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Ephemeral stream sensor design using state loggers

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Abstract

Ephemeral streamflow events have the potential to transport sediment and pollutants downstream, which, in predominantly agricultural basins, is especially problematic. Despite the importance of ephemeral streamflow, the duration and timing of the events are characteristics that are rarely measured. Ephemeral streamflow sensors have been created in the past with varying degrees of success and this paper presents a solution which minimizes previous shortcomings in other designs. The design and setup of the sensor network in two agricultural basins, as well as considerations for data processing are explored in this paper with regard to monitoring ephemeral streamflow at high spatial and temporal resolutions.

1 Introduction

Streamflow mainly originates from groundwater sources and surface or near-surface runoff draining surrounding hillslopes. Runoff is frequently the greatest cause for concern because it plays the dominant role in flooding and sediment and pollutant transport (Arnell, 2002). It is the degree of hillslope-channel coupling within a drainage basin that often controls the character and quantity of water transported by its rivers. Hillslope-channel coupling is a dynamic phenomenon that is largely controlled by variation in a basins surface saturated area (Dunne and Black, 1970; Quinn et al., 1991; Bardossy and Lehmann, 1998; Burt and Butcher, 1985) and the expansion and contraction of ephemeral headwater streams (Day, 1978, 1980; Gregory and Walling, 1968; Morgan, 1972). While our understanding of surface saturated area dynamics is comparably mature, variations in the extent of flowing streams are still poorly understood, leading Bishop et al. (2008) to call for a new international initiative dedicated to the exploration of headwater streams.

A river networks ephemeral streams expand and contract with variations in basin moisture conditions (Gregory and Ovenden, 1979). Some ephemeral streams flow

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during wet seasons and others are episodic, only flowing during and for short periods following heavy rainfall or snow melt. Although ephemeral streams are rarely mapped, they often account for the majority of a catchments total stream length and drain large portions of their basins (Meyer et al., 2007). Therefore, ephemeral streams are important conveyances for water, sediment, nutrients, and pollutants. These wet-weather features provide valuable habitat for aquatic and terrestrial species (Labbe and Fausch, 2000) and affect storm runoff (Poff et al., 1997). Their small channels have comparably high water-sediment contact, providing a means for the reduction of phosphorus and nitrogen from runoff (Mulholland et al., 2000; Peterson et al., 2001; Ensign and Doyle, 2006). Additionally, ephemeral streams are important for the cycling of carbon and the retention of sediment within basins (Gomi et al., 2002; Meyer and Wallace, 2001). Ephemeral streams are undoubtedly landscape hotspots and periods of network expansion are hot moments (McClain et al., 2003) of basin process functioning. Unfortunately, our understanding of how stream length varies over a range of spatial and temporal scales is still quite limited. This reflects the difficulty in observing the expansion/contraction of flowing streams over long periods at appropriate spatial and temporal resolutions.

While the early research regarding monitoring stream network expansion was an important first step into understanding the processes involved in network expansion and contraction (Day, 1980; Blyth and Rodda, 1973), the research was largly hindered by the limits of manual field observation. Our understanding of how stream length varies over a range of spatial and temporal scales and in a variety of landscape types is still quite limited as a result. Recent advances in environmental monitoring techniques for streamflow duration and timing provide the greatest potential for addressing this current gap in knowledge.

Sensor designs for monitoring the presence of water in a channel have been explored previously (Blasch et al., 2002, 2004; Goulsbra et al., 2009; Adams et al., 2006), but few have been used specifically to study the spatial and temporal distribution of ephemeral streamflow with the notable exception of Goulsbra et al. (2009). While the Goulsbra

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et al. (2009) design was successful, improvements were still needed to address the consistency of the sensors as well as the reduction of post-processing needed to interpret the data. Further refinement of these monitoring techniques may eventually allow the catchment controls on stream network expansion and contraction to be studied.

