GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L24401, doi:10.1029/2006GL027979, 2006

Click Here for Full Article

Fiber optics opens window on stream dynamics

John Selker,[1] Nick van de Giesen,[2] Martijn Westhoff,[2] Wim Luxemburg,[2] and Marc B. Parlange[3]

Received 27 September 2006; revised 7 November 2006; accepted 15 November 2006; published 19 December 2006.

[1] A new approach to monitoring surface waters using distributed fiber optic temperature sensing is presented, allowing resolutions of temperature of 0.01°C every meter along a fiber optic cable of up to 10,000 m in length. We illustrate the potential of this approach by quantifying both stream temperature dynamics and groundwater inflows to the Maisbich, a first-order stream in Luxembourg (49°47′N, 6°02′E). The technique provides a very rich dataset, which may be of interest to many types of environmental research, notably that of stream ecosystems. **Citation:** Selker, J., N. van de Giesen, M. Westhoff, W. Luxemburg, and M. B. Parlange (2006), Fiber optics opens window on stream dynamics, *Geophys. Res. Lett.*, *33*, L24401, doi:10.1029/2006GL027979.

1. Introduction

[2] Detailed temperature distributions of streams and lakes can provide hydrologists, ecologists, and geochemists with new insights into the dynamics of these water bodies. Surface water temperature is controlled by a complex ensemble of processes [*Boyd and Kasper*, 2003]. Precise temperature measurements in space and time have been valuable in quantifying these processes via inverse modeling [*Kobayashi*, 1985; *Shanley and Peters*, 1988; *Constantz*, 1998]. To date, two strategies for stream temperature measurement have been employed: time-series measurements at a set of points, and snapshot measurements across space [*Torgersen et al.*, 1999]. In this article we present a new approach using a fiber optics Distributed Temperature Sensor (DTS), typically used in industrial process control, which makes it possible to monitor stream temperature continuously in both time and space, along a fiber optic cable of up to 10,000 m. With a particularly rugged cable (BRUsens, Brugg Cables, Switzerland), we demonstrate the system's capabilities through quantification of groundwater inflow into the Maisbich, a small stream in Luxembourg (49°47′N, 6°02′E).

[3] Stream flow is determined by gains and losses from groundwater stores, and by direct runoff during intense rainfall or snowmelt. Where groundwater or runoff enters a water body, there is typically a shift in water temperature. Groundwater has more stable temperatures than surface water, which is affected by energy exchange with the atmosphere and radiation. Groundwater inflows are often localized, in which case abrupt changes in temperature may be observed due to local groundwater upwelling. Whether abrupt or distributed, it is possible to compute groundwater inflow through measurement of stream temperatures [*Constantz*, 1998].

2. Materials and Methods

[4] Raman-backscatter Distributed Temperature Sensing (DTS) along multimode fiber optic cable was employed using the Sensornet system (Sentinel DTS-LR, London, England) with temperature precision of 0.01°C every meter. The principle behind the measurements is that parts of a laser pulse sent into the cable is reflected back along the cable. By timing the return time, the distance from where the light was reflected can be calculated. Most energy will be reflected at the wavelength of the original pulse, but part of the energy will be absorbed and re-emitted at shorter and longer wavelengths. These frequency-shifted reflections are called Raman-backscatter. The reflection with the longer wavelength is referred to as Stokes backscatter, and has an amplitude that is not temperature dependent. The reflection with the shorter wavelength is called Anti-Stokes backscatter, and has an amplitude that linearly depends on temperature. By measuring the Stokes/Anti-Stokes ratio, one can measure the temperature everywhere along the cable. For a detailed overview of fiber-optic temperature measurements, see *Selker et al.* [2006]. The system consists of a dedicated desktop computer with built-in data-acquisition and processing software. The system is almost plug-and-play because it immediately produces ASCII files with temperatures along the attached fiber optics cable. Normally, a fiber optics cable would be too vulnerable to use in the field. This problem was overcome by using a stainless-steel housed fiber (BRUsens, Brugg, Switzerland) that was impact and tensile resistant. The thickness of the steel housing is only one millimeter, giving the cable a mass of only seventeen grams per meter. In laboratory tests monitoring abrupt step-wise changes in temperature with time, it was found that more than 95% of the real change in temperature was apparent within the 15 seconds minimum time between readings. Since we are here considering only changes in temperatures separated by hours, the responsiveness of the device is not significant to this analysis. An added advantage of stainless steel housing is that it gives the cable a high density so it stays in the same position on the streambed. The cable was installed by laying it on the streambed and fixing it by placing stones from the streambed on or right next to the cable at approximately fifty centimeter intervals. At the end of the measurement period, the stones were still in place, from which it can be assumed that the cable had not moved.

