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TECHNICAL NOTE

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Key Points:

- Surface flow affects apparent seep temperature
- Sediment texture affects sensitivity to lateral flow
- Burial of sensors is the most robust approach to thermal seepage detection

Supporting Information:

- Electronic Supplement 1
- Electronic Supplement 2

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Flume testing of underwater seep detection using temperature sensing on or just below the surface of sand or gravel sediments

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Abstract Temperature anomalies can identify locations of seeps of groundwater into surface waters. However, the method's sensitivity to details such as thermometer burial depth, sediment material, seep velocity, and surface water current are largely unknown. We report on a series of laboratory flume experiments in which controlled seeps under variable sediment texture, surface currents, burial depth, and temperature differentials were imposed. The focus of the study is temperature effects at the sediment surface to a few centimeters below the sediment surface, as these locations are of particular interest when using fiber-optic distributed temperature sensors (DTS). The data demonstrate: (1) without surface water flow, seep-related thermal anomalies were apparent in all cases, i.e., the method is feasible in such cases; (2) probe burial is helpful for fine sediment although not effective with coarse bed sediment, i.e., the method is strongly sensitive to sediment properties; (3) placing a thin rubber sheet over an unburied thermal probe increases detection of seeps in some circumstances, but not in others, and is generally not as robust as probe burial; and (4) local surface flow velocity, details of probe position and depth, and seepage velocity all influence observed temperature anomalies, limiting the opportunity to quantify seepage velocity, particularly with unburied temperature sensors. Overall, these findings suggest optimal installation would be at a well-defined depth within fine sediment, that installation in gravel and coarser sediment is not suited to the method if there are any significant surface currents, and that more data would be required to obtain accurate estimates of seepage velocity, though a single sensor may be sufficient to identify the location of seepage.

1. Introduction

The temperature difference between surface and groundwater may be used to locate groundwater seeps into surface waters [e.g., Stonestrom and Constantz, 2003; Selker et al., 2006a, 2006b; Constantz, 2008; Hoes et al., 2009; Lautz and Ribaudo, 2012; Luce et al., 2013; Mwakanyamale et al., 2013]. Fiber-optic distributed temperature sensors (DTS) have enhanced the method by offering continuous, accurate temperature measurement at thousands of locations on or in sediment [Selker et al., 2006a, 2006b; Vogt et al., 2010; Krause et al., 2012]. While the value of the method has been demonstrated [e.g., Mamer and Lowry, 2013; Lauer et al., 2013; Blume et al., 2013], and many useful theoretical approaches have been published [e.g., Luce et al., 2013, and citations therein], questions remain regarding the sensitivity and specificity of the method to seeps as a function of environmental conditions and installation strategy given the paucity of validation of the method under controlled conditions of seepage, lateral flow, and bed material.

Computer simulation and analytical solutions may be used to investigate certain questions about temperature signal dependence on sensor placement, bed texture, flow velocity, and seepage velocity. For example, Figure 1 shows a 1-D analytical solution for temperature versus depth for three different seep velocities. However, in the turbulent, complex environment of natural water bodies and natural hydrogeology, experimental results are needed to gain confidence in the range of conditions. Specifically, this technical note explores the interacting impacts of details of seep velocity, streamflow rate, bed texture, and degree of burial or probe coverage upon the magnitude of thermal signals at the sediment surface or up to a few centimeters below that surface, which is the typical location that is measured with DTS methods. We seek to identify conditions that might render the measurements either ineffective or relatively robust for seep detection.