The purpose of this paper was to develop and test an improved sensor and monitoring network designs for measuring stream flow timing and duration in ephemeral streams within agricultural landscapes.

2 Sensor design

The sensor was designed to suit the environment typically found in the predominantly agricultural catchments in Southern Ontario. Conditions in Southern Ontario headwater streams include diverse soil types and a range of land covers. Local headwater channels frequently experience high sediment transport and deposition and possess substantial vegetative debris because of the surrounding land-cover which is typically a mixture of agriculture and forest. Another consideration is that with many small animals utilizing the dry channels, there is potential for the sensors to be destroyed by trampling or entanglement with the wires.

The sensor is made up of two distinct parts that were considered independently to meet a set of criteria. The sensor head is the part of the sensor which contains the electrodes and is located in the channel while the logger is a dedicated unit designed to measure and record the responses of the sensor heads.

2.1 Sensor

Several environmental factors were considered during the sensor design. Southern Ontario agricultural basins, where the sensors were to be deployed, are made up clayey and sandy soils which are prone to erosion. As such, consideration for how the sensors respond to high sediment transport is important. Along the same lines, many channels have debris which is carried downstream when flow occurs. Thus, the sensor head needed to be designed such that the chances of it being covered in sediment, destroyed by debris in the channels or trampled by local wildlife was minimized. The size of the sensor heads was also an important consideration since the set up and take down of the network would mean transporting them through various terrain types. For this study, a balance between building a small, lightweight sensor and one which could withstand the rigors of the environment needed to be struck. To ensure that these two main criteria were met, various sensor heads were tested in the lab.

A variety of sensor head designs were lab tested in a river tray containing sediment with an average grain size of 0.3 µm. Flow was initiated from the channel head, flowing downstream. While this is not always how channels initiate, it is representative of the channel when flow is occurring. For each tested sensor head, the slope of the tray was set to 15, 10 and ~0 degrees to represent various rates of flow as well as various rates of sediment mobilization. Each sensor head was tested at three locations within the river tray (top, middle and bottom) for a minimum of thirty minutes to ensure that sediment transport results were consistent and comparable between sensor heads. As well, each sensor head tested was oriented in the ideal position, parallel to flow, as well as at a 45 degree angle to the direction of flow. Doing so ensured that the design would not fail in the event that the direction of flow in the channel was not as expected during set up. Each sensor head was also set up in a "clean" state, sitting above the bed as they would be set up in the field, as well as starting them off buried slightly under the bed to simulate the result of a sensor being covered by sediment. Refinements were made on sensor heads that showed promise until a final design was chosen.

For this study, the final sensor head design was created using 2 mm thick acrylic glass which was curved using a heat gun to the specification in Fig. 1. Acrylic glass was used due to its strength, light weight and the ability to mold it using non-specialized tools. Its plasticity also reduced the chance of a sensor cracking when struck with debris in the channel. The base plate was made of the same thickness acrylic glass cut to 38×38 mm squares and attached using the same marine glue used to seal the

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holes in the logger housing. The design was chosen over others due to its simplicity, consisting of only two parts, the cost per sensor (<0.50 per sensor head) as well as its ability to prevent sediment settling on the electrodes. Unlike the design used by Goulsbra et al. (2009), which had the water run through a container using screens to keep out sediment, this design places the electrodes on the outside and avoids the chance of the screens being blocked by sediment. This "open" design means that care needs to be taken to ensure that sediment and other debris do not settle on the electrodes, potentially causing a false-positive (i.e. recording flow when no flow exists). The design mitigates this by placing the electrodes in the areas where erosion around the sensor were shown to occur (Fig. 2). The curved design of the sensor head created an area of higher relative pressure which ensured the sediment did not build up around the electrodes as well as allowing for debris in the channel (e.g. leaves, sticks, etc.) to be deflected away from electrodes rather than being caught up on the front surface. Elevating the electrodes above the baseplate minimized the chance of sediment building up around them as well as ensuring that a signal was not present when water was stagnant (i.e. standing water) on the baseplate prior to it evaporating. By placing the electrodes on either side of the sensor head, the chance of this occurring was further avoided as was the chance that the wires would contact each other (i.e. short circuit). While the sensor head design is an important consideration for detecting flow, the choice in data logger also has an impact on how that flow is recorded and interpreted.

