HYDROLOGICAL PROCESSES
Hydrol. Process. **30**, 888–898 (2016)
Published online 23 September 2015 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10677

Monitoring ephemeral headwater streams: a paired-sensor approach

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Abstract:

This paper introduces a paired-sensor approach to monitoring ephemeral streamflow. Part of this approach includes the design of a new flow detection sensor. This flow detection sensor addresses the limitation of previous electronic resistance sensors that use water presence as a proxy for flow for assessing hydrological connectivity, by explicitly measuring flow presence. Using paired electronic resistance and flow detection sensors, this paper evaluates the performance of each sensor individually, and as a pair. Individually, the sensors were tested for the amount of noise they contain and the types of errors they were prone to committing. As a paired set, the sensors were analysed by the percent of time they were in valid states *versus* invalid states. Valid states included when water was present but flow was absent, when water and flow were both present and when water and flow were both absent during a storm. One invalid case existed, where the sensors recorded flow presence but not water presence. These valid and invalid cases were assessed using data collected from sensor networks established at two study sites in southern Ontario. This analysis was completed for the overall corroboration at each site, for each storm at each site and based on the relative position of the sensors in the channel at each site. The sensors were in valid states 83% and 94% of the time at each respective study site. Differences in local site conditions were found to affect the performance of the sensor network; however, no significant correlation was found between storm characteristics and sensor performance. Particularly, bed roughness was found to be a factor as it restricted the placement of the sensors. Despite this, the paired-sensor network helps to increase the understanding of the flow dynamics within headwater streams by explicitly separating the two hydrological characteristics. A discussion of the challenges, limitations and opportunities of monitoring ephemeral flow is presented, and insights into how to address those limitations are provided. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS ephemeral streams; sensor network; instrumentation; headwater; hydrology; hydrological connectivity

Received 13 November 2014; Accepted 20 August 2015

INTRODUCTION

Studies have assessed changes to discharge in perennial streams under different meteorological and climate conditions (e.g. Peterjohn and Correll, 1984; Hill, 1996; Mayer, 2005). However, one aspect not well studied by looking at discharge alone is the changes in hydrological connectivity in the low-order headwater streams where intermittent flow regimes tend to dominate. All streams exist on a continuum of flow, ranging from perennial to episodic (Uys and O'Keeffe, 1997). Uys and O'Keeffe (1997) designated two thresholds along the continuum where streams are no longer considered perennial but rather intermittent or ephemeral: where surface water is present, but not flowing (i.e. contain stagnant water), and where surface water is not present (i.e. completely dry). The position of a stream on the continuum of flow can vary seasonally and inter-annually, where streams can be perennially seasonal during the spring and autumn months but episodic during the dry summer months (Blyth and Rodda, 1973; Day, 1978; Gurnell, 1978). The ability to predict flow in streams decreases as streams become more episodic while the variability in flow increases (Uys and O'Keeffe, 1997). This decrease in prediction is attributed to a low degree of monitoring in headland areas, especially in temporary streams (Bishop *et al.*, 2008).

Bishop *et al.* (2008) highlighted the dearth of data pertaining to headwater streams; the further upstream from the mouth of a river you travel, the less data that exist. Bishop *et al.* (2008) was referring to all types of data, including ecological data; however, with regard to hydrology, this has resulted from a lack of monitoring in these zero and first-order streams. This is despite ephemeral and intermittent streams having important hydrological (Gomi *et al.*, 2002; Wigington *et al.*, 2005), geomorphological (Chin and Gregory, 2001; Gomi *et al.*, 2002) and ecological (Labbe and Fausch, 2000; Gomi

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et al., 2002; Meyer *et al.*, 2007) significance. The increase in drainage density of the network can affect downstream water quantity and quality, by increasing hillslope connectivity (Day, 1978; Burt and Butcher, 1985; Quinn *et al.*, 1991; Arnell, 2002; Goulsbra *et al.*, 2014). The scarcity of monitoring data has to do in part with the technical challenges of monitoring a spatially distributed, highly variable phenomenon like stream network expansion and contraction. Some studies have attempted to monitor these landscape hot spots (McClain *et al.*, 2003) using a variety of techniques. Observation-based monitoring methods have been used in the past to determine the extent of the flowing network (Blyth and Rodda, 1973; Day, 1978); however, the major shortcoming was poor spatial and temporal resolution. The use of inexpensive sensors and data loggers allowed for significant improvements in both spatial and temporal resolutions. Temperature sensors buried under the bed have been used, but the complexity associated with interpreting the results reduced the effectiveness (Constantz *et al.*, 2001). Blasch *et al.* (2002) created an electronic resistance (ER) sensor by removing the thermistor from the temperature sensors. Over time, refinements of the ER sensor design improved the accuracy and interpretation of the data (Blasch *et al.*, 2002; Goulsbra *et al.*, 2009; Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014). Later, Bhamjee and Lindsay (2011) found that state loggers further simplified the interpretation of ephemeral streamflow monitoring records while reducing data volume and increasing the temporal resolution of observations. The primary limitation of using bed temperature sensors (Constantz *et al.*, 2001) or electrical resistance sensors (Blasch *et al.*, 2002; Goulsbra *et al.*, 2009; Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014) has been that they monitor the presence or absence of water within the channel and are unable to detect whether that water is flowing. Bhamjee and Lindsay (2011) found that persistent standing water within pools can occur commonly within headwater channels.

