Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor

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[1] Discrete zones of groundwater discharge in a stream within a peat-dominated wetland were identified on the basis of variations in streambed temperature using a distributed temperature sensor (DTS). The DTS gives measurements of the spatial (±1 m) and temporal (15 min) variation of streambed temperature over a much larger reach of stream (>800 m) than previous methods. Isolated temperature anomalies observed along the stream correspond to focused groundwater discharge zones likely caused by soil pipes within the peat. The DTS also recorded variations in the number of temperature anomalies, where higher numbers correlated well with a gaining reach identified by stream gauging. Focused zones of groundwater discharge showed essentially no change in position over successive measurement periods. Results suggest DTS measurements will complement other techniques (e.g., seepage meters and stream gauging) and help further improve our understanding of groundwater–surface water dynamics in wetland streams.

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1. Introduction

[2] Identifying areas of groundwater discharge in a wetland-stream complex is often critical for quantifying wetland dynamics. However, temporal and spatial variability of groundwater discharge is generally unknown. Work by others has shown that the variability can be high, especially in areas with "soil pipes" [*Holden*, 2004, 2005]. The objective of this work is to characterize fine-scale temporal and spatial variability of groundwater discharge in a wetland-stream complex. Focused zones of groundwater discharge, possibly caused by soil pipes, are thought to control groundwater–surface water interactions within the wetland-stream complex.

1.1. Groundwater Discharge to Wetland Streams

[3] Conceptual models of groundwater-stream interactions commonly assume relatively uniform diffuse flow along the length of a stream [e.g., *Winter et al.*, 2002] although spatial variability of diffuse flow in streams can be influenced by variations in streambed sediments [*Alley et al.*, 2002]. However, the diffuse flow conceptual model may not be valid in peat-dominated wetland-stream complexes because of potential preferential flow through soil pipes [*Holden*, 2004, 2005]. Focused groundwater discharge has been identified in both lakes and streams [*Schmidt et al.*, 2006; *Selker et al.*, 2006b; *Conant*, 2004; *Sebestyen and Schneider*, 2004; *Rosenberry et al.*, 2000; *Krabbenhoft and Anderson*, 1986], but traditional methods of measuring groundwater discharge to streams, such as stream gauging and seepage meters, integrate discharge from larger areas (stream gauging) or may miss fine-scale variations in groundwater discharge, especially focused discharge that occurs in discrete zones (seepage meters). In the work presented here, spatial variability in groundwater discharge along a relatively long segment of a stream in a peat-dominated wetland was characterized using a distributed temperature sensor (DTS), a relatively new technology [*Selker et al.*, 2006a].

[4] Groundwater discharge has been related to biological abundance and diversity [*Hunt et al.*, 2006], and the spatial variability of groundwater-stream interactions has implications for identifying "hot spots" for biological processes and biogeochemical cycling [*McClain et al.*, 2003]. Biogeochemical processes taking place within hot spots have been shown to be directly related to areas of groundwater discharge [*Hedin et al.*, 1998]. However, identifying these areas over a large stream reach is difficult and labor intensive using traditional approaches.

1.2. Temperature as a Groundwater Tracer

[5] Temperature is used as a natural tracer in groundwater studies in a wide array of applications [*Fairley and Nicholson*, 2006; *Anderson*, 2005; *Becker et al.*, 2004; *Conant*, 2004; *Stonestrom and Constantz*, 2003; *Constantz et al.*, 1994; *Silliman and Booth*, 1993]. Commonly, temperature measurements are made at multiple depths at a single location. Groundwater flux can then be calculated using an analytical solution [*Hunt et al.*, 1996; *Lapham*, 1989; *Stallman*, 1965], time series analysis [*Hatch et al.*, 2006], and/or a groundwater flow and heat transport model [e. g., *Thorne et al.*, 2006; *Clauser*, 2003; *Bravo et al.*, 2002; *Voss and Provost*, 2002; *Kipp*, 1997, 1987; *Healy and Ronan*, 1996].

[6] Distributed temperature measurements using fiber optics is a new technology that allows for much finer spatial and temporal resolution. Distributed temperature sensors

