Flow pathways in the Slapton Wood catchment using temperature as a tracer

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Abstract

This study investigates the potential of temperature as a tracer to provide insights into flow pathways. The approach couples fieldwork and modelling experiments for the Eastergrounds Hollow within the Slapton Wood catchment, South Devon, UK. Measurements in the Eastergrounds Hollow were carried out for soil temperature, spring temperature, and the stream temperature and use was made of an existing 1989-1991 data set for the entire Slapton Wood catchment. The predominant flow in this hollow is a result of subsurface stormflow, and previous work has suggested that the water flows vertically down through the soil and then subsurface stormflow occurs at the soil/bedrock interface where the water is deflected laterally. The depth of the subsurface stormflow was previously thought to be around 2.2m. However, analysis of the new spring, stream and soil temperature data suggests a deeper pathway for the subsurface stormflow. Modelling of water flow and heat transport was carried out using SHETRAN and this was calibrated to reproduce the water flow in the entire Slapton Wood catchment and soil temperatures in the Eastergrounds Hollow. The model was tested for the entire Eastergrounds Hollow with two different soil depths. A depth of 2.2m, based on previous knowledge, was unable to reproduce the Eastergrounds spring temperature. A depth of 3.7m produced an excellent comparison between measured and simulated stream and spring

temperatures in the Eastergrounds Hollow. This work suggests that the depth of the flow pathways that produce the subsurface stormflow are deeper than previously thought. It also provides a demonstration on the use of temperature as a tracer to understand flow pathways.

Introduction

The understanding of flow pathways in the subsurface has improved greatly in recent years. It is now accepted that in many catchments the hydrograph is dominated by the displacement of pre-event water (McDonnell, 2003; Beven, 2006). As Kirchner (2003) notes, catchments store water for considerable periods of time but then release it promptly during storm events. The mechanisms of infiltration-excess overland flow and saturation excess do not help to explain the prompt release of 'old' water within a flashy hydrograph. One explanation for displacement of pre-event water is the difference between the celerity of the discharge response and the velocity of the water (and conservative tracer) particles. The storage-discharge response is governed mainly by the celerities with which pressure effects are transmitted through the system (Beven, 2006). However, underlying the celerity by which water is transmitted through the subsurface is the flow of the water particles. As Beven (2006) points out, we still have much to learn about the velocity distributions and residence time characteristics of the water particles.

Catchments are extremely complex with great heterogeneity at small spatial scales. At the larger catchment scale, some of the complexity collapses but other processes such as macropore flow become important (Blöschl, 2001). One approach to understand the complexity of the processes that are occurring at the catchment scale is to use tracer experiments (Kirchner *et al*. 2001; Uhlenbrook *et al*. 2004; Soulsby *et al*. 2006). For example, Soulsby *et al.* (2006) argues that tracers, when combined with modelling, can aid the identification of runoff sources and provide a means of estimating catchment residence times and help to infer processes that are taking place at the catchment scale. The problem with many tracer experiments is the poor resolution of the data and the expense of analysing the water samples. Kirchner *et al.* (2004) found that daily or monthly data miss much information and argued that high-frequency measurements of chemical behaviour will provide new insights into the subsurface storage of water within catchments and the flowpaths by which water reaches the stream. The use of high frequency temperature, instead of chemical, measurements has the potential as a means of improving understanding of subsurface hydrology. Stream temperature can be measured cheaply and simply at a resolution of 15 minutes or less. Soil temperature at shallow depths can also be measured easily by digging pits and installing monitors.

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 in the Slapton wood catchment. The modelling uses the SHETRAN model, which is physically-based spatially-distributed water flow and heat transport model. 1-D vertical column and catchment scale water flow and heat transport simulations are run to constrain the model and so provide insights into the flow pathways. Testing of this approach at Slapton Wood will indicate the potential for application in other catchments.

