North American Journal of Fisheries Management 31:134–137, 2011

ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1080/02755947.2011.561172

MANAGEMENT BRIEF

An Evaluation of Underwater Epoxies to Permanently Install Temperature Sensors in Mountain Streams

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Abstract
Stream temperature regimes are of fundamental importance in understanding the patterns and processes in aquatic ecosystems, and inexpensive digital sensors provide accurate and repeated measurements of temperature. Most temperature measurements in mountain streams are made only during summer months because of logistical constraints associated with stream access and concerns that large annual floods will destroy sensor installations. We assessed six underwater epoxies to determine whether sensors could be attached to large rocks already in streams to provide durable installations and whether temperature measurements would be biased by heat conduction through the rocks. Only one of the six test epoxies bonded the sensors firmly to rock surfaces in laboratory trials. In subsequent field trials, 9 of 11 sensors attached to rocks with this epoxy successfully weathered above-average floods in four Idaho and Nevada streams in 2010. Comparisons of daily maximum, minimum, and mean temperatures between rock-mounted sensors and control sensors at 10 rocks suggested temperature measurements were not biased by attachment to rocks. We also assessed the effect of direct sunlight on sensors by removing solar shields from some sensors and noted rapid and statistically significant increases in daily means (+0.21°C) and maxima (+0.54°C), but not minima (−0.01°C). Use of underwater epoxy for permanent installation of temperature sensors in mountain streams is a viable technique if an appropriate epoxy is chosen, sensors are shielded from direct sunlight, and rocks large enough to withstand floods are used. Moreover, installations using epoxy are rapid (approximately 20 min), and firm attachments to rock surfaces over a range of stream temperatures (5–20°C) are possible.

Thermal regimes are fundamental to understanding aquatic ecology given the ectothermic physiologies of most aquatic organisms. Increasing evidence suggests that significant departures from historical thermal conditions are underway in response to a warming climate (Hari et al. 2006; Isaak et al. 2010b; Kaushal et al. 2010; Rieman and Isaak 2010). Although considerable amounts of stream temperature data are now routinely collected with inexpensive digital temperature sensors, most data in mountain streams are collected during the summer after annual snowmelt floods have abated and logistical access to mountain streams is easiest. This provides a narrow view of stream thermal regimes and misses ecologically relevant information such as the date of spring onset, the annual accumulation of thermal units, and length of the growing season (Neuheimer and Taggart 2007; Olden and Naiman 2009). Moreover, it is inefficient to visit field sites twice each year (first to install a sensor, second to retrieve the sensor), especially when many modern temperature sensors have batteries and memory capacities that often last several years.

Collection of annual stream temperature data has been limited in mountain streams because it requires labor-intensive instrumentation of permanent sites capable of withstanding large annual floods associated with snowmelt runoff. Typically, steel cables or other obtrusive structures are used to hold temperature sensors in streams but oftentimes instrument loss rates remain high. An ideal installation method would require minimal effort and materials, be largely foolproof, and provide durable installations that withstand floods and associated bed load movement. Moreover, it would be desirable if installations were relatively innocuous so that sensors were not stolen or vandalized during lengthy deployments. Here, we report on an assessment of underwater epoxies to directly attach temperature sensors to large rocks in mountain streams. Our study had two primary objectives: (1) to determine whether sensors attached to rocks with epoxy could withstand annual floods and (2) to determine whether attachment to rocks biased temperature measurements from heat conduction through the rock. As a secondary objective, we also tested whether the lack of a solar shield affected temperature measurements.

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Received September 16, 2010; accepted November 12, 2010

METHODS

Numerous temperature sensors are commercially available, but the TidbiT version 2 Temperature Data Logger[2] (UTBI-001 TidbiT version 2; Onset Computer Corporation, Pocasset, Massachusetts) was selected for use in these trials because of its compact size (35 mm diameter; 23 g) and durable, waterproof casing made of high-density plastic. These sensors are also good choices for long-term deployments because of relatively large memories and battery lives (up to 5 years) and the capacity for in situ data retrievals with an underwater data shuttle (U-DTW-1 HOBO Waterproof Shuttle, Onset Computer Corporation, Pocasset, Massachusetts). The manufacturer specifications describe a measurement precision of ±0.2°C for the TidbiT version 2, which is close to the precision we observed in calibration trials with 266 sensors in a common temperature environment (95% of sensors were within 0.17°C of the average temperature).