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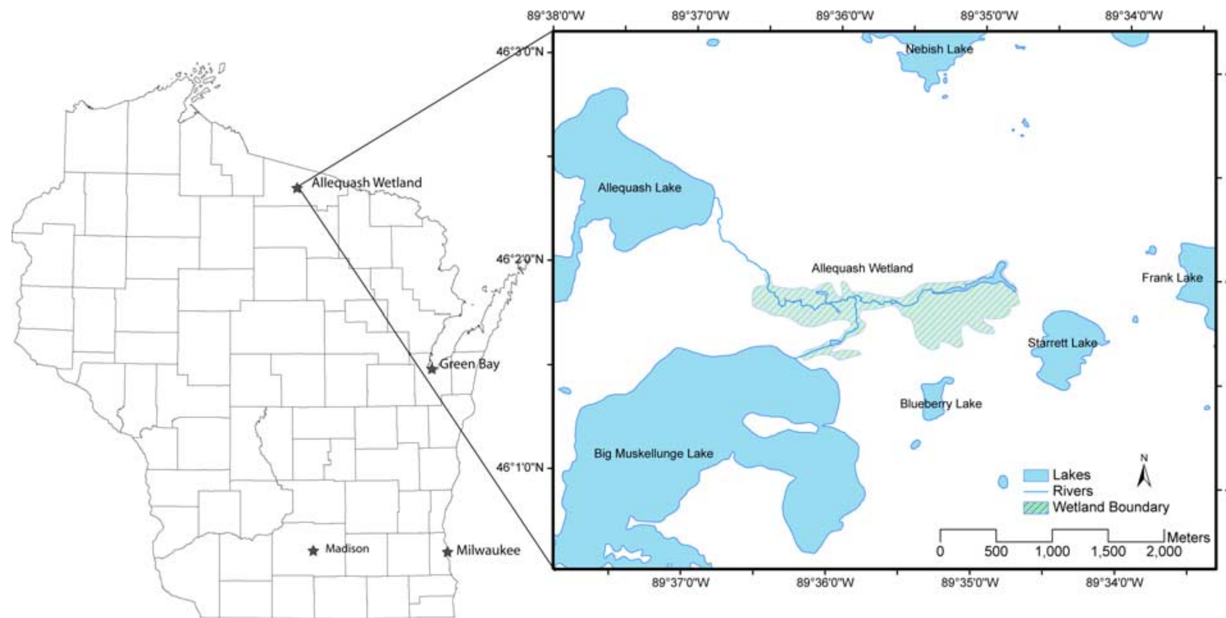

Figure 1. Site map showing the location of the Trout Lake watershed and the Allequash Creek wetland.

rely on scattering of light along a fiber-optic cable to determine temperature [*Selker et al.*, 2006a]. Laser light is sent down the length of the fiber-optic cable where variations in temperature cause differences in backscatter, changing the wavelength and intensity of light. The scattered light travels back up the fiber-optic cable as a higher (Stokes) and lower (anti-Stokes) wavelength. Variation in the intensity of the Stokes wavelength is not affected by temperature, but the variation in intensity of the anti-Stokes wavelength is affected by temperature. On the basis of the ratio of the two intensities, temperature at a given section of the cable can be calculated. Measurements are recorded over 1-m sections along the length of the cable approximately every 15–20 s, depending on the system used. Measurements along each meter of the cable are then averaged over a specific time period to reduce instrument noise.

[7] In contrast to placing multiple temperature probes at varying depths at a single location, the DTS is placed on or embedded in the streambed along a relatively long stretch of stream (with commercial systems utilizing up to 30 km of fiber). The advantage of the DTS is that continuous temperature measurements can be made concurrently in many locations along the length of the cable as opposed to single point measurements made at different times; thus the DTS has the ability to detect concurrent spatial variability in discharge, which may be missed in point measurements or be confounded by nonsynoptic measurements. An additional advantage of the DTS is the ability to make continuous measurements in time at the groundwater–surface water interface; thus temporal variations can be characterized on the stream reach scale. Other spatially distributed temperature measurements such as forward looking infrared thermal imaging only take snapshots of temperature in time [*Loheide and Gorelick*, 2006; *Torgersen et al.*, 2001] and only on the water surface. The DTS also does not alter stream levels or flow patterns. Similar to other heat-based methods, a disadvantage of the DTS is that groundwater flux into or out of the streambed cannot be directly quantified. Another disadvantage is that the current generation of fiber-optic cables is relatively fragile, unlike wire-type instruments such as thermocouples.

2. Study Site

[8] The Trout Lake watershed (Figure 1) is in the Northern Highlands geographic province of Wisconsin. The 118 km^2 watershed consists of low-relief glacial terrain set in 30–50 m of relatively uniform outwash sand. Because of the highly conductive nature of the outwash sand and the hydrology of the watershed, streamflow is dominated by groundwater contributions. The watershed is heavily forested, with a history of selective logging episodes. Precipitation averages around 79 cm/yr, and recharge to the water table is approximately 27 cm/yr [*Pint et al.*, 2003; *Walker et al.*, 2003]. The difference between precipitation and recharge is assumed to be lost to evapotranspiration and canopy interception, as overland runoff is negligible.

[9] The Trout Lake site is part of the Long-Term Ecological Research (LTER) network [*Magnuson et al.*, 2006] and one of five sites operated by the U.S. Geological Survey as part of the Water, Energy and Biogeochemical Budgets (WEBB) program [*Walker and Bullen*, 2000].

[10] Allequash Creek (Figure 1), which is the focus of this work, flows through a peat-dominated wetland. The creek is commonly less than 50 cm deep, with relatively few shrubs along the stream banks to provide shading from direct solar input to the streambed. The width of the stream ranges from 2.7 to 8.8 m, with an average stream discharge entering the wetland at 0.037 m^3/s from the east and exiting the wetland at 0.053 m^3/s to the northwest. The streambed consists of loose peat on the order of 1 m thick, making it difficult to walk along the streambed.

