Using temperature as a tracer to understand flow pathways in the Slapton Wood and Dunsop catchments

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Abstract
Temperature is regularly used as a tracer in several fields within hydrology such as the study of interactions between the river channel and the local hyporheic environment and in the investigation of deeper groundwater flow pathways. However, it is rarely used to help investigate flow pathways within river catchments, and two examples of its use in this field are demonstrated here. The work uses recent advances that allow simple, cheap, yet accurate stream and soil temperature measurements in combination with existing physically-based models for the full energy and water cycle. Measurements of stream and soil temperatures in the Eastergrounds hollow in the Slapton Wood catchment, Devon, have been carried out. Analysis of the data and modelling of water flow and heat transport using SHETRAN suggests deeper pathways for the subsurface stormflow that had previously been thought. Measurements of stream temperatures in paired subcatchments of the Dunsop catchment, Bowland Forest, Lancashire, are on-going. These catchments are dominated by surface or near-surface flow but show very different stream temperature responses.

Introduction

The use of temperature as a tracer is widespread in several aspects of hydrology. Measuring and modelling of stream-bed temperatures have become a very useful tool for investigating flow paths between the river and the local hyporheic environment (e.g. USGS, 2003; Anderson, 2005; Arrigoni *et al.,* 2008; Acuña and Tockner, 2009). The reasons it is such a useful tool is because groundwater temperature at a sufficient depth remains nearly constant throughout the year while stream water temperatures vary seasonally and diurnally. Analysing stream-bed temperatures therefore supplies information on flow pathways between the groundwater and the surface water, and is especially well suited for delineating small-scale flow paths. The use of temperature in studying groundwater problems is also fairly widespread. For example, Woodbury and Smith (1988) and Bravo *et al.* (2002) have used temperature and head data jointly to estimate groundwater velocity and hydraulic conductivity, by attempting formal inversion of a coupled groundwater flow and heat transport model. However, temperature is less often used as a tracer to understand the flow pathways within river catchments, although Shanley and Peters (1988) employed water temperature measurements to investigate streamflow generation during storms in a forested Piedmont watershed in Georgia, USA, while Kobayashi *et al*. (1999) used stream and soil temperatures (and specific conductance) to study flow pathways at an experimental site in Japan.

One important difficulty with using temperature to trace flow pathways is that, as soon as water reaches the river channel, its temperature is subject to modification by atmospheric and other heat fluxes associated, for example, with net radiation, sensible and latent heat transfer, bed conduction and friction (Webb and Zhang, 2004). Separating these effects from the influence of the flow pathways by which soil water reaches the streams is difficult and has previously limited the use of temperature as a catchment tracer. However, there are two factors which now make it feasible. Firstly, temperature sensors have become cheap, accurate, and easy to install at many points throughout a catchment. Secondly, physically-based models for the full energy and water cycle are available to help unravel the complexities of the system.

The objective of this work, therefore, is to use temperature as a natural tracer to investigate if stream and soil temperature measurements will yield insights into catchment flow pathways. The aim is to achieve this through a combination of data analysis and modelling. Two contrasting catchments are considered: Slapton Wood, Devon, UK, and Dunsop, Bowland Forest, Lancashire, UK.

Slapton Wood catchment

The Slapton Wood catchment (0.94 km^2) is located in South Devon, UK. Full details of the work summarized here can be found in Birkinshaw and Webb (2010). The predominant flow in the Eastergrounds Hollow within the Slapton Wood catchment is a result of subsurface stormflow. This produces delayed peaks in the hydrograph after rainfall, with the peak discharge occurring between 12 and 48 hours after the rainfall event. It is thought that rainfall flows vertically down through the soil and head deposits before being displaced laterally along the soil/bedrock interface. The depth at which this lateral flow takes place is unknown but in previous modelling work (based on 20 years of data analysis and modelling) a depth of 2.2 m was used (Birkinshaw, 2008). In this study, soil and stream temperatures were measured in the Eastergrounds Hollow to provide more insights into the depth of the flow pathways that cause the subsurface flow. Analysis of the ephemeral Eastergrounds spring temperature during subsurface stormflow events showed very little variation in temperature which, as can be seen in Figure 1, ranges from 10.6 ºC to 11.5 ºC. Figure 2a shows the soil temperatures, which were measured on the side of the spur above the ephemeral spring at 4 depths down to 80 cm below the surface. A simple sinusoidal curve was fitted to the measured data which has decreasing amplitude and increasing

