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Key Points:

- High-resolution, long-duration, intermittent stream flow, and temperature monitoring
- Provides relative conductivity information and can estimate specific conductivity
- Simple, low-cost, robust design, operates when frozen or buried in sediment

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Robust, low-cost data loggers for stream temperature, flow intermittency, and relative conductivity monitoring

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Abstract Water temperature and streamflow intermittency are critical parameters influencing aquatic ecosystem health. Low-cost temperature loggers have made continuous water temperature monitoring relatively simple but determining streamflow timing and intermittency using temperature data alone requires significant and subjective data interpretation. Electrical resistance (ER) sensors have recently been developed to overcome the major limitations of temperature-based methods for the assessment of streamflow intermittency. This technical note introduces the STIC (Stream Temperature, Intermittency, and Conductivity logger); a robust, low-cost, simple to build instrument that provides long-duration, high-resolution monitoring of both relative conductivity (RC) and temperature. Simultaneously collected temperature and RC data provide unambiguous water temperature and streamflow intermittency information that is crucial for monitoring aquatic ecosystem health and assessing regulatory compliance. With proper calibration, the STIC relative conductivity data can be used to monitor specific conductivity.

1. Introduction

Water temperature fundamentally influences aquatic ecosystem health, because the distribution, reproduction, fitness, and survival of ectothermic organisms are inextricably linked to the thermal regime of their environment [e.g., *Eaton et al*., 1995; *Rahel and Olden*, 2008; *McCullough et al*., 2009]. Similarly, many life-history characteristics of lotic organisms are tightly coupled to the natural flow regime as low flow conditions can define the lower extent of physical aquatic habitat availability, as well as the quality and hydrological connectivity of that habitat [*Poff et al*., 1997; *Lake*, 2003; *Levick et al*., 2008; *Rolls et al*., 2012]. In the contiguous USA, nearly 60% of streams are classified as ephemeral or intermittent and that proportion rises to 80–90% in the arid southwest U.S. [*Nadeau and Rains*, 2007; *Levick et al*., 2008]. In order to protect resident aquatic life from anthropogenic thermal influences, various U.S. states have recently developed or revised biologically based aquatic life water quality criteria for water temperature [e.g., *Todd et al*., 2008]. Similarly, the U.S. Environmental Protection Agency recently issued a proposed rule which clarifies protection of intermittent and ephemeral streams under the Clean Water Act [*U.S. Environmental Protection Agency*, 2014]. Monitoring and assessment of the compliance status of water bodies frequently requires the collection of site-specific, high temporal resolution, water temperature, and streamflow intermittency information.

Inexpensive digital temperature logger technologies are increasingly being employed for stream temperature monitoring, and many protocols have been developed to help ensure the quality of water temperature data, including guidance on instrument calibration, field deployment, and post recovery data processing and interpretation [e.g., *Schuett-Hames et al*., 1999; *Ward*, 2003; *Dunham et al*., 2005]. Temperature data "cleaning" (rejecting data where the temperature sensor is out of the water) is critical to ensure that the resultant water temperature data are accurate and reliable for decision-making purposes, but data "cleaning" methods that rely on human interpretation are inherently subjective [*Sowder and Steel*, 2012].

1.1. Prior Work on Intermittent Stream Sensors

Several novel approaches have been developed to measure and record the presence or absence of streamflow. Streambed thermograph arrays have been employed to infer the streamflow timing and extent through the visual and/or statistical interpretation of changes in the amplitudes of diel temperature signals [*Constantz et al*., 2001; *Blasch et al*., 2004; *Gungle*, 2005]. As noted above, interpretation of temperature logger data is subjective, time consuming, and subject to false indications of actual wet or dry conditions [*Blasch et al*., 2004].

