Geosci. Instrum. Method. Data Syst., 5, 45–51, 2016
www.geosci-instrum-method-data-syst.net/5/45/2016/
doi:10.5194/gi-5-45-2016
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Geoscientific Instrumentation Methods and Data Systems
Open Access

Proof of concept: temperature-sensing waders for environmental sciences

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Received: 8 November 2015 – Published in Geosci. Instrum. Method. Data Syst. Discuss.: 11 December 2015
Revised: 6 February 2016 – Accepted: 10 February 2016 – Published: 29 February 2016

Abstract. A prototype temperature-sensing pair of waders is introduced and tested. The water temperature at the streambed is interesting both for scientists studying the hyporheic zone and for, e.g., fishers spotting good fishing locations. A temperature sensor incorporated into waders worn by members of the public can give scientists an additional source of information on stream-water–groundwater interaction. A pair of waders was equipped with a thermistor and calibrated in the lab. Tests with both the waders and a reference thermometer in a deep polder ditch with a known localized groundwater contribution (i.e., boil) showed that the temperature-sensing waders are capable of identifying the boil location. However, the temperature-sensing waders showed a less pronounced response to changing water temperature compared to the reference thermometer, most likely due to the heat capacity of the person in the waders. This research showed that data from temperature-sensing waders worn by the public and shared with scientists can be used to decide where the most interesting places are to do more detailed and more expensive research.

1 Introduction

The zone surrounding a stream, the hyporheic zone, plays an important role in many hydrological and ecological processes. In the zone the interactions between surface water and groundwater take place, which can potentially cause large changes in stream water chemistry, quality, and ecology, due to the difference in composition between the groundwater and stream water (Findlay, 1995; Sophocleous, 2002; Briggs et al., 2011; Mwakanyamale et al., 2013). Stream discharge, water-level fluctuations, transport of contaminants, and heat exchange all depend on the interaction within the hyporheic zone (Anderson, 2005; Boano et al., 2012). Interactions in the hyporheic zone between groundwater and surface water is often complex. Because their quantity and quality can significantly affect each other, understanding the principles of the processes in the hyporheic zone is necessary for effective water resources management (Boulton et al., 1998). Various methods exist to measure the groundwater–surface-water interactions within the hyporheic zone. Methods that provide point measurements in space and time include thermal profiling (Constantz, 1998; Anderson, 2005), sequential stream gauging (Kaleris, 1998), seepage sensors (Rosenberry, 2008), and tracers (Morrice et al., 1997). Also by measuring the streambed temperatures, groundwater upwelling can be detected (Anderson, 2005; Rosenberry and LaBaugh, 2008). Temperature sensors located at, or just below, the streambed can detect seeps (Selker and Selker, 2014). However, temperature measurements have spatial and temporal constraints (Tyler et al., 2009). Recent development and application of fiber-optic distributed temperature sensing (DTS) has been shown to overcome these limitations in space and time. The ability to monitor with both a high spatial and high temporal resolution has been shown to help reveal processes and to contribute to the improvement of understanding them (Selker et al., 2006). Many examples exist of measuring water bodies (e.g., Van Emmerik et al., 2013; Hilgersom et al., 2016) and groundwater discharge into streams or seepage (e.g., Selker et al., 2006; Lowry et al., 2007; Westhoff et al., 2007; Hoes et al., 2009; Vogt et al., 2010; Briggs et al., 2012; Krause et al., 2012; Vandenbohede et al., 2014) using DTS. Although DTS is superior in the spatial and temporal measurement resolution, it unfortunately remains an expensive and sometimes cumbersome method.

A promising approach to obtaining frequent and spatially distributed data is by actively engaging the public in measurement campaigns. New developments in sensing technology, data processing, and analysis have increased the opportunities for citizen science (Buytaert et al., 2014). Nowadays, a large share of the general public is equipped with GPS data loggers as part of their smartphones. Researchers have made use of the smartphone as an environmental sensor, either by actively asking the public to take measurements (Snik et al., 2014) or by using background data collected by the phone (Overeem et al., 2013). With this paper we aim to show that by using simple and low-cost temperature sensors mounted on the boots of a wading suit, reliable qualitative measurements can be done with a high temporal and spatial resolution. If successful, these sensors can send their value automatically to the smartphone of the person in the waders using (for example) Bluetooth low energy (BLE). The phone can then add its GPS location and upload the data to a central database. This has been shown to work by Snik et al. (2014) and Overeem et al. (2013) and will not be the focus of this paper. This paper focuses on testing whether temperature-sensing waders can be used to localize differences in groundwater temperature, such as those introduced by hyporheic exchange or groundwater boils. This is beneficial not only to scientists but also to (recreational) fishermen who are interested in stream temperature as proven by the existence of a number of existing temperature sensors for their niche market (BassPro, 2015; Fish Hawk Electronics, 2015). Recreational fishing is enjoyed by many people globally. In the USA alone, there are an estimated 27 million freshwater (Great Lakes excluded) anglers (Southwick Associates, 2012). By developing a citizen science strategy, upwelling sources in streams can be identified by the data collected by (recreational) fishermen, seepage sources in polder ditches by data collected by farmers, or groundwater sources in shallow urban lakes by data collected by dredgers.