Temperature is already used regularly as a tracer in several aspects of hydrology. Recently, measuring and modelling of stream-bed temperatures have become a very useful tool for investigating river-aquifer flow paths (USGS, 2003; Anderson, 2005). 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 standard modelling approach is to couple heat flow and water flow modelling using a finite difference representation. The heat is modelled using an advection term (for the flow of heat with water) and a conduction term (for the flow of heat through the soil-water matrix). Examples of using heat as a tracer include Hoehn and Cirpka (2006), Cox *et al*. (2007), Kalbus *et al*. (2007) and Lowry *et al*. (2007). 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. James *et al*. (2000) and Manga and Kirchner (2004) have used large-volume cold-spring temperatures to interpret the pattern of groundwater flow in the Cascade mountains, USA. The most similar work to that considered here is by Shanley and Peters (1988), who used water temperature measurements to investigate streamflow generation during storms in a forested Piedmont watershed in Georgia, USA, and by Kobayashi *et al*. (1999), who used stream and soil temperatures (and specific conductance) to study flow pathways in an experimental site in Japan.

The signal associated with the water pathways is a temperature difference between the water and its surroundings. For example, water arriving from the deeper subsurface tends (in the UK) to be at around $10^{o}C$ in both summer and winter. This signal decays as the water naturally comes into thermal equilibrium with its surroundings. One important difficulty with using temperature to trace flow pathways is therefore 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). Air temperature can be used as a surrogate measure for the net heat exchange affecting water courses, and has a first-order effect on river temperature (Smith, 1981; Erickson and Stefan, 2000). Second-order effects on water temperature include riparian vegetation cover and channel morphology which affect shading, and differences in substratum e.g. rock or gravel which influence heat transfers at the water-bed interface (e.g. Ward, 1985). 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.

There is a wide variety of physically-based spatially-distributed models for water flow in a catchment. Examples include MIKE SHE (Graham and Butts, 2006), SWAT (Arnold *et al.*, 1998) and WATFLOOD (Bingeman *et al.*, 2006), MODHMS (Panday and Huyakorn, 2004), and a review of the mathematical basis of eleven of these models can be found in Borah and Bera (2003). There are considerably fewer models which also consider the full energy balance, and these include SHETRAN (Ewen, 2001) and HydroGeoSphere (Sudicky *et al.*, 2006). In this work SHETRAN will be used. SHETRAN will not be used to make predictions but rather to aid understanding of catchment flowpaths by making use of stream and soil temperature data. It might be thought that a requirement for good correspondence between simulated and observed temperatures data would introduce additional parameters to a type of model which has already been criticised for being over parameterized (Beven, 2001). However, the velocities required to calibrate the heat-flow model must also calibrate the groundwater flow model and the thermal properties including thermal conductivity vary over a much smaller range than hydraulic conductivity (Constantz and Stonestrom, 2003).

Slapton Wood Catchment and monitoring

The Slapton Wood (0.94 km^2) is located in South Devon, UK. The catchment has a long history as a research catchment (Burt and Butcher, 1985; Burt and Heathwaite, 1996; Burt and Horton, 2001). The catchment is probably best known for its double-peak hydrographs. The first peak has been attributed to a combination of infiltration-excess and saturation-excess overland flow in the hillslope hollows. The second (delayed) peak is regarded as the product of subsurface stormflow. Most of the stream-flow within the catchment occurs during the delayed peak (Burt and Butcher, 1985).