This paper introduces a new paired-sensor ephemeral stream monitoring approach. This includes a new flow detection sensor that addresses the limitation of previous sensor designs to distinguish between periods where the channel is wet (i.e. stagnant water) and periods of flow (i.e. moving water). This paper will demonstrate that a paired-sensor approach is more advantageous than using either a flow or water detection sensor alone by evaluating the performance of the sensor pairs.

METHODS

Sensor design and materials

The ER sensor was based on the design of Bhamjee and Lindsay (2011) and constructed from the same acrylic thermoplastic, bonded with marine glue. The flow detection sensor (Figure 1) is based around a vane design that closes a circuit when water is flowing, while opening the circuit when water is not flowing, regardless of whether stagnant water is present (Figure 2). The ability to distinguish between the presence of water and the presence of flowing water is how the flow detection sensor improves upon previous sensor designs. As water passes through the mouth of the sensor, it forces the vane to open. When the vane opens, the magnet on the end of the vane moves away from a normally closed reed switch, opening the circuit and triggering a logger reading. Using a normally closed reed switch on the main sensor body, with the magnet on the vane, allows for an open circuit when there is no water (i.e. the vane is closed and the magnet has opened the circuit) and a closed circuit when the magnet moves away from the reed switch, thus leaving it in the normally closed position. This characteristic allows for better battery life for the loggers, as the sensors tend to be in the no-flow state for longer periods of time over a given season.

The sensors were constructed from 3 mm acrylic thermoplastic. The material was chosen because it was easy to work with, lightweight and strong. In addition, it is not susceptible to corrosion and is relatively inexpensive, thus keeping costs to a minimum and ensuring that the sensors can endure many deployments. The hinge for the vane was made from stainless steel welding rod as it is rigid but easy to cut to size. The reed switches used for the design were single-pole, double-throw, normally open/normally closed (part #: GC Electronics 35-752), although a single-pole, single-throw, normally closed reed switch would also work effectively. The reed switches were soldered to the provided tip-ring-sleeve connectors supplied with the HOBO U-11 data loggers using a 22-gauge solid-core wire. The magnets used to trigger the reed switches were small cylindrical rare-earth magnets. These were used because of their strength, small footprint and weight, allowing them to be attached to the end of the vane without interfering with the closure of the vane nor adding too much additional weight. The various parts of the sensor were bonded using marine glue.

Sensor setup

Setting up the two types of sensors in the field required a mounting system to be added to the sensor. For this study, a base plate with holes for pins, or a strap over the top were used, as well as using heavy weights on top of the sensor. This latter configuration was especially useful in rock-bed streams where pinning the sensor to the bed was difficult. Ultimately, there are numerous methods of anchoring available to match the channel characteristics and ensure the sensors stay stationary (e.g. Isaak *et al.*, 2013).

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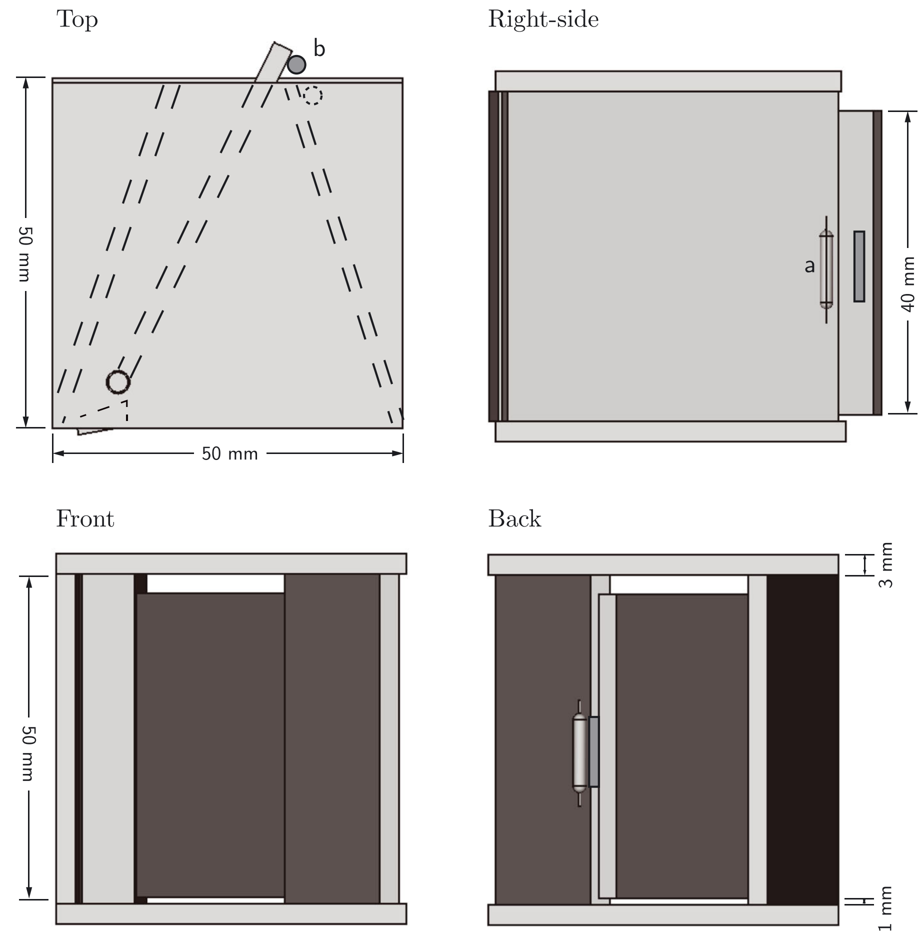