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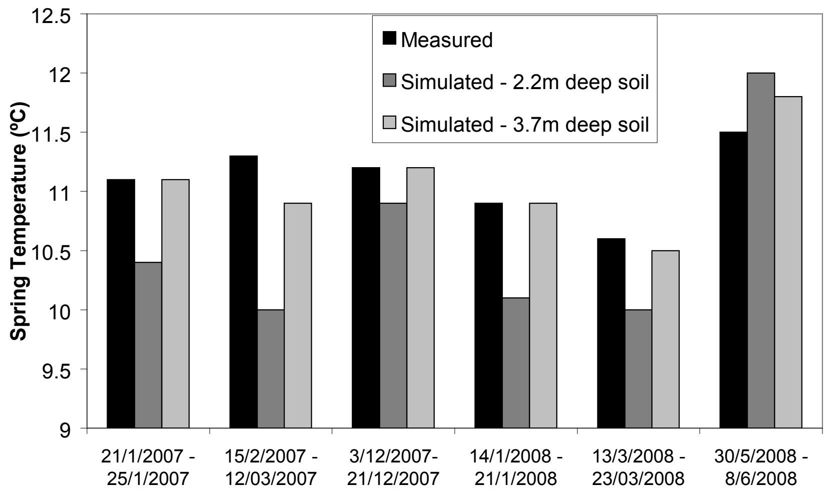

Figure 1 *Measured and simulated spring temperatures in the Eastergrounds Hollow. Measured and simulated temperatures are the mean value in each of the six periods (there is little variation over each period).*

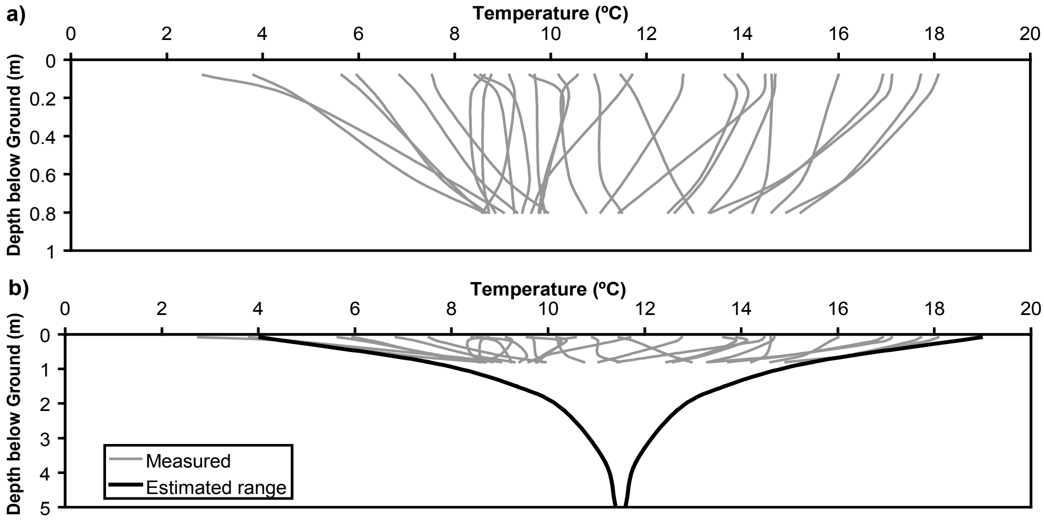

Figure 2 *Soil Temperatures in the Eastergrounds hollow. a) Measured data every 10 days. b) Measured data and the estimated range in temperatures from the fitted sinusoidal curve*

time lag with depth. The curve was then extended down to 5 m below ground. The annual maximum and minimum values for the curve can be seen in Figure 2b. This shows the measured values were well constrained by the fitted curve down to 80 cm below ground. At 2.2 m, the seasonal range of temperatures is 2.3 ºC whereas at 5 m it is 0.2 ºC. This suggests the depth of the flow pathways is between 2.2 m and 5 m. Thus a comparison of the measured soil temperature with the spring temperature suggests that the depth of the subsurface flow pathways was deeper than originally thought.