Figure 1 shows that 60% of the catchment lies above the 90m contour. Above 90m, the slopes are gentle, generally less than 5%, and the land is intensively farmed, mainly as grassland and for cereal and root crops. Below 90m, the slopes are steeper, up to 25%, and there is permanent grassland and a wood (which covers 13.5% of the catchment). The soils are mainly freely-draining acid brown soils with a clay-loam texture (Trudgill, 1983). Solifluction head deposits have been found below the soils (Chappell and Franks, 1996), mainly on the western side of the catchment, and were observed to produce a saturated layer, above the unsaturated slate below. Percolation is impeded because of the fine matrix and the presence of local ‘fragipan’ layers. The head deposits are underlain by extensively folded slates (Chappell and Franks, 1996) with a dip of 70° to the south. Figure 1 shows that the stream is fed by three large hillslope hollows on the western side. The work here is focused on the Eastergrounds Hollow, which is highlighted in Figure 1. The Eastergrounds Hollow was monitored thoroughly during 1981 and 1982 (Butcher, 1985), and this included the measurement of discharge in the Eastergrounds stream, where a very similar response to that seen at the Slapton Wood outlet, was found. In particular, delayed hydrographs of a similar shape occurred at both sites as a result of subsurface stormflow.

The present study is based on data collected in two separate periods. Firstly, intensive water flow monitoring was carried out during 1989-1991 for the entire Slapton Wood catchment and, secondly, soil and stream temperature measurements were undertaken during 2006-2008 in the Eastergrounds Hollow. In the first phase of data collection, precipitation, net radiation, wind speed, air temperature and vapour pressure deficit data were available from an automatic weather station for the period 16/11/1989 to 31/3/1991. Three ground-level storage gauges were read manually on a weekly basis and the data used to calculate the spatial variation of precipitation. A V-notch weir installed in 1971 provided 15-minute discharge data for the period from 13/9/1989 to 31/3/1991. Soil water potential was measured using mercury manometer tensiometers at arable, grassland and woodland plots from 6/9/1989 to 31/3/1991, approximately twice a week at depths from 0.2m to 1.2m. In order to record potentials for dry conditions, gypsum blocks were installed at the grassland plot in September 1990. The second phase of data collection occurred from November 2006-April 2007 and from October 2007-July 2008 and involved monitoring of stream temperatures (every 15 minutes) in the ephemeral Eastergrounds spring and stream and stage measurements in the Eastergrounds stream. The latter were carried out using a pressure transducer which, because of instability in the stream-bed, provided only an indication of the timings of stream rises and falls, rather than a time series of stage. Soil temperatures were also measured every 15 minutes on the side of the spur above Eastergrounds Hollow at 4 depths down to 80cm below the surface. This was achieved by digging a pit and inserting the probes into the side of the pit (at 8. 20, 40, 60 and 80cm below ground) and then back filling. Air temperature (every 15 minutes) was measured at the same site as the soil measurements. Hourly precipitation data were collected at the nearby Slapton Ley Field Centre and hourly measurements of other meteorological data were obtained from the Meteorological Office for nearby sites.

Considerable modelling work has been carried out at Slapton Wood (Birkinshaw and Ewen, 2000; Beven and Freer 2001; Bathurst *et al*. 2004; Ewen and Birkinshaw, 2007). Most recently Birkinshaw (2008) undertook modelling to elucidate the flow pathways by which the delayed peak is produced. This work suggested that lateral subsurface stormflow was occurring along the soil/bedrock interface, which was thought to be located at *ca*. 2.2m below the ground surface.

SHETRAN Model

SHETRAN Version 5 (Ewen, 2001) is a finite-difference model for water flow and heat and solute transport in river catchments in which the physics-based governing partial differential equations for flow and transport are solved on a three-dimensional grid. It is usually described as a physically-based spatially-distributed modelling system, to distinguish it from, simpler, and less-flexible, conceptual and lumped models. The advantage of using a physically-based spatially-distributed model in this work is that it gives a direct, three-dimensional, representation of the catchment and direct representations of physical processes.

The grid used for Slapton Wood has a 50 m square mesh when viewed in plan (Figure 1). The columns associated with mesh squares are called sub-units (Figure 2). These are divided into many cells, by horizontal slicing, varying in thickness from 0.02m at the ground surface to 0.5m at the bottom of the column. Physical properties can vary from sub-unit to sub-unit and cell to cell, and the state of the catchment at any time is simply represented by the states (e.g. head, moisture content and temperature) of the cells.