2.2 Logger

Since measuring ephemeral stream flow ultimately involves identifying periods of flow and no-flow, there is no advantage to recording the specific electrical conductivity coming from the sensor head such as in the modified temperature logger found in Goulsbra et al. (2009). Rather than recording the electrical resistance of the water, which is not needed to determine flow, state loggers were chosen. State loggers have internal resistance thresholds which are interpreted as being an open or closed circuit, that in

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the case of ephemeral flow monitoring can be inferred as no-flow and flow states, respectively. State loggers record a value only when there is a change in the information coming from the sensor. By contrast, interval loggers will record a value at a predetermined interval, regardless of whether a change has occurred. This monitoring strategy leads to a reduced memory capacity in the loggers when a short interval is used or the trade off of a longer measurement interval (i.e. lower temporal resolution) which is not ideal as stream network expansion is likely to be rapid after intense rainfall events in some catchments. For monitoring ephemeral stream flow timing and duration, event logging is not suitable, as there is concern about both the start and end of flow events. Measurement of ephemeral streamflow timing and duration up to this point have used interval loggers at the expense of temporal resolution.

The use of state logging, as opposed to measuring relative resistance (Goulsbra et al., 2009), eliminates the subjectivity involved in determining the threshold value of electrical resistence seperating open and closed states. Measuring relative resistance, the threshold values are specific to each logger and sensor combination and must be determined through calibration. With state logging, this calibration is not needed as the threshold values are predetermined and constant. The removal of this calibration process speeds up data interpretation as well as reduces inconsistencies between data loggers. The internal processing of the loggers allowed for consistency between loggers which meant that no calibration was needed. The use of modified temperature sensors in previous studies meant that the data was collected at a predetermined interval to strike a balance between a fine temporal scale and a long data collection period.

The chosen data logger for this study was the Onset HOBO U-11 state logger. The U-11 includes three state logging inputs as well as one event input (not used) which allowed for a reduced cost in data loggers compared to previous studies, where each sensor head had a dedicated logger. This reduced per-sensor cost meant that a greater spatial resolution could be achieved at a lower cost. The U-11 logger has a temporal resolution of 1 s, a far higher resolution than the phenomenon being measured, which

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in combination with the statelogging meant that it had the ability to drastically increase the temporal scale of ephemeral flow data compared to previous designs where logger memory was a limiting factor for temporal resolution.

To test how the U-11 response time compared to previous designs, notably the ER sensors used in Goulsbra et al. (2009), the electrodes were placed into a pan of water to determine the lag times for recording the onset and cessation of flow. Table 1 shows the lag times for the prominent sensor designs used in the literature. Lag times with negative numbers denote where the sensor recorded a false-positive (i.e. the presence of water in the channel, when there was no water present). This is especially an issue with the sensors that were located beneath the surface as they recorded saturated soil as being flow events, thus making them less suited to consistently being able to compare ephemeral streamflow at different sites. With sensors raised above the surface, the lag time is determined by the interval which the logger can record data as well as the time it takes for the water to reach the height of the electrodes. The example in Goulsbra et al. (2009) used a 30 s interval as it allowed for the best trade off between temporal resolution and the logger memory available. Since the U-11 loggers check for a change of state every one second, this allows for a very fine temporal resolution, with minimal lag and unlike with an interval logger, the state logger minimizes the trade off.