The modelling work was carried out using SHETRAN Version 5 (Ewen, 2001), which is a physically-based distributed water flow and heat transport model. The model was calibrated for the entire Slapton Wood catchment based on a previous model (Birkinshaw, 2008) and for the 1-D simulations of the Eastergrounds soil temperature. The model was then tested on the Eastergrounds Hollow sub-catchment with soil depths to the slate bedrock of 2.2 m and 3.7 m. With a depth of 2.2 m, the model showed too much temporal variation in the Eastergrounds spring temperature, whereas with a depth of 3.7 m, the model was able to capture the nearly constant Eastergrounds spring temperatures (Figure 1). An excellent comparison between the measured and simulated Eastergrounds stream temperature was also captured by the model (Figure 3). The worst comparison is in the spring 2007 when the simulated temperatures are lower than the measured temperatures.

Overall, both the data analysis and the modelling suggest that the flow pathways which produce the subsurface stormflow are deeper than previously thought. Further progress in understanding the flow pathways would be gained by two methods. Firstly, by augmenting existing stream and spring temperature monitoring with more soil temperatures measurements at different locations within the Eastergrounds Hollow and to greater depths. Secondly, by detailed borehole investigations of the subsurface structures and properties (e.g. thickness and depths of the different layers and their hydraulic conductivity at various locations in the catchment).

Dunsop catchments

The Dunsop catchments (Figure 4 and Table 1) are located within the Bowland Forest and form part of the upper river Ribble catchment, Lancashire, UK. The upper Ribble is undergoing major changes in land-use/ management under the United Utilities Catchment Management Plan (SCaMP). This includes moorland grip blocking, changes in stocking density and woodland planting, with the aim of improving water quality and improvement of the upland conservation sites. Details of the work carried out and the effect of the land-use changes on flood risk can be seen in O'Donnell *et al.* (2008), Ewen *et al.* (2009) and Ewen *et al.* (2010) and. As part of the SCaMP project, pressure transducers measuring water depth

