Ground Water Monitoring&Remediation

Evaluation of an Inexpensive Small-Diameter Temperature Logger for Documenting Ground Water–River Interactions

by Adam N. Johnson, Brian R. Boer, William W. Woessner, Jack A. Stanford, Geoffrey C. Poole, Steven A. Thomas, and Scott J. O'Daniel

Abstract

Increasing numbers of studies are recording detailed temperature data for characterization of ground water–stream exchange. We examined laboratory and field operation of a small-diameter, stand-alone and inexpensive temperature logger capable of investigating stream–ground water exchange was examined. The Thermochron iButton is a 17.35-mm-diameter by 6-mm-thick instrument that costs <$10 when ordered in quantity. Testing of the loggers in a controlled temperature bath revealed a precision of ±0.4°C and an accuracy of ±0.5°C for a group of 201. More than 500 loggers have been installed in channels and in subchannel and floodplain ground water environments in two gravel-bedded rivers in the western United States. Loggers were placed as single devices and in vertical arrays in monitoring wells with diameters of 10.16, 5.08, 2.54, and 1.9 cm. We determined that the loggers have four principal advantages over more commonly used wired and currently available stand-alone logging devices: (1) the wireless nature does not require the instrument location to be associated with a control-recording system; (2) the small size allows for installation in small hand-driven or direct-push monitoring wells and thus intimate contact of the instruments with the hydrologic environment; (3) multiple loggers are easily suspended in a single fully perforated monitoring well, allowing for the collection of high-resolution temperature profile data; and (4) the low cost of the loggers allows for the deployment of large numbers, thus improving spatial resolution in shallow ground water floodplain scale studies.

Introduction

Spatial and temporal patterns of temperature in aquifers result from (1) conduction due to temperature gradients and/or (2) advection, the movement of heat with ground water flow (Stallman 1963; Malard et al. 2001). Temperature is an important physical parameter that is used in concert with ground water flow and transport studies to address a number of aspects of ground water systems (Stonestrom and Constantz 2003). Examples include ground water flow in the vicinity of Yucca Mountain (Painter et al. 2003), quantification of recharge (Ferguson et al. 2003), and identification of the interaction between ground water and streams draining glaciers (Malard et al. 2001). Lapham (1989) used temperature data to estimate ground water velocity and aquifer hydraulic conductivity. In the past decade, ground water scientists have investigated the use of temperature to characterize the rates and timing of water exchange between river channels and the underlying ground water system (e.g., Lapham 1989; Silliman and Booth 1993; Silliman et al. 1995; Constantz and Thomas 1996; Constantz et al. 2001; Bartolino and Niswonger 1999; Constantz et al. 2002; Constantz et al. 2003). Temperature has also been used to map zones of ground water recharge and discharge in riparian areas (e.g., White et al. 1987; Dumouchelle 2001).

Hydrogeologists are becoming more involved in efforts to characterize stream–ground water exchange as they join teams of multidisciplinary researchers who assess natural stream function and develop methods for stream renaturalization (Woessner 2000). As ground water scientists expand into this area in both research and education, they recognize the advantage of being able to identify the time-varying, three-dimensional temperature distribution in channel, subchannel, and floodplain settings (e.g., Stonestrom and Constantz 2003). Standard monitoring methods used to characterize these systems include handheld point temperature probes, wired thermistors, and stand-alone temperature logging devices.

In our research, we sought a wireless stand-alone logging tool that could be installed in small-diameter wells located in the stream channel, subchannel sediments, and the floodplain, and was inexpensive enough so that hundreds of devices could be deployed simultaneously. A sensor originally developed for the food shipment industry was evaluated under laboratory and field conditions to determine if it could be used to characterize temperature distributions in streams and associated ground water systems.

Temperature Monitor

A search for wireless/stand-alone monitors revealed a number of commercially available tools which did not meet our criteria of low cost and small size, and one that did, the Thermochron iButton (Dallas Semiconductor, Dallas, Texas; http://www.ibutton.com/) (Table 1). These loggers were initially developed for monitoring temperature-sensitive cargo during transportation and storage and have seen other creative applications (e.g., recording the temperature history of curing concrete). Although the devices have seen limited application in ecological and physiological studies (Badyaev et al. 2003; Mzilikazi et al. 2002; Shine et al. 2003), we are not aware of their application in hydrogeologic investigations.