3. Methods

[11] A DTS (Lios Technology Generation 2 optical temperature system (OTS), Cologne, Germany) was installed in

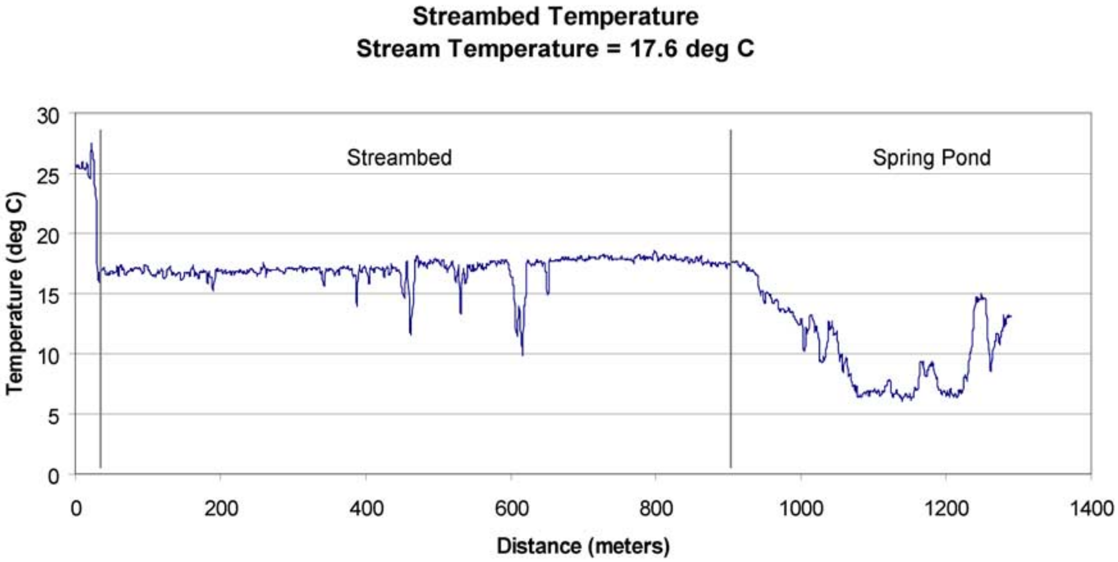

Figure 2. Snapshot of streambed temperature along Allequash Creek collected on 2 September 2006 at 1346. Stream temperature is 17.6°C, while groundwater temperature is 6°–7°C. Distances up to 800 m are shown in Figure 3.

the streambed of Allequash Creek during September 2006. Streambed temperature measurements were made by laying more than 1300 m of fiber-optic cable just below the sediment-water interface. After an initial deployment of the DTS the fiber broke, most likely caused by beaver or muskrat activity within the stream. Cable breaks reduced the effective length of the cable from 1300 to 650 m. To prevent future breaks, the fiber-optic cable was protected by installing the cable inside a flexible conduit. Conducted over a 3-hour period at temperatures varying from 7° to 20°C, laboratory tests of the DTS showed no difference in temperature or time lag between the original fiber-optic cable and the fiber-optic cable enclosed in the protective conduit. The cable was pushed into the peat of the streambed so that measurements were made just below the sediment-water interface. Small weights were attached to the fiber-optic cable every 1–2 m to hold the cable in position in the streambed. After installation the cable was inspected to ensure it was below the sediment-water interface. In sections where the cable was exposed, attempts were made to push the cable into the sediments; however, wood and other debris prevented the cable from being buried in some portions of the stream. The location of the cable was georeferenced using a real-time kinematic global positioning system (Topcon, Paramus, New Jersey).

[12] The DTS ran for three periods, approximately 48 hours each, in September 2006. Measurements were recorded along the length of the cable approximately every minute and averaged to approximately every 15 min, which resulted in a measurement of ±0.03°C accuracy, averaged over 1-m sections. Self-contained temperature loggers (Hobo pendent loggers, Onset Computer, Bourne, Massachusetts) were attached at specific locations along the length of the cable to verify the temperature reading given by the DTS. Hobo temperature loggers were attached directly to the fiber-optic cable, and small weights were placed on either side of the logger in order to secure the loggers in the streambed sediments. Gaining portions of the stream were identified by noting the differences in temperature between groundwater and surface water. Stream gauging was conducted at seven locations along the stream to compare gaining and losing reaches to variations in the streambed temperature profile. Surface water temperatures were generally 5°–16°C warmer than groundwater temperatures during the September 2006 measurement period. Stream temperatures vary seasonally as well as diurnally; inference of groundwater discharge is most reliable when the difference between surface water and groundwater temperatures is at a maximum. The distribution of temperature along the length of streambed is expected to be relatively constant if groundwater discharge is dominated by diffuse flow. However, if focused groundwater discharge predominates, more abrupt changes in temperature are expected along the length of the streambed. Seepage meters [*Lee*, 1977] were installed in three zones within the streambed in order to quantify discharge in zones identified using the DTS.