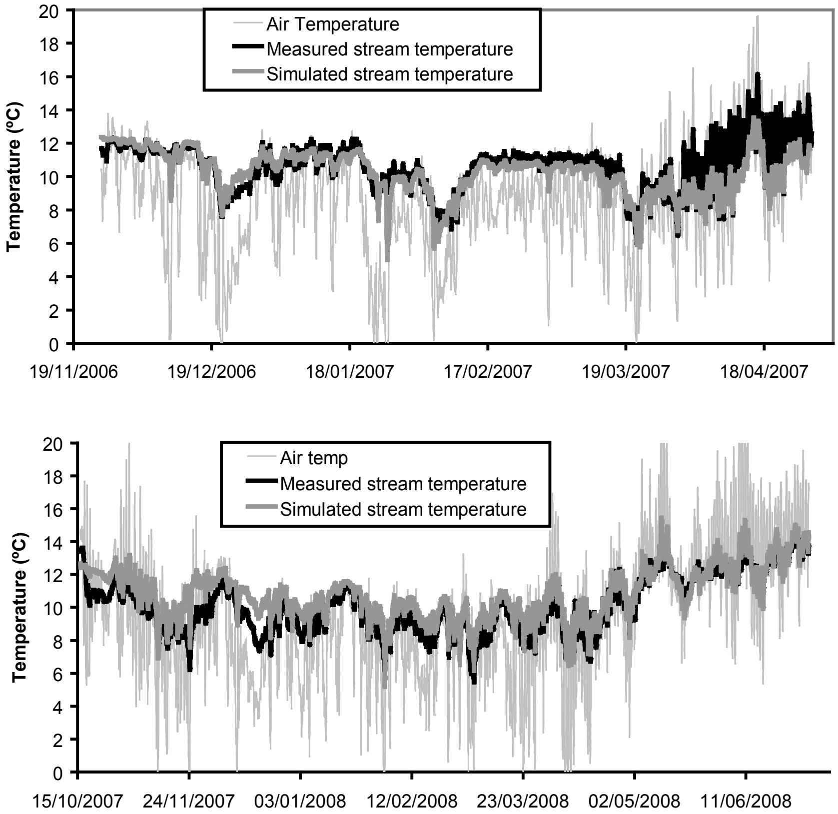

Figure 3 *Measured and simulated (3.7m deep soil) stream temperatures in the Eastergrounds hollow*

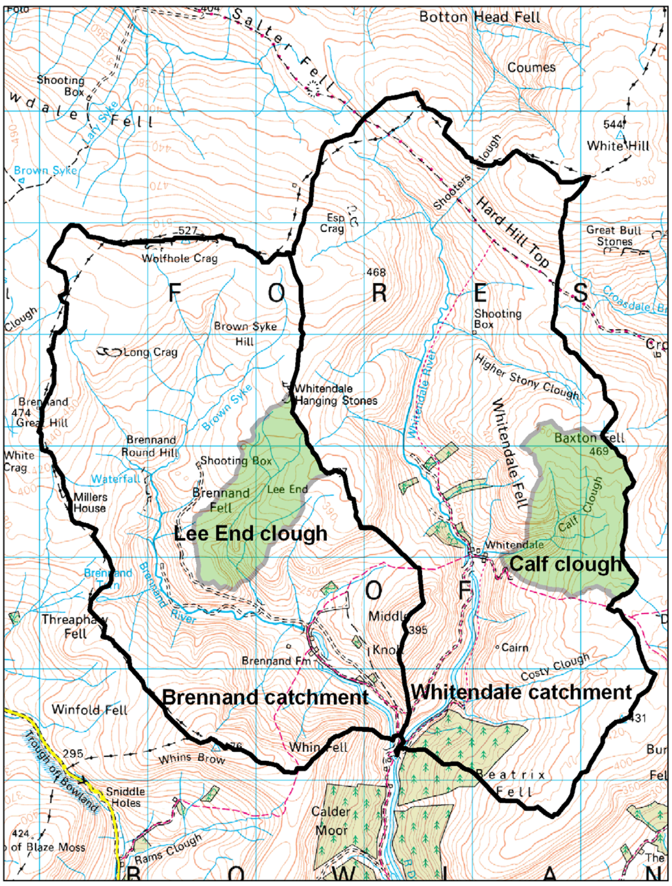

Figure 4 *The Dunsop catchments*

(corrected for barometric pressure) and water temperature sensors were installed at the outlet of the Brennand and Whitendale catchments. These two catchments (Table 1) have similar areas, similar elevations and both drain in an approximately north–south direction. Initial analysis of the data suggested that stream temperatures in the Whitendale catchment were warmer in winter and cooler in summer than the Brennand catchment. In order to try to understand what was happening, 50 spot water temperature measurements were taken throughout both catchments on 24/9/2008 and 9/7/2009. As a result of this, the two sub-catchments Lee End Clough and Calf Clough (Figure 4 and Table 1) were selected for continuous monitoring during the winter of 2009/2010. Three months of 15-minute stream temperatures were recorded from December 2009 to February 2010, although many of these data are missing as the streams were partially frozen for a considerable amount of time.

Table 1 *Catchment areas and elevations of the Dunsop catchments*

	Catchment area (km²)	*Elevation range (m)*
Brennand	11.0	180–530
Whitendale	13.6	180–530
Lee end clough	1.06	240–435
Calf clough	1.30	250–470

It is important to note that water flow within the catchments has been modified considerably as a result of the abstraction scheme designed in the 1880s and now run by United Utilities. This includes two major surface intakes on the main Brennand and Whitendale rivers and three minor intakes. Compensation flow is put back into the river at Footholme (downstream of the Brennand and Whitendale confluence).