There are several versions of temperature logging iButtons; the DS1921Z-F5 best suited our needs (Table 1). The logger is a little more than 17 mm in diameter and considerably smaller than other stand-alone loggers (Table 1; Figure 1). Communication with the device occurs through a receptor that is pressed onto the surface of the instrument (supplied by Dallas Semiconductor for $15). Data are downloaded via a computer or personal digital assistant. Each logger has a unique identification code, allows for a variety of sampling regimes, and can be used for multiple deployments (2048 measurements at a time) up to a maximum of one million total measurements over the lifetime of the device.

According to the manufacturer, the loggers are water resistant; the manufacturer successfully tested the devices under 1 m of water for 1 h. We discussed the proposed submerged use of the loggers with the manufacturer, and they suggested coating the flange between the logger top and bottom with a sealant such as clear nail polish to improve water resistance. However, we found this practice did not improve the longevity of the loggers. As a result, we tested and installed only uncoated loggers in investigations, deployed to depths of up to 5 m for as long as 12 months. We did find that one company, Kooltrak Inc. (North Palm Beach, Florida; http://www.kooltrak.com/), offers waterproof iButtons (continuous operation at up to 100 m depth) for a cost of $84 each. A researcher studying lakes successfully deployed the loggers to depths of >15 m (Wayne Wurtsbaugh, personal communication, 2004). After using the loggers in the field as received directly from the manufacturer for 20 months, we suggest that efforts to further seal these tools are not necessary when used to depths of our testing (up to 5 m).

For our needs, the iButton logger had four principal advantages over more common wired and stand-alone logging devices (Table 1): (1) the wireless nature does not require the instrument to be located near a control-recording system; (2) the small size allows for installation in small-diameter, hand-driven or direct-push monitoring wells and thus provides for intimate contact of the instruments with the hydrologic environment; (3) multiple loggers are easily suspended in a single, fully perforated monitoring well allowing for the acquisition of high-resolution temperature profile data; and (4) the low cost of the loggers allows for detailed spatial and temporal resolution since ~10 instruments can be deployed for the price of one currently available stand-alone recorder (Table 1). The minimum time interval of 1 min is longer than that of some other loggers and may preclude accurate assessment of rapidly changing temperatures (i.e., applied heat tracer experiments). More recently developed (and not reviewed here), higher-performance iButtons are available with improved resolution (read to 0.0625°C), greater recording interval range

Table 1
Selected Stand-Alone Temperature Loggers: Manufacturer's Specifications

Logger Name	iButton DS1921Z-F5	Minilog 8 bit	Stowaway Tidbit	Optic Stowaway 8k	Levelogger
Company	Dallas Semiconductor	Vemco Ltd.	Onset Computer Corp.	Onset Computer Corp.	Solinst
Cost per logger[1]	$13[2]	$135	$119	$129	$850[3]
Readings stored	2048	8000	32,520	7943	48,000
Battery life (years)	10[4]	5	5	6	8 to 10
Accuracy (°C)	1.0[5]	0.2	0.2	0.2	0.1
Resolution (°C)	0.125[6]	0.1	0.2	0.2	0.01
Range (°C)	−5 to 26[6]	−4 to 20	−4 to 37	−4 to 38	−20 to 80
Sampling interval	1 m to 4.25 h	1 s to 6 h	0.5 s to 9 h	0.5 s to 9 h	0.5 s to 99 h
Weight (g)	3	41	23	54	160
Dimensions (mm)	17.35 × 6	22 × 95	30 × 41× 17	123 × 20 × 25	22 × 125

[1]Cost of loggers often requires additional start-up costs for logger readers, computer adapters, and software.
[2]Most manufacturers offer quantity discounts. For example, when iButtons are ordered in lots of 100, the cost is $9.31 each.
[3]Records water level and temperature.
[4]Or 1 million measurements.
[5]0.5°C recorded in this study.
[6]iButtons with a −20°C to 85°C range are available with a resolution of 0.5°C.

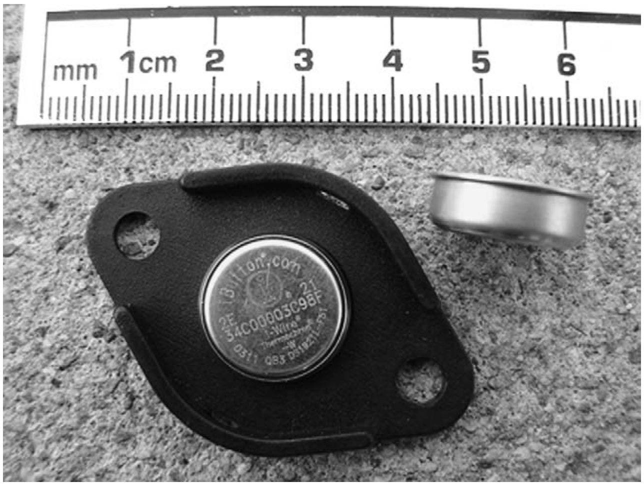

Figure 1. iButtons with mounting bracket. Unique identification code is stamped onto top of stainless steel housing. Side view is on the right.