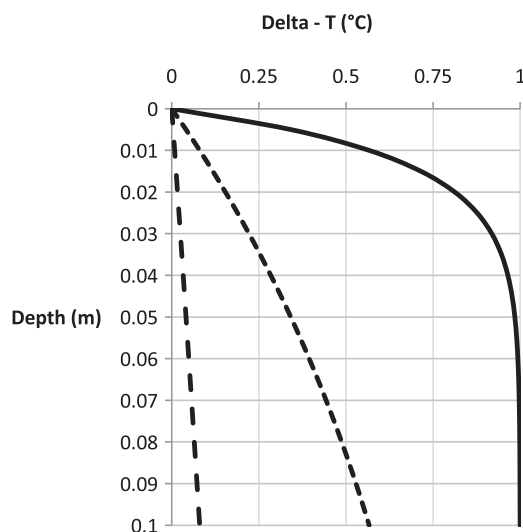


Figure 1. 1-D analytical predictions for temperature as a function of burial depth in sand for three seep velocities ($5e-7$ m/s, dashed line; $5e-6$ m/s, dotted line; and $5e-5$ m/s, solid line). Delta-T (ΔT) is the fraction of difference between surface (10°C) and groundwater temperature (20°C) occurring at each depth. Delta-T reaches 75% (17.5°C) at 0.017, 0.17, and 1.7 m of depth for the fastest to slowest flows, respectively. This illustrates how seepage can substantially change the temperature profile and also the potential benefit of burial of sensors. See supporting information S1 for full details.

2. Flume Design

Many recent flume studies have been produced to explore flow-driven hyporheic processes, as discussed in *Hassan et al.* [2014], but to our knowledge, none with the control required here to obtain uniform seepage. To address our objectives, we built a flume with capabilities to control surface water currents, seep velocity, and the temperatures of surface water and groundwater (Figure 2).

The mean surface current across the tank section could be varied between zero and 0.125 m/s. This near-sediment velocity would correspond to a substantially higher average velocity in a large river due to the expected logarithmic velocity profile with depth [e.g., *Dingman*, 2008, equation (F-5), p. 611]. The Darcy velocity (specific discharge) could be varied continuously from zero to 7.8×10^{-5} m/s (0.28 m/h). The seepage velocity

of water movement through the sediment is higher than the Darcy velocity due to the sediment porosity. For instance, the fine sediment had a porosity of about 0.3, which would imply a seepage velocity through the sediment of up to 2.4×10^{-4} m/s (0.84 m/h).

A data logging thermometer with two thermistor probes with accuracy of 0.01°C was used to monitor temperature (Fluke 1524 with Fluke 5665-P probes). To mimic a fiber-optic cable, the probes were installed in approximately 0.2 m long aluminum cables designed as conductors. The cable had a seven-strand aluminum core with O.D. of 0.0072 m surrounded by polyethylene insulation with an outside diameter of 0.01 m (Figure 3). The central conductor was removed and the internal hole drilled to accommodate the 0.0032 m O.D. of the fluke probe. This probe presents similar dimensions so that flows around it will be similar to

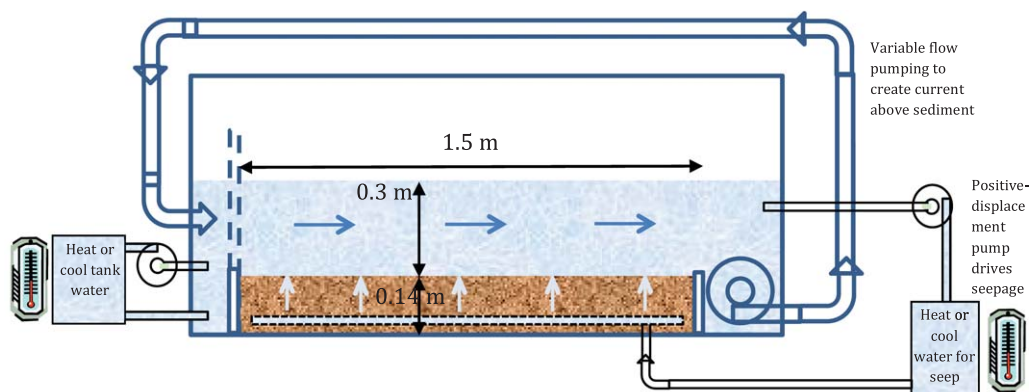


Figure 2. Schematic of seeping-bed flume including a pump-induced surface current and a positive-displacement pump delivering water to a plenum made up of 17 m of 0.02 m diameter sintered rubber irrigation hose in a sediment bed (for further images, see supporting information). The groundwater was heated or chilled relative to the surface water to create a temperature differential. Continuous heating and cooling of the tank water was used to offset changes in temperature caused by seeps and current pumping. The dotted vertical lines indicate a slotted surface intended to spread inflow across depths. Total flume length is 1.8 m, sediment bed length 1.5 m, flume and bed width 0.46–0.58 m, sand depth 0.14 m, and water depth above sediment 0.3 m.