Figure 1. Flow presence sensor design. Part (a) shows a single-pole, double-throw normally closed reed switch. Part (b) represents the rare-earth, cylindrical magnet used to activate the switch

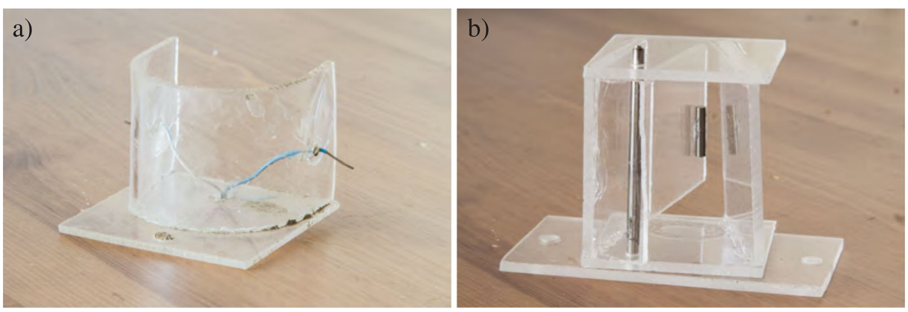

Figure 2. Photographs of the (a) water presence sensor and (b) flow detection sensor

Sensor siting within the cross section of the channel was within the thalweg to maximize the probability of water flowing through the sensor even during the lowest flows. Areas with substantial debris (e.g. leaves and twigs) were avoided during installation as these could have potentially blocked the opening of the flow detection sensor, keeping the vane in the open position, or inundating the ER sensor. Proper installation of the flow detection sensor required angling it on the bed so the vane remained closed during periods of no flow but took minimal effort to open when flow was initiated. This was tested during installation by opening the vane and releasing it. The vane should close completely. Placing the sensor on too steep of an angle may have resulted in missed flow events, as more energy is needed to open the vane. The ER sensors were placed so the electrodes were level with each other. Each sensor was plugged into a state port on the data logger. Each sensor in the pair was positioned ahead of the other, trying to place them as close together as the site would allow, while leaving enough space to reduce flow interference between sensors. The spacing of sensor pairs was far enough apart so as to decrease redundancy but close enough to capture variability in expansion and contraction. A spacing of approximately 10 m was chosen for this study, although appropriate spacing will depend on the environment and the application.

Field sites

Field-based sensor performance and evaluation were undertaken at two field sites in southern Ontario. Each site contained at least one ephemeral channel. Site 1 (43.7580 N, 79.9392 W) was located in a predominantly agricultural area in southern Ontario, west of the town of Cheltenham (Figure 3). The study reach of ephemeral channel was located in a forest adjacent to active corn fields and an apple orchard. The stream originates in the surrounding fields and is bounded by a riparian buffer where it bisects the field. In the forested section, the active stream is greatly incised in the banks and has a mix of bed-surface sediment conditions. At the head of the study reach, there were large cobbles and boulders across the width of the channel; however, the bed surface exhibited noticeable sediment fining downstream. The lower reaches of the channel had few rocks on the bed surface and appeared sandier. Grain-size analysis showed that in the 30 cm below the bed, there was more longitudinal consistency along the study reach. The channel was on average 53.7% sand, 12.1% silt and clay, with the remainder being grains larger than sand. The site had an average organic matter content of about 5.1% with a standard deviation of 1.3% along the entire study reach. The channel flattens and widens towards the mouth, with an approximate average channel width of 2.5 m; however, flow tends to be concentrated in a far narrower area. The forest is composed of large, mainly deciduous, trees with minimal understory. This lack of understory resulted in leaf litter accumulation in the autumn months and increased the debris load in the channel. The channel empties into the Credit River near Cheltenham, Ontario.

Site 2 (43.3798 N, 80.3433 W) was located in a conservation area with a wet (Figure 4). The catchment is long and narrow in the study reaches, and the stream is bounded by rock cliffs approximately 15 m away from each bank. The channel has an average width of 1.5 m. Similar to Site 1, Site 2 has marked changes with regard to substrate on the channel surface (Figure 5). The channel surface was less rocky near the head of the study reach than closer to the mouth. Based on grain-size analysis, the upper 30 cm section of the bed averaged 64.7% sand, 19.4% silt and clay and 15.9% pebbles. In terms of organic matter, Site 2 had an average of 8.6% and a standard deviation of 2.7%. The forest surrounding the study reach is composed of predominantly deciduous trees but has a dense understory, protecting the channel from leaf litter. The upper contributing hillslopes include forest, as well as active and fallow agricultural fields. The channel flows into the Grand River near the confluence with the Speed River, in Cambridge, Ontario.