2 Methods and materials

To make the temperature-sensing wader prototype, a hole was drilled in the left boot of a pair of waders. A 470 ΩNTC disk thermistor was placed in the hole. Two wires were soldered to the thermistor, with the joints isolated using shrinkwrap. The hole was filled with epoxy. The same epoxy was used that is used to repair waders in case of a leak and is supplied together with the waders. The sensing part of the thermistor was positioned on the outside part of the hole, in contact with the water. The two wires run up to a pocket on the front of the wader, where they connect to a breadboard that contains the rest of the electronics.

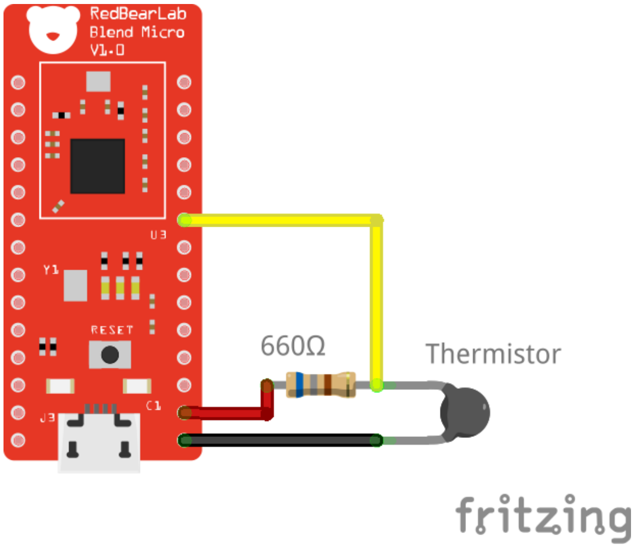

Figure 1. Schematic overview of the circuit used to read out the measurements from the thermistor.

The thermistor is connected to a resistor of 660 Ω and to a Red Bear Lab Blend Micro (Red Bear Lab, 2015) according to the scheme in Fig. 1. The Blend Micro is a development board that is based on the Arduino platform and can be programmed using the Arduino IDE. The Blend Micro is chosen in this research over more obvious choices such as the Arduino because it includes a BLE module, which will be used in follow-up research where the temperature-sensing waders will be connected to a mobile phone using BLE. On the Blend Micro, the example program "read analog value" that ships with the Arduino IDE is running. This program reads the voltage on the A0 (see Fig. 1) using the onboard analog-to-digital converter (ADC) (10 bits). The raw measurement value is sent to a laptop connected to the Blend Micro using serial communication every 5 s. On the laptop a logger program is running that stores any incoming serial communication in a file. The code for this program is available (Hut, 2016).

2.1 Calibration

To calibrate the temperature-sensing waders, they were placed in a 40 L bucket. A brick was placed underneath the boot of the waders to make sure the sensor was not too close to the bottom of the bucket. On the brick, within 3 cm of the thermistor in the boot, were placed two waterproof internally logging temperature sensors (ONSET TidBits; Onset, 2015). The TidBits were set to sample and store the temperature every 10 s. The wader was set to send a temperature measurement to the laptop every 5 s. The bucket was first filled with warm water and allowed to cool down. Then the bucket was filled with ice and water and allowed to melt and heat up. Finally the bucket was filled with tap water that was allowed to heat up to room temperature. To obtain calibration constants A, B, and C, the Steinhart–Hart equation,

$$\frac{1}{T} = A + B\ln R + C(\ln R)^3, \tag{1}$$

was fitted to the data from the TidBits and the wader. T is the temperature of the water, and R is the resistance of the thermistor. The melting ice experiment was used to bias-correct the TidBits. All calculations were done in MATLAB, and all of the code used for the calibration is available in the Supplement.

