The Use of Electrical Resistance Sensors to Monitor Hydrological Connectivity at High Resolutions

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1. Hydrological Connectivity

Hydrological connectivity has been defined as '*the passage of water from one part of the landscape to another and is expected to generate some catchment runoff response*' (Bracken and Croke, 2007: 1749). This water can travel through the landscape via various different flow pathways including surface pathways (overland flow), subsurface pathways (including pipeflow) and channelised streamflow. In many environments, the amount of water travelling via these pathways and the connectivity between them can vary dramatically over both time and space. This has important implications as the timing and magnitude of catchment discharge and the source areas of sediments and solutes are all intimately linked to the dynamic connectivity within a catchment. As such, the ability to characterise how this changes over space and time is central to our understanding of the functioning of hydrological systems.

2. The Use of Electrical Resistance Sensors

The use of Electrical Resistance (ER) sensors has shown potential for monitoring changes in connectivity as they can distinguish between the presence and absence of water between a pair of electrodes (Blasch *et al.*, 2002). When water is present between the electrodes (a 'wet' reading), an electrical circuit is supported and the measured conductivity is high (low resistivity). When there is no water present (a 'dry' reading), no circuit is supported and the conductivity is low (high resistivity). This enables a binary distinction to be made between the presence and absence of water.

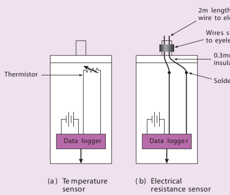

Figure 1. Schematic representation of (a) the Onset HOBO pendant temperature data loggers and (b) Onset HOBO pendant temperature data loggers following conversion to an ER sensor.

Commercially available temperature data loggers can be converted to ER sensors by replacing the thermistor with 2 m lengths of 0.3 mm, single strand, plastic-insulated wire. The ends of the lengths of wire are stripped to form the electrodes of the ER sensor, shown in Figure 1. The loggers used here are Onset HOBO pendant 4 K temperature data loggers (product ID UA-001-64). Laboratory testing of the converted sensors revealed that they can consistently differentiate between the presence and absence of water of varying conductivity between the sensor electrodes (see Goulsbra *et al.*, 2009). The loggers are inexpensive which allows for the deployment of extensive sensor networks and have user-selectable sampling intervals of between one second and 18 hours with a 64 K memory storing over 52,000 readings. This enables a high density of observations, both in space and time.

In order for this technology to be used effectively for the collection of data on connectivity the basic ER sensor design must be developed further by the addition of a 'sensor head' which houses the electrodes and situates them in an optimal position for monitoring. The design of the sensor head will vary according to the specific process being monitored, as shown in sections 4 - 6.

3. Study Site

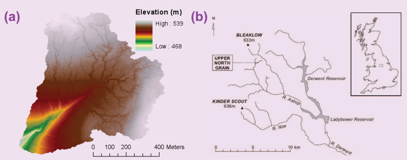

Figure 2. (a) The Upper North Grain catchment; (b) its regional setting.

The sensors were deployed the Upper North Grain catchment, a small peatland headwater catchment in the south Pennines, UK. The catchment is 0.43 km^2 in size and lies between altitudes of around 480 and 540 m. The principle landcover is blanket peat. Peatlands are renowned for their flashy hydrological regime and as such connectivity varies dramatically over relatively short time periods. The topography of the catchment is shown in figure 2 (a) and its regional setting is shown in Figure 2 (b).

4. Ephemeral Stream Flow Sensors

Ephemeral Stream Flow and Previous Monitoring Methods

Intermittent and ephemeral streams have been observed in a variety of environments as the extent of the flowing stream network expands from the perennial channels into headwater reaches. A fully expanded drainage network represents a significantly higher degree of connectivity within a catchment than the contracted perennial network. Empirical data on the dynamics of drainage network extent is very limited, mainly due to the logistical difficulties of accurate monitoring. Previous methods include manual observations, which are necessarily limited in temporal resolution (Morgan, 1972), and temperature sensors, which often involve a high degree of subjectivity in their interpretation and introduced large errors in estimates of streamflow timing (Gungle, 2006).