During initial laboratory trials, six underwater epoxies were assessed for possible inclusion in field trials: (1) AquaMend from Polymeric Systems, Inc., (2) AquaStik from DuPont, (3) Waterweld from J-B Weld Company, (4) Mr. Sticky's Underwater Glue from Advanced Adhesion, Inc., (5) HIT-RE 500 from Hilti, and (6) FX-764 Splash Zone Epoxy from Fox Industries. Each epoxy was used to glue four TidbiT sensors (two sensors each within a cold- [5°C] and warmwater bath [20°C]) to the surface of cobble-sized rocks (30 cm^2) obtained from local streams. After waiting 2 d (which exceeded the time specified by the manufacturers for the epoxies to set), attempts were made to pry the sensors from the rocks by hand and to dislodge them with a chisel. Only two products (Mr. Sticky and FX-764) were sufficiently difficult to remove from the rock surfaces that they were deemed viable candidates for subsequent field trials.

To assess the first objective regarding whether sensors attached to rocks with epoxy could withstand large floods, we attached 16 sensors to four large rocks (four sensors per rock, two sensors with each epoxy) in Mores Creek, a steep stream draining a forested catchment in central Idaho. Sensor attachment occurred during low flows in February 2010 at stream temperatures of approximately 5°C. Rocks selected for sensor attachment were large relative to the other rocks comprising the channel bed and were chosen for their assumed immobility during floods. Sensors were attached to the downstream side of rocks, which allowed the bulk of the rock to act as a shield against bed load movement and debris during subsequent floods. Another selection criterion for these rocks was that they had relatively flat, vertical, downstream attachment surfaces that were in water sufficiently deep to ensure submersion for the entire year. More details regarding rock selection criteria and specific steps that were followed to attach sensors with epoxy are described in a companion user's guide that is available for download through the Boise Aquatic Sciences Laboratory Stream Temperature website (Isaak et al. 2010a).

Two weeks after the Mores Creek installations, we equipped three additional rocks in three small, high-gradient northern Nevada streams with single sensors with the FX-764 Splash Zone Epoxy. In total, therefore, 19 sensors (8 with Mr. Sticky and 11 with FX-764) were installed during low winter flows. All temperature sensors were set to record 18 or 24 temperatures each day and each sensor was outfitted with a solar shield that consisted of a flexible neoprene flap attached to the top of the sensor with plastic cable ties.

To assess the secondary objective regarding whether heat conduction through the attachment rocks could bias temperature measurements, we compared data from the Mores Creek sensors with control data over a 3–7-d period in late July with sensors suspended in short sections of open pipe (used as a solar shield) that were held on the stream bed with rocks. To provide a larger sample size for assessing possible heat-conduction effects, six additional rocks in six central Idaho mountain streams were equipped with single sensors with FX-764 during low flows in late July 2010 at water temperatures ranging from 10°C to 20°C. Control data were also collected at these sites as described above.

The stream sites where sensors were attached to rocks varied in wetted width from 2 to 15 m and had slopes from 0.2% to 7.1% (slope values were obtained from the National Hydrography Dataset–Plus available at: www.horizon-systems.com/nhdplus/). The rocks to which sensors were attached at these sites varied in size from 0.4 to 1.3 m^2 and had daily sun exposures that ranged from minimal (one small stream with a dense riparian canopy) to more than 8 h of direct sunlight during the summer. To assess whether the lack of a solar shield affected temperature measurements, we removed shields from one of the replicate sensors on three rocks in Mores Creek near the end of the field trial while control stream temperature data were being collected.

Temperature measurements were summarized by calculating a daily maximum, minimum, and mean temperature for each sensor on those days when control data were collected at a site. These daily values were averaged across days to obtain a single maximum, minimum, and mean temperature value for a sensor at a site. For the four rocks in Mores Creek with replicate sensors, the daily summary values were calculated as averages across the replicates before the subsequent averaging to determine the site values so that each rock constituted only a single observation in the analysis. The control values for a site were subtracted from the rock values and we tested whether the average differences in minima, maxima, and means across the 10 rocks were zero by calculating 95% confidence intervals (CIs) around the differences. To test the solar-shield effect, paired *t*-tests were used to examine differences in temperature metrics between sensors before and after removal of the solar shield. For this test, the control data were from a sensor attached to the same rock that retained its solar shield for the duration of the trial.