Since the Hobo U-11 loggers were not designed for outdoor use, logger housings were built using waterproof, sealable storage containers. To accommodate the logger's data input cables, holes were drilled in the side of the housing, allowing just enough room to insert the cables. The use of a marine glue to seal the holes allowed for a reliable waterproof seal and since the glue is able to dry in wet conditions it allowed for the repair of logger housings in the field regardless of the weather, rather than taking a logger offline until it could be redeployed. Finally, both the logger and the sensor were connected to create a field deployable unit.

2.3 Field-ready sensor

To create a field ready set of sensors, the sensor heads needed to be attached to the data logger. With three inputs on the U-11 data logger, the sensor heads were spaced at 10 m intervals which provided an adequate spatial resolution. To accomplish this, the outer sensors had two 10 m 22-gauge solid core wires, while the middle sensor had a shorter 30 cm lead as it would be sitting near the logger when set up. Since two wires ran to each sensor, the pairs were twisted together, which prevented tangling both during transportation and set-up. The ends of the wires on the sensor head side were stripped to expose 2 mm of wire which minimized the loss of strength and flexibility of the wire when it was exposed, while reducing the chance that fluctuations in temperature would expand the plastic insulation over the end of the wire. The wires were pushed through two holes drilled on either side of the sensor head and were held in place by the same marine glue used to seal the logger housing. In doing so, the wires were held firmly in place and by using marine glue, the chance of having the glue disintegrate when wet was reduced. The sensor heads were held down by two metal pegs, one in front of the sensor head and one behind. The placement of the front peg, other than acting as an anchor, also helped to protect the sensor from larger debris moving downstream.

3 Field set-up and siting considerations

While extensive lab testing was completed, the sensors needed to be tested in the field to truly determine their usability. Unlike the controlled environment of the lab, the individual constraints on each sensor head were less structured, but tried to account for as many scenarios as the study sites would allow.

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3.1 Study sites

Field testing occurred at the RARE Charitable Reserve (Fig. 3), which is a part of the Grand River watershed in Ontario, Canada as well as in the Rondeau basin (Fig. 4) in Southwestern Ontario.

The RARE Charitable Reserve is mainly composed of active and fallow agricultural fields, forest and low-lying boggy forested areas. The wide variety of land-use/land cover types and sediment types meant the sensors could be tested in many of the characteristic types of landscapes to be found in Southern Ontario. Testing on the site was around Cruickston Creek, which is a tributary of the Grand River. Ephemeral channel widths available on at the site ranged from 10 cm to over 30 cm with degrees of slope similar to those used in the lab tests. Available channel depths at the study site ranged from 5 cm to 15 cm. Vegetation at RARE included mixed deciduous and coniferous forests, fallow fields with tall grasses and plants (e.g. thistle), winter wheat and ground cover type plants in the boggy areas (e.g. skunk cabbage – *Symplocarpus foetidus*).

The Rondeau basin is located in Southwestern Ontario and drains into Lake Erie through a series of deep headwater gullies, which originate on a plateau in the north, and larger streams further downstream in the channel network. Many of the gullies in the area experience emphemeral flow. There are many problems with sediment and nutrient transport within the watershed, especially off of agricultural fields, that have led to severe eutrophication of Rondeau Bay (Lambert, 1997). Frequent in-filling of channels that cross through fields is done to reduce the amount of sediment loss from agricultural fields. Likewise, gullies adjacent to fields tend to be deepened to promote quick removal of water off of tile-drained fields. As a result of steep gullies and anthropogenic modification, the basin has many ephemeral channels in the headlands that run through different types of land-uses/land covers as well as vary in size and depth. The channel widths used for the study ranged from 15 cm to over 200 cm while the depths used were between 10 cm to over 200 cm. Vegetation in the basin is mainly

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agricultural, with wheat, corn and soybeans being the predominant crop types, however, the catchment also includes deciduous forests and hedgerows separating fields. Unlike the RARE site, the sites in Rondeau did not feed into a single, perennial stream nearby, but rather had a greater spatial distribution and less connectivity via a common stream network.