(1 s to 273 h), greater storage (8192 data points), and greater cost ($17.25 to $41.50 ea.) (http://www.maxim-ic.com/products/ibutton/ibuttons/thermochron.cfm).

Laboratory Testing

In an effort to check the manufacturer's claims of ±1°C accuracy (Table 1), predeployment testing and calibration experiments were conducted in a constant-temperature water bath. Two hundred and one loggers were held at 11 temperatures ranging from 0.4°C to 25.9°C for at least 20-min durations. The true (standard) temperature was monitored with an American Society for Testing and Materials (ASTM)-certified mercury thermometer (uncertainty <0.05°C). The manufacturer's reported accuracy of ±1.0°C captures 100% of the observed variability (Figure 2). The iButtons tested did not behave uniformly over the selected temperature range and generally read lower than the standard temperature at high temperatures and higher than the standard temperature at low temperatures (Figure 2). The median error across all 201 loggers was <0.1°C across the range of temperatures from 6°C to 26°C. At the lower range of temperatures, the error was slightly larger. Individual button calibration data was used to correct field measurements and make all measurements comparable based on the ASTM calibration temperatures.

In order to assess whether the iButtons tended to drift over time, a group of previously calibrated and deployed loggers was placed in a stream (at 8.4°C to 8.7°C) with an ASTM thermometer. Eighteen loggers had been field deployed over a 6- to 7-month period, and 54 loggers had been in place for <1 month. These data suggest that the iButtons do not behave uniformly over time and should be calibrated at least every half year (Figure 3). Original lab calibration at a number of temperatures was necessary for this comparison, and only the lab calibration results closest to the temperature of the stream were used (7.3°C to 9.6°C). For studies requiring an accuracy of near 1°C, recalibration (or even calibration) may be unnecessary.

Field Design and Installation

The loggers were deployed in a variety of wells using a number of methods. Polyvinyl chloride (PVC) wells (10.16, 5.08, and 2.54 cm in diameter, perforated over various intervals) and 1.9-cm-diameter, perforated steel pipes were used. The larger-diameter wells were typically installed in the floodplain, while the smaller-diameter piezometers were installed in river bars and directly in the channel bottom. In the simplest case, a single logger was positioned adjacent to a perforated interval by attaching it to a logger bracket and cable and lowering it into place. To characterize the temperature distribution in wells with long perforated intervals, multiple loggers were attached to a single cable and suspended in the well. A third installation technique was developed using an inexpensive logger-baffle system to isolate portions of a perforated section of a well to limit borehole water circulation. This design was

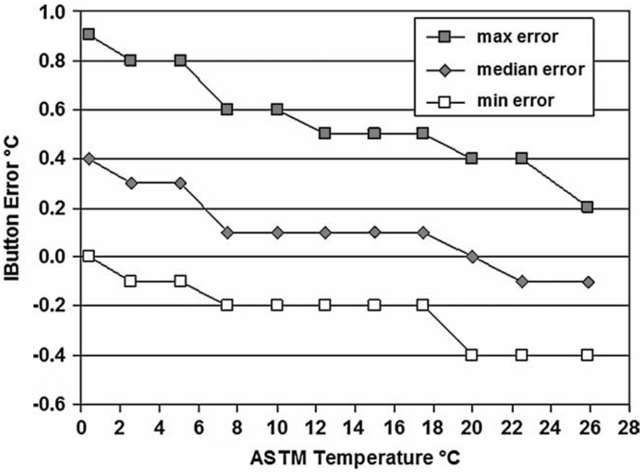

Figure 2. Results of calibration testing for 201 iButtons. Median iButton error = median iButton temperature−ASTM standard temperature.

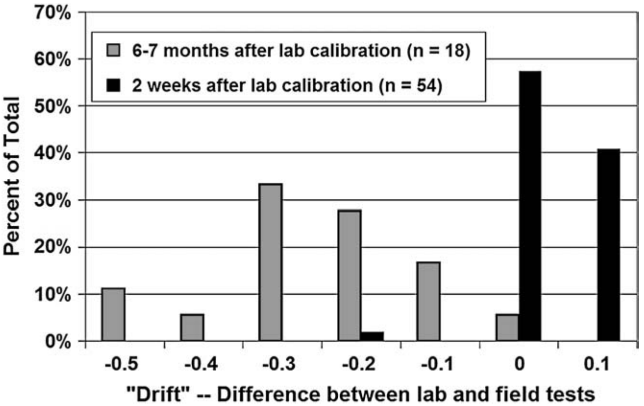

Figure 3. Drift analysis. Drift value of 0 indicates that the field-measured corrected value was the same as the lab-measured corrected value.

also adapted for use in the 1.9-cm-diameter steel wells installed in the stream channel and floodplain vadose zone.