In recent years, electrical resistance (ER) sensors have emerged as an alternative, cost-effective means of inferring streamflow intermittency. Most ER sensors use water contact electrodes which record a large signal when wet and a small or zero signal when dry [*Blasch et al*., 2002]. Previous ER studies have modified commercially available temperature loggers by removing the thermistor, adding water contact electrodes, and using the repurposed temperature circuitry to record ER response [*Blasch et al*., 2002; *Goulsbra et al*., 2009]. Similarly, "event state" sensors use water contact electrodes connected to external data loggers to record wet or dry conditions [*Fritz et al*., 2006; *Bhamjee and Lindsay*, 2011]. These types of ER sensors have successfully identified changes in flow condition in wetland, spring, and stream environments [*Blasch et al*., 2002; *Adams et al*., 2006; *Goulsbra et al*., 2009; *Bhamjee and Lindsay*, 2011; *Jaeger and Olden*, 2012]. Estimates of streamflow timing using ER sensors have been documented to be more accurate than temperature data interpretation methods [*Blasch et al*., 2002].

2. Methods: STIC Modifications

The STIC was designed to provide both water temperature and stream intermittency logging in one rugged, low-cost, easy to build instrument. The STIC was created by modifying an Onset HOBO Pendant waterproof temperature and light data logger (Model UA-002-64, ~\$65 USD, Onset Computer Corp, Bourne, MA, USA) (Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government). The STIC modifications repurposed the light sensor circuitry for electrical conductivity logging while preserving the temperature logging capability. Sample timing was user controlled and the nonvolatile data storage held over 28,000 temperature + relative conductivity measurements, providing 300 days at 15 min sampling or 600 days at 30 min sampling. STIC instrument control and data download used the Onset Base-U-4 USB Base Station or Onset U-DTW-1 waterproof shuttle, running standard HOBOware Pro software.

The external electrodes for the STIC loggers were made from 100 mm 24 gauge male-male jumper wires with chrome plated brass machine pin heads cut in half to create the two electrode pins (Digikey #438-1074-ND). The machine pin electrodes were coated with a two part marine epoxy (Fluid Polymers HMP-85 slow), inserted through predrilled holes on the underside of the housing cap, and carefully bent 90° so the electrical leads laid flat against the underside of the black housing cap. The machine pin electrodes extended a minimum of 3–4 mm from the top of the housing cap and were ~1.6 cm apart. Additional epoxy was applied around the machine pin electrodes to ensure a waterproof seal. After >24 h of drying, the waterproof housing was reassembled (without electronics) and submerged in 1 m of water for 48 h to test for leaks.

The coin battery was removed and the light sensor on the UA-002-64 board was carefully desoldered and discarded. The machine pin leads from a leak-tested black housing cap were trimmed to remove excess wire and soldered to the two exposed light sensor contact pads.

The battery was reinstalled and the desiccant pack was placed indicator side up on the electronics board below the battery holder. The housing cap and O-ring were inspected, lubricated with silicone grease, and the STIC was reassembled. Care was taken to insure that the electrode wires were not severely pinched by the electronics board during final assembly.

Protective field deployment housings for were constructed from 1.9 cm (3/4") PVC unions cut in half and the final housing dimensions were 5 cm wide by 6.3 cm tall. Holes were drilled into the PVC housings sides and STICs were attached to steel anchor stakes (45 cm with predrilled holes) with plastic coated 16 gauge wire (Figure 1). STICs were not attached by the lanyard loop on top of the black housing cap, since this increased the chance that the sensor electrodes could rub against the anchor wire and jeopardize the waterproof epoxy seal. Total STIC modification time was 15 min/unit (excluding epoxy drying) and we have built 40 STICs in 8 h of work time. The cost for the electronics parts, epoxy, PVC housing, and anchor stake was <\$10 USD/unit and the total cost for a field deployed STIC was <\$75 USD.

The unmodified HOBO light data channel measured light intensity from 0 to 330,000 lux with 10 bit resolution. With the light sensor removed and the electrodes connected, the light data channel now recorded an

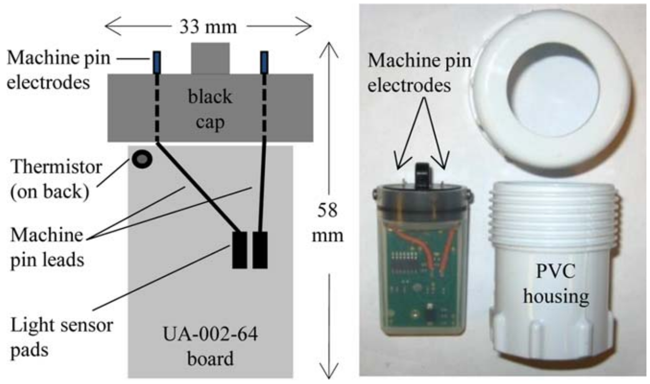

Figure 1. STIC electronics modifications and PVC deployment housing. The STIC can be concealed with rocks if vandalism is a concern.