Ephemeral Stream Flow Sensor Design

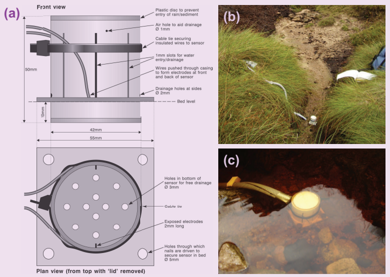

Figure 3.(a) Front and plan schematic diagram of the EFS sensor head (Source: Goulsbra et al., 2009); (b) and (c) examples of ESF sensors in the field.

The design presented here uses ER technology, housing the electrodes in a custom-made sensor head to make a fully-functioning ephemeral streamflow (ESF) sensor. The sensor head has several unique design features including a sub-surface sediment trap to prevent the retention of damp sediments around the electrodes, drainage holes and slots to allow the entry of water during flow conditions whilst minimising the entry of sediment and to allow water to drain out of the body of the sensor once flow has ceased, and relatively long connecting wires between the sensor head and the data logger which allow the logger to be placed away from channel flow. The short length of the sensor electrodes (~2 mm) and their location on opposite sides of the sensor head prevents a false positive connection being made. The sensor design in shown schematically in Figure 3 (a) and in the field in Figures 3 (b) and (c).

Ephemeral Stream Flow Sensor Data

Figure 4 (a) shows an example of a raw dataset collected by one of the ES sensors in the field. The data are then processed by, firstly, setting a threshold with all readings below this being defined as 'dry' or not flowing and those higher being defined as 'wet' or flowing. The significant difference ER reading between times when flow was present and when it was not allowed this threshold to be set with confidence. Secondly, any artefacts of data collection are removed. A simplified dataset can then be produced clearly showing when each sensor is in flow and when it is not, as shown in Figure 4 (b).

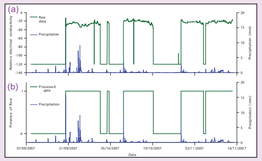

Figure 4. (a) Raw data collected by an ESF sensor in the field and (b) the same data set after being processed.

Applications of Ephemeral Stream Flow Sensors

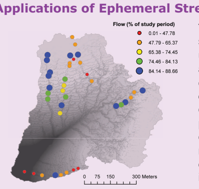

Figure 5. The distribution of 'wet' and 'dry' sites in terms of % flow.

This binary data on when each ESF sensor reads wet and dry can then be used to extract various information about the degree of catchment connectivity. Specifically, we can deduce the drainage density in the catchment at any time, the timing and pattern of network expansion and contraction in response to specific rainfall events, and the cumulative time each monitoring site is inundated, as illustrated in Figure 5. This then allows the controls on network expansion to be investigated at various spatial and temporal scales.

5. Overland Flow Sensors

Overland Flow and Previous Monitoring Methods

Overland flow is a feature of most hydrological systems and its spatial and temporal distribution can have important implications for the relative speed of water movement through the landscape and the nature of nutrient and sediment fluxes (Holden and Burt, 2003a). Traditional methods of monitoring overland flow include the use of crest-stage tubes (Burt and Gardiner, 1984; Holden and Burt, 2003b), which need to be manually monitored thereby limiting the temporal resolution of measurements, and overhead image analysis (i.e. Smith *et al.*, 2011), which is limited in both its spatial and temporal extent. Therefore, it seems that there is considerable scope to improve on these methods.

Overland Flow Sensor Design

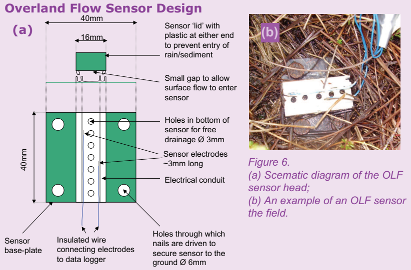

Figure 6. (a) Scematic diagram of the OLF sensor head; (b) An example of an OLF sensor in the field.