Data collection

Stream network expansion data was collected at both sites utilizing paired ER and flow detection sensors along the study reaches with 14 sensor pairs at Site 1 and 12 sensor pairs at Site 2 (Figures 3 and 4). Simple meteorological stations were setup at each site to capture rainfall, temperature and wind speed using HOBO tipping bucket rain gauges with integrated temperature sensors in

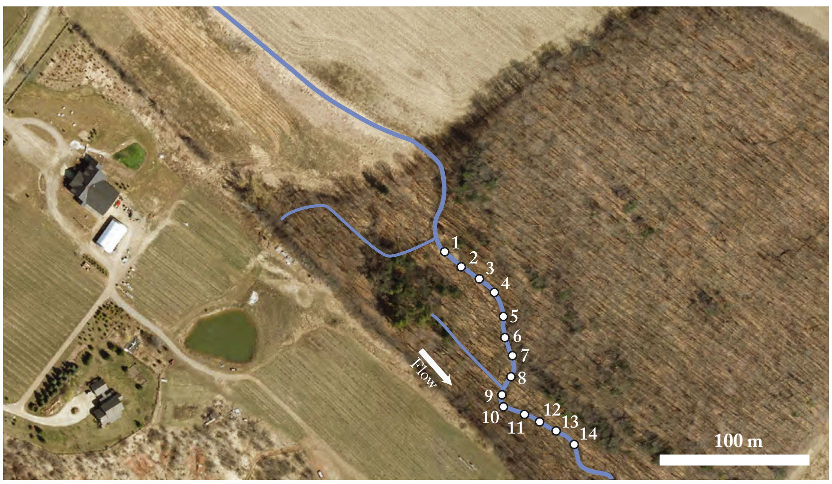

Figure 3. Site 1 study area including the positioning of the sensor pairs

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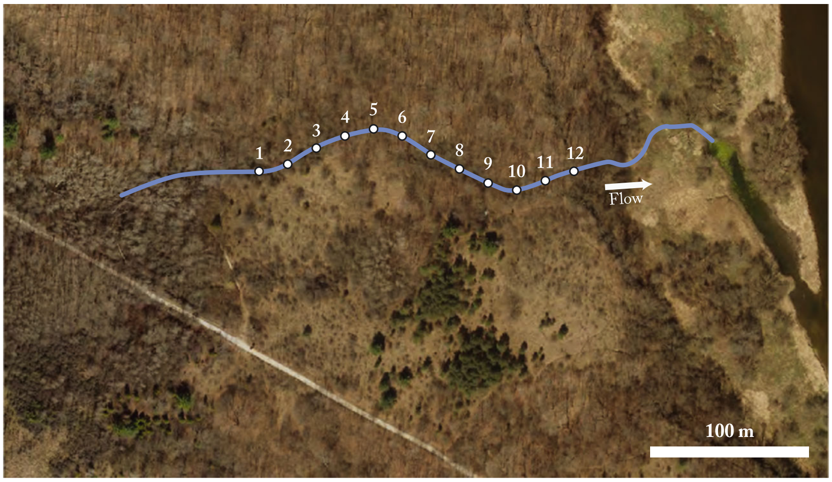

Figure 4. Site 2 study area including the positioning of the sensor pairs

Figure 5. Photos of channel surface characteristics at Site 1. (a) The upper parts of the channel were deeply incised and contain lots of pebble-sized grains on the bed surface. (b) The lower reaches of the channel had a relative absence of larger grains on the surface. (c) In the mid-to-upper reaches, there was a mix of pebbles, cobbles and boulder-sized grains on the bed surface, which lead to potential siting issues. Site 2 exhibits similar channel surface characteristics, with the downstream area similar to (c) and the upstream area similar to (b). There were no channel surfaces similar to (a) at Site 2

Stevenson screens and three-cup anemometers. Meteorological data were collected close to each site because localized rainfall events are common in both areas.

Sensor-data processing

Data processing for the sensors was completed to reduce the noise found during the onset and cessation of flow. Noise occurred in both sensors when the sensor was at the threshold for measurement. In the flow detection sensor, this was when the water was flowing just enough to turn it on, but any perturbations, or drops in flow velocity below the threshold caused the sensor to close momentarily. In the ER sensor, this noise occurred when the water was at the height of the electrodes and opening and closing the circuit if one electrode was removed from

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the water. This noise was expressed as high-frequency noise and was easy to distinguish from lower-frequency events. To reduce this noise, the same 30-s filter used by Bhamjee and Lindsay (2011) was applied to the collected data. The filter first determined the previous state of the sensor. If it was reporting water or flow presence, and less than 30 s had elapsed before it reported water or flow absence, the state was changed to show that water or flow was present. If the change from water or flow presence to absence had occurred outside of the 30-s buffer, then no change was made. Water and flow presence were prioritized over water and flow absence because if there was enough water in the channel to turn on either sensor, even for a few seconds, then it was likely that water or flow was present during brief moments of the sensor not reporting the variable. The percent of records changed for each sensor is presented in Table I. At both sites, ER 2 showed no changes in the data as this sensor was plugged into an event channel on the logger and only recorded the initial presence of water, not the cessation of water. This meant that only every other sensor pair in the network could be used for corroborating invalid cases (i.e. cases where the flow detection sensor records flow, but the ER sensor does not detect water). Despite this limitation of using the event port on the HOBO U-11 logger, the valid cases were assessed and the data were still considered.