2.2 Flume experiment

Ideal temperature sensors have as low a heat capacity as possible to match the temperature of the surrounding environment as fast as possible. The human leg in the wader constitutes a significant heat capacity, and, as any experimental hydrologist can confirm, the thermal insulation the wader provides between the leg and the water is not perfect; i.e., both the body temperature of the wearer of the wader and the heat capacity of the combined wader–leg system can influence the accurate determination of the water temperature using the thermistor. To test the influence of both the heat capacity and the body temperature, six experiments were done in a flume in the lab of Delft University of Technology. The waders were first placed in a 40 L bucket of warm water. When the temperature stabilized, the waders were put in the streaming water of the flume. This was repeated with a leg in the wader and without a leg; in the latter case the wader was pressed down into the water using a rod. This was done at three different flow velocities (0.2, 0.17 and $0.38\,\mathrm{m\,s^{-1}}$), creating a total of six experiments. The step response of the temperature-sensing waders are assumed to be exponential, i.e.,

$$T(t) = T_0 + (T_1 - T_0)\left(1 - e^{-\frac{t}{\tau}}\right), \tag{2}$$

where $T(t)$ is the temperature as measured by the thermistor, T_0 is the temperature at the start of the experiment, T_1 is the temperature of the water, and τ is the typical time constant of the entire temperature-sensing wader. After τ seconds the temperature of the sensor has converged to 61 % of the temperature of the water. T_1 and T_2 are considered parameters and are estimated by fitting Eq. (2) to the measured data. The water of the flume is also monitored using a simple handheld thermometer, for comparison.

2.3 Field evaluation

As the location of the fieldwork, we chose a ditch known to have a seepage boil from the work of De Louw et al. (2010) and Vandenbohede et al. (2014). Our field location corresponds to boil 25 V in De Louw et al. (2010). The ditch is located in the Noordplas Polder (52.094692° N, 4.521272° E), at 4 m below mean sea level. The upwelling groundwater has a constant temperature of approximately 11° C (De Louw et al., 2010). Field evaluation took place on 6 July 2015. Air temperature was approximately 22° C. The ditch was between 40 and 100 cm wide and between 30 and 80 cm deep. See Fig. 2 for an overview of the ditch. Upstream of the boil the water did not (visibly) move; downstream of the boil the surface velocity of the water was approximately $2\,\mathrm{cm\,s^{-1}}$. A tape measure of 30 m was laid out parallel to the ditch, with the location of the boil approximately in the center. Temperature in the ditch was measured by the waders by walking slowly through the entire length of the ditch. Temperature as measured by the waders was logged every 5 s. Every meter along the ditch (as indicated by a colleague walking along the tape measure) an additional manual measurement was taken by the waders. In addition to that, the researcher in the waders also measured the water temperature using a Fluke 54 (Fluke, 2015), a high-precision temperature probe. The probe was pressed into the soil at the bottom of the ditch. Care was taken to press the probe as deep into the soil as the researcher had sunk into it. Results were processed in MATLAB; all scripts used are available in the Supplement. The time stamps in the manual measurements of the wader were used to map the automatic measurements to a location along the length of the ditch.

3 Results

3.1 Calibration

Figure 3 presents the results of all calibration experiments, i.e., the measurements with and without the body heat in the wader. Since all the data fit very well on the Steinhart–Hart relation, we conclude that there is no additional temperature gradient due to body heat between the heel of the boot and a Tidbit approximately 3 cm away from the boot, that is, the wader measures the temperature of the water just outside of the boot. The body heat could still have warmed the water surrounding the boot; this depends on the water flow around the boot. At low flow, such as when the wader is in the mud, the body heat will penetrate further out from the boot compared to flowing streams. This is not discernible in the current calibration setup but will be researched in future research.

3.2 Flume experiment

Figure 4 shows the results of the flume experiment. Measured data are presented in black, and the curves fitted to the measurements are shown in red. The fitted time constants are shown in each graph, both for the heating in the 40 L bucket (τ_{bucket}) and for the cooling in the flume (τ_{flume}). The left column shows the results for the experiment where the wader was empty, i.e., no human body heat. The right column shows the results for the wader with a human in the wader. The rows indicate different flow velocities. Comparing the with- and

Figure 2. (a) The ditch used in the field evaluation. **(b)** A close-up of the boil, identifiable in the landscape by the collapsed banks of the ditch. **(c)** A schematic overview of the experiment during the field evaluation. **(d)** For scale-reference: Rolf Hut during the experiment in the ditch.