The predominant soils in the Dunsop catchments are peat (Winter Hill and Belmont associations), with depths of around 1–3 m, and remain waterlogged for much of the year. Beneath the peat in the valley floor areas and the steep valley sides, head deposits are prevalent, particularly in the Whitendale catchment. These heterogeneous deposits comprise weathered near-surface bedrock (typically unsorted sandstone fragments) and / or drift material, mobilised through freeze-thaw forces and transported down slope by solifluction. The base rock is relatively impermeable mostly consisting of the Carboniferous Pendle and Brennand Grit formations of the Millstone Grit Group.

Figures 5 and 6 show the river stage and stream temperatures for a period of 16 days in July 2009 and December 2009. Stage data in the Brennand and Whitendale catchments have a very similar response to precipitation events. The stage rises rapidly during these events and peaks less than 30 minutes after the peak in precipitation. There is then a fairly fast recession after the precipitation event finishes. This suggests that surface and near-surface processes are the main flow pathways by which water enters the stream.

Stream temperatures generally follow the pattern of the air temperature quite closely. In July 2009 (Figure 5) the stream temperatures follow clearly diurnal variations in air temperature. In December 2009 (Figure 6) there is not an obvious diurnal pattern but again the stream temperatures closely match the air temperatures. The air temperature produces the first order effect on stream temperatures, but the aim here is to try to understand if the stream temperature data provide some information about the pathways by which water flows through the peat and soil and into the stream. This is best achieved by comparing the stream temperature data from the paired catchments. In summer, the Whitendale stream temperature is consistently cooler than the Brennand (by around 1–2 ºC) and in winter the Whitendale is consistently warmer than the Brennand (again by around 1–2 ºC). Stream temperature data at Lee End Clough are available for one point measurement during July 2009 (Figure 5) and the whole of the period in Figure 6. This subcatchment flows into the Brennand and it follows quite closely the measured temperature data at the Brennand outlet, although, as expected, the Brennand stream temperatures are smoothed compared with the Lee End Clough temperatures. Stream temperatures at Calf Clough are also available for one point measurement during July 2009 (Figure 5) and the whole of the period in Figure 6. This subcatchment flows into the Whitendale but the point measurement in July 2009 is cooler than the value in the Whitendale (assuming the Whitendale stream temperature follows the same pattern on 9/9/2009 as it does on the 7/9/2009 and 8/9/2009) and in December 2009 it is generally warmer than the Whitendale temperatures. The difference between Calf Clough stream temperature and Whitendale stream temperature in December 2009 is greatest when the air temperature is very low. This is expected as

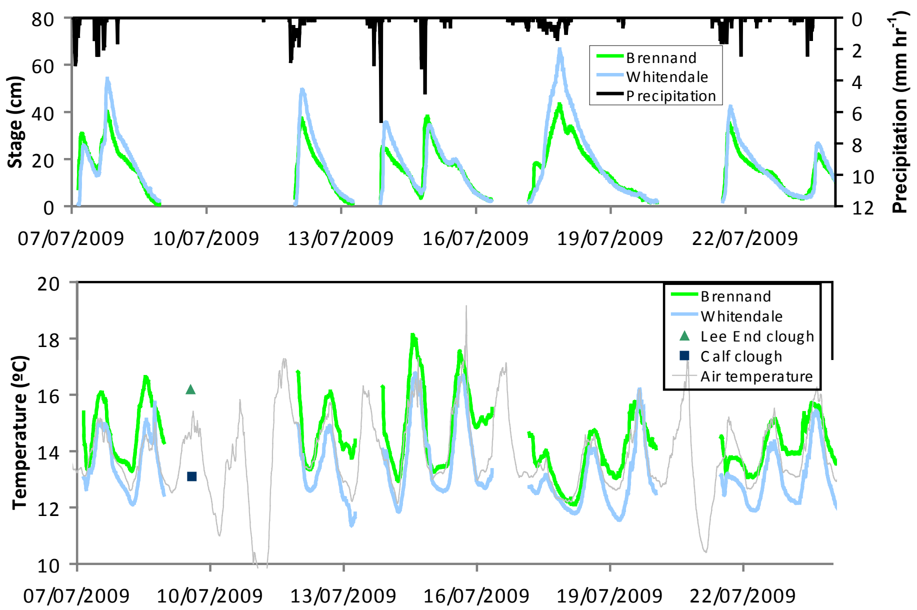

Figure 5 *Measured stage and stream temperature data in the Dunsop catchment, July 2009. There are missing data when the water level falls below the sensor.*