Table I. Percent of records changed from no-flow to flow based on a 30-s filter for noise

Pair ID	Flow presence	Water presence
Site 1		
1	42.96	2.44
2	5.91	0.00
3	0.75	52.91
4	46.32	0.00
5	0.21	13.30
6	48.83	0.00
7	0.08	45.61
8	0.88	0.00
9	0.00	49.08
10	0.00	0.00
11	7.38	40.18
12	0.32	0.00
13	4.59	41.34
14	16.40	0.00
Site 2		
1	8.61	32.52
2	13.31	0.00
3	12.24	18.83
4	3.32	0.00
5	1.68	45.23
6	0.23	0.00
7	44.23	0.86
8	4.67	0.00
9	40.07	1.14
10	0.07	0.00
11	3.75	5.96
12	17.10	0.00

Loggers are sorted by location from the most upstream to most downstream.

Sensor performance

The performance of the flow detection sensor design was analysed by direct comparison to the ER sensor from Bhamjee and Lindsay (2011). The Bhamjee and Lindsay (2011) ER sensor was more likely to commit errors of omission (i.e. under-report water) than it was to commit errors of commission (i.e. report water presence when there is none present), as the water needs to be at the level of the electrodes to record a state change. The exception to this robustness against errors of commission regarding water presence is if the sensor became buried under sediment and was then measuring the moisture rather than channelized flow. However, the ER sensor was likely to commit errors of commission when recording whether the water is flowing or stagnant.

Because the ER sensors determined the presence and absence of water, while the flow detection sensors determined the presence of flowing water, corroboration was sought for valid recorded periods. The valid periods included water presence with no flow, water presence with flow and complete absence of water and flow during the storm periods. In addition, invalid cases were identified, where flow was recorded, but water presence was not (Figure 6). To determine a valid presence of water, the ER sensor needed to be reporting water, while the flow detection sensor needed to be reporting no flow. For valid flow presence, both sensors needed to be reporting water and flow, respectively. For a valid dry channel, both sensors needed to be reporting no-water and no-flow, respectively. Finally, any other combination was recorded as being an invalid occurrence (i.e. cannot have flow without water present in the channel). These occurrences were recorded both as a function of how much time elapsed in the state and the number of changes to a particular state.

The valid cases were compared at both the site-level, on a per-storm basis, and by the relative position of the pairs in the channel. Site-level data were combined to show the overall corroboration between the ER and flow detection sensors for each of the four cases as a percent of time spent in a particular state. For overall sensor corroboration, only data during storm periods were included, as water and flow absence dominates these ephemeral streams, and would inflate the degree of corroboration. Reporting of storm-level results was carried out for each site individually, as a percent of the storm time in a given state. A single-storm event was defined as the period where rainfall events recorded by a tipping-bucket rain gauge were less than 24 h

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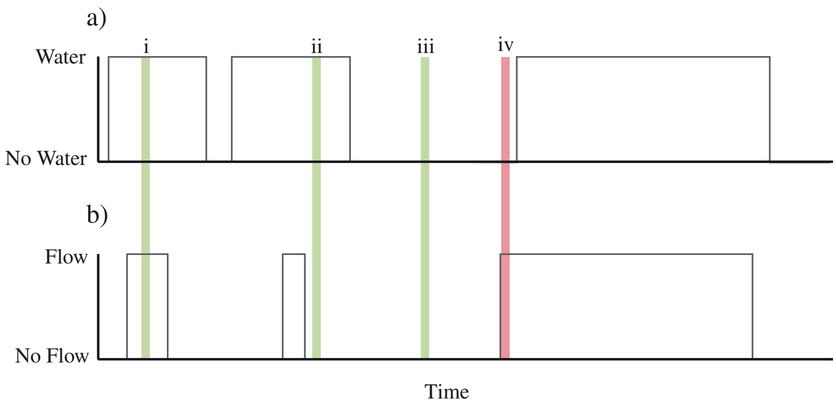

Figure 6. Valid and invalid cases between sensors. Panel (a) represents the electronic resistance sensor, describing the presence and absence of water in the channel, while panel (b) represents the flow detection sensor, describing the presence and absence of flow in the channel. Line (i) is the valid case of both water and flow being present. Line (ii) is the valid case of water present but flow absent. Line (iii) is the valid case of neither water, nor flow, being present. Line (iv) is the invalid case where there is flow present, but no water in the channel

apart. Once the 24-h threshold was overcome, a new storm event was created at the beginning of the next record. This allowed for long, less intense storms with breaks in rainfall to be better classified. Last, the percent of time spent in a valid or invalid state for each sensor was completed and analysed by their relative location in the study reach.

RESULTS

The sensor pairs were tested over 14 and 28 storms, respectively, at Sites 1 and 2. Site 1 had fewer storms over the testing period because the stream entered an ephemeral regime later in the season. Both sites experienced similar median rainfall amounts over the study period. Figure 7 depicts a full season of data for one sensor pair.