4. Results

4.1. Spatial Changes in Temperature

[13] An initial temperature profile was measured with the full 1300-m length of cable prior to breakage of the fiber. The temperature profile at one snapshot in time (Figure 2) shows an initial increase in temperature as the fiber-optic cable runs from the measurement enclosure to the stream (0–10 m). The measurement enclosure was placed next to the stream and was used to house the power supply, laptop computer, and DTS controller. Several abrupt variations in temperature are evident within the streambed from 10 to 900 m. (These abrupt variations in temperature are referred to as temperature anomalies in the following text.) From 900 to 1300 m on the north side of the wetland (Figure 3) the cable was looped back and forth along a large spring pond with maximum depth greater than 2 m, causing a drop in temperature owing to groundwater discharging into the pond. Groundwater temperature is generally on the order of

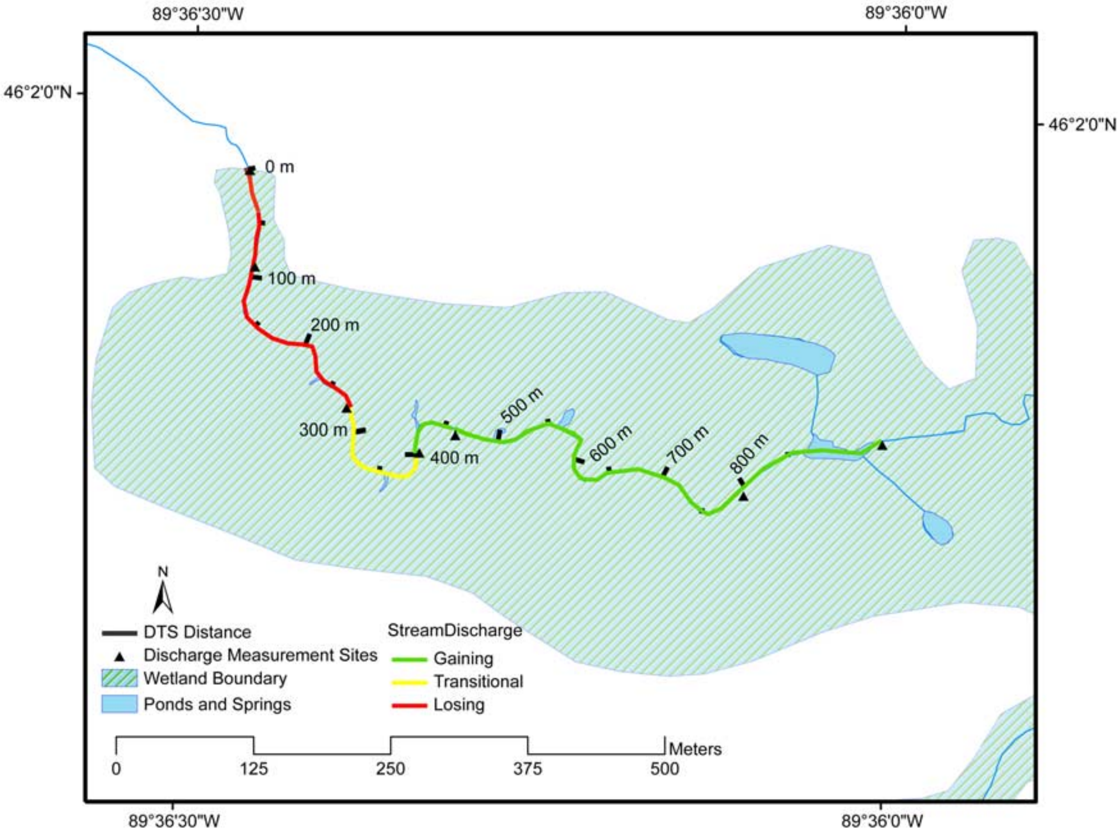

Figure 3. Study site along Allequash Creek. The green, yellow, and red lines represent net streamflow gains, transitional flow, and streamflow losses over the stream reach, respectively, as determined by discharge measurements using an acoustical flowmeter. Allequash Creek flows from east to west.

6°–7°C on the basis of these measurements and is in agreement with temperature measured in wells within the wetland and previous measurements made in the streambed using temperature probes [*Spitzer-List*, 2003]. The zones showing an increase in temperature between 900 and 1300 m represent areas where the cable moved into solar-heated shallow water along the shore of the spring pond.

[14] Streambed temperatures between 10 and 900 m show a number of temperature anomalies along the length of the fiber-optic cable (Figure 2), which are expected to correspond to zones of focused discharge within the streambed. Because the DTS averages temperature over the length of a meter, the measured temperature in focused discharge zones is warmer than groundwater (6°–7°C) yet cooler than the stream. At some locations the DTS records temperatures that are warmer than the surface water, indicating solar heating of the streambed where the fiber-optic cable could not be buried.