SHETRAN Version 5 has previously been used to simulate water flow in catchments (Birkinshaw *et al.*, 2005; Birkinshaw, 2008). The heat transport component was also tested and verified on the data set from the Boreal Ecosystem Atmosphere Study (BOREAS) in central Canada. The verification was against point measurements of soil temperature, soil moisture content, soil heat flux, sensible and latent heat and snow temperatures and depths. Water flow in an entire catchment fed by snow melt was also simulated (Birkinshaw and Ewen, 2004). This paper uses SHETRAN Version 5 to simulate the flow of water and temperature in the Slapton Wood catchment, focusing on the Eastergrounds Hollow.

Data Analysis

The primary mechanism for runoff in the Slapton Wood catchment is a result of subsurface stormflow. The water is thought to flow vertically through the soil until the soil-bedrock interface is reached. It is then deflected laterally along the interface before flowing up into the stream. However, despite 20 years research at Slapton Wood, the depth of these flow pathways is still unknown. Analysis of the temperature data provides some insight into this.

The Eastergrounds spring produces significant flows only during subsurface stormflow events. The measured mean temperatures for six major events in 2007 and 2008 and occurring in the months from December to June (it is unusual to find a subsurface stormflow event in June but the Spring of 2008 was very wet) are presented in Table 1. The spring temperatures show relatively little variation between the different events. The temperature was lowest at 10.6ºC from 13/3/2008 to 23/03/2008 and highest at 11.5ºC from 30/5/2008 to 8/6/2008. Considering the events from 15/2/2007 to 12/3/2007 and 30/5/2008 to 8/6/2008 in more detail, stage data (Figure 3), which is high during, and low before and after, the events, suggest that subsurface stormflow occurred. Spring temperature was nearly constant at 11.2ºC from 15/2/2007 to 12/3/2007 and at 11.5ºC from 30/5/2008 to 8/6/2008. The Eastergrounds stream temperature is similar to the spring temperature but exhibited slight rises and falls at a corresponding time to the changes in air temperature. From 15/2/2007 to 12/3/2007, the stream temperature was generally slightly lower than the spring temperature, reflecting air temperatures that were lower than the spring temperatures, whereas from 30/5/2008 to 8/6/2008 stream temperature was generally higher than the spring temperature as air temperatures were higher than the spring temperatures. Table 1 and Figure 3 show the spring temperature varies very little throughout the year and is not affected by the air temperature (or radiation affects). This suggests the water in the spring is flowing from deep within the soil and can be considered to be 'old water' generated by the celerity of the pressure wave.

The soil temperature measurements provide information on the depth of the flow pathways. Soil temperatures for 6/3/2007 (Figure 4a) varied between 8ºC and 8.5ºC in the measured profile down to 80cm, while the spring temperature was 11.2ºC, which clearly indicates the water in the 15/2/2007 to 12/3/2007 event came from a depth much greater than 80cm. Soil temperatures recorded on 2/6/2008 (Figure 4a) varied between 17ºC and 14ºC at 8 cm and 80cm depth, respectively, while the spring temperature was 11.5ºC, suggesting again that water in 30/5/2008 to 8/6/2008 event was coming from much deeper than 80cm. Profiles of the soil temperature every 10 days throughout the measured period (Figure 4a), which excluded the months of August to October, shows a considerable range of temperatures for the shallow soils and a smaller range for deeper soils. The range is about 16ºC and 8ºC at 8 cm and 80cm depth, respectively. The temperature range seen in the spring is 10.6ºC to 11.5ºC in the measured period but may be slightly higher outside of this period.