RESULTS AND DISCUSSION

Two days after the 16 sensors were installed on Mores Creek in February 2010, the sites were revisited to check initial attachment success. At that time, seven of the eight sensors attached with Mr. Sticky were easily removed from the rock surfaces by hand and this epoxy was dropped from further consideration. All of the sensors attached with FX-764 were strongly bonded to the rock surfaces and were left in place for exposure to subsequent floods later in the spring. Records from nearby U.S. Geological Survey gauges suggest that peak flows the following May and June were 12–15 times higher than flows at the time of sensor installations and the highest flows were 70–110% higher than the median peak flows based on the previous 50 years of gauge data. After flows subsided in mid-July, sites were revisited and 9 of 11 (82%) sensors attached with FX-764 the previous winter were successfully relocated and fully functional at their rock attachment sites. In one instance where a sensor was lost, the attachment rock had a low profile that may not have prevented substrates mobilized during high flows from traveling over the rock's surface. As these substrates dropped over the back of the rock, the sensor could have been impacted and dislodged from the rock surface. In the second instance of sensor loss, the bed of the channel was significantly restructured by large amounts of bed load transport and the sensor rock could not be relocated.

Stream temperatures measured with sensors attached to rocks differed by 0.03°C or less from those measured with control sensors and these differences were not statistically significant, as indicated by CIs that encompassed zero (Table 1). Significant differences were observed, however, in our assessment of the solar shield effect. Both mean temperatures (average difference across three rocks = +0.21°C; t-statistic = 15.0, $P = 0.04$) and maximum temperatures (average difference = +0.54°C; t-statistic = 39.1, $P < 0.01$) increased significantly after the removal of solar shields. Minimum stream temperatures did not change (average difference = −0.01°C; t-statistic = 0.33, $P = 0.46$). Solar effects were obvious in a graph of the temperature traces before and after the removal of a solar shield, as enhanced heating of the exposed sensor began each day with the incidence of direct sunlight on the sensor (Figure 1). Figure 1 also illustrates the strong overlap in temperature measurements among sensors at this site (two controls and two rock sensors) that was characteristic of patterns at other sites.

Based on the results from these field trials, we were confident enough in the FX-764 epoxy that it was used to install approximately 300 additional temperature sensors later in 2010 as part of a regional monitoring network of streams across the Pacific Northwest. These subsequent installations allowed us to apply the epoxy technique in a wide range of stream environments and to further refine the methods for attaching sensors to rocks (Isaak et al. 2010a). This additional experience leads us to conclude that selection of an appropriate rock is the most important step to establishing a durable sensor installation. The best rocks are those that not only remain immobile during floods, but also are wide and protrude well above the low flow water surface to provide an effective shield against moving rocks and debris. Application of these simple criteria would have prevented the use of several rocks included in our field trials and could have increased sensor retention rates above those observed.

Rocks suitable for sensor attachments are more common in some stream channels than in others; however, finding suitable rocks was the norm rather than the exception in the mountain streams we sampled. Once a suitable rock is located, it takes approximately 20 min for an experienced technician to install a sensor. The attached sensors are innocuous which should help minimize losses due to theft or vandalism. The FX-764 epoxy bonded strongly to rock surfaces across the range of stream temperatures we encountered but did become more fluid and friable as temperatures approached 20°C. Those interested in applications in warmer waters are advised to run additional tests

TABLE 1. Differences between stream temperature attributes measured with sensors attached to rocks and control sensors adjacent to rocks in July 2010. Differences were calculated by subtracting the control temperature values from the rock temperature values.