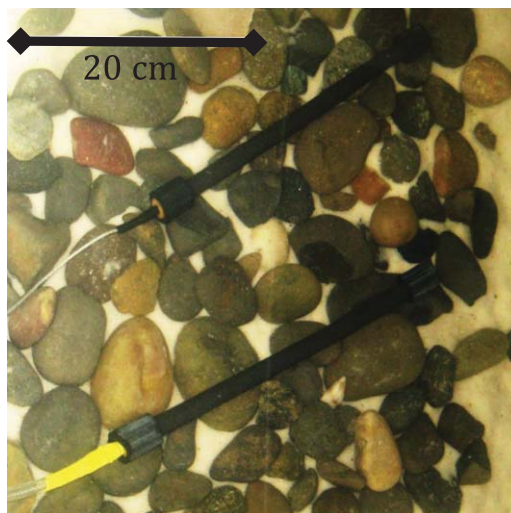


Figure 3. Precision thermistor probes installed within aluminum cables with HDPE jackets. Thermal insulators were placed on the ends to cover exposed aluminum. Here they are shown on rocks on a bed of sand.

comparisons were made using locations identified to have comparable temperature behavior within the tank. Three media were employed: clean silica sand with d_{50} of 0.25 mm (seen in Figure 3), gravel with d_{50} of 5.7 mm, and gravel with a d_{50} of 20 mm (seen in Figure 3).

3. Results

We present data exploring the impact of the following features on seep detection: burial depth; substrate permeability; seepage and streamflow velocity; and the influence of applying impermeable coverings over sensors. Experimental conditions were tested varying seepage velocity, surface water flow rate, temperature contrast, burial depth, and cable protection (0.8 and 1.6 mm thick rubber sheets of 0.10 m width laid over cable). Overall results for selected configurations are presented in Table 1. In this table, “dense” refers to seeps with temperatures below that of the streamflow, while “buoyant” indicates the seep was warmer than the surface flow. Buoyancy of groundwater may occur when warm groundwater emerges into cool surface water (e.g., 20°C water is about 0.1% less dense than 15°C water) or when fresh groundwater emerges into saline surface water (e.g., freshwater is about 2.5% less dense than seawater). We wished to investigate whether buoyancy of groundwater changed the way emerging groundwater was detected. With temperature differences between groundwater and flume water in the range of 5°C, the density differences investigated were small relative to those associated with fresh/saline mixing and were expected to offer negligible contributions to water movement in the presence of surface water currents. In Figure 4, we present a typical experimental result to illustrate the nature of the data used to develop this table.

In this example, we explore how system performance varies with probe burial, sand versus gravel, and surface flow velocity. To quantify the sensitivity, we define three parameters: ΔT , ΔT -gravel, and ΔT -sand. ΔT is the true difference in temperature between seep source water and surface water temperatures. ΔT -gravel is the reported difference between surface and probe temperature for the probe buried in gravel and ΔT -sand is for sand. The detection fractions are defined as ΔT -gravel/ ΔT and ΔT -sand/ ΔT . Prior to the start of current the gravel and sand had identical detection fractions of $4.6/5.0 = 0.92$, whereas after the current was started the detection fraction fell to 0.2 for the probe buried in gravel, while remaining essentially unchanged for the sand-buried probe. Here it is evident that the burial in both materials provided identical and excellent sensitivity to seepage without surface current, but in gravel the signal was largely lost with surface flow. We did not investigate whether the loss in signal was due to mixing of groundwater and surface water or to changing subsurface flows that may result in a detectable signal elsewhere in the gravel, but not at the sensor. However, the sensor was centrally located in the flume with seepage occurring upstream of it, suggesting that mixing with surface water was occurring.

those around a 1 cm diameter DTS cable. It also provides a thermal lag that is similar to a 1 cm diameter DTS cable, although that is not likely to be important since changes in conditions were slow relative to such lag.