It is possible to fit a simple sinusoidal curve to the measured data which has decreasing amplitude and increasing time lag with depth. Hillel (1998) shows that:

$$T(z,t) = T_{ave} + A_o \, [\, \sin(\omega t - \varphi_o - z/d)]/ e^{z/d} \qquad \text{(Eqn. 1)}$$

where T (ºC) is the soil temperature at each depth z (m) and time t (day). T_{ave} is the average temperature at the soil surface. A_0 (ºC) is the amplitude of the annual change in soil surface temperature (i.e half the difference between the maximum and minimum soil surface temperatures). ω is the radial frequency of the annual cycle = $2\pi / (365 \times 86400)\ s^{-1}$. φ_o is the phase constant, which can be altered to change the time of the minimum soil surface temperature. d (m) is the damping depth which is equal to $(2 D_h / \omega)^{1/2}$ where D_h ($m^2\ s^{-1}$) is the soil diffusivity. With T_{ave} set at 11.5 ºC and A_o set at 8 ºC the soil diffusivity was fitted ($1.3 \times 10^{-7}\ m^2\ s^{-1}$) to give the best fit for the measured data down to 80cm below ground. The curve was then extended down to 5m below ground. The annual maximum and minimum values for the curve can be seen in Figure 4b. This shows the measured values were well constrained by the fitted curve down to 80cm below ground. At 2.2m, the seasonal range of temperatures is 2.3 ºC whereas at 5m it is 0.2 ºC. This suggests the depth of the flow pathways is between 2.2m and 5m. However, this method makes a variety of simplifications, in particular, that the diffusivity remains constant in time and depth when the type of material, its density and its soil moisture content are all known to affect the value.

Measured soil temperature data at a range of depths from the soil surface to over 5m have been carried out at a number of other sites. Taniguchi (1993) measured soil temperatures in Japan and found that seasonal ranges in temperature became less than 2ºC at a depth of around 7m. Measurements of a soil temperature profile at a site in the Netherlands (Bense and Kooi, 2004) showed that the seasonal range in temperature was less than 2ºC at a depth of around 5m. The climate of Devon, UK is more equitable than at the sites measured in Japan and the Netherlands, which suggests that the range in spring temperatures similar to that seen at Slapton Wood (0.9 ºC in the period from December to June) might be produced by water originating at less than, but approaching, 5m depth. In the absence of sufficient measured data to determine the depth of the flow pathways supplying the spring, further modelling work was carried out.

Model calibration

The aim of the model calibration was to produce a model of the Eastergrounds Hollow that is able to reproduce the soil and stream temperatures and the likely water flow pathways supplying the spring. Two different scenarios (Table 2) were considered to provide insights into the depth of the flow that produces the subsurface stormflow. The standard soils correspond to those used in the previous model of

Slapton Wood using SHETRAN (Birkinshaw 2008). The deeper soils have a thicker head deposit (2.3m deep but with a total depth of 3.7m above the slate bedrock layer) and so produce deeper flow pathways. Three models were calibrated for both scenarios (although the vertical 1-D models are identical in both scenarios as they only simulate to a depth of 2m).

1. Vertical one-dimensional (1-D) water flow in columns, at each of the three representative plots in the Slapton Wood catchment (arable, grassland and woodland) using 1989-1991 data. The model was calibrated against a time series of soil water potentials at each site and against annual estimates of total evaporation.

2. 3-D water flow of the entire Slapton Wood catchment using 1989-1991 data. The model was calibrated against the outlet discharge.

3. Vertical one-dimensional (1-D) flow in columns at the Eastergrounds Hollow site using 2006-2008 data. The model was calibrated against the measured soil temperatures.

Each calibrated model uses the same parameter values which as far as possible are based on measurements. The process to achieve the best calibration for all three models was an iterative one. The starting point for the 1-D and 3-D water flow models using 1989-1991 data was the model from Birkinshaw (2008). However, the parameters were modified so that a good comparison was also achieved for 1-D model for the Eastergrounds Hollow using 2006-2008 data.