Sensor performance

Overall, sensor performance at Site 1 resulted in the ER and flow detection sensor being in valid states 83.26% of the time during storm periods. At Site 2, the sensors were in valid cases 94.86% of the time during storm periods. Both sites had sensors recording the presence of water and flow in the channel (‘case i’ in Figure 6) for more than half of the storm time (Table II). Case ii was the next most prevalent case at both sites, where standing water was present in the channel but not flow. Case iii, when the channel was dry, was minimal with regard to storm duration percentage. However, Case iii would be very prevalent in the overall season statistics, as the channels were dry between storms. Finally, case iv, the invalid cases, showed that overall, Site 2 performed better than Site 1. Site 1 was in an invalid case 16.74% of the storm time, while Site 2 was in an invalid case 5.14% of the storm time. The valid and non-valid cases were parsed by storm to better examine the differences for each site.

Examining the valid/invalid cases on a per storm basis, there was more variability in invalid cases at Site 1 than at Site 2, where Site 2 was less variable over the season (Table III). The sensors performed better at Site 2, with

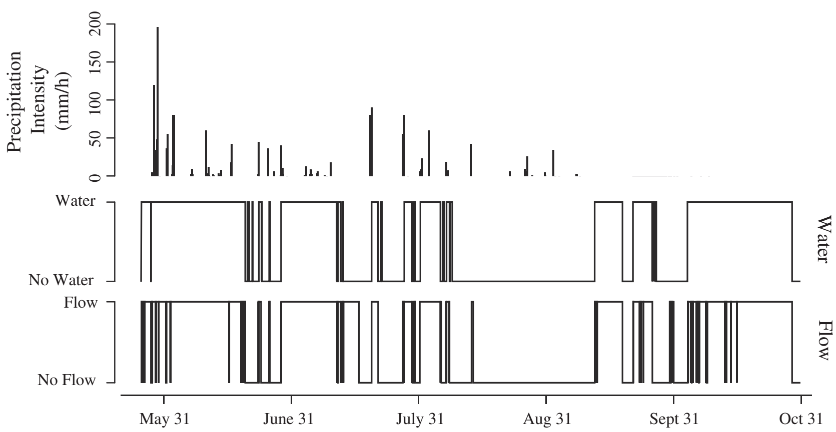

Figure 7. An example of a full season of data for a sensor pair including precipitation intensity. Where lines appear thicker, this is the result of noise in the data (i.e. the sensors are turning on and off at short intervals). The lack of response in August to precipitation may be a result of very localized storms over the precipitation gauge but not over the study site

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Table II. Overall corroboration between electronic resistance and flow detection sensors during storm events at both sites, by time (in percent)

	Valid cases			Invalid cases
	Case i	Case ii	Case iii	Case iv
Site 1	53.79	27.11	2.36	16.74
Site 2	64.52	20.46	9.88	5.14

higher levels of corroboration overall. The sensor performance was not related to the duration or intensity of the storm itself. Sensor-pairing agreement was further analysed based on siting position along the study reach.

Performance of sensor pairs by location within the study reach can be observed in Table IV. Only every second sensor pair is presented as the pair with the ER sensor connected to the event port (ER 2 in Table I) could not be tested for invalid cases. Upstream sensor pairs were in an invalid state more often than those downstream at Site 1. However, at Site 2, the furthest downstream sensor pair (Pair ID 11) was in an invalid state the most, over 20% of the time. The sensor pairs with the poorest performance were in areas that were rockiest at both sites. At Site 2, where the worst performing sensor pair was located (Pair ID 11), the sensor pair upstream of it performed notably better. Given that it was around 20 m upstream and out of the rocky terrain, this difference is understandable.

DISCUSSION

Sensor performance

The ER sensors contained more noise than the flow detection sensors at both sites (Table I). However, at both sites, some flow detection sensors had orders of magnitude more noise than others, even those sensors immediately upstream or downstream. Examining Site 1, Vane 1 on Logger 1, 42.96% of the records were altered by the noise-reduction algorithm, while the flow detection sensor 10 m away, Vane 2, Logger 1, showed a low degree of noise reduction, at just under 6%. Comparing the flow detection sensors with high noise levels (>40%) with their corresponding ER sensor in the pair, the ER sensors were some of the least noisy sensors in the dataset. Examining the sensors with high ER noise and comparing them to their paired flow detection sensors, the opposite was observed in most cases. This inverse relationship between the amount of noise for each sensor type in the pair may result from the physical placement of each sensor and/or the physical characteristics of the channel. The channel at Site 1 contains larger rocks in the headward portions than in the downstream areas where it was flatter, wider and sandier (Figure 5). At Site 2, the lower portion of the reach had larger rocks, while the upstream area had a sandier bed. The rockier areas generally resulted in better noise performance from the ER sensors than from the flow detection design. Because

Table III. Corroboration between ER and flow detection sensors at both sites for each storm, by time (as a percent of the storm time)