electrical conductivity signal ranging from 0 in air to a maximum signal of 330,000 when a wire connected the two electrodes. Each STIC had a different electrical conductivity response so, instead of reporting raw signal, we will use the term Relative Conductivity (RC) to describe the STIC electrode response (%RC = current signal/maximum observed signal during deployment* 100).

Each STIC was laboratory tested for relative conductivity response with sampling rates of 5–60 s. Conductivity tests were performed by submerging STICs in a series of conductivity standards (Oakton) ranging from 84 to 2746 μS/cm. Temperature studies were performed in a Neslab RTE-7 digitally controlled temperature bath or a laboratory freezer. Sediment tests were carried out by pushing the STIC, electrode side down, into various sediments (fine sand, gravel, mud, etc.) and recording the STIC response.

STICs were deployed in small shallow streams in southern Colorado, USA to test their utility in long-term monitoring of stream temperature, intermittency, and relative conductivity. Our purpose in this paper is to illustrate the general capabilities of the STIC instrument with selected field data so detailed information about the stream sites and location (e.g., map) are not necessary or included. All field deployed STICs were set for 15 or 30 min sampling resolution with deployments lasting 2–12 months. Field RC data were temperature corrected to 25°C with the industry standard conductivity correction of 2.1%/°C. An Onset HOBO conductivity logger (model U24-001) was codeployed with a STIC for one deployment to compare specific conductivity estimates.

3. Results and Discussion

3.1. Comparison of STIC Design to Previous Intermittency Sensors

Previous low-cost (~$75-$150 USD) intermittency sensor designs used modified temperature loggers [*Blasch et al*., 2002; *Adams et al*., 2006; *Goulsbra et al*., 2009; *Jaeger and Olden*, 2012] or event state loggers connected to water contact electrodes [*Fritz et al*., 2006; *Bhamjee and Lindsay*, 2011]. These ER sensors did not measure stream temperature and, while adding a separate temperature logger would be simple, the cost and complexity of field deployments would increase. Intermittency sensors with stream bank data loggers connected by long wires to a separated ER sensing head were designed to minimize false "wet" readings due to sediment contact. However, these instruments were vulnerable to failures due to nonwaterproof data loggers, vandalism, and ER sensor wire breakage when struck by debris or animals [*Goulsbra et al*., 2009; *Bhamjee and Lindsay*, 2011].

Our goal with the STIC was to record both stream temperature and stream intermittency in a rugged, low-cost design. The STIC's small hardened machine pin electrodes eliminated the potentially fragile external wires used in designs with separated ER sensing heads. The waterproof in-stream design avoided weatherproofing issues associated with stream bank data loggers and the PVC deployment housing allowed the STIC to be concealed with rocks to deter vandalism. The screw-cap protective housing enabled quick deployments and on-site data retrieval and increased the number of field sites visited in a day and greatly reduced field costs. Our STIC design permitted stream intermittency detection during challenging conditions such as freezing conditions or sediment burial (sections 3.3 and 3.4), while the temperature corrected RC data presented useful information on stream water electrical conductivity (section 3.5). Our multifunctional STIC sensor simultaneously collected reliable data on the presence, timing, state (frozen or flowing), and quality (temperature and relative conductivity) of water flowing within a given stream.