4.2. Temporal Fluctuations in Temperature

[15] Because groundwater is more thermally stable than surface water, temperature should fluctuate less in zones of focused discharge than in areas with little or no groundwater discharge. These zones appear as vertical columns of constant temperature through time (Figure 4a). Examples of the constant temperature columns can be observed at 150 and 500 m (Figure 4a). Standard deviations in temperature along each meter of cable, calculated from hourly data from two measurement periods (22–24 September 2006 and 28 September 2006) (Figure 4b), show little change in the relative standard deviation for a given location along the cable, suggesting that the temperature profile in Figure 2 is representative. Moreover, zones with low standard deviation (Figure 4b) typically correspond to columns of constant temperature through time (Figure 4a).

4.3. Comparison of DTS Results to Temperature Data Loggers and Streamflow Measurements

[16] Temperatures measured using Hobo self-contained temperature loggers with the associated error of ±0.47°C typically fall within measurements taken with the DTS (with an error of ±0.03°C) (Figure 5). However, exceptions do occur and are likely a result of slight vertical differences in the placement of the Hobo pendants relative to the fiber-optic cable, which allow the Hobos to receive sunlight that the fiber-optic cable did not. Also, the DTS records an average value of temperature over a 1-m length of cable, which may partially account for the difference in the point measurement using the Hobo loggers.

[17] Streamflow measurements along Allequash Creek using an acoustical flowmeter (Flow Tracker, SonTek/YSI, San Diego, California) identified gaining and losing reaches within the wetland on the basis of differences in measured streamflow at the upstream and downstream ends of a measured reach (Figure 3). The transition from losing to gaining conditions corresponds to the DTS distance between 275 and 400 m. The zone between 275 and 400 m is labeled as a transitional zone because changes in discharge