	Valid cases			Invalid cases
Storm	i	ii	iii	iv
Site 1				
1	57.85	10.35	0.00	31.79
2	79.10	18.10	0.00	2.79
3	29.90	63.24	3.76	3.10
4	53.33	20.43	0.04	26.20
5	69.21	3.63	0.00	27.16
6	58.68	34.93	0.01	6.38
7	1.07	44.88	1.28	52.77
8	0.23	27.03	28.39	44.34
9	57.11	32.67	0.17	10.05
10	66.68	0.00	0.00	33.32
11	97.60	0.00	0.00	2.40
12	96.43	0.00	0.00	3.57
13	97.60	1.73	0.40	0.27
14	89.66	0.00	0.00	10.34
Site 2				
1	94.90	0.06	0.02	5.02
2	100.00	0.00	0.00	0.00
3	100.00	0.00	0.00	0.00
4	66.80	33.20	0.00	0.00
5	99.83	0.16	0.00	0.01
6	99.96	0.04	0.00	0.00
7	12.04	55.75	32.21	0.00
8	0.00	78.36	21.64	0.00
9	0.00	78.22	21.78	0.00
10	83.55	3.71	2.25	10.48
11	77.28	19.08	0.00	3.64
12	99.67	0.33	0.00	0.00
13	77.30	22.70	0.00	0.00
14	12.50	49.77	37.73	0.00
15	66.85	11.14	5.30	16.70
16	78.66	12.23	0.00	9.11
17	85.20	14.45	0.19	0.16
18	34.88	55.67	7.29	2.16
19	1.33	49.34	49.34	0.00
20	0.00	100.00	0.00	0.00
21	0.00	67.90	32.10	0.00
22	0.00	62.90	37.10	0.00
23	1.24	36.81	61.95	0.00
24	0.00	99.47	0.53	0.00
25	56.79	22.89	13.72	6.60
26	78.11	18.15	1.70	2.04
27	90.67	7.77	0.00	1.56
28	99.83	0.00	0.00	0.17

Case iii only accounts for dry periods during the storm period, not during the interflow time.

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Table IV. Percent corroboration between ER and flow detection sensors at the sensor-pair level, for all storms, by time

	Valid cases			Invalid cases
Pair ID	i	ii	iii	iv
Site 1				
1	27.48	44.39	6.89	21.24
3	5.44	0.00	0.06	94.50
5	79.35	0.00	0.00	20.65
7	42.47	49.19	1.68	6.65
9	52.86	42.71	0.30	4.13
11	91.14	0.00	0.00	8.86
13	91.26	0.03	8.68	0.03
Site 2				
1	90.91	9.06	0.01	0.02
3	25.96	62.61	11.33	0.09
5	65.63	7.46	25.61	1.29
7	68.21	29.43	2.36	0.00
9	84.02	15.98	0.00	0.00
11	59.29	8.62	11.87	20.22

This includes only the upper pair of each logger due to the event-logging constraint. The data for each site are sorted from the most upstream sensor pair to the most downstream pair. Case iii only accounts for dry periods during the storm period, not during the interflow time.

the flow detection design relies on careful setup to ensure that the vane can open and close freely, in areas with a high density of larger rocks this became problematic, as individual rocks influenced where the sensor actually obtained positioned to avoid contact with rocks. Rocks were removed from in front, and behind, the flow detection sensor in some cases to avoid contact with the sensor while still allowing it to be sited in the thalweg. Where the flow detection sensor outperformed the ER sensors was generally in areas with shallower gradients and wider channels, resulting in flow depths at, or just below, the level of the ER electrodes. Bhamjee and Lindsay (2011) described this scenario as being the likely cause of noise in the sensor data. Examining the data, these constant on-to-off and off-to-on state changes were prevalent at the start and end of periods of activity within the channel.

Noise in the data was the main contributor to invalid cases between the two sensors at each location. These invalid cases occur mostly during the onset and cessation of flow, when the water level was around the level of the electrode for the ER sensor and around the threshold for opening the vane on the flow detection sensor. Using a 30-s filter on both datasets helped to reduce, but not eliminate, this noise. Where sensor pairs were setup slightly further apart, the local site conditions affected how quickly the sensors reacted to changes in flow within the channel. This lag period lead to invalid cases, although usually for short periods of time. This phenomenon can be seen just prior to 31 July in Figure 7. In this case, the flow detection sensor is activated, however noisy, prior to ER sensor being activated.

Generally, the ER sensors were more likely to under-report flow, committing errors of omission, than they were to over-report flow, committing errors of commission. The flow detection sensor design, when setup correctly, should result in the same types of errors. However, possible errors of commission were committed when the vane was held open during dry periods as a result of improper setup, or in areas with high debris load. Errors of commission can be compounded storm to storm if the vane is not closed. To reduce such errors, initial placement of the sensor was important, trying to choose locations that were minimally impacted by debris and large sediment during flow periods. However, these areas were not always avoidable, and in these cases, it was important to take other actions, such as frequent site visits, to ensure the vane was closed after periods of flow. Other possible actions that can be taken include trying to deflect debris and sediment around the sensor, although this can be often be impractical without disrupting the flow through the sensor. Large-aperture screening could be used in front of the sensor if very large debris is an issue, but must be performed only to the degree that the debris is diverted, but the flow is not altered in any major way.