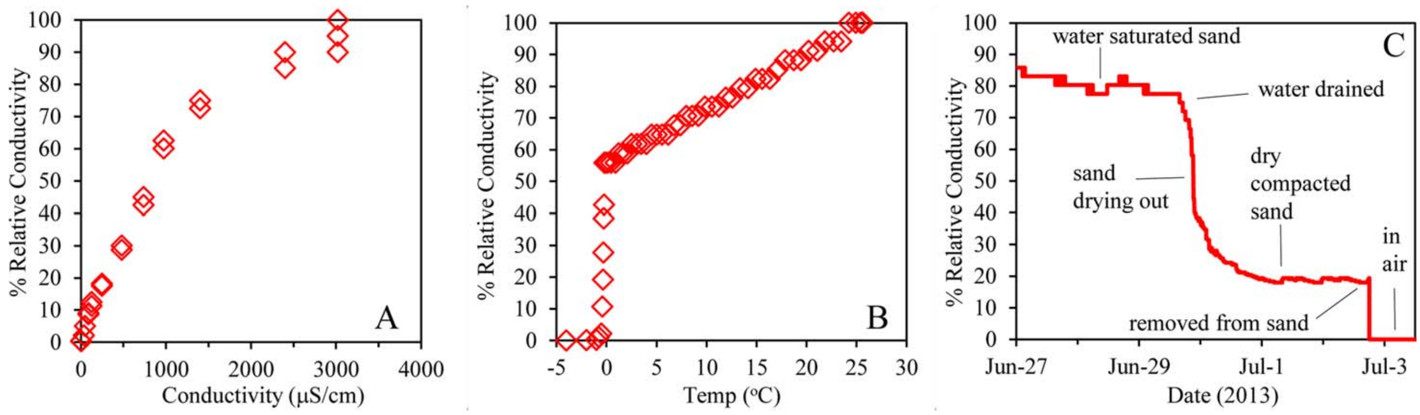

Figure 2. STIC RC response to water conductivity (a), temperature (b), and sediment contact (c) STICs showed a linear conductivity response up to 1000 µs/cm. Figure 2a Ion exclusion during ice formation led to a rapid decrease in RC as the electrodes were frozen in ice but the frozen ice signal (~0.5%) was distinguishable from an air signal (0%). Dry sediment in contact with the electrodes can complete the electrical circuit but the response is clearly discernable from a water or air signal in Figure 2c.

3.2. Laboratory Results

We have built over 250 STICs and the dry air response was always no signal (raw signal = 0), a result also observed with thermistor-based ER sensors [*Goulsbra et al*., 2009]. The STIC electrodes were very responsive to low-range conductivity changes. A linear relationship was documented in the laboratory between STIC RC response and water conductivity up to ~1000 μS/cm, with curvature observed from 1000 to 3000 μS/cm (Figure 2a). The STIC relative conductivity response from 1 to 1000 μS/cm was consistent across instruments with an average slope of 17 ± 1.6 μS/cm per 1% change in RC (R^2 =0.98, n=20). Functionally, the STIC acted as a simple two pole conductivity sensor without the precision electrodes and circuitry found in high-cost water conductivity loggers.

The STIC RC response was also sensitive to the changing water temperature (Figure 2b). A linear relationship between STIC RC response and temperature was observed when liquid water was present (slope = 1.7%/°C, R^2 = 0.99, n = 20), similar to the standard conductivity temperature correction of 2.1%/°C. When water around the STIC electrodes began to freeze, we observed ion exclusion during ice formation and a dramatic drop in the STIC RC signal from >60% at −0.2°C to 1–2% at −0.5°C (Figure 2b). At temperatures well below freezing (<−10°C), the STIC RC signal of ice was ~0.2% (raw signal =10–50) and the frozen ice RC signal was distinguishable from the zero signal of air.

STIC field deployments in watersheds with intermittent streams were likely to experience episodic flow events, stream bed movement, and sediment deposition. Sediment burial of STIC sensors was not a problem since the STIC RC response from electrode contact with sediment was easily distinguished from the water or air signal. A STIC was buried in fine grain quartz sand (>150 μm) with standing water above and the initial RC signal was a water signal of >80% demonstrating that water filled the void spaces in the sand (Figure 2c). Standing water was drained and the sand was allowed to dry out over several days. The compacted dry sand RC signal was ~18%, well above the air signal of zero (Figure 2c). Dried sand or mud can generate a STIC RC response since these materials can complete the electrical circuit between the electrodes, but sediment RC signals were clearly different from the air signal of zero. If one was concerned about sediment contact, the STIC PVC deployment housing provided the option for placing a plastic mesh screen (100 μm) above the electrodes to prevent sediment contact.