3.2 Network installation

Five sets of loggers, each set containing three sensor heads, were installed within headwater channels of the RARE site to capture each type of land-use in the area. In Rondeau, seven set of loggers, also with three sensor heads were installed within ephemeral channels at the study sites within the basin. Within the channel, sensors were placed in the thalweg to ensure they were in the path of the flow which was not always in the centre of the channel. Each sensor was placed on a local riffle rather than in a pool to minimize the possibility that sensors could be situated in standing water (i.e. puddles within pools) for extended periods. In doing so, the responsiveness of the sensors to actual flow periods was increased. To reduce the likelihood of animals interfering with the wire cables connecting the sensors to the loggers, cables were buried or placed under rocks or logs.

Data loggers were situated near channel banks closest to the middle sensor and were secured in place to prevent movement. The loggers allowed for about 1.5 months of data logging depending on the number of events. Whenever data from the loggers were downloaded, sensors were checked to ensure they were not covered in sediment and if a channel cross-section had changed significantly between field visits, sensors were re-situated within the thalweg.

The sensor design proved to be successful as even in the channels that experienced substantial sediment transport, the electrodes were clear of sediment and debris. Debris in the channel did not affect the sensors despite its presence in many channels. The data loggers and housings were able to withstand the environments they were placed in.

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4 Data processing

Figure 5 shows a sample data set both in raw and post-processed form. In the raw data set, around the time of a change of state (i.e. from flow to no-flow or vise versa), the state change is associated with numerous and frequent records that can be considered noise. This noise was also observed in lab testing, especially when the channel slope was low. Noise in the data originates as the loggers record the continuous rise and fall of the stream over the electrodes as the channel fills and empties.

Noise in the data results from the high temporal resolution at which the loggers record the rising and falling of water above and below the electrodes. This rise and fall of the stream depth can be due to ripples forming on the surface of the water and covering the electrodes momentarily when the water level is at a similar height. Based on either explanation, it can be inferred that water is present in the channel when these data points are recorded in rapid succession.

Noise was removed from the dataset where these changes of state occurred at frequencies greater than 30 s. A 30 s interval was selected due to fact that it was unlikely that a channel could fill and empty in less than 30 s. This is evident in the data, where high frequency noise is evident at the start and end of events, but long interval events are quite rare, only occurring during periods of intense rainfall. Where relatively high frequency intervals were recorded (i.e. around 30 s), there were no cases where more than one sensor responded. To remove noise, the first wet state recorded was selected for the start of a flow event, while the last dry state in the was selected. It can be assumed that the first wet state is when the water has reached the height of the electrodes, while the subsequent dry and wet data points are the water level fluctuating above and below the electrodes. The last dry state signifies where the water is no longer in flux over the electrodes, meaning that there was either no water in the channel, or very little water which is either stagnant or reducing in depth. By removing noise from the data, individual flow events were more easily highlighted and better represented the situation in the channel at the time of the event.

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5 Discussion

Previous ER sensor designs were assessed before designing the sensor in this study. The chosen design has improved the ability to monitor streamflow timing and duration semi-autonomously. However, the sensor design was not without its own limitations.

The main limitation of the ER sensor design is that it is only measuring wet and dry states, rather than flow or no-flow states. While it can be assumed that in many situations, a wet state will be a flowing state due to the fact that the sensors were places on riffles, it cannot be guaranteed. This has been a limitation of all previous approaches as well, including methods based on ambient bed temperature and ER. Lab experiments have been conducted previously to explore the possibility of measuring flow and no-flow timing directly. These sensor designs were seriously hindered by their lack of robustness in the presence of sediment transport.

