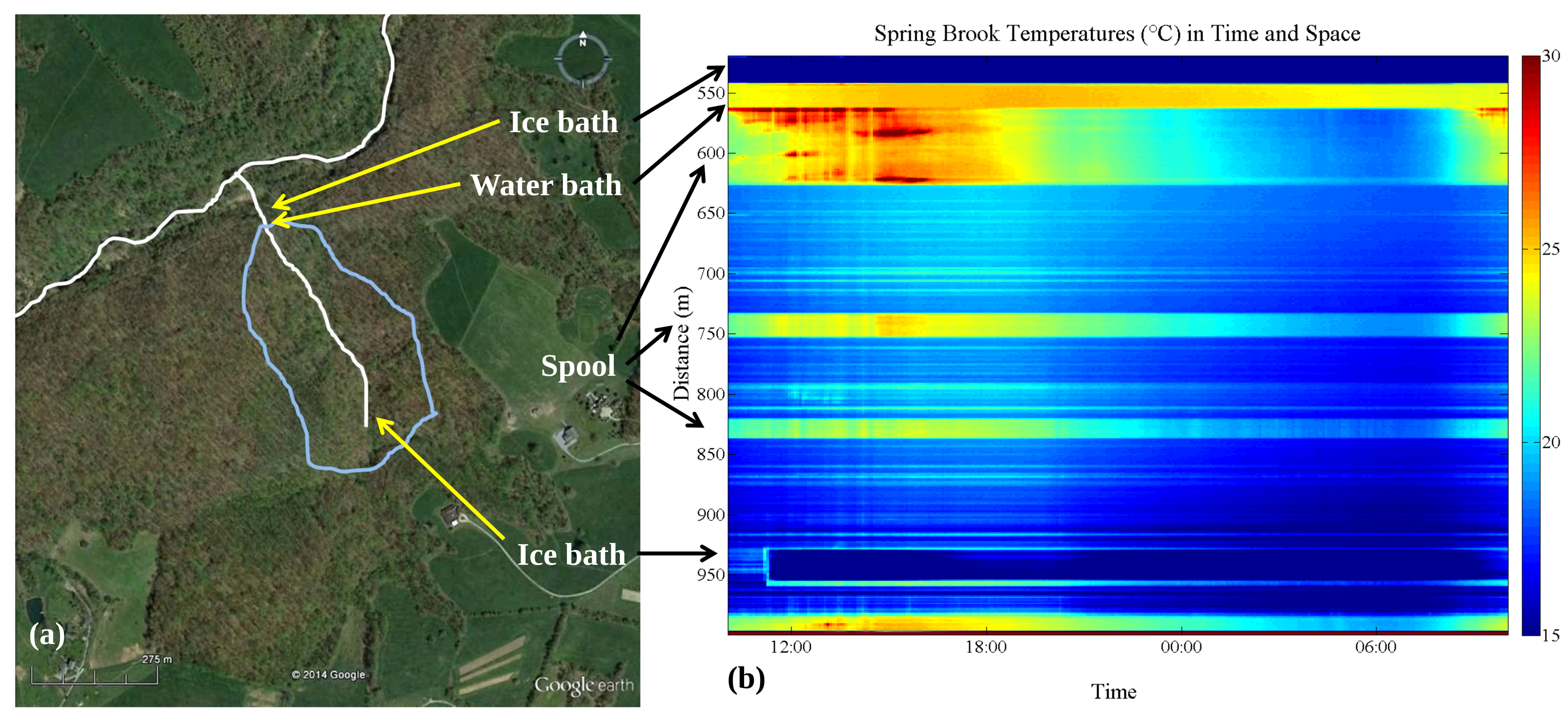

Figure 4. (a) Aerial image of the watershed containing Spring Brook and the location of the calibration baths. (b) Time series of temperature data collected from a 481 m cable from 10:00 am July 11, 2014 to 10:00 am July 12, 2014.