The baffle system consisted of a rigid piece of PVC or hot water–grade PVC, typically 1.9 or 1.27 cm in diameter, to which instruments were either screwed in place using a manufacturer's bracket or placed in a pair of threaded PVC couplers glued into the center blank rod (Figure 4A). When couplers were used, holes were drilled into this section of pipe to allow water contact with the instrument (Figure 4A). Next, a section of pipe, 15 to 20 cm long, above and below the iButton was wrapped with a piece of closed-cell insulating foam typically used to insulate home hot water pipes. The insulation (such as manufactured by Industrial Thermopolymer, Brampton, Ontario, Canada, or a similar material) is available as tubes with a slit along the length so that it can be fit onto a pipe. Depending on the inside diameter of the well, different diameters and widths of the foam were used so that the baffle just fit into the casing (a small amount of resistance would occur as the packer was inserted or removed). If the size of the baffle needed some reshaping, duct tape was used to wrap the outside of the foam to assure a better fit. The baffle system was pushed into the well by hand and seated at the desired depth. When the iButtons needed to be accessed, the center rod and baffles were removed and the iButtons downloaded and restarted.

For piezometers placed in the river, a 1.9-cm-diameter steel pipe perforated at selected intervals was outfitted with a vertical iButton array using a modified version of the baffle system described for the larger-diameter wells. Figure 4B illustrates the piezometer setup and installation of iButtons. After insertion of the center rod into the piezometer, the iButtons, washers, and foam baffles were installed. The foam is pushed to the desired depth using a 1.27-cm PVC pipe and serves to support the iButtons at the perforations. In Figure 4B, the uppermost iButton measures surface water temperature. A PVC cap protects the top of the instrumentation and is held in place by drilling two holes in the sides and installing screws until tight with the steel pipe. For instrument retrieval, the PVC cap is removed and the exposed portion of the steel rod is pulled up, bringing the iButtons, washers, and foam to the surface (Figure 4B).

Field Testing and Applications

More than 500 iButtons were deployed in the channel and floodplains of two study sites: the Umatilla River, Oregon, and the Middle Fork of the Flathead River, Montana. These river and floodplain systems carry streams with mean annual discharges of ~11 and 70 m^3/s, respectively. Channel and floodplain sediments are composed of sand, gravel, and cobbles. Average horizontal hydraulic conductivity (200 to 1000 m/d), horizontal gradient determinations (0.001 to 0.005), and estimates of porosities (0.15 to 0.20) suggest ground water velocities average from 1 to 26 m/d and exceed 300 m/d in some locations.