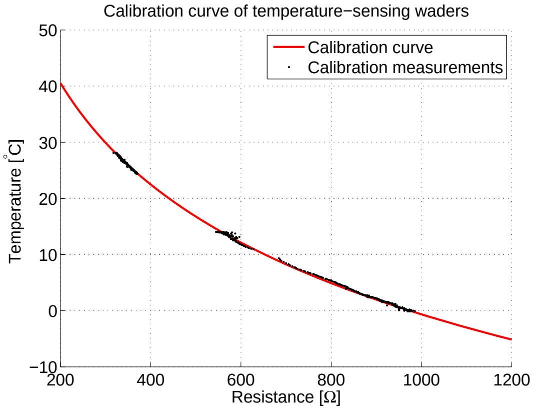

Figure 3. Results of the calibration experiment, showing the resistance of the waders (x axis) versus the temperature of the water as measured by TidBits (y axis). The red line is the fitted Steinhart–Hart relation.

without-human-body-heat experiments shows that all experiments in the flume converge to the same temperature. This shows that the effect of the human body generating heat is negligible in the current setup of the temperature-sensing waders. The water in the flume was constant at 20° C over all experiments. The temperature that the measurements by the waders converged to was slightly lower, which is most likely due to a bias between the sensors used to measure the flume temperature and those used to measure the calibration experiment. The time constant decreases with higher flow velocities but remains very high even for high flow. This indicates that the temperature-sensing waders can only be used quantitatively when the wearer is not moving too much and when the water does not change temperature too abruptly. Otherwise, the temperature-sensing waders, in its current prototype form, are only useful for qualitative assessments like identifying the location of groundwater inflow and/or boils.

3.3 Field evaluation

The results of the field evaluation are shown in Fig. 5. The measurements from the waders show a less pronounced response to the influx of cold water, compared to the Fluke, as was expected from the results of the flume experiment. Another factor that explains (part of) the difference in temperature between the wader and the Fluke is that the Fluke was pressed deeper into the soil than the boot of the wader. Given the very weak peat soil in the ditch, it was easy to press too deep with the Fluke. A few centimeters deeper would have meant relatively more groundwater and, thus, a lower temperature. Finally, in the calibration setup, TidBits were used to measure the water temperature, while in the field a Fluke was used. The TidBits were bias-corrected using melting ice, but other than that, factory calibration was used. This could potentially cause part of the difference between the waders and the Fluke measurements in the field. Despite the differ-

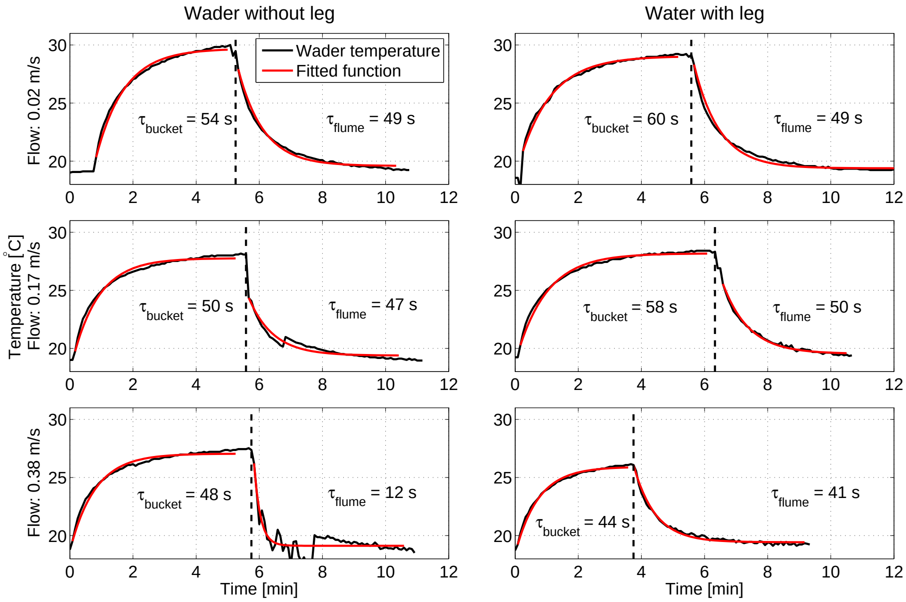

Figure 4. Results of the flume experiment. The left column of graphs shows the results when no leg is present in the wader; the right column shows when a leg is present. The temperature measured by the waders is shown in black. The fit of Eq. (2) is shown in red. The fitted time constants for the heating of the wader in the bucket τ_{bucket}, and for the cooling of the wader in the flume τ_{flume} are printed in the graphs. The dashed line indicates when the wader was put from the bucket into the flume. The high turbulence in the situation with high flow ($0.38\,\mathrm{m\,s^{-1}}$) and no leg made it hard to keep the boot at a constant location in the stream, causing erratic measurements. For identical flow velocity ($0.02\,\mathrm{m\,s^{-1}}$), the situation with and without a leg in the wader converges to identical temperatures, indicating a neglectable effect of the human body temperature. The time constant is large compared to state-of-the-art temperature sensors and only decreases slightly with increased flow.