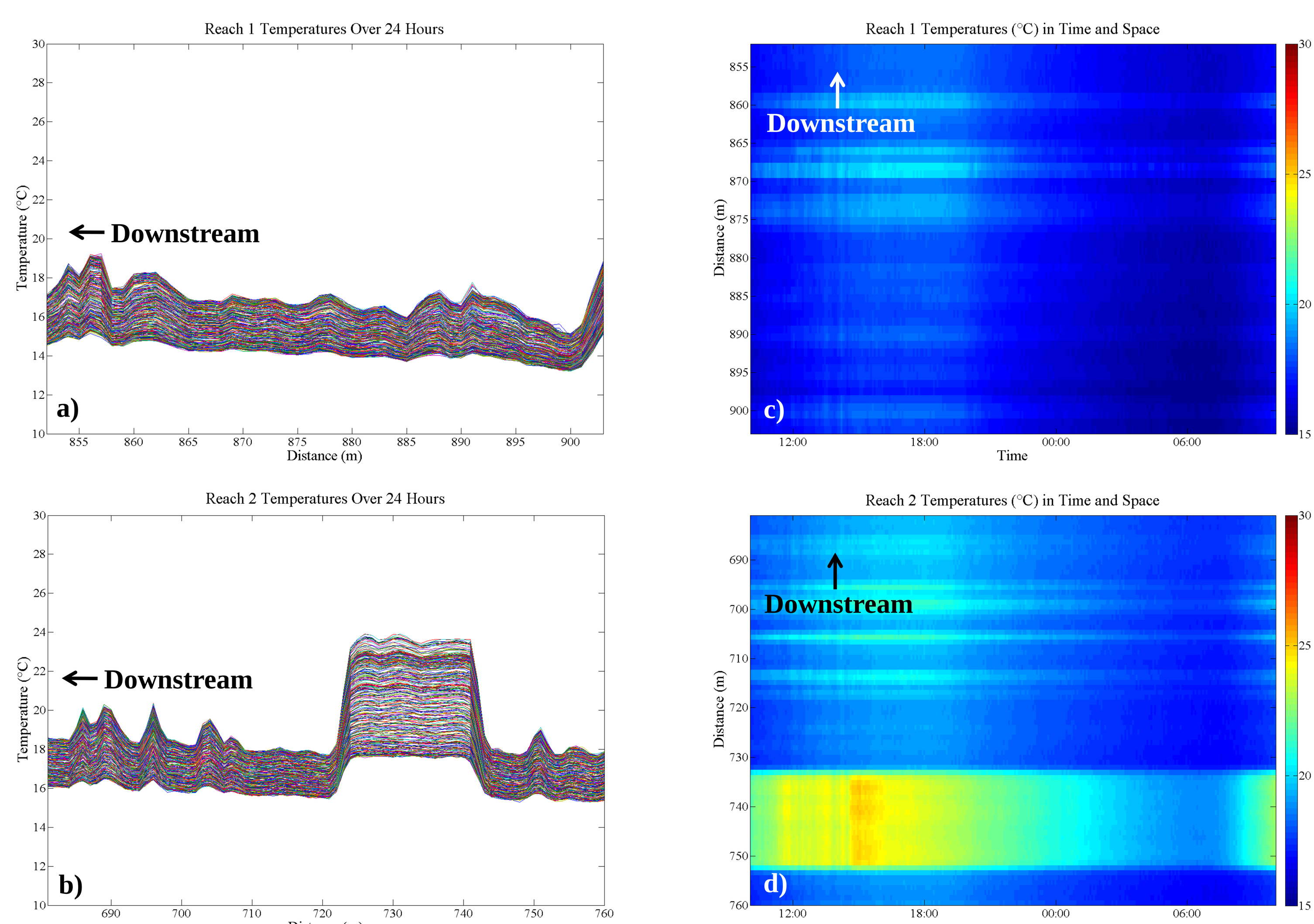

Figure 5. (a) and (b) Spring Brook temperature data from Reach 1 and Reach 2 over a 24 hour period. (c) and (d) Time series of temperature data from Reach 1 and Reach 2.