Precise and accurate water temperature readings are vital in the monitoring and assessment of regulatory water temperature standards. The Onset Pro-V2 is a widely used water temperature logger with 0.02°C resolution and a listed accuracy of 0.21°C. The temperature logger used in the STIC, also made by Onset, has 0.14°C resolution, a listed accuracy of 0.53°C. The STIC temperature response closely tracks the Pro-V2 (STIC Temp = 0.999*Pro-V2 temp + 0.198, n = 10, not shown). Both units have a similar thermal response time but we observed a +0.2°C average offset relative to the Pro-V2 at all temperatures (−5 to 30°C) and in all STICs tested (n>100). The 0.2°C offset most likely represented differences in the thermistor and

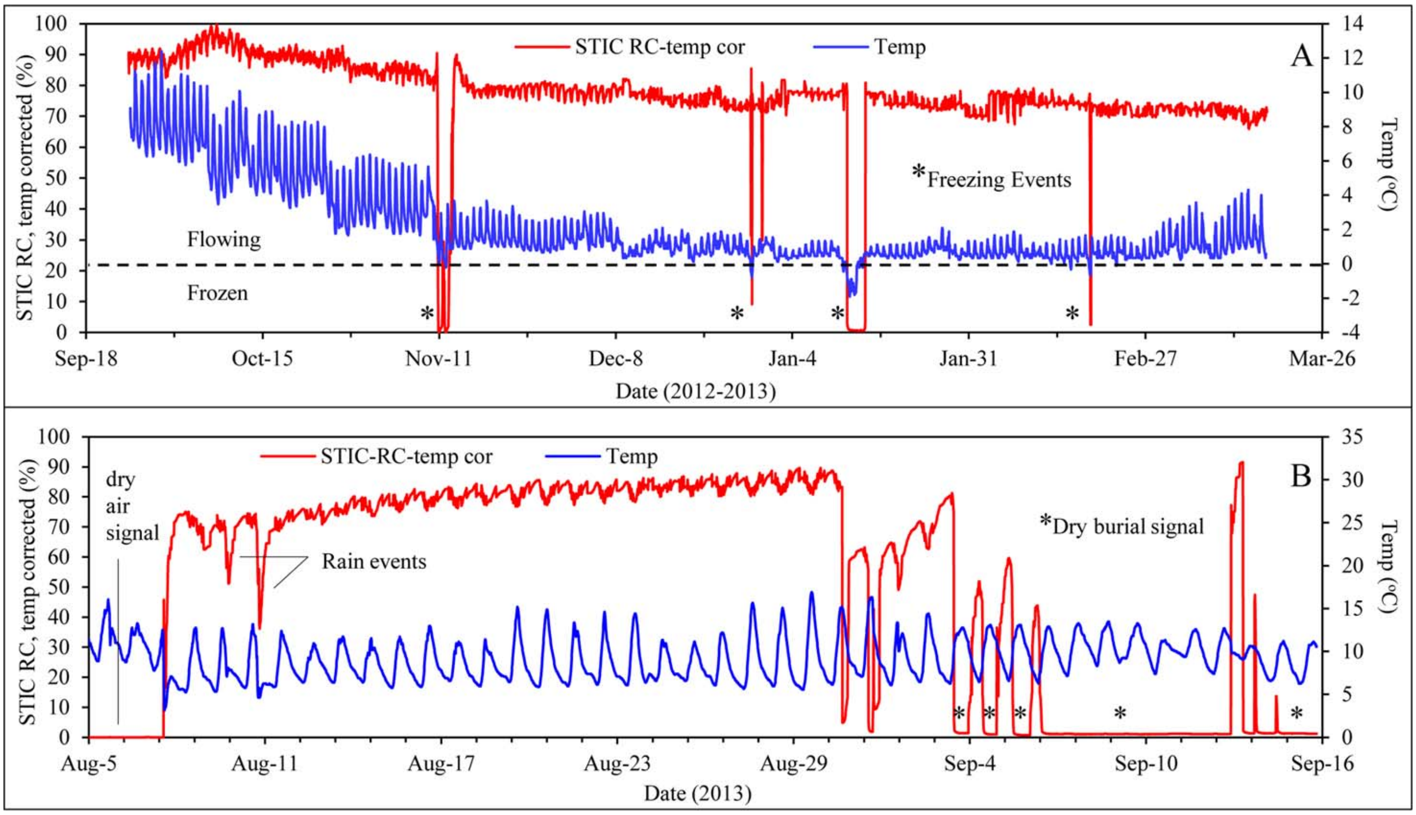

Figure 3. Seven month overwinter STIC deployment in the thalweg of Trinchera Creek, CO (a). Frozen conditions and flow cessation were recorded 4 times during the winter. The ice RC signal was 0.5% and distinguishable from an air signal (RC=0). The effects of sediment burial with diel wet-dry cycles in Cat Creek, CO (b). Note that the RC dry signal was 1% and not an air signal (RC=0) and temperature data alone did not indicate multiple dry-wet events in Figure 3b.

temperature circuitry used by Onset in each instrument. With proper calibration, the STIC can provide temperature response and accuracy comparable with the Onset Pro-V2, which is over twice the cost of the STIC.