[1]Department of Biological and Ecological Engineering, Oregon State University, Corvallis, Oregon, USA.
[2]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands.
[3]School of Architecture, Civil and Environmental Engineering, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

0094-8276/06/2006GL027979$05.00

Figure 1. Topographic map of the Maisbich, indicating the positions of the upper and lower v-notches, which are 600 m apart.

[5] The upper 1100 m of the Maisbich in central Luxembourg was studied (Figure 1). The area of the watershed of this stream is 1.16 km^2. The mean stream slope is steep (8%) as are the side slopes bordering the stream (15% to 35%). The geology consists of fractured slate with near-vertical strata. The soils are shallow (0–30 cm) and the proximity of the bedrock prohibits installation of piezometers to directly monitor groundwater level and temperatures. The stream bed is stony with a well-graded matrix composed of silts and sands of local origin. The soils are shallow throughout and the bedrock is visible at many places in the streambank. Consequently, the aquifers are close to the surface and have relatively small local recharge areas.

[6] Three v-notch stream gauges (logged each 10 minutes, calibrated May 2, 2006) were installed in the main stream, and one on its major tributary. Cable positions (CP) are reported as distance from the uppermost v-notch, which was installed where flow coalesced into a recognizable stream. The fall is continuous with riffles and step-pools ($\prec$ 1 m cross-section, $\prec$ 20 cm high steps) and one 30 m section of cascading falls (CP 575 m to 605 m). Past the second v-notch, the stream joins a stream of approximately equal flow (CP 607 m). It should be emphasized that the stream is very small indeed with average flows between one and two liters per second.

[7] Analysis of groundwater temperatures and inflows uses the energy balance over a control section into which a source flows:

$$Q_i^j \cdot T_i^j + Q_g^j \cdot T_g^j = Q_o^j \cdot T_o^j \qquad (1)$$

with stream flow, Q, temperature, T, at time j. Water entering the control section has subscript i, outflow has subscript o, and groundwater inflow has subscript g. With conservation of mass, $Q_o^j = Q_i^j + Q_g^j$, the ratio of Q_i^j and Q_g^j is:

$$\frac{Q_i^j}{Q_g^j} = \frac{T_o^j - T_g^j}{T_i^j - T_o^j} \qquad (2)$$

[8] Equations similar to those above are given by *Kobayashi* [1985]. If T_g is known, the outflow for any given time (no j superscript) is:

$$Q_o = Q_i \cdot \left[\frac{T_g - T_i}{T_g - T_o}\right] \qquad (3)$$

[9] Points must be identified above and below the source where surface water and groundwater are well-mixed. Inflow and outflow temperatures were estimated by projecting the slope of the inflow and outflow temperatures to the center of the mixing reach. Projected lines were fit to temperature data for 10 m on either side of the mixing reach. Lines with poor fits (sum of residuals $\succ$ 0.15°C), were rejected from analysis. Lines need to be fit because the spatial variability of temperature in small and shallow streams, such as the Maisbich, is very large. Point measurements with a standard thermometer showed temperature variations of more than one degree Celsius within a single cross-section. These rapid variations over space are caused by the fact that small differences in local warming and cooling have a large effect on this small stream. Because the distributed temperature method measures with a high spatial resolution (1 m), enough data are actually available to obtain good fits. With point-wise temperature measurements, it would be very difficult to obtain similarly reliable results. Figure 2 shows examples of the fitting and projecting of line into the mixing reach.