The overland flow sensors presented here use changes in ER to detect the presence or absence of water. The sensor electrodes are housed in electrical conduit with a lid which prevents entry of rainwater and debris. Drainage holes and a small gap at the bottom of the front end of the sensor lid allow the entry of surface flow via upwelling and surface runoff from upslope. The electrodes are short (~3 mm) and offset slightly to minimise the chances of a connection being made by isolated drops of water. The sensors are installed as close to the ground surface as possible to ensure that even low flows are detected. The sensor design in shown schematically in Figure 6 (a) and in the field in Figure 6 (b).

Overland Flow Sensor Data

The 'wet'/'dry' threshold was set at each individual site on the basis of sensor response. Examples of the data collected by some of the OLF sensors are shown in Figure 7. One type of sensor response is illustrated by OFS ID 608 where following rainfall, a sharp and distinct rise in ER can occur. This is short lived and sensor ER quickly returns to zero. For sensors which display this type of response, it was relatively straightforward to identify periods of overland flow generation, allowing a 'wet'/'dry' threshold to be set with relative ease, shown by the red dashed line in Figure 7. Some sensors showed a similar response to OLF sensor ID 617 in Figure 7. At these sites, a sharp rise in ER can be observed after rainfall. Following the cessation of rainfall, ER declines, although this can be slow and low ERB values can be maintained for long periods after rainfall has ceased without returning to zero. In these cases, again it is thought that these prolonged 'recession limbs' may be a function of the sensor drying out once overland flow has ceased. Here, the 'wet'/'dry' threshold was set based on the break in slope on the recession limbs of the sensor, shown in Figure 7.

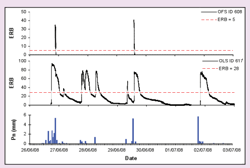

Figure 7. Response from 2 OLF sensors and the 'wet'/'dry' threshold applied to each sensor (shown by the red dashed line in each case).

Applications of Overland Flow Sensors

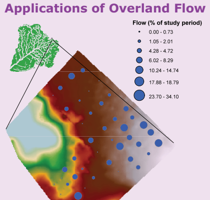

Figure 8. The spatial pattern of overland flow production at a gully head.

This binary data can then be used to investigate the spatial and temporal pattern of overland flow, including the extent and configuration of overland flow production in response to specific rainfall events and an the identification of parts of the landscape which produce overland flow more frequently than others, as shown in Figure 8. In conjunction with other environmental monitoring data this can provide us with information on the controls on overland flow production.

6. Pipeflow Sensors

Pipeflow and Previous Monitoring Methods

Soil pipes have been reported on every continent, except Antarctica, and in a broad range of environments (Holden, 2006). Piping is significant in terms of its impact on the size of the contributing area during storm conditions (Jones, 1979), the enhanced vertical and lateral connectivity of water, solutes and sediments supplied to the stream network (Holden *et al.*, 2002), and the increase in the length of channelised flow (Jones, 2010). These factors lead to considerable impacts on the timing, quality and quantity of water delivered to the main channel network. Many previous studies on pipes do not monitor pipeflow directly and instead use indirect estimates. Where pipeflow has been directly monitored, this has been done by setting custom-made weirs into excavated sections of soil pipe and installing water level recorders linked to data logging devices (Jones *et al.*, 1984). However, this method involves a degree of expense and disturbance, as well as issues with equipment availability and an inability to detect low flows (Holden and Burt, 2002).

Pipeflow Sensor Design

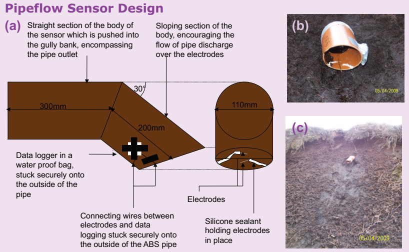

Figure 9. (a) Schematic diagram of the Pipeflow sensor head (b) and (c) examples of Pipeflow sensors in the field.