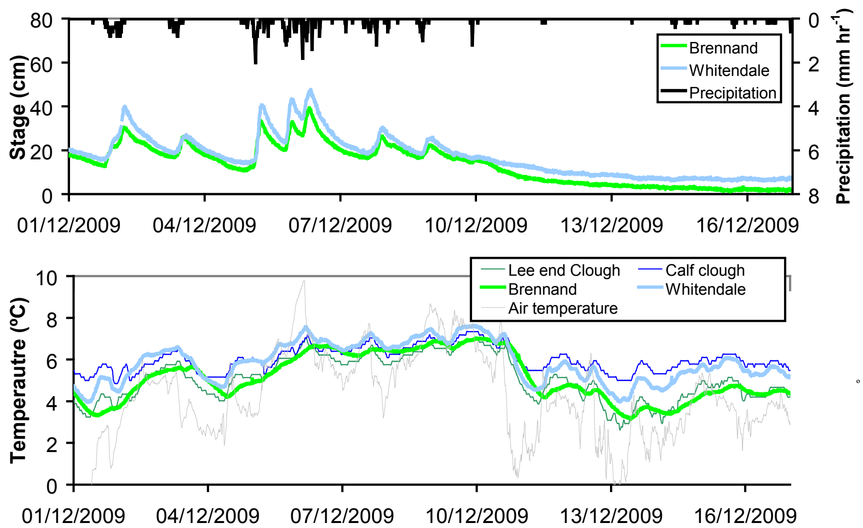

Figure 6 *Measured stage and stream temperature data in the Dunsop catchment, December 2009*

the low air temperature would cool any water draining Calf Clough as it flows along to the Whitendale outlet.

Comparing the Lee End Clough and Calf Clough catchments, which are similar in terms of area and elevations (Table 1), there is a consistent and quite large difference between stream temperatures. It appears that Calf Clough is up to 3 ºC cooler in the July 2009 and up to 3 ºC warmer in December 2009. For example, from 11–16 December 2009 there is little precipitation and the air temperature is consistently lower than the stream temperatures, and during this period the Calf Clough stream temperature remains around 2–3 ºC warmer than the Lee End Clough stream temperature.

Overall, the data suggest that the flow pathways in the Calf Clough catchment are likely to be considerably deeper than those found in the Lee End Clough catchment, despite the dominant flow in both catchments being surface or near-surface flow. The most likely explanation for these differences would seem to be the head deposits found in the area around the Calf Clough catchment which have not been found at the Lee End Clough catchment. Work on the Dunsop catchments is on-going and there are currently limited data to make any firm conclusions about water flow pathways. A time series of stream temperature data for the Calf Clough and Lee End Clough is planned for summer 2010. In addition, stage measurements at these two sub-catchments, soil temperature measurements and water table depth measurements would all be useful in understanding the hydrological processes occurring in the catchments.

Conclusions

This work has shown the use of temperature as a tracer to understand the flow pathways in river catchments at two locations. The techniques have suggested that flow pathways producing subsurface stormflow in the Slapton Wood, Devon, UK, catchment are deeper than previously thought. It has also indicated that in the Dunsop catchments, Lancashire, UK, where the main flow is surface or near-surface, the depths of flow pathways are different in paired catchments. The use of temperature as a tracer does not provide definitive answers on the depth of flow pathways in river catchments; however, it is one piece of the jigsaw in understanding the pathways. It is also simple and cheap to measure stream temperature and so it is suggested that it should be a technique that is used more widely.

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