Dye testing (pumping FD&C blue dye #1) verified that seepage occurred fairly uniformly over the central area of the tank sediment surface (see supporting information S2). Temperature testing showed that thermal edge effects in the flume were below our measurement resolution beyond 0.10 m from tank edges: all testing was done at least 0.15 m from edges so measurements should be unaffected by edge effects. Seep temperature was found to vary across the bed due to differing groundwater path lengths in the plenum below the tank. For this reason,

Table 1. Effect of Seeps on Temperature Sensor for Selected Sensor Positions and Conditions in Flume Tank^a

Substrate	Flume Current (m/s)	Sensor Position	Cover on Sensor	Buoyancy of Seep	Estimated Fraction of ΔT
Gravel d_{50} 5.7 mm	0	Buried	Uncovered	Dense	90%
			Covered	Dense	50%
		Surface	Uncovered	Dense	10–50% ^b
	0.125	Buried	Uncovered	Dense	10%
			Covered	Dense	10%
		Surface	Uncovered	Dense	10%
Rocks on sand Rocks d_{50} 20 mm	0	On sand between rocks	Uncovered	Buoyant	90%
			Covered	Dense	90%
		On top of rocks	Uncovered	Buoyant	65%
	0.125	On sand between rocks	Covered	Dense	90%
			Uncovered	Dense	50%
		On top of rocks	Covered	Buoyant	10–60% ^b
Sand d_{50} 5.7 mm	0	On sand between rocks	Uncovered	Buoyant	10–30% ^b
			Covered	Dense	25%
		On top of rocks	Uncovered	Dense	30%
	0.125	On sand between rocks	Covered	Dense	20%
			Uncovered	Dense	0%
		On top of rocks	Covered	Dense	0%
Sand d_{50} 0.25 mm	0	Buried	Uncovered	Buoyant	75%
			Covered	Dense	75%
		Surface	Uncovered	Dense	25–40%
	0.125	Buried	Uncovered	Buoyant	85%
			Covered	Dense	75%
		Unburied	Uncovered	Dense	85%

^aIf there is no seep effect on the sensor, the sensor will be at the temperature of the flume water and ΔT will be zero. As groundwater has an increasing effect on the sensor temperature, ΔT will increase, reflecting the temperature difference between the sensor and the surface water. If the sensor were to reach the groundwater temperature, and so was completely unaffected by surface water, ΔT would reach 100%. Values are rounded and approximate due to long durations required to reach thermal equilibrium, intermittency of flume and seep temperature measurements, and variability of seep velocities (Darcy velocity of 15 cm/h for most experiments, but some data were also collected at Darcy velocities down to 7.5 cm/h, without influence on results based on repeat tests done at both flow rates). For these reasons, we focus only on large differences in ΔT as indicating important performance differences. Several cover designs and thicknesses were tested, but results are for a 1.6 mm thick, flexible (durometer 40 A) polymer (EPDM) cover that extends about 3 cm beyond the probe ends and about 7 cm on each side, with the edges weighted with rocks or sand to hold the cover down and in position. Data are provided in supporting information S3.

^bVariability in results observed.

Several general features can be derived from the results presented in Table 1. In gravel, seeps are detected best in the absence of current, with optimal performance with burial. Current degrades performance even if buried or covered, perhaps because the current forces flow through the gravel. For rocks on top of sand, performance is improved by placing the sensor down on the surface of the sand, between the rocks, rather than being placed on top of the rocks. Covering the sensor also enhances performance. Current degrades performance, but placement against the sand preserves some ability to detect seeps. Sand appears better suited to the method than gravel, with substantial seep impact on sensor temperature in most conditions. Burial and covering preserve performance even with currents.