[10] Groundwater temperatures were estimated using two methods. For the first method, it is assumed that inflows, outflows, and influent groundwater temperatures be constant over the period of analysis. The period of analysis was,

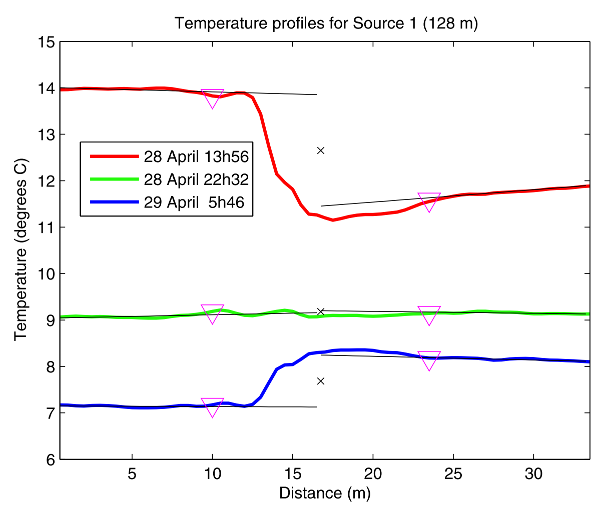

Figure 2. Temperature profiles just up- and downstream from the uppermost source (CP 128) for three times. The red line shows the large cooling effect that the source has during the early afternoon, the blue line shows the warming up by the source during the night. The green line is flat, indicating that at 22h32 the source temperature is equal to the up- and downstream water temperature. The triangles mark the beginnings and endings of the mixing region and the ×-s mark the centers. The thin black lines are the regression lines over 10 m up- and downstream from the mixing region, extrapolated from the triangle to the ×-s.

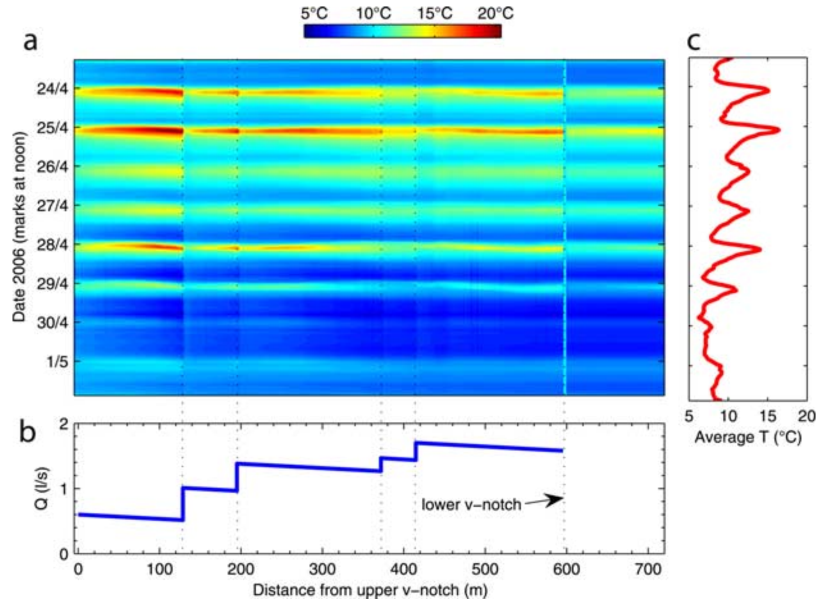

Figure 3. (a) Temperature distribution over time (vertically) and space (horizontally). (b) Amount of water flowing through the stream with the gains from the different sources and the losses as inferred from the temperature profiles and the up- and downstream v-notch measurements. (c) Average temperature development over time with sunny days early on and cloudy days toward the end of the measurement period.

in this case, one day, during which no rainfall or surface runoff was observed. The inflow at the top and the outflow at the bottom of the reach, as measured by the V-notches, varied within three percent of the average. With these almost constant flows, groundwater temperature can then be calculated using temperatures upstream and downstream of the groundwater inflow at two times:

$$T_g = \frac{T_o^m \Delta T^n - T_o^n \Delta T^m}{\Delta T^n - \Delta T^m} \quad (4)$$

[11] Where ΔT^m is the change of temperature across the input at time m, and ΔT^n the change at time n.