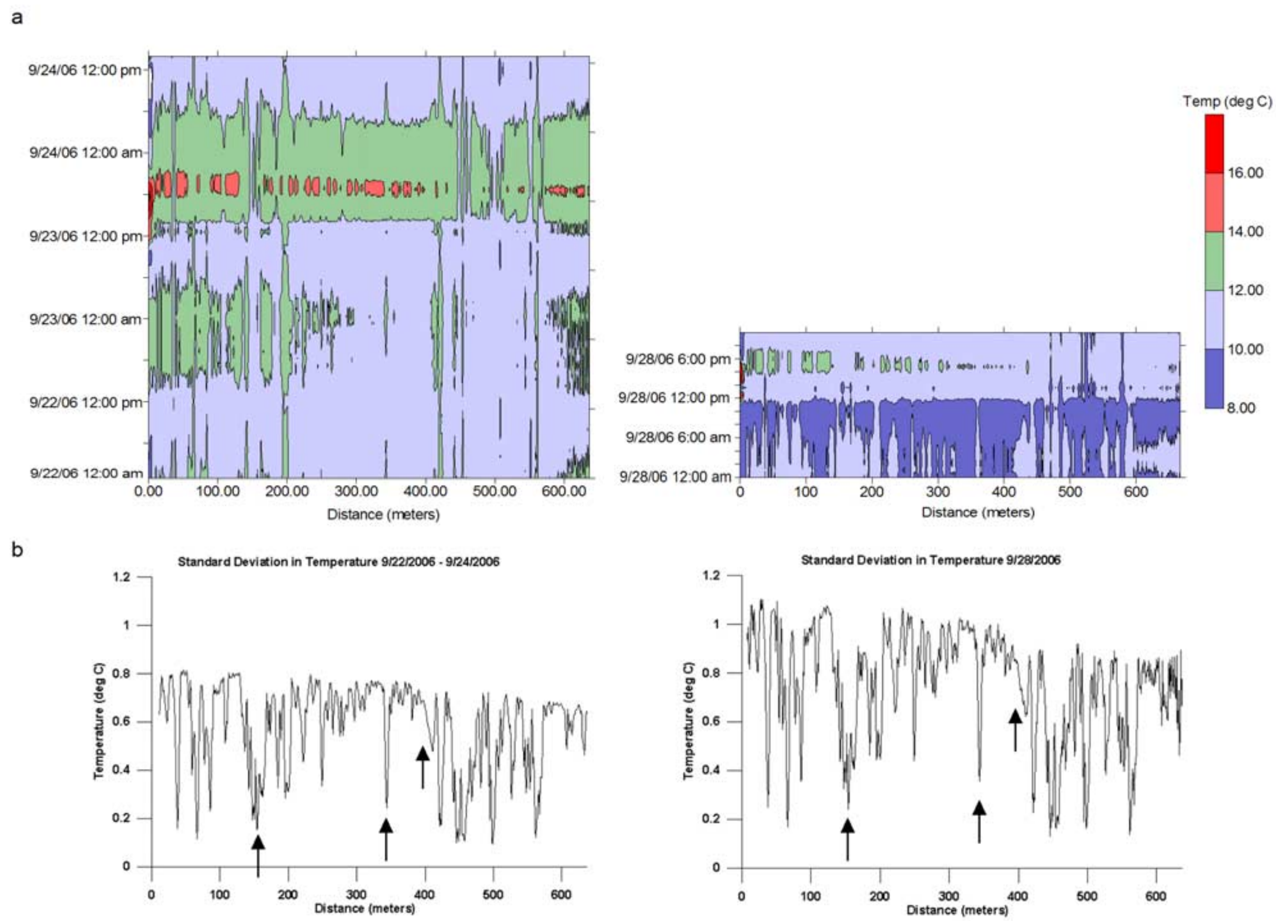

Figure 4. (a) Change in groundwater temperatures within the streambed along Allequash Creek for two deployment periods through time and (b) the standard deviation in temperature over each deployment period. Vertical columns of the cool colors (Figure 4a) typify groundwater discharge areas, which have low standard deviation in temperature (Figure 4b). Arrows show locations of seepage meter installation.

were within the expected measurement accuracy of the flowmeter (Figure 3). The increase in the importance of temperature anomalies, as demonstrated by the average DTS temperature, at locations greater than 400 m is consistent with the streamflow measurements that demonstrate the stream is gaining at distances greater than 400 m. The increase in the number of temperature anomalies at distances greater than 400 m is also consistent with increased focused groundwater discharge in gaining reaches (Figure 5).

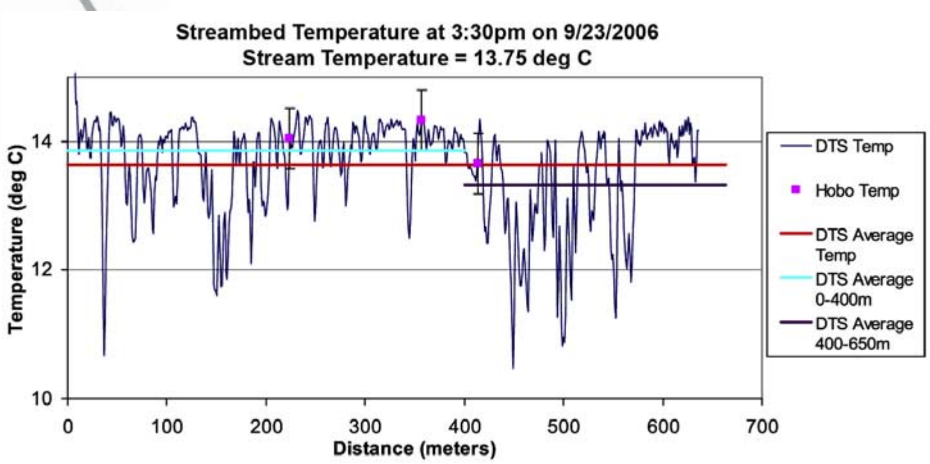

Figure 5. Snapshot of streambed temperature in Allequash Creek using the distributed temperature sensor (DTS) fiber-optic system and discrete Hobo pendants. Average temperatures are compared in gaining and losing reaches along the length of the fiber-optic cable. Distances are shown in Figure 3.