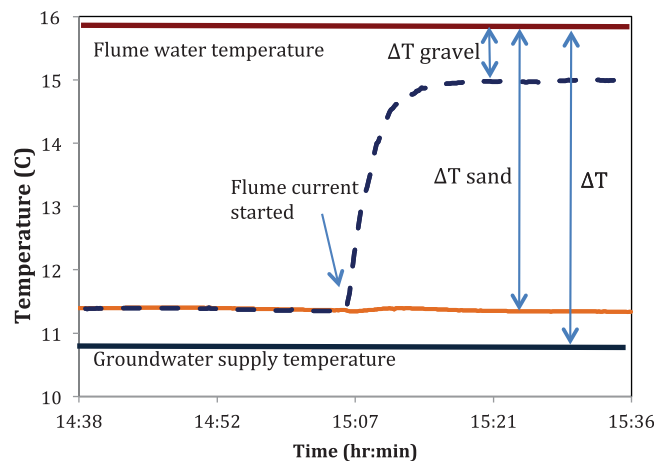


Figure 4. Example of data set from buried probe experiment with cool groundwater entering warmer flume water. The orange line is data from a probe buried 0.02 m in sand, dashed blue line is probe buried 0.02 m in gravel. Both are equally cooled by seep until flume current begins at 0.125 m/s, rinsing warmer flume water through the gravel, reducing the temperature effect of the seep on the probe in gravel (ΔT gravel), but not in sand (ΔT sand). Here temperatures are corrected for a 2°C/h heating rate of the system due to the energy from the pumping system and flume and seep temperatures are estimates.

The performance of the sensor in each circumstance is consistent with whether groundwater remains in proximity to the sensor prior to mixing. For example, current eliminates the signal unless

the sensor is protected by either burial in a limited-permeability material (sand) or sealed against the surface of such a material with a sealing, insulating cover. Current-driven flow within gravel prevented even buried or covered sensors from detecting seeps. Seep density did not have clear effects.

Seep rate was also adjusted, and did not change qualitative results, but changed the sizes of signals and differentials in sensitivity between alternative configurations (data not shown; data are available for analysis in supporting information S3). For example, when comparing sensors on top of rocks in the presence of a buoyant seep, the benefit of the cover diminished as seep velocity increased.

4. Discussion and Conclusions

Our findings reinforce the hypothesis that temperature sensors located at the surface of sediment or a few centimeters below that surface, which are typical locations for DTS, can detect seeps. However, findings also highlight the sensitivity of the method to details of the installation. Details of flows and convection, which may be hard to visualize and vary on small spatial and temporal scales, affect performance. The values obtained were particular to the experimental setup, but the qualitative results are general. Given the complexity of water movement, a seepage flume that matches a natural system being investigated offers insights regarding field results that are difficult to adequately model. However, questions of scale and the feasibility of matching natural systems in a flume must be considered.

The effectiveness of burial creates both challenge and opportunity. A key challenge is the sensitivity to depth of burial, particularly in the presence of currents. At the same time, a sensor buried in a permeable substrate with nonbuoyant seeps will be highly sensitive to currents, since the seep will “fill” the substrate in the absence of current, but will be rinsed away in the presence of currents. This may create opportunities for high sensitivity in places with transient currents, such as tidally affected waters. The test flume provided clear evidence of the importance of the details of installation to observed temperature signals. These results will assist interpretation of temperature findings in field applications, and could be extended to the utility of alternative approaches, such as heated cables [Sayde *et al.*, 2010] and multiple cables [Mamer and Lowry, 2013].