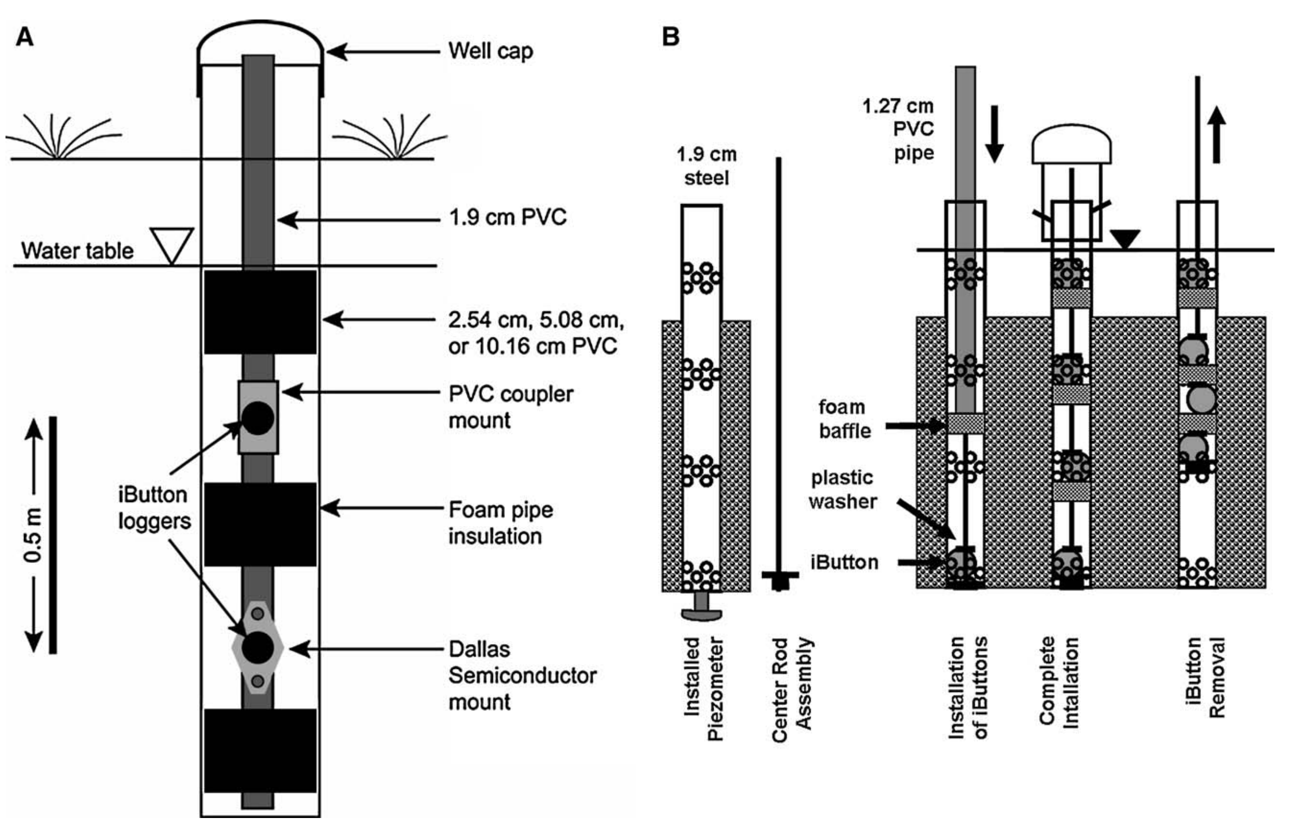

Figure 4. (A) Well baffle system for iButton installation in PVC monitoring wells that are 2.58 cm to 10.16 cm in diameter. (B) iButton installation and removal in a 1.90-cm-diameter steel piezometer with multiple perforated intervals installed in the stream channel. The piezometer is pulled back slightly to remove the drive bolt from the end. The center rod assembly consists of a 0.32-cm-diameter steel rod threaded at the end with washer and nut attached. A description of the installation procedure is in the text.

Floodplain and channel monitoring wells we instrumented with single and multiple loggers in baffled and unbaffled installations. Instruments were submerged up to 5 m below the water table and have been operating for up to 12 months under field conditions. To date, 8% of 500 loggers tested and/or field deployed have failed. The brackets supplied by the manufacturer worked well to suspend strings of instruments in open and fully perforated wells and to secure the loggers to the central rod in baffled wells. At one site, >130 instruments were installed in a study area of 25 hectares to characterize temporal, three-dimensional stream-floodplain exchange.

The data recorded by loggers were of similar quality to those reported in the literature from multiple-wired thermisters and the few studies that have used stand-alone loggers (Bartolino and Niswonger 1999; Constantz and Thomas 1996; Constantz et al. 2001; Constantz et al. 2003; Lapham 1989; Silliman et al. 1995; Stallman 1963; Stonestrom and Constantz 2003). Figure 5 shows results from a 1.9-cm-diameter well containing baffled loggers placed in a losing stream channel (vertical hydraulic gradient measured independently as −0.29). The data show diel temperature variations during August 2004. The deeper data points reflect advective transport and the nonconservative behavior of the stream-generated temperature pulse. These processes delayed the arrival of the temperature peak. The combined cost of the four temperature loggers used to instrument this well was ~$40.

As an illustration of the versatility of these instruments, vertical baffled arrays were placed in a floodplain transect (along a flowline) where river water was flowing into the adjacent floodplain (Figure 6). The use of 15 iButtons

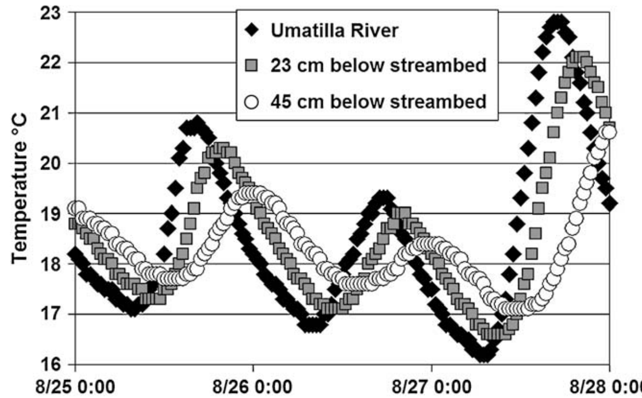

Figure 5. Vertical temperature profiles below the bed of a section of losing stream (Umatilla River, Oregon) in August 2004. The x-axis shows month and day (8/25) and the 0:00 represents midnight on that day. The 95% confidence interval for all measurements is ±0.4°C.