The final soil and bedrock parameters used in the model are presented in Table 3, which indicates that the saturated hydraulic conductivity for all the soil layers was calibrated. The van Genuchten parameters for the soil and head deposits were calibrated to give a better fit between the measured and simulated heads for the 1-D water flow simulation. It is important to note the parameters for the head deposits. A wide variety of different residual moisture contents, saturated hydraulic conductivities and van Genuchten parameters were tested in order to reproduce the fast lateral flow that appears to be taking place within this layer. The final calibrated parameters have a saturated moisture content of 0.4, a residual moisture content of 0.38 and a saturated hydraulic conductivity of 864 m/day. It is thought this layer is close to saturation most of the time (hence the high residual soil moisture) and a small increase in moisture content will produce a very large increase in hydraulic conductivity (hence the high saturated hydraulic conductivity). The same values for the thermal conductivity were selected for each layer based on published data (Anderson, 2005). These are a dry thermal conductivity of 0.2 W/mK, and a thermal conductivity for saturated soils/bedrock of 2.5 W/mK. Soil thermal conductivity parameters vary over a much smaller range than hydraulic conductivity and in this case, the parameters were not calibrated. Hence the requirement to also calibrate the 1-D model against soil temperatures provides a further constraint on the existing parameters.

The vegetation parameters used in the model are presented in Tables 4 and 5. The values in Table 4 are similar to those used in Birkinshaw (2008). However, in Birkinshaw (2008) a constant value was used for the fraction of energy absorbed by the canopy (the rest of the energy is absorbed by the soil surface). This value is important in simulating how much of the net radiation is used to warm up the vegetation and soil (sensible heat) and how much to evaporate the water (latent heat). The parameter was calibrated for each month based on the monthly variations in leaf area index.

The simulated and measured soil water potential for the grassland plot in the1-D water flow simulation using 1989-1991 data can be seen in Figure 5. Similar results exist for the woodland and arable sites. Figure 5 shows good agreement between the simulated and observed potentials at both 0.2m and 1.2m. In particular, the timings of the drying in the spring and wetting up in the autumn are accurate. Annual evaporation was estimated by the Institute of Hydrology (1993) and Table 6 shows the comparison between these estimated values and simulated annual evaporation for the three vegetation types. There is excellent correspondence between the measured and simulated totals with the woodland plot having the largest annual evaporation followed by the grassland and the arable plots. The simulated and measured outlet discharge for the 3-D water flow simulation using 1989-1991 data can be seen in Figure 6 (for the deeper soils). This shows results for the winter of 1989/1990 and there is excellent correspondence between the measured and simulated discharges. In particular, the peaks that occur as a result of the subsurface stormflow are well captured. The comparison for the rest of the data is also good with an overall r^2 efficiency (Nash and Sutcliffe, 1970) of 0.93. The 3-D water flow simulation was carried out for both soil depths (Table 2). Due to the very high hydraulic conductivity in the head deposits, the simulated discharge produced almost identical results in the two cases.

The simulated and measured soil temperatures for the 1-D plot using 2006-2008 data is shown in Figure 7. The comparison is for the shallowest measured depth (8cm) and the deepest measured depth (80cm). As expected, the temperatures at 8cm respond quickly to change in the meteorological data whereas at 80cm the response is much smoother and slightly lagged. During the spring months, the soil temperatures at 8cm depth show a diurnal variation which is not seen at 80cm. Overall, the comparison is excellent for both the 2006/2007 and the 2007/2008 data. The poorest correspondence is during March 2007 when the simulated temperatures are too low at both 8cm and 80cm. It is not clear why this occurs since comparisons are good for March 2008.

Model Testing

The calibrated model of Slapton Wood was tested for two different soil depths (Table 2) – the "standard soils" and the "deeper soils". It should be noted that as well as using the "deeper soils" additional tests were carried with other different depths of head deposits but these produced less good results and are not shown.