	Temperature attribute (°C)			
Stream site name	Minimum	Mean	Maximum	Sun exposure
Canyon Creek	0.10	0.00	−0.06	High
Grimes Creek, rock 1	−0.01	−0.02	−0.08	High
Grimes Creek, rock 2	0.06	0.02	−0.03	High
Little Rattlesnake Creek	0.07	0.02	−0.15	Medium
Mores Creek, rock 1	0.11	0.07	0.16	Low
Mores Creek, rock 2	−0.11	−0.07	−0.02	High
Mores Creek, rock 3	−0.13	0.10	0.31	Low
Mores Creek, rock 4	−0.03	0.01	0.16	High
No Name Creek	0.13	0.09	0.03	Low
Rattlesnake Creek	0.02	0.00	0.00	Medium
Average difference[a]	0.02 (−0.05, 0.09)	0.02 (−0.02, 0.06)	0.03 (−0.07, 0.13)	

[a]Values after the average differences are 95% confidence limits.

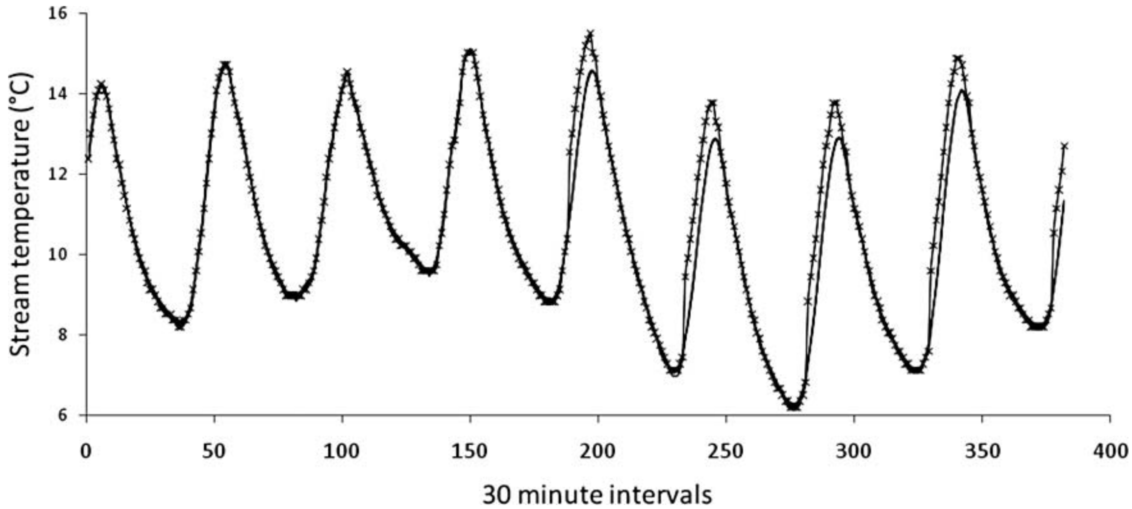

FIGURE 1. Stream temperatures measured with four sensors at a large rock in Mores Creek during an 8-d field trial in July 2010. Two sensors were attached to the rock with epoxy and two control sensors were adjacent to the rock. On day 5 (at time interval 185), the solar shield was removed from one of the two sensors attached to the rock (line with points marked with × symbols) to assess the effectiveness of the solar shield. Concordance among the temperature measurements makes it difficult to discern individual time-series.

to confirm the epoxy's performance. Another potential caveat is how well FX-764 would work with other temperature sensors that are larger or have casings constructed of different materials. We suspect these applications would prove successful, given the compact size of most temperature sensors and the propensity of the epoxy to form strong chemical bonds with rock, plastic, metal, and other materials, but again recommend that interested parties run their own tests. More problematic, in some instances, is that the strength of adhesion makes it difficult to remove sensors from the surface to which they are attached. A few well-placed blows with a chisel or screwdriver at the base of the epoxy, however, successfully displaces most sensors. Sensor removals are less of a concern if they are to be left in place for the duration of their service life, but may be relevant in studies with shorter-term data requirements.

In conclusion, the use of underwater epoxy to attach temperature sensors to rocks provides a reliable, easy, and unbiased means of collecting full-year data in mountain streams. When combined with inexpensive and accurate sensors, the epoxy technique could facilitate development of improved regional and river-basin temperature monitoring networks or sensor deployments for a host of ecological applications that could improve our understanding of thermal ecology in fish populations.

ACKNOWLEDGMENTS

This project was supported by the Rocky Mountain Research Station. An earlier draft of this manuscript was improved by comments from Brett Roper and Bruce Rieman. Mention of trade names does not imply endorsement by the U.S. Forest Service.

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