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References

- Blume, T., S. Krause, K. Meinikmann, and J. Lewandowski (2013), Upscaling lacustrine groundwater discharge rates by fiber-optic distributed temperature sensing, *Water Resour. Res.*, *49*, 7929–7944, doi:10.1002/2012WR013215.
- Constantz, J. (2008), Heat as a tracer to determine streambed water exchange, *Water Resour. Res.*, *44*, W00D10, doi:10.1029/2008WR006996.
- Dingman, S. L. (2008), *Physical Hydrology*, 2nd ed., Waveland Press, Long Grove, Ill.
- Hassan, M. A., D. Tonina, R. D. Beckie, and M. Kinnear (2014), The effects of discharge and slope on hyporheic flow in step-pool morphologies, *Hydrol. Processes*, doi:10.1002/hyp.10155, in press.
- Hoes, O. A. C., W. M. J. Luxemburg, M. C. Westhoff, N. C. van de Giesen, and J. Selker (2009), Identifying seepage in ditches and canals in polders in the Netherlands by Distributed Temperature Sensing, *Lowland Technol. Int.*, *11*(2).
- Krause, S., T. Blume, and N. J. Cassidy (2012), Investigating patterns and controls of groundwater up-welling in a lowland river by combining Fibre-optic Distributed Temperature Sensing with observations of vertical hydraulic gradients, *Hydrol. Earth Syst. Sci.*, *16*(6), 1775–1792.
- Lauer, F., H.-G. Frede, and L. Breuer (2013), Uncertainty assessment of quantifying spatially concentrated groundwater discharge to small streams by distributed temperature sensing, *Water Resour. Res.*, *49*, 400–407, doi:10.1029/2012WR012537.
- Lautz, L. K., and R. E. Ribaudo (2012), Scaling up point-in-space heat tracing of seepage flux using bed temperatures as a quantitative proxy, *Hydrogeol. J.*, *20*, 1223–1238.
- Luce, C. H., D. Tonina, F. Gariglio, and R. Applebee (2013), Solutions for the diurnally forced advection-diffusion equation to estimate bulk fluid velocity and diffusivity in streambeds from temperature time series, *Water Resour. Res.*, *49*, 488–506, doi:10.1029/2012WR012380.
- Mamer, E. A., and C. S. Lowry (2013), Locating and quantifying spatially distributed groundwater/surface water interactions using temperature signals with paired fiber-optic cables, *Water Resour. Res.*, *49*, 7670–7680, doi:10.1002/2013WR014235.
- Mwakanyamale, K., F. D. Day-Lewis, and L. D. Slater (2013), Statistical mapping of zones of focused groundwater/surfacewater exchange using fiber-optic distributed temperature sensing, *Water Resour. Res.*, *49*, 6979–6984, doi:10.1002/2012WR015257.
- Sayde, C., C. Gregory, M. Gil-Rodriguez, N. Tuffillaro, S. Tyler, N. van de Giesen, M. English, R. Cuenca, and J. S. Selker (2010), Feasibility of soil moisture monitoring with heated fiber optics, *Water Resour. Res.*, *46*, W06201, doi:10.1029/2009WR007846.
- Selker, J. S., L. Thévenaz, H. Huwald, A. Mallet, W. Luxemburg, N. van de Giesen, M. Stejskal, J. Zeman, M. Westhoff, and M. B. Parlange (2006a), Distributed fiber optic temperature sensing for hydrologic systems, *Water Resour. Res.*, *42*, W12202, doi:10.1029/2006WR005326.
- Selker, J. S., N. van de Giesen, M. Westhoff, W. Luxemburg, and M. Parlange (2006b), Fiber optics opens window on stream dynamics, *Geophys. Res. Lett.*, *33*, L24401, doi:10.1029/2006GL027979.
- Stonestrom, D. A., and J. Constantz (Eds.) (2003), *Heat as a tool for studying the movement of groundwater near streams*, Circ. 1260, U.S. Dep. of the Inter., U.S. Geol. Surv., Reston, Va.
- Vogt, T., P. Schneider, L. Hahn-Woernle, and O. A. Cirpka (2010), Estimation of seepage rates in a losing stream by means of fiber-optic high-resolution vertical temperature profiling, *J. Hydrol.*, *380*, 154–164, doi:10.1016/j.jhydrol.2009.10.033.