allowed for evaluation of the thermal response of the ground water to a saturated depth of ~3 m over a distance of 33 m. The time sequence shows that 23°C river water entered the shallow floodplain ground water system during the day. The high temperature pulse (generated by diel variations in river temperature) migrated and deteriorated over the next 16 h.

Other Ground Water Applications

The small diameter and low cost of the iButtons seems likely to spawn additional applications by ground water scientists. Recording of ground water and surface water

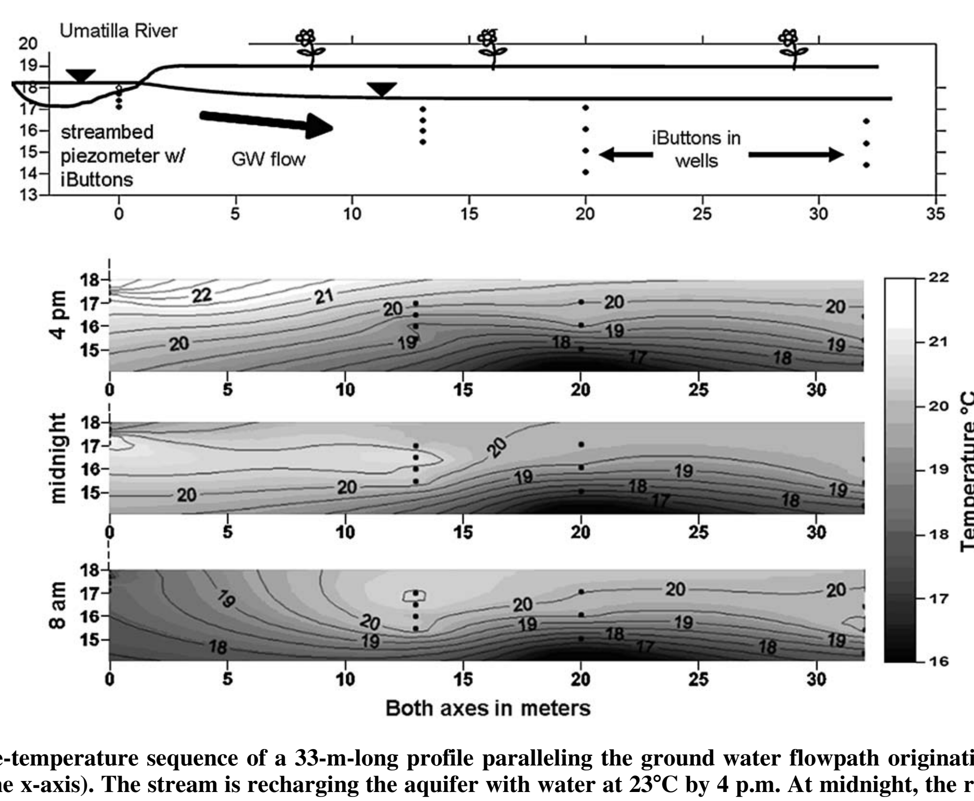

Figure 6. A time-temperature sequence of a 33-m-long profile paralleling the ground water flowpath originating at the Umatilla River (~0m on the x-axis). The stream is recharging the aquifer with water at 23°C by 4 p.m. At midnight, the river was 19°C, and it dropped to 18°C by 8 a.m. The solid dots represent iButtons in vertically baffled arrays.

temperatures as we have demonstrated is as easy as calibrating the loggers and installing them in wells or surface water. For example, other applications include the use of vertical arrays of instruments in the vadose zone to detect and establish the timing of recharge and to document the role of surface heating on shallow ground water temperatures (Constantz and Thomas 1996; Constantz et al. 2002). They can also be used to monitor heat tracer tests in conductive aquifers as described by Constantz et al. (2003). We are currently examining this application. We are also evaluating the use of vertical sequences of iButtons to monitor river and ground water stages. For example, by exploiting the difference between diel patterns of air and water temperature, continuous logging of river stage is possible by placing iButtons at multiple levels on a stream gauge. The time at which an iButton is immersed by an increase in river stage corresponds to the time at which the thermal record abruptly shifts from air to water temperature. The development of additional applications and reporting of the advantages and limitations of using these tools in other settings is encouraged.