An issue that was encountered in a few field deployments was a sporadic electronic "ringing" response. During these ringing events, the STIC RC response would oscillate from a normal wet response to a RC value that was dramatically lower, but well above the zero "dry" signal. The electronic noise would start and stop randomly during a long deployment and the cause remains unclear. In these instances, the lower value of the ringing oscillation was easily identified and removed from the wet/dry response data.

3.3. Field Results: Detection of Stream Intermittency During Freezing Conditions

During a 7 month overwinter deployment in the thalweg of Trinchera Creek, CO, we observed four freezing events, two lasting a few days and two lasting a few hours (Figure 3a). During the freezing events, the STIC RC reading of 0.5% (raw signal = 10–20) was a frozen ice signal and not a dry air signal (which was always 0 signal). The below 0°C temperature data provided further support that the STIC was frozen in ice and not exposed to air. Future research utilizing the STIC technology could characterize, in situ, the spatial, and temporal dynamics of freezing and ice processes in streams and rivers, a current information gap [*Huusko et al*., 2007].

3.4. Field Results: Detection of Stream Intermittency and Sediment Burial

Debris and high sediment transport during intermittent flows are common in intermittent streams and the rugged STIC design (machine pin electrodes with no external wires) provided long-duration detection of wet and dry periods even when buried by sediment. A STIC was deployed in the thalweg of Cat Creek, CO in early June 2013 and recovered in mid-September, where it was noted that the STIC was partially buried in sediment. The STIC recorded a dry air signal (RC = 0) until August 7 when the STIC was submerged