While attaching three sensors to a single logger reduced the overall cost of the sensor network, allowing for greater spatial resolution of measurements, logger memory capacity was filled more quickly than it would have if each sensor had a dedicated logger. However, since the logger recorded changes of state, the memory lasted much longer than previous sensor designs where each sensor had its own logger. Another trade-off with having three inputs into one logger was that if a logger failed, three points of measurement along a stream would be lost. While there is no guaranteed way to ensure a logger will not fail for a variety of reasons, frequent monitoring of the sites reduces the chance of this happening. Noise in the data was another factor which needed to be accounted for in the sensor network design and data post-processing.

While compared to previous attempts, using ER sensors (Goulsbra et al., 2009; Adams et al., 2006), or the bed-temperature method (Blasch et al., 2004) the use of a state logger has allowed for a drastic reduction in post-processing of data while also increasing the temporal resolution because there is no need to determine a sensor-specific threshold in ER. Noise in the data was due to the high temporal resolution of the loggers recording ripples forming on the surface of channel at the level of the

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electrodes. Site conditions, mainly saturation of soil, affected how quickly streams began to flow. Some channels responded very quickly and showed no noise, while others displayed a slower rise, thus leading to rippling and in turn, noise. While the sensitivity of the current design allows for a very fine temporal resolution which shows the instantaneous rise and fall of the water level above and below the electrodes, a decrease in the sensitivity of the sensor head would allow for cleaner data set for studying longer time frames without the need for post-processing work.

Performance in the lab, under ideal flow patterns, showed significantly less noise in the data compared to the field, except at the lowest channel slopes, and allowed for the controlled testing of various sensor head designs under repeatable, consistent conditions.This would suggest that the noise was caused by small ripples, likely caused by wind, in the surface of the water as it approached the height of the electrodes. While field conditions were far less consistent between channels, the lab testing ensured that the sensors worked as expected under the tested flow conditions. The sensors performed well in the field, with the main drawback being that if they were not correctly placed in a channel cross-section, it was possible that low flows were missed as they diverted around the sensor head. This issue was minimized by constantly verifying the placement of the sensors after major storm events. Noise as a result of debris contacting the electrodes was not noticed at any of the sites. The sensor design has allowed for the study of ephemeral streamflow duration and timing in a more quantitative manner.

The ability to deploy the sensors for long periods of time, in a variety of physical environments, has allowed for an improvement in the ability to study the expansion and contraction of stream networks. The cost and ease of setup and maintainance mean that the sensors can be setup at a variety of locations within different regions. This greatly improves the ability to quantitatively compare the behaviour of channels to each other. In doing so, characteristics of each channel can be compared to determine the controls on expansion and contraction as well as observe the manner in which stream networks expand and contract. Knowing this allows for a better understanding of the

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role headland areas play in the dynamics of the entire watershed. In predominently agricultural basins, such as Rondeau, this is especially important as the modification and location of these streams has a great affect on downstream water quality and quantity. Being able to set a baseline for how a basin responds under current conditions allows for a better understanding in the future when modifications to the hydrology of a basin occur.

6 Conclusions

This study describes a novel sensor and monitoring network design for measuring stream flow timing and duration in ephemeral channels in Southern Ontario. The following conclusions can be drawn from this work:

1. State logging lessened the amount of noise in the data and the subjectivity in the interpretation of events when compared to previous attempts at measuring ephemeral streamflow using electrical resistance, while also increasing the responsiveness to flow events and eliminating the need for per-sensor calibration.

2. Spatial and temporal resolution was increased through the use of the state logger. Three inputs allowed for a greater spatial scale due to the lower relative cost and since only changes in state were recorded, temporal resolution was increased relative to previous sensor designs as the logger checked for a change of state every second.

3. Monitoring ephemeral stream duration and timing is needed to understand the dynamics of the flowing stream network. In doing so, the understanding of the migration and fate of pollutants can be enhanced.

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Table 1. Lag times for sensor designs.