[12] The second method can be used when inflow temperature varies in such a way that it brackets the groundwater temperature. In this case, water temperature will be constant over the control section at a certain time. The temperature at that moment is equal to groundwater temperature. When both methods give very similar results, the confidence in the methods would be large.

3. Results

[13] The fiber optic system provided data along the cable for every two minutes. Independent of the environment in which the measurement takes place, the accuracy of the temperature measurement depends on the number of laser pulses that underlie the measurement. The standard deviation of the measurement error reduces with the square root of time. For the system used here, this means that when values are averaged over one hour periods, temperature is measured for each meter of stream length with 0.01°C precision (Figure 3a). Figure 3a clearly shows the richness of the dataset with spatial discontinuities where sources exist. The data also reveal the daily patterns, with the warming up of the stream downstream from sources during the day, and cooling of during the night. Also the differences from day to day become clear, with sunny days at the beginning of the period and cloudy days toward the end.

[14] These measurements revealed the location of four groundwater sources, at 128 m, 202 m, 371 m, and 414 m. For the 8.5 days of data analyzed, the respective averaged groundwater source temperatures found, using the constant temperature method, with standard deviations given in parentheses, were 9.08 (0.25)°C, 8.70 (0.15)°C, 8.77 (0.25)°C, 8.44 (0.15)°C. An overview of the main results is given in Table 1. At these sources, bedrock was visible in the streambank, as is the case at many places along the stream. Given the fact that the geology consists of near-vertical strata, there is no reason to assume that the different sources are fed by one aquifer with one temperature, which is reflected in the slightly different temperatures. In this relatively small headwater catchment, one would only expect large temperature differences if the groundwater pathways through the respective aquifers are very different. Such may be the case when sources are fed by recharge relatively far from the sources. The measured source temperatures are almost equal, which strongly suggests that all sources are fed locally. All temperatures are close to the April air temperature of 8.0°C, and to the average yearly Luxembourg air temperature of 8.3°C. Because the monthly and yearly air temperatures happen to be almost the same as the groundwater temperature, we can not conclude if the groundwater temperature is stable over the year or follows air temperature. Statistically, only the highest and lowest sources differ significantly in temperature at the 95% level.

[15] Using the data from April 28 and 29, we employed the temperature differences upstream and downstream (equation (4)) from the sources during day and night [*Kobayashi*, 1985], we found groundwater source temperatures of 9.32°C, 8.80°C, 8.86°C, and 8.84°C. These may be compared to those found using the constant temperature

Table 1. Overview of Flow and Groundwater Temperature Results[a]

Feature	CP, m	T_{mean}, °C	sd, °C	2Δ T, °C	Const T, °C	Q, l/s
Upper v-notch	0					0.60
Source 1	128	9.08	0.25	9.32	9.18	1.01
Source 2	202	8.70	0.15	8.80	8.83	1.38
Source 3	371	8.77	0.25	8.86	8.99	1.47
Source 4	414	8.44	0.15	8.84	8.64	1.70
Lower v-notch	605					1.58

[a]Nine day period mean temperature (T_{mean}) with standard deviation (sd), groundwater temperature result with two-time method (2Δ T) for April 28 and 29, constant temperature method (Const T) for April 28, and calculated discharge just downstream from the feature (Q).

method just before 11 PM on April 28 of 9.18°C, 8.83°C, 8.99°C, and 8.64°C, respectively. Figure 2 shows the temperature profiles for these dates that were used for the analysis for the most upstream source. The methods are very consistent, showing the robustness and consistency of the two groundwater temperature estimation methods for this stream.