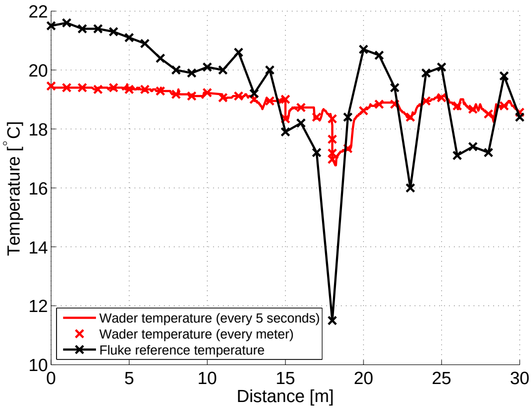

Figure 5. Results of the field evaluation. The location of the boil can be clearly seen in the measurements by the reference thermometer (Fluke) and the waders. The waders show a less pronounced response to the influx of cold water than the Fluke.

ence in temperatures, the location of the boil is easily identified in both measurement series.

4 Conclusions and discussion

The temperature-sensing waders are capable of measuring the location of the seepage boil in the field evaluation. This first prototype proof of concept shows that if people that already use waders, such as fly fishermen, were to be equipped with temperature-sensing waders, the data they collect could be used by scientists and operational water managers to better understand the interplay between surface water and groundwater. In this research this was demonstrated by identifying the location of a seepage boil in a deep polder in the Netherlands. Another application would be to identify hyporheic exchange hot spots in streams.

The temperature as sensed by the waders showed less sensitivity to the temperature changes of the water compared to the reference thermometer (Fluke). This is first and foremost explained by the slow response time of the temperature-sensing waders, caused by the heat capacity of the wader and the human in it, as the flume experiments (Fig. 4) shows. In the field evaluation, the wader sunk into the soil and mud at the bottom of the ditch with every step. In these conditions of low water flow, the time constant of the system would be at a maximum. In faster-flowing water, this would be less of a problem. If the waterflow around the boot were known, an (inverse) model could be used to calculate the water temperature from the reading of the thermistor. Alternatively, the sensor could be placed higher up on the boot. This would limit the usability for hyporheic research but would be valuable for ecological research on stream temperature. All this remains for future work.

If manufacturers of waders were to equip waders with thermistors, several improvements on the current design would be necessary. First, the wires currently run along the outside of the leg and should be incorporated into the waders. Secondly, the flume experiment showed that the response time of the wader is too slow to quantitatively capture water temperature when someone is moving through the water in the waders. This could be improved by having a thermally insulating layer between the sensor and the boot, decoupling the sensor from the heat capacity of the wader. Currently the measurements are sent to a laptop using serial communication. The vision of the authors is that the waders should send the measurements to a mobile phone using BLE. The mobile phone can add its geo-location to the data and upload it to online repositories. A first demonstration of the waders communicating measurements to a mobile phone using BLE was given at the EGU General Assembly 2015 (see Hut and Tyler, 2015). Previous research showed that geo-location of geoscientific measurements by mobile phone is a solved problem (Overeem et al., 2013; Snik et al., 2014) that we choose not to include in this work. Future work will need to integrate BLE communication and geo-location with the results of this work: that it is feasible to use temperature-sensing waders to localize strong changes in water temperature such as those generated by hyporheic exchange or groundwater boils.

This research showed that temperature-sensing waders worn by the public could be a new source of data for scientists. The waders would allow the identification of locations of groundwater upwelling. Using this information, scientists can decide, based on measurements, the locations for more detailed, end more expensive, fieldwork.

The Supplement related to this article is available online at doi:10.5194/gi-5-45-2016-supplement.

Acknowledgements. The authors would like to thank Perry de Louw for his help in picking a good location for the field evaluation and Jan Dorrepaal, owner of the field where the field evaluation took place, for granting the authors access to his property. This work was partially developed within the framework of the IAHS-MOXXI working group. We are thankful for the constructive feedback from Peter Marchetto and Salvatore Grimaldi.

Edited by: W. Schmidt

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