The test was carried out on the Eastergrounds Hollow by selecting part of the Slapton Wood catchment (Figure 1). The 50m grid resolution and the cell depth in each column were kept unaltered from the 3-D Slapton wood catchment simulation. For both tests, the first check was that the simulated discharges in the Eastergrounds Hollow stream produce the expected response. There are no measured discharge data but some stage measurements were carried out at the Eastergrounds stream. This was not at a stable site and so the stage at different times cannot be compared but it does provide an indication as to whether the simulated discharge rises and falls and at the correct time. Figure 8 for the deep soils shows the measured and simulated discharge for the February and March 2007 period (a very similar figure can be seen for the standard soil depths). This shows that the simulated discharge does indeed rise and fall at the same time as the measurements. Despite there being no calibration of the Eastergrounds Hollow model, this good comparison between the simulated and measured response is expected. This is because a similar measured response in the Eastergrounds Hollow compared to that seen in the entire Slapton Wood catchment has been found (Butcher, 1985) and a similar simulated response in the two cases can be expected, as there is no spatial distribution of soil types incorporated in the modelling.

A comparison of the measured and simulated Eastergrounds spring temperature for the standard and deep soils is presented in Figure 9. As discussed previously, there is little variation in the measured spring temperature. However, the standard soils show a lower simulated value than the measured values for events from December to March and higher simulated values than measured values for the 30/5/2008 to 8/6/2008 event. This suggests a subsurface stormflow pathway that is too shallow. The simulated temperature is showing too much variation throughout the year and follows the air temperature time series too closely. The deeper soils show a much improved comparison, although the simulated temperature for the event from 30/5/2008 to 8/6/2008 is too high. Thus the inclusion of deeper flow pathways in the model (3.7m of soil and head deposits above the bedrock) produced much better simulations. For the deep soil, the modelled and measured Eastergrounds stream temperatures were compared and generally showed an excellent correspondence (Figure 10). The worst comparison (as for the soil temperatures) is in the spring 2007 when the simulated temperatures are lower than the measured temperatures.

An analysis of simulated soil temperature at different depths in the Eastergrounds Hollow for 22/2/2007 is presented in Figure 11. This day was during the subsurface stormflow event of 15/2/2007 to 12/3/2007 when the Eastergrounds spring temperature was 11.2ºC. The simulation shows that for most of the hollow at a depths of 0.1m and 1.5m, the soil temperature is around 8.5-9ºC. It is only at 3.5m depth that the temperature increases to 10.5-11ºC. The water in the Eastergrounds spring and stream appears to be coming from this depth flowing laterally along the soil/bedrock interface. It then flows up into the stream (and the area around the stream) hence the higher temperatures found in these areas at shallower depths.

Both the data analysis and the modelling suggest that the flow pathways which produce the subsurface stormflow are deeper than previously thought. Butcher (1985) suggest subsurface lateral flow pathways of less than 1m depth in some parts of the Eastergrounds hollows and Chappell and Franks (1996) give the maximum measured depth to the slate bedrock of 2.5m (compared to 3.7m in the model used here). This discrepancy probably reflects the few physical determinations of the depth of soil and head that have been made in the Slapton catchments, and the spatial variability in soil and head depths. For example, head deposits are generally shallower over most of the Eastergrounds Hollow and the Slapton Wood catchment but deeper along the axis of the hollow and around the Slapton Wood Stream. It is also possible that the subsurface stormflow is occurring in the much deeper slate bedrock. However, the low hydraulic conductivities in the slate bedrock and other measurements suggest that this is unlikely. For example, measurement of nitrate concentrations over many years (Burt and Arkell, 1987) revealed high nitrate concentrations during subsurface stormflow events when water was flowing along the soil/bedrock interface and low nitrate concentration in the summer when the stream is largely supplied from the slate bedrock. 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).