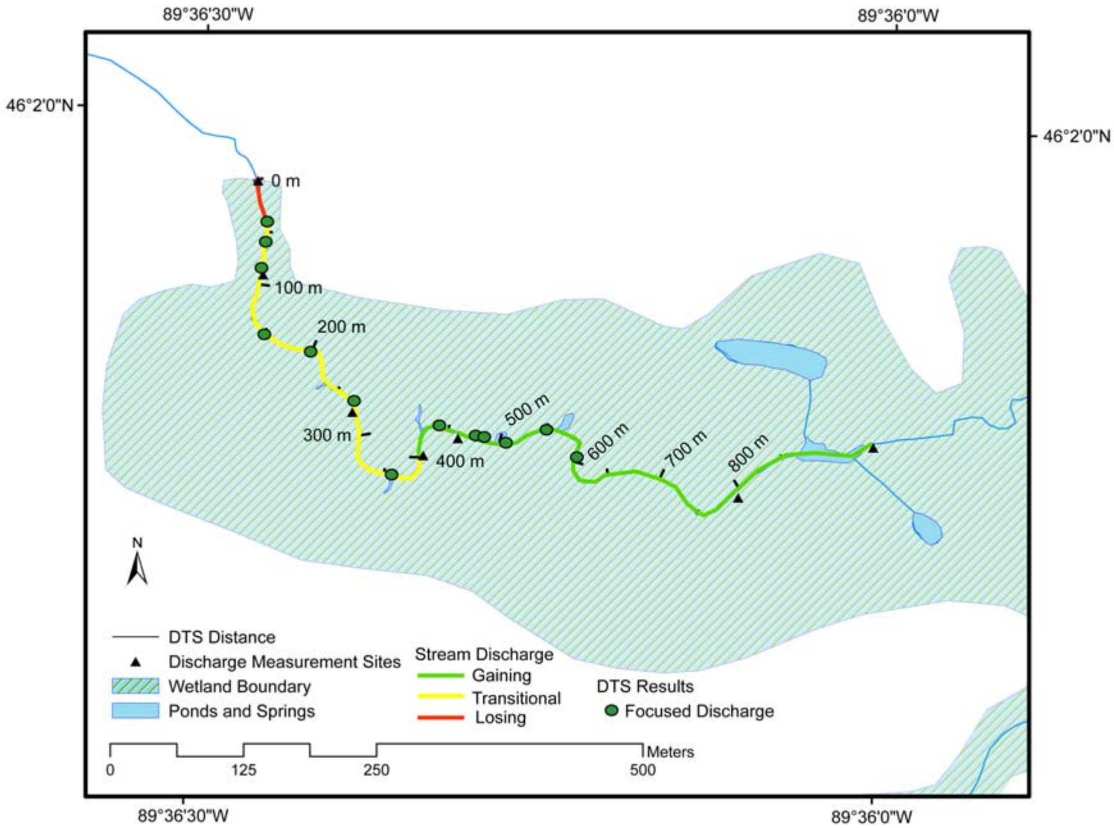

Figure 6. New conceptual model of groundwater–surface water interactions along Allequash Creek. The green, yellow, and red lines represent net streamflow gains, transitional flow, and streamflow losses over the stream reach, respectively. Green dots represent focused zones of groundwater discharge in the transitional reach identified using the DTS. Allequash Creek flows from east to west.

[18] Several temperature anomalies occur at locations less than 400 m (Figure 5), suggesting that focused groundwater discharge occurs in zones that streamflow measurements indicate are, on average, transitional or losing. We believe this is the result of the scale of the measurement. That is, the net flux over the portion of the stream from 0 to 275 m is losing on the basis of streamflow measurements that integrate the groundwater–surface water interactions along the entire reach, but the loss is likely concentrated near the downstream end (0–40 m) of the reach, where the stream stage is raised by an artificial constriction in the stream because of a culvert at a road crossing (0 m in Figure 3). *Born et al.* [1979] noted that a surface water feature can intersect both a shallow and a deep groundwater flow system such that the stream loses water to the shallow system and gains water from the deep system. However, at a location of 200 m along the stream the evapotranspiration rate was not large enough to lower shallow groundwater levels below stream levels during our study; thus it appears that both the shallow and deep groundwater system are discharging to the stream. On the basis of the DTS data, which show focused groundwater discharge, and the lack of measured gradients showing the stream losing to the wetland, perhaps the "losing" zone along the lower stream reach (40–275 m; Figure 3) is better described as a transitional zone (Figure 6). In this conceptualization the transitional zone from 40 to 400 m would represent focused zones of groundwater discharged (green circles on Figure 6) intermixed with zones of little or no discharge or recharge (yellow line on Figure 6).

4.4. Comparison of DTS Results to Seepage Meters

[19] Two of the expected focused zones of groundwater discharge at approximately 156 and 360 m were identified on the basis of temperature anomalies and the analysis of the standard deviation (Figure 4b). These locations and a third zone at 400 m were instrumented with seepage meters [*Lee*, 1977]. The third zone was instrumented as a background measurement (Table 1). Multiple readings were taken at each of the three locations (Table 1). Seepage meters were installed after the DTS cable was removed and are thought to be within ±5 m from the respective DTS distances. A 15-cm-diameter hole or spring in the streambed sediments was observed near the 360-m location; water discharging from the spring suspended small leaves and sediment moving along the streambed up into the water column. The peat surrounding the spring was light brown as compared to typical streambed peat, which is dark brown to black. The seepage meter was placed over the hole, and strong discharge was measured there whereas discharge at 156 m was similar to the 400-m background measurement (Table 1).

[20] Measuring focused groundwater discharge by means of a seepage meter is highly dependent on placing the meter exactly over an area representative of the discharge zone

Table 1. Seepage Meter Results

Location, m	Discharge,[a] cm^3/s	Sample Period
156	8.8E-5	1
156	2.8E-5	2
360	1.8E-3	1
360	1.7E-3	2
400[b]	2.5E-4	1
400[b]	5.5E-5	2
400[b]	3.2E-5	3
400[b]	2.5E-5	4

[a]Read 8.8E-5 as 8.8×10^{-3}.
[b]The 400-m location is a background measurement.

[*Rosenberry and Morin*, 2004]. Temporal fluctuations in temperature (Figure 7) show a much smaller variation in temperature at DTS locations at 156 and 360 m than at the 400-m background site. The DTS results show that the 156- and 360-m temperature anomalies have the smallest variation in temperature through time, which implies strong constant groundwater discharge, yet only one of the two locations had seepage-meter-derived discharge larger than the background value. It is likely that strong discharge was not measured at 156 m using seepage meters because the meter (expected to be within ±5 m of the DTS location) did not enclose the focused zone of groundwater discharge identified by DTS. At 360 m, however, the focused discharge point was easily identified and thus could be encompassed by the seepage meter. This suggests that while the DTS can identify possible locations of discrete groundwater discharge, some level of additional field investigation will likely be needed to accurately locate small-scale areas of discrete flow. As one might expect, the sensitivity of seepage meter measurements to location in space is also expected to be greater in systems dominated by discrete groundwater discharge than in systems dominated by diffuse groundwater discharge.

