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A comparison of thermal infrared to fiber-optic distributed temperature sensing for evaluation of groundwater discharge to surface water

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SUMMARY

Groundwater has a predictable thermal signature that can be used to locate discrete zones of discharge to surface water. As climate warms, surface water with strong groundwater influence will provide habitat stability and refuge for thermally stressed aquatic species, and is therefore critical to locate and protect. Alternatively, these discrete seepage locations may serve as potential point sources of contaminants from polluted aquifers. This study compares two increasingly common heat tracing methods to locate discrete groundwater discharge: direct-contact measurements made with fiber-optic distributed temperature sensing (FO-DTS) and remote sensing measurements collected with thermal infrared (TIR) cameras. FO-DTS is used to make high spatial resolution (typically m) thermal measurements through time within the water column using temperature-sensitive cables. The spatial–temporal data can be analyzed with statistical measures to reveal zones of groundwater influence, however, the personnel requirements, time to install, and time to georeference the cables can be burdensome, and the control units need constant calibration. In contrast, TIR data collection, either from handheld, airborne, or satellite platforms, can quickly capture point-in-time evaluations of groundwater seepage zones across large scales. However the remote nature of TIR measurements means they can be adversely influenced by a number of environmental and physical factors, and the measurements are limited to the surface "skin" temperature of water features. We present case studies from a range of lentic to lotic aquatic systems to identify capabilities and limitations of both technologies and highlight situations in which one or the other might be a better instrument choice for locating groundwater discharge. FO-DTS performs well in all systems across seasons, but data collection was limited spatially by practical considerations of cable installation. TIR is found to consistently locate groundwater seepage zones above and along the streambank, but submerged seepage zones are only well identified in shallow systems (e.g. <0.5 m depth) with moderate flow. Winter data collection, when groundwater is relatively warm and buoyant, increases the water surface expression of discharge zones in shallow systems.

1. Introduction

Groundwater (GW) discharge to surface water (SW) supports flow stability and stream habitat, particularly during seasonal low-flow periods. Upwelling GW often has a thermal, isotopic, and geochemical signature that is distinctly different from the receiving SW body, and these GW signatures are comparatively stable through time (Hayashi and Rosenberry, 2002). Distinct GW characteristics can be used as tracers to indicate seepage dynamics; the usefulness of each tracer typically depends on the degree of contrast with SW. Temperature is a parameter that offers contrast during certain times of the year, as diurnal and annual temperature oscillations strongly influence SW, whereas GW temperatures typically remain near the annual air temperature mean (Constantz, 1998). Therefore, GW seepage zones are often cooler in summer and warmer in winter than the receiving SW. Yet even in the transition seasons, when these water end-members are closer in temperature, seepage zones can be identified by reduced thermal variance (Anderson, 2005; Silliman et al., 1995; Stonestrom and Constantz, 2003). In contrast to geochemical tracers, which are often highly variable in space, the GW temperature

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end-member can be readily identified and/or predicted for a given area (Anderson, 2005; Thoreau, 1854). Temperature measurements are relatively easy to collect and interpret, and recent advances in direct and remotely-sensed temperature measurements have allowed heat tracing to be applied from m to km scales.

Temperature is an indicator of GW seepage as well as a critical SW ecological parameter; many aquatic species of commercial and recreational interest survive within a thermal range that may be exceeded episodically during summer low flows. In response to a warming climate (Cook et al., 2013; Orr et al., 2015), many temperate streams will continue to warm (Isaak et al., 2011). Stream sections moderated by strong GW influence will likely provide some of the most stable future aquatic habitat (Snyder et al., 2015). In streams with small contributions of GW discharge, unmixed thermal anomalies will be more locally important. These localized zones create thermal refugia that are critical to the survival of thermally stressed species, particularly during extreme events (Brunke and Gonser, 1997; Ebersole et al., 2003a,b). Preserving and potentially augmenting areas of thermal refugia is a topic relevant to ongoing and future fisheries management strategies (Kurylyk et al., 2014). Although thermal refugia are most relevant when SW is warmest, fish may also seek out GW upwelling zones when spawning in late-fall to promote egg survival when GW is relatively warm (Geist et al., 2002).

Not all unmixed GW inflows will serve as refugia. GW quality in seepage zones can be impaired if the contributing aquifer is contaminated or has properties that provide unsuitable habitat (Briggs et al., 2012a,b; Conant, 2004; Krause et al., 2013; Weatherill et al., 2014). When an adjacent shallow aquifer is contaminated, areas of focused GW seepage become pollution point-sources that can discharge significant chemical mass-flux into SW. For example, Briggs et al. (2012a,b) used heat tracing methods to locate a contaminated GW seepage zone in Syracuse, NY, and estimated a mass – loading of over 100,000 metric tons of chloride to a stream over a 13 year period.