Discussion and Conclusions

The iButton provides ground water scientists and stream ecologists with a low-cost, self-contained tool to collect temporally variable, two-dimensional and three-dimensional temperature data. At two floodplain research sites we are investigating, >500 iButtons (an ~$5000 investment) have been deployed and are operating. The cost of using standard stand-alone instruments (Table 1) at these research sites would exceed $50,000, with additional costs being incurred to construct wells of sufficient diameter to hold the instruments.

Our efforts to examine, in laboratory and field settings, the performance of the iButtons are presented to introduce the reader to a new tool that we believe will expand the collection of temperature data in stream/ground water studies. The reader is referred to the references cited in the Introduction, including the work of Stonestrom and Constantz (2003), for presentations of appropriate methodologies used to interpret the data collected.

Our experience suggests that iButtons generate accurate data. Because of their small size and low cost, the loggers are appropriate tools to characterize complex, three-dimensional temperature distributions in stream and floodplain systems, though more accurate loggers may be required for sites where thermal variations are very small. Since our application only required shallow deployments (<5 m) for <12 months, iButton functionality at greater depths or longer times is unknown. Nonetheless, our initial evaluation has been positive. The loggers should provide many different types of environmental scientists with an appropriate, flexible, and affordable tool for monitoring temperatures over time.

Acknowledgments

This work was supported by a variety of sources including the University of Montana Department of Geology, the National Science Foundation under Grant No. EAR-0120523, a NASA Earth Science Enterprise, Stennis Space Center, MS. Grant No. NAG13-02030, BPA Innovative Project No. 5044, and a fellowship from the Inland Northwest Research Alliance. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the supporting agencies. We are grateful to our reviewers and thank Jim Constantz for his valuable suggestions.

References

Badyaev, A.V., M.L. Beck, G.E. Hill, and L.A. Whittingham. 2003. The evolution of sexual size dimorphism in the house finch. V. Maternal effects. *Evolution* 57, no. 2: 384–396.

Bartolino, J.R., and R.G. Niswonger. 1999. Numerical simulation of vertical ground-water flux of the Rio Grande from ground-water temperature profiles, central New Mexico. USGS Water Resources Investigations Report 99–4212. USGS, Reston, Virginia.

Constantz, J., M.H. Cox, and G.W. Su. 2003. Comparison of heat and bromide as ground water tracers near streams. *Ground Water* 41, no. 5: 647–656.

Constantz, J., A.E. Stewart, R. Niswonger, and L. Sarma. 2002. Analysis of temperature profiles for investigating stream losses beneath ephemeral channels. *Water Resources Research* 39, no. 12: 52-1 to 52-3.

Constantz, J., D.A. Stonestrom, A.E. Stewart, R.G. Niswonger, and T.R. Smith. 2001. Evaluating streamflow patterns along seasonal and ephemeral channels by monitoring diurnal variations in streambed temperature. *Water Resources Research* 37, no. 2: 317–328.

Constantz, J., and C.L. Thomas. 1996. The use of streambed temperature profiles to estimate depth, duration, and rate of percolation beneath arroyos. *Water Resources Research* 32, no. 12: 3597–3602.

Dumouchelle, D.H. 2001. Evaluation of ground-water/surface-water relations, Chapman Creek, west-central Ohio, by means of multiple methods. USGS Water-Resources Investigations Report 01-4202. USGS, Reston, Virginia.

Ferguson, G., A.D. Woodbury, and G.L.D. Matile. 2003. Estimating deep recharge rates beneath an interlobate moraine using temperature logs. *Ground Water* 41, no. 5: 640–646.

Lapham, W.W. 1989. Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity. USGS Water Supply Paper 2337 USGS, Reston, Virginia.

Malard, F., A. Mangin, U. Uehlinger, and J.V. Ward. 2001. Thermal heterogeneity in the hyporheic zone of a glacial floodplain. *Canadian Journal of Fisheries and Aquatic Sciences* 58, no. 7: 1319–1335.

Mzilikazi, N., B.G. Lovegrove, and D.O. Ribble. 2002. Exogeneous passive heating during torpor arousal in free-ranging rock elephant shrews, *Elephantus myurus*. *Oecologia* 133, no. 3: 307–314.

Painter, S., J. Winterle, and A. Armstrong. 2003. Using temperature to test models of flow near Yucca Mountain, Nevada. *Ground Water* 41, no. 5: 657–666.