5. Conclusions

[21] Discrete zones of groundwater discharge in a stream within a peat-dominated wetland were identified on the basis of variations in streambed temperature using a distributed temperature sensor (DTS). During September, groundwater in northern Wisconsin is 5°–16° cooler than surface water, creating the necessary contrast required when using the DTS so that the temperature difference can be used as a natural tracer for identifying groundwater discharge to the stream. The DTS gives a relatively comprehensive view of the stream reach through accurate measurements of the spatial and temporal variation of streambed temperature over a much larger reach of stream than can be obtained using seepage meters, temperature probes, or thermocouples.

[22] DTS technology has several limitations related to both installation and environmental factors. Care must be taken during field emplacement to ensure the fiber-optic cable is placed at a consistent depth below the sediment-water interface. Artifacts of variations in cable placement could be observed in the temperature record if the cable is not below the sediment-water interface. Animal activity can also impact field studies, causing breaks along the fiber-optic cable. In this research, animal activity reduced the length of the fiber-optic cable from 1300 (Figure 2) to 650 m (Figure 5). Placing the fiber-optic cable within a protective conduit extended the life of the cable. It is also important that the DTS be deployed during those times of the year and/or day when there is a large difference between stream and groundwater temperatures.

[23] Isolated temperature anomalies observed along Allequash Creek correspond to focused groundwater discharge zones, likely caused by soil pipes within the peat. A hole, consistent with the presence of a soil pipe, was observed within the streambed of Allequash Creek, and its location corresponded to a temperature anomaly along the DTS profile as well as strong discharge measured in a seepage meter. The DTS also recorded variations in the number of temperature anomalies per unit length of stream, which correlated with a change from a gaining to a losing reach.

[24] Focused zones of groundwater discharge in Allequash Creek showed no change in position over successive measurement periods on the basis of an analysis of the standard deviation of temperature through time (Figure 4).

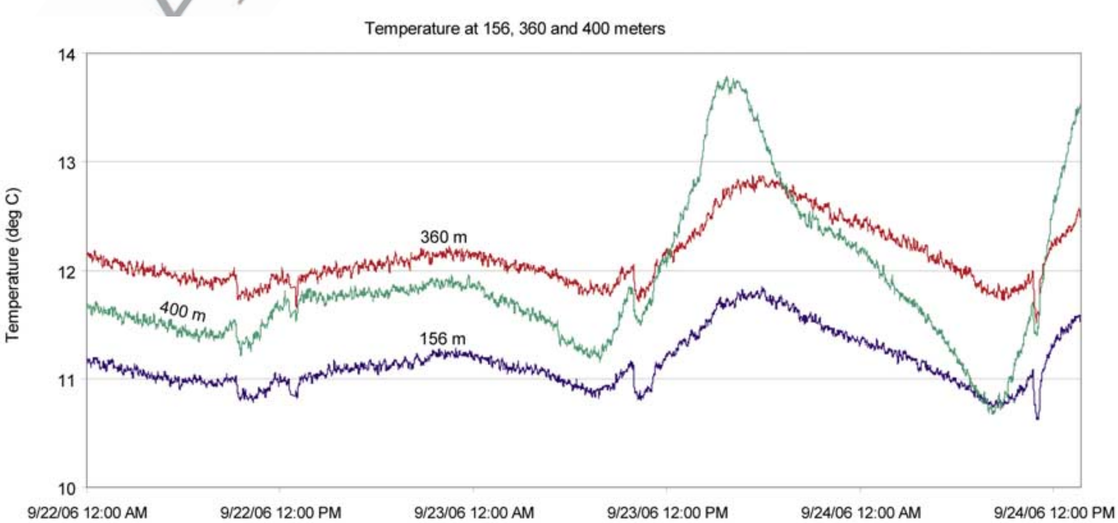

Figure 7. Temperature histories at three locations where seepage meters were installed.

The steady position of these zones implies relatively stable groundwater flow locations within the peat over the timescale investigated. However, locating the exact location of discharge zones with standard seepage meter investigations in wetland streams underlaid by peat can be problematic; indeed, at this study site it would be exceedingly labor-intensive to find hydrologically active locations in the stream without the DTS. The DTS measurements allowed us to target specific locations in the streambed for field investigations using seepage meters. Seepage meter measurements showed a two orders of magnitude difference in groundwater flux to the stream between focused and diffuse discharge zones. However, even with a 1-m averaged DTS measurement, additional field characterization was required to accurately locate the discharge zone (Figure 7).

[25] This work demonstrates the utility of a DTS for characterizing discrete flow and piping in wetland-stream systems. Coupling DTS measurements with other complementary techniques (e.g., seepage meters, thermocouple probes, and forward looking infrared images) will lead to better estimates of groundwater flux in wetland-stream systems.

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