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Sensor size and customization

A possible explanation for the variation in the performance of the flow detection sensor is the ability

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for the water to physically open the vane. The flow detection sensor was bench tested in a stream table with relatively low flows, at various angles to see if the flow detection sensor vane would open and close. However, observations during field visits showed that the flow detection sensors perform especially well when the channel was full and the water level was at, or near, the top of the sensor head. This flow depth also helped to reduce some of the noise associated with the vane opening and closing over short periods. Knowledge of typical flow depths in the channel would be useful to help customize the physical size of the sensor to keep flow at the sensor height. Scaling down the size of the sensor allows for a greater percent of surface area contact between the water and the vane allowing it to be opened more easily. Smaller sensors could be more prone to sediment settling and debris jamming, however, resulting in potential errors of commission when the vane is stuck open.

Challenges of monitoring ephemeral streams

The variation of channel and flow characteristics along a reach can complicate longitudinal spacing of sensor pairs. If the sensor spacing is too sparse, some of the expansion and contraction patterns will be missed, and very little redundancy will be built into the network. However, if they are too densely spaced, then there will be too much redundancy or autocorrelation between sensors. This autocorrelation can be good for verifying if sensors are working correctly by comparing them to their neighbours; however, in terms of resources, it is less efficient. For example, at Site 2, sensor pairs 9 and 11 (Table IV) performed quite differently, with the latter having a high degree of invalid cases. By examining these two pairs, indications of the problem in one pair can be sought out by looking for differences in the adjacent pairs. A better approach would be variable spacing depending on the reach characteristics. The most efficient technique would be to site sensor pairs more densely in areas that are prone to errors (e.g. rocky beds, like at Site 1 and pairs 1, 3 and 5) or where the active channel is more mobile within the banks, while setting them up further apart in areas where there is little change to channel morphology, or bed material differences. This variable spacing should capture any features in the channel, such as confluences (e.g. Site 1 and pairs 8 and 9), and changes to the morphology of the channel. Ultimately, the purpose of the monitoring study should be considered so as to select an appropriate scale. Scaling up of monitoring data can be complicated by the dynamic nature of ephemeral channels, especially those that are more episodic. These paired sensors are point measurements that are being used to represent connectivity of a linear feature, and while inferences can be made about the dynamics, they must be framed within the context of the spatial scale being measured.

Many of the technical limitations in previous ephemeral stream monitoring studies can be improved by using a paired-sensor approach. Previous studies have used a single sensor to detect water presence and infer that the water was flowing (Constantz *et al*., 2001; Blasch *et al*., 2002; Adams *et al*., 2006; Goulsbra *et al*., 2009; Bhamjee and Lindsay, 2011; Goulsbra *et al*., 2014; Peirce and Lindsay, 2014). However, the assumptions that once water is present in the channel it is immediately flowing, or will flow at all, can be misleading. Just over 27% and 20% of the storm times, there was water present in the channel but no flow at the study sites (Table II). Bhamjee and Lindsay (2011) showed that there are three main types of channel expansion. The most dominant expansion regime, coalescence, resulted from pools of water within the channel joining and forming a flowing network. However, the study also concluded that there was no practical way to distinguish the difference between discontinuous flow and this pooling effect in the data. This uncertainty would be minimized with the paired-sensor network introduced here. However, simply replacing the ER sensor with the flow detection sensor is not advised, as there is no way to know when the pooling begins to occur. Having a pair of sensors, each with a dedicated purpose, ensures both of these characteristics are being captured. In addition, being able to determine what is occurring below the bed would be useful in studies where groundwater interaction with the bed is needed. If a paired-sensor approach is sought, either a two-channel state logger should be used for each pair to minimize wiring or a four-channel state logger could be use to marginally reduce costs. In either case, a paired-sensor approach would benefit from having all sensors connected to state ports unlike the one ER sensor that was connected to an event port on each logger in this study due to logger availability. Doing so allows recording not only the onset and cessation of both water and flow for all sensor pairs, but also for testing for the three valid cases and one invalid case, and can help to minimize setup problems early in a monitoring effort.

CONCLUSIONS

This study introduced a new paired-sensor approach to monitoring connectivity in ephemeral streams. This included the design of a flow detection sensor to be used alongside an ER water presence sensor. As well, the setup and considerations required to successfully deploy this type of network were presented, and the merits of a paired-sensor approach. Finally, customizations and

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considerations that could help improve the performance of the sensors in certain environments were discussed. The major conclusions of the paper are

1. Pairing ER sensors with the flow detection sensor design provides a means of assessing the performance of individual sensors within a sensor network. This paired approach can also be used as a means of optimizing sensor configuration as well as increasing the types of information that can be derived from the monitoring data.
2. The overall performance of the flow detection sensor design was good, with residual noise in the ER sensor accounting for many of the invalid cases. Customizations such as altering the size of the sensors could allow for better performance by ensuring that the water levels are not at the critical thresholds required to activate the sensors.
3. Care needs to be taken in rocky beds as the location of the sensors can greatly degrade performance. Other potential considerations with siting include ensuring that debris does not keep the vane open, and the spacing of each sensor pair. The former problem can be alleviated in many cases by diverting debris around the sensor, or using large-aperture screening to stop debris ahead of the sensor. Increasing the density of sensor pairs in rocky beds would give a better idea of whether sensors are performing correctly. Regardless, frequent site visits will ensure that sensors are working as expected.

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