Summary and conclusions

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 a rainfall event 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 2.2m 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, with a range from 10.6ºC to 11.5ºC. A comparison of the measured soil temperature with the spring temperature suggests that the depth of the subsurface flow pathways deeper than originally thought.

The modelling work was carried out using SHETRAN Version 5, which is a physically-based distributed water flow and heat transport model. The model was calibrated using 1989-1991 data for the entire Slapton Wood catchment 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 2.2m and 3.7m. With a depth of 2.2m, the model showed too much temporal variation in the Eastergrounds spring temperature, whereas with a depth of 3.7m, the model was able to capture the nearly constant Eastergrounds spring temperatures. An excellent comparison between the measured and simulated Eastergrounds stream temperature was also captured by the model.

Overall, this study has suggested that the flow pathways producing subsurface stormflow in the Slapton Wood catchment are deeper than previously thought. The work has also indicated the potential of combining field monitoring and modelling approaches for improving understanding of flow pathways in other catchments.

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Table 1 Eastergrounds Spring Temperatures during major subsurface stormflow events. Temperatures are the mean value in each of the six periods (there is very little variation over each period).

Date	Eastergrounds Spring Temperature (ºC)
21/1/2007 - 25/1/2007	11.1
15/2/2007 - 12/03/2007	11.3
3/12/2007- 21/12/2007	11.2
14/1/2008 - 21/1/2008	10.9
13/3/2008 - 23/03/2008	10.6
30/5/2008 - 8/6/2008	11.5

Table 2 Soil and bedrock layers used for the model testing

Soil	Standard soils	Deeper soils
Clay loam	0-1.4m	0-1.4m
Head Deposits	1.4-2.2m	1.4-3.7m
Slate 1	2.2-2.7m	3.7m-4.2m
Slate 2	2.7m-20m	4.2m-20m
Clay loam under stream	0-2.2m	0-3.7m

Table 3 Soil and bedrock parameters. * indicates a parameter has been calibrated

Soil	Saturated moisture content (-)	Residual moisture content (-)	Saturated hydraulic conductivity (m/day)	Van Genuchten α parameter (/m)	Van Genuchten n parameter (-)
Clay loam	0.4	0.12	3.5*	1.8*	1.6*
Head Deposits	0.4*	0.38*	864*	1.8*	1.6*
Slate 1	0.18	0.03	0.002*	2.68	1.92
Slate 2	0.18	0.03	0.1*	2.68	1.92
Clay loam under stream	0.4	0.12	70.0*	1.8*	1.6*

Table 4 Vegetation parameters. * indicates a parameter has been calibrated

Parameter	Arable	Grassland	Woodland
Transpiration reduction factor at –3.3m head	0.4*	0.8*	0.9*
Canopy storage capacity	8 x 10^{-4} m	1 x 10^{-4} m	15 x 10^{-4} m
Canopy resistance	80 s/m	100 s/m	150 s/m
Maximum vegetation height	0.7m	0.3m	5.0m
Maximum fraction of energy absorbed by the canopy	0.85	0.85	0.85
Maximum rooting depth	0.5 m	0.3 m	2.0 m
Maximum leaf area index	1.5	1.0	3.0

Table 5 Fraction of the net radiation absorbed by the canopy. These values have been calibrated with the monthly values corresponding to the changes in the leaf area index

Month	Arable	Grassland	Woodland
January	10	40	20
February	10	40	20
March	10	40	20
April	10	50	20
May	25	75	60
June	50	85	85
July	75	85	85
August	85	85	85
September	5	70	80
October	5	60	50
November	10	50	20
December	10	40	20

Table 6 Annual evaporation (mm) for 1-D water flow simulations using 1989-1991 data

Plot	Simulated canopy evaporation	Simulated surface evaporation	Simulated transpiration	Totals simulated	Total estimated from measurement
Arable	70	14	316	400	404
Grassland	79	12	360	451	466
Woodland	170	22	288	480	487