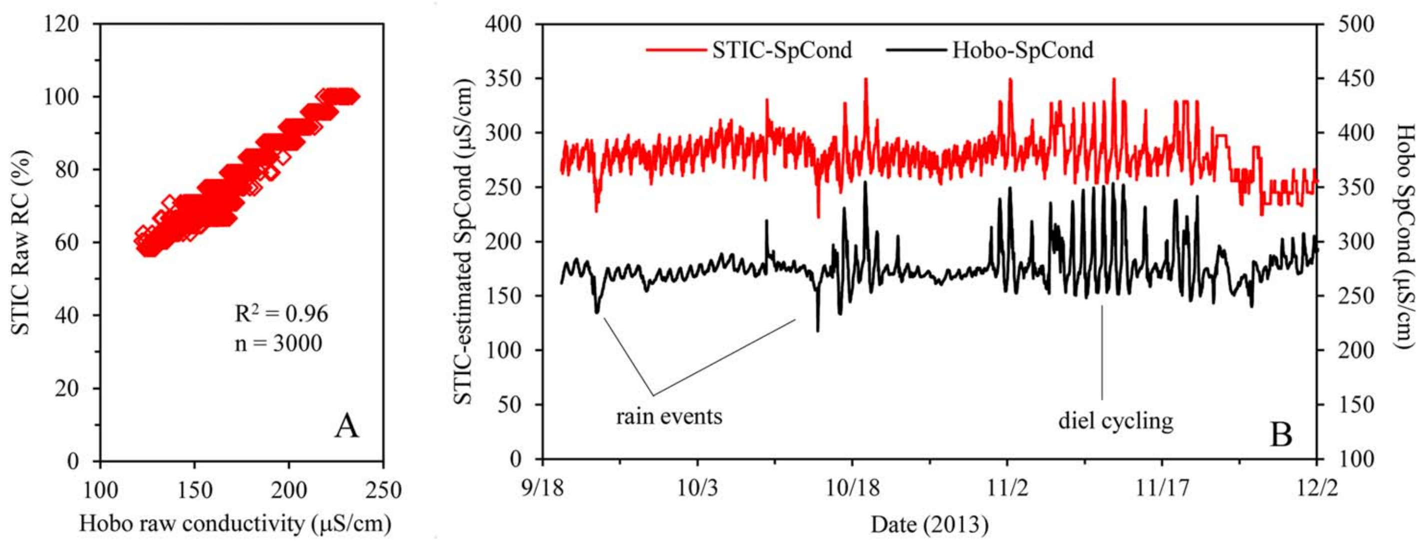

Figure 4. Comparison of raw STIC RC data and raw conductivity data from an Onset conductivity logger (a). Comparison of STIC estimated specific conductivity versus specific conductivity measured by Onset HOBO conductivity logger (b, note *y* axis scale offset to separate data). Rain events and diel conductivity cycling were captured by both instruments.

(Figure 3b). The temperature corrected RC data identified conductivity decreases due to rain events on August 9 and 10, a drying signal at the end of August, and diel dry-wet signals in early September (Figure 3b). In contrast to the air signal (raw signal $= 0$) observed in the beginning of August, the dry signal in early September had RC values of $\sim$1% (raw signal $>$50) indicating that the STIC electrodes were dry but covered with sediment (Figure 3b). The diel change in wet-dry conditions in Cat Creek, most likely caused by evapotranspiration processes, showed a wet instrument from midevening until midmorning and a dry instrument from midmorning until midevening (Figure 3b). The shape and magnitude of the diel temperature signal during the dry periods were not distinctly different from the wet patterns. However, the STIC RC signal, even partially buried in sediment, clearly distinguished wet and dry periods in Cat Creek (Figure 3b). We have observed sediment burial many times in STIC deployments and the ability to distinguish dry air, dry sediment, and wet conditions was a major advantage of the instrument.

3.5. Field Results: STICs as Conductivity Loggers

The simultaneous relative conductivity and temperature data collected by the STIC provided the opportunity to evaluate STICs as low-cost conductivity sensors in addition to stream intermittency and temperature loggers. Commercially available conductivity loggers typically cost $750–$1400 USD, record temperature, and measure water conductivity with noncontact sensors or four pole electrodes with specialized electronics. Results of a side by side field deployment of a STIC ($75) and an Onset HOBO conductivity logger ($750) in Sangre de Cristo Creek, CO, show nontemperature corrected STIC RC values were well-correlated with raw conductivity measured by the HOBO conductivity logger ($R^2 = 0.96$, Figure 4a). Calculated STIC-specific conductivity closely tracked the specific conductivity results from the more expensive HOBO logger (Figure 4b). The STIC's simple two pole electrode, the absence of precision electronics, and the lower 10 bit resolution of the repurposed light sensor circuitry yielded a noisier signal than the HOBO conductivity logger but the STIC was clearly able to discern conductivity changes due to rain events and diel cycling (Figure 4b). Polarization and electrolysis of the STIC electrodes are a potential concern and long-term field tests of instrument stability are currently underway. With pre and post deployment conductivity calibration, STICs can provide low-cost, long-duration, high-resolution monitoring of specific conductivity changes in stream water, another useful indicator of water quality.

4. Conclusions

STICs are new sensors that provide high-resolution, long-duration monitoring of two parameters important to both ecological and regulatory process; stream temperature and streamflow intermittency. The simultaneous temperature and relative conductivity data minimizes the need for human interpretation of "dry sensor" events in stream temperature data and provide estimates of stream water-specific conductivity. The low-cost, easy to build design of the STIC presents opportunities for student research projects and the deployment of extensive intermittent stream sensor networks. The STIC design has proven very dependable with over 300 field deployments, 100% field data recovery, and zero instrument failures to date. The STIC is a promising tool for many in stream applications, including the assessment of water conductivity, the timing and duration of streamflow intermittency, the characterization of winter ice formation dynamics, and the unambiguous assessment of water temperature regime.

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