Sensor	Onset lag	Cessation lag
Temperature at 1 m [a]	−19.8 min	−108 min
Temperature at 0.05 m [a]	−7.31 min	−568 min
Electrical resistance at 0.15 m [a]	3.88 min	72.5 min
Electrical resistance at surface [a]	−12.1 min	70 min
Electrical resistance above surface [b]	30 s	30 s
Electrical resistance w/state logger	1 s	1 s

[a] (Blasch et al., 2002)
[b] (Goulsbra et al., 2009)

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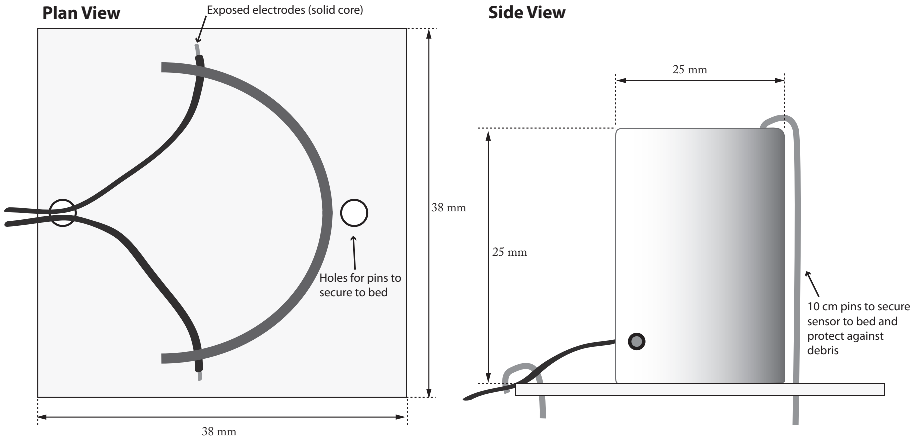

Fig. 1. Electronic resistance (ER) sensor schematic.

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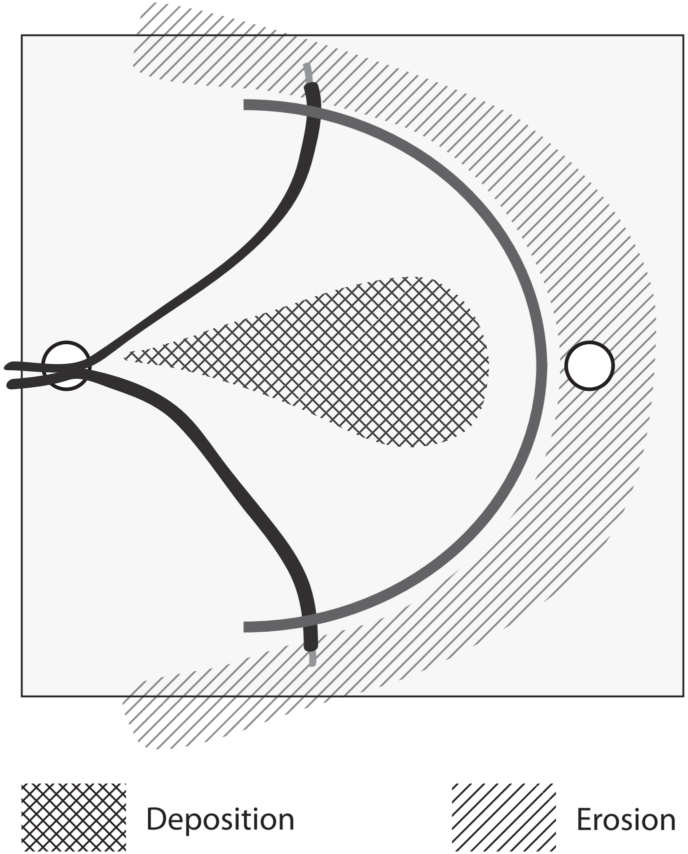

Fig. 2. Movement of sediment around the sensor head.

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Fig. 3. RARE study sites.