[16] When differences between upstream and downstream temperatures are known for two times, relative groundwater inflow can be calculated using equation (2). Through v-notches, the inflow and the outflow of the Maisbich were measured directly. The temperature information then allowed us to calculate the inflow from each source as well as the average flow losses per unit length. Around April 28, the four sources contributed 0.49 l/s, 0.42 l/s, 0.20 l/s, and 2.6 l/s. The loss rate from the stream was found to be $0.66 * 10^{-6}$ l/s m (Figure 3b). As with all tracer-type methods, losses from the stream can not be localized directly. An abrupt gain from a source will lead to an abrupt temperature change. A loss, be it gradual or abrupt, only results in a gradual change of the temperature profile due to changes in warming or cooling. Losses can only be resolved if a complete coupled mass and energy balance is available for the stream. Here, we assume that the losses are equally distributed along the stream. A pattern of gradual loss is reasonable when the losses consist of water from the stream infiltrating into the steambanks due to the increased stage. Clearly, without the DTS observations, it would not have been possible to conclude that both gains and losses do occur between the v-notches. It is of course possible that the sinks along the streams are just as sharp as the sources but the likelihood is low because such sinks would quickly be plugged due to silting or clogging of fractures.

4. Conclusions

[17] Our interpretation provides insight into the hydrology of the stream. Temperature measurements along the fiber-optic cable allow for precisely locating groundwater sources along the stream. The precision is such that the temperature of the groundwater sources can be established with two different methods. With the groundwater temperatures, it was possible to determine the relative contribution of each source. The same temperature data would be of great value to ecologists for identifying ecotomes in rivers. Identification of habitat extent and migration patterns based on time-temperature criteria [*Torgersen et al.*, 1999] can be employed to determine the extent of expected distribution of selected species. Similarly, temperature- dependent water quality and geo-chemical models can be improved with measured temperature values at high temporal and spatial resolution. The expectation is that this technique will find many applications in environmental sciences.

[18] **Acknowledgments.** This research was in part supported by the Water Research Centre Delft. The support by the municipality of Ettelbruck is gratefully acknowledged, as is the field support by Jan Friesen, Jens Liebe, Martine Poolman, Martin Baptist, Rémy Schilperoort, Ellen Tromp, and Bas Baartman.

References

Boyd, M., and B. Kasper (2003), Analytical methods for dynamic open channel heat and mass transfer, technical report, Oreg. Dep. of Environ. Qual., Portland, Oreg.

Constantz, J. (1998), Interaction between stream temperature, streamflow, and groundwater exchanges in Alpine streams, *Water Resour. Res.*, *34*(7), 1609–1615.

Kobayashi, D. (1985), Separation of snowmelt hydrograph by stream temperatures, *J. Hydrol.*, *76*, 155–162.

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 (2006), Distributed fiber optic temperature sensing for hydrologic systems, *Water Resour. Res.*, *42*, W12202, doi:10.1029/2006WR005326.

Shanley, J. B., and N. E. Peters (1988), Preliminary observations of streamflow generation during storms in a forested Piedmont watershed using temperature as a tracer, *J. Contam. Hydrol.*, *3*, 349–365.

Torgersen, C. E., D. M. Price, H. W. Li, and B. A. McIntosh (1999), Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon, *Ecol. Appl.*, *9*(1), 301–319.

W. Luxemburg, N. van de Giesen (corresponding author), and M. Westhoff, Department of Water Management, Delft University of Technology, 2628 CN Delft, Netherlands. (n.c.vandegiesen@tudelft.nl)

M. B. Parlange, School of Architecture, Civil and Environmental Engineering, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland.

J. Selker, Department of Biological and Ecological Engineering, Oregon State University, Corvallis, OR 97331, USA.