Results (continued)

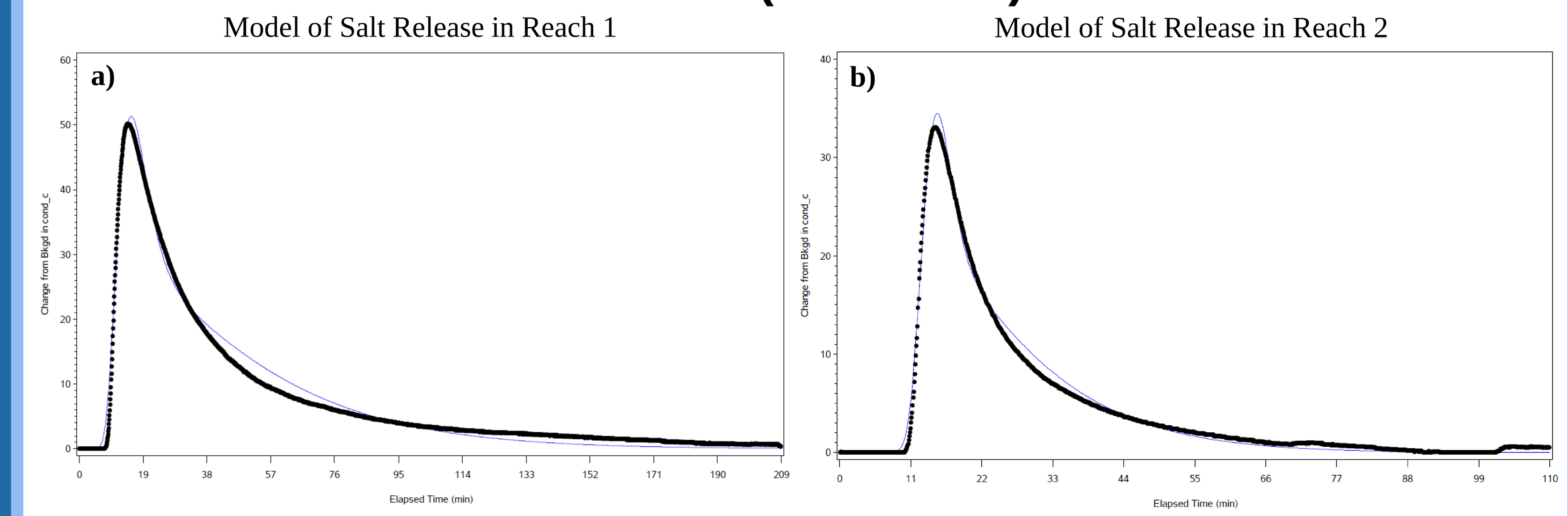

Figure 6. Displays the specific conductance over time (min) after an injection of salt in Reach 1 (a) and Reach 2 (b).

	Reach 1 (upstream)	Reach 2 (downstream)
Flow (L/s)	1.0089	1.6781
A_s/A	1.326	0.672
Hydraulic uptake length (m)	39.58	51.43
Transient storage residence time (s)	1075.97	467.33

Figure 7. Hydrologic parameter results from the USGS OTIS model.

Discussion and Conclusions

Temperature regime:

- Contrary to our first hypothesis, the DTS results did not show distinct cool spots in Spring Brook, associated with large woody debris or otherwise, indicating that hyporheic exchange may be limited in both scope and thermal influence in this system.
- The longitudinal downstream trend of increasing temperature can be attributed to distance from the channel head spring source and energy exchange with the atmosphere. The steady downstream trend suggests no substantial groundwater contributions to stream flow beyond the spring-head.
- Diurnal temperature changes in the stream are buffered compared to atmospheric diurnal patterns, as documented by DTS cable coils located outside the stream water.
- Shallow water depth and debris in the substrate made it difficult to lay/secure the cable underwater for the stream's entirety, so future work will include surveying the cable and noting these points.

Transient storage:

- Reach 1 had greater transient storage properties than Reach 2, contrary to our second hypothesis.
- The abundant large wood obstacles in Reach 2 do not form substantial surface transient storage features like pools, but rather function to trap large amounts of fine sediments (sands and organics) which may be clogging substrate pore spaces in the reach. This could be the mechanism responsible for the observed reduced transient storage areas (A_s/A) and residence times in Reach 2.
- Reach 1 was comparatively free of large wood obstructions as well as fine substrate materials. Although also free of surface transient storage features such as pools, the cobble-gravel substrate of Reach 1 likely has more available pore space to function as transient storage area (A_s/A).

Summary:

- Our findings suggest that the influence of large wood obstacles in streams may by highly dependent on their specific hydraulic and geomorphic effect.

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