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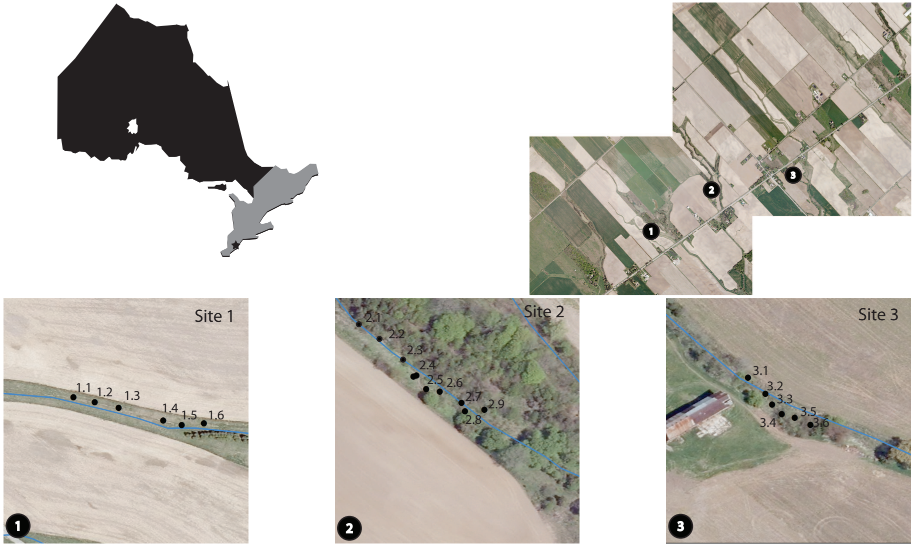

Fig. 4. Rondeau study sites.

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Fig. 5. Raw data **(a)** and post-processed data **(b)** with the noise removed for one sensor head.

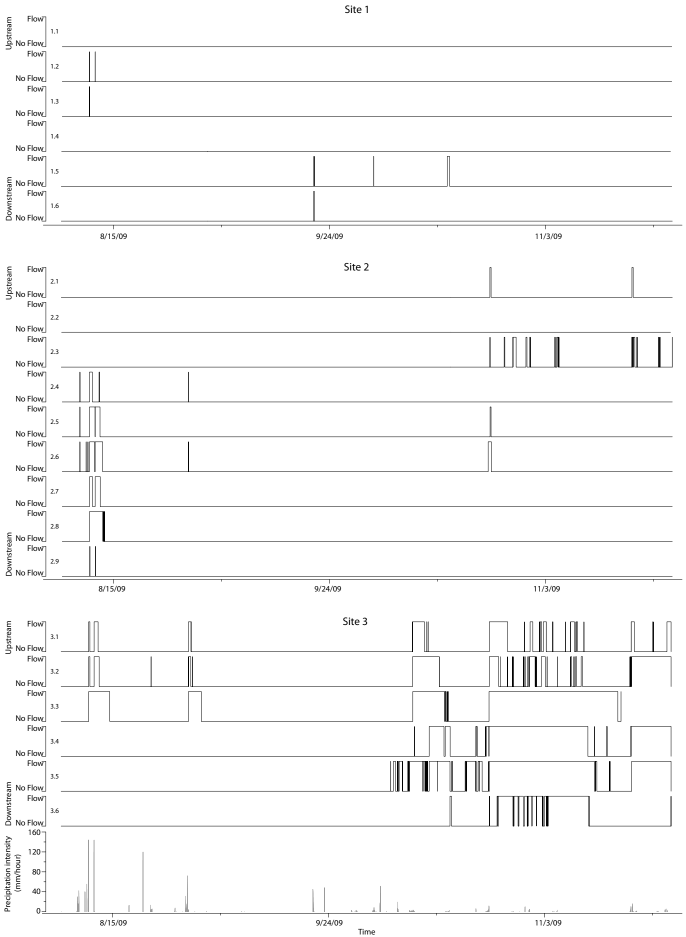

Fig. 6. Final flow data from field with noise removed.

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