In order to monitor pipeflow at high spatial and temporal resolution, a low-cost reliable sensor was developed. As with the other types of sensor, the pipeflow sensors use changes in ER to detect the presence or absence of water. The pipeflow sensors consist of longer electrodes (~15 mm) housed in ABS plastic pipe which encloses sub-surface soil pipe outlets. Pipe discharge was routed through the ABS plastic pipe and over the sensor electrodes at the mouth of the ABS pipe which are connected to a data logger. The sensor design in shown schematically in Figure 9 (a) and in the field in Figure 9 (b) and (c).

Pipeflow Sensor Data

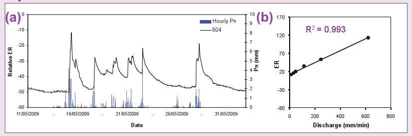

Figure 10. (a) Example of 'typical' data collected by a pipeflow sensor; (b) The relationship between discharge and ER in laboratory experiments.

Figure 10 (a) shows an example of data collected by one of the pipeflow sensors. As opposed to the distinct flow/no flow data recorded by the ESF and OLF sensors, the data is far more continuous, resembling hydrograph data. As the pipeflow sensor electrodes are much longer than the other two designs it is possible that, as the amount of discharge from the pipe varies, the degree of connection between the electrodes may vary proportionally, producing a much more continuous change in ER. This was tested in the laboratory and it was found that there was a strong linear relationship between discharge passed through the sensor and measured ER, as shown in Figure 10 (b). Although this strong relationship could not be replicated under field conditions due to the influence of environmental factors, the magnitude of the influence of discharge on ER is though to be much greater than any other factor and as such the sensors can be used to extract information about the timing of the start and peak of pipe stormflow using semi-automated techniques.

Applications of Pipeflow Sensors

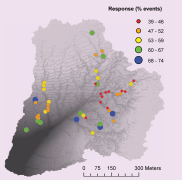

Figure 11. The spatial pattern of overland flow production at a gully head.

The data on the start and peak of pipe stormflow timing can be used to tell us which rainfall events each monitored pipe responds to (see Figure 11), and allows us to determine the conditions on pipe response. It is also conceivable that the design could be further developed to provide quantitative information about pipe discharge volume.

7. Integrated Catchment Monitoring

The three types of sensor can be used together to produce integrated monitoring data for various flow processes in a catchment, providing us with high resolution on the timing, extent, and interaction of various different runoff pathways, and therefore, an overview of the dynamic connectivity within the catchment. An example of this can be seen in Figure 12 which shows various flow processes in a single gully and its contributing area in the Upper North Grain research catchment.

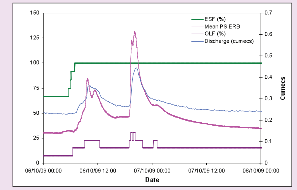

Figure 12. Overland flow (purple), ephemeral streamflow (green), pipeflow (pink) and discharge (pale blue) response in a sub-catchment of Upper North Grain.

8. Summary

- ER technology can be used to differentiate between the presence and absence of water in the landscape.
- The inexpensive nature of the sensors and user-selectable sampling intervals allow a high density of measurements in space and time.
- Placing the sensor electrodes in unique sensor heads developed specifically to monitor different processes allows various components of catchment connectivity, including ephemeral streamflow, overland flow and pipeflow, to be monitored and characterised.
- All three designs presented here represent considerable improvements on previous methods in terms of the density and resolution of measurements and the accuracy and interpretability of the resultant data.
- There is considerable scope for these sensors to be employed in a variety of environments, and for ER technology to be utilised in the detection of other hydrological processes where the differentiation between wet and dry conditions is desirable.

9. References

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