Researchers use a variety of temperature-sensing technologies to investigate aquatic systems. Direct temperature measurements can be made within the water column or along the streambed, while the temperature of the water surface (“skin”) can be evaluated remotely using thermal infrared (TIR) cameras. Because there are inherent spatial scale and data collection efficiency trade-offs between different methods, several thermal methods are often used in concert (Briggs et al., 2013; González-pinzón et al., 2015). Thermal methods commonly used across increasing spatial scales are (1) snapshot-in-time point-scale measurements (Conant, 2004; Ebersole et al., 2003a,b; Lautz and Ribaudo, 2012); (2) point-scale temperature logging through time (Constantz et al., 1994; Daniluk et al., 2013; Hatch et al., 2006; Kelleher et al., 2012; Lautz et al., 2010; Leach and Moore, 2011); (3) longitudinal “Lagrangian” drag-probe surveys (Gendaszek, 2011; Lee, 1985; Vaccaro and Maloy, 2006); (4) fiber-optic distributed temperature sensing (FO-DTS) (Henderson et al., 2009; Selker et al., 2006a,b; Tyler et al., 2009); and (5) TIR data collected by ground, airborne, and satellite systems (Banks et al., 1996; Baskin, 1998; Deitchman and Loheide, 2009; Handcock et al., 2006; Whiting, 1984). FO-DTS and TIR can be used to collect data over large areas and, therefore, are well-suited for stream-reach (10’s of m) to basin-scale evaluations of GW discharge. For example, Dugdale et al. (2015) used airborne TIR to map potential thermal refugia over approximately 700 km of Canadian streams, the occurrence of which was related to geomorphic variables. However, one primary difference between the two technologies is the location of the measurement: FO-DTS measurements are typically made along a submerged lakebed or streambed, whereas TIR is a surface measurement sensitive only to ground temperature or water surface skin temperature.

A common use of FO-DTS deploys fiber-optic cables to collect continuous temperature data along the streambed interface to identify zones of GW seepage based on temperature anomalies (Briggs et al., 2012a,b; Krause et al., 2012; Selker et al., 2006a,b; Westhoff et al., 2007) and/or thermal variance (Lowry et al., 2007; Selker et al., 2006a). Other studies have applied temperature signal analysis methods to assess SW/GW exchange and quantify temporal variability in response to dam operations and tides (Henderson et al., 2009; Mwakanyamale et al., 2012). A commonly used FO-DTS method utilizes the Raman-spectra backscatter of laser light emitted along optical fibers to evaluate temperature (Dakin et al., 1985), with spatial sampling typically as fine as 1.0 m. Linear distance along the sensor cable is determined using the known speed of light transmission and the timing of backscatter arrival. Due to inherent light loss in glass fibers, temperature-dependent anti-Stokes frequency data are scaled to the Stokes frequency data to determine temperature along the fiber. Random noise increases with distance due to attenuation of the light signal along the fiber; therefore, the range of most commercially available FO-DTS systems is currently limited to approximately 6 km of total fiber length, although greater distances are possible (e.g. Selker et al., 2006b). FO-DTS data are unique in the fact that data precision is a function of integration distance (measurement increments along the fiber) and time (stacking), and therefore precision is in-part user defined (Tyler et al., 2009); a typical value is approximately 0.1 °C. Although FO-DTS measurements are direct, the cable and adjacent streambed sediment can be thermally affected by penetration of solar energy through the water column (Neilson et al., 2010). Mobile bed material can either bury the cable or separate it from the bed, complicating data interpretation (Sebok et al., 2015). FO-DTS also can require significant effort to install and georeference.

TIR data are typically collected within the 8–14 μm “long-wave” radiation range. TIR data indicate the temperature of an object’s surface scaled by the object’s surface emissivity; emissivity values of natural waters are typically close to 1 (Handcock et al., 2012). Data are obtained in the form of discrete quantitative images or video using handheld (Andrews et al., 2011; Briggs et al., 2013; Cardenas et al., 2008; Schuetz and Weiler, 2011), manned airborne (Dugdale et al., 2015; Loheide and Gorelick, 2006; Rayne and Henderson, 2004; Sheibley et al., 2010; Torgersen et al., 2001), and unmanned airborne systems (UAS) and satellite-based instrumentation (Anding and Kauth, 1970; Handcock et al., 2006; Parkinson, 2003). Similar to FO-DTS data, TIR data are used to identify thermal anomalies or gradients in temperature throughout aquatic systems, but data collection with TIR may be much less labor-intensive, and larger-scale surveys are much more practical and efficient. However, using thermal variance to identify inputs of constant temperature (GW) is not commonly done with TIR as spatially consistent temporal data are more difficult to collect, and most surveys are “snapshot” in nature. Further, the “surface-skin” temperature evaluated by TIR may not reveal submerged seepage zones, and are subject to the confounding effects of reflection from surface features (e.g. surface vegetation, bank shadow, sun-glare, etc).

Due to resource and time limitations, environmental research, habitat, and remediation studies often have to choose between an effort-intensive submerged thermal monitoring system (e.g. FO-DTS) and remotely-collected TIR when evaluating the distribution of GW seepage to SW. We hypothesize that the snapshot (in time) and surface-skin nature of most TIR data will limit GW seepage detection in many streams; but under the right set of conditions TIR will detail similar seepage dynamics to submerged FO-DTS, for a fraction of the effort. In other types of SW not as easily covered with fiber optic cables (e.g. peatlands), TIR may more reasonably provide a spatially distributed understanding of