Shine, R., M.J. Elphick, and E.G. Barrot. 2003. Sunny side up: Lethally high, not low, nest temperatures may prevent oviparous reptiles from reproducing at high elevations. *Biological Journal of the Linnean Society* 78, no. 3: 325–334.

Silliman, S.E., J. Ramirez, and R.L. McCabe. 1995. Quantifying downflow through creek sediments using temperature time series: One-dimensional solution incorporating measured surface temperature. *Journal of Hydrology* 167, no. 2: 99–119.

Silliman, S.E., and D.R. Booth. 1993. Analysis of time-series measurements of sediment temperatures for identification of gaining vs. losing portions of Juday Creek, Indiana. *Journal of Hydrology* 148, no. 1–4: 131–148.

Stallman, R.W. 1963. Computation of ground-water velocity from temperature data. In *Methods of Collecting and Interpreting Ground-Water Data*, ed. R. Bental, H36–H46. USGS Water-Supply Paper 1544-H. USGS, Reston, Virginia.

Stonestrom, D.A., and J. Constantz, ed. 2003. Heat as a tool for studying the movement of ground water near streams. USGS Circular 1260. USGS, Reston, Virginia.

White, D.S., C.H. Elzinga, and S.P. Hendricks. 1987. Temperature patterns within the hyporheic zone of a northern Michigan river. *Journal of the North American Benthological Society* 6, no. 2: 85–91.

Woessner, W.W. 2000. Stream and fluvial plain ground-water interactions: Re-scaling hydrogeologic thought. *Ground Water* 38, no. 3: 423–429.

Biographical Sketches

Adam Johnson *received a B.A. in geology from Macalester College and an M.S. in hydrogeology from the University of Montana. He has worked for the U.S. Geological Survey on water quality projects in Virginia, Vermont, and Montana. He currently teaches earth sciences and hydrology at the Environmental Science Department, Salish Kootenai College, PO Box 70, Pablo, MT 59855; (406) 275-4897; adam_johnson@skc.edu.*

Brian R. Boer*, corresponding author, is a Ph.D. candidate in the Department of Geology, University of Montana, 32 Campus Drive, Missoula, MT 59812; (406) 550-3464; brian.boer@umontana.edu, boerbrian@hotmail.com. His dissertation research focuses on heat and water exchange between streams and alluvial floodplain aquifers.*

Scott J. O'Daniel*'s research interests in floodplain landscapes have included passive and active remote sensing, temperature interactions, and machine learning. He is currently a graduate student in geography at the University of California—Santa Barbara. He is particularly interested in water temperature dynamics of alluvial floodplains in the interior Pacific Northwest. During the past 8 years, he has been supported by the Confederated Tribes of the Umatilla Indian Reservation, 72329 Confederated Way, Pendleton, OR 97801; (805) 886-5232; sodaniel@icess.ucsb.edu.*

Geoffrey C. Poole *applies simulation models, remote sensing, and GIS to study interactions among geomorphology, hydrology, and ecology in floodplain and river networks. He operates an independent ecosystem research firm, Eco-metrics Inc., 2520 Pine Lake Road, Tucker, GA 30084-3611, and is an adjunct faculty member at the University of Georgia's Institute of Ecology, Ecology Building, University of Georgia, Athens, GA 30602-2202; (770) 621-0266; gpoole@eco-metrics.com.*

Jack A. Stanford *is the Jessie M. Bierman professor of ecology and director of the Flathead Lake Biological Station, Division of Biological Sciences, University of Montana, Poison, MT 59860-9659; (406) 982-3301, ext. 235; fax (406) 982-3201; jack.stanford@umontana.edu, where he has worked since 1971.*

Steve A. Thomas*' research addresses the two predominant and competing characteristics of streams, downstream transport and in situ retention of nutrients and energy, by focusing on the linkage between hydrology and ecology. He may be reached at Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, NY 14853; (607) 255-1067; sat43@cornell.edu.*

William W. Woessner *has been teaching applied hydrogeology at the University of Montana since 1981 including classes in hydrogeology, advanced hydrogeology, ground water modeling, applied ground water modeling, surface water–ground water interaction, and ground water remediation. He was named a Regents' Professor in 2005. He received his B.A. in geology from the College of Wooster, an M.S. in geology from the University of Florida, and an M.S. in water resources management and a Ph.D. in geology (hydrogeology with a minor in civil and environmental engineering) from the University of Wisconsin—Madison. He may be reached at Department of Geology, University of Montana, 32 Campus Drive, Missoula, MT 59812; (406) 243-5698; willlam.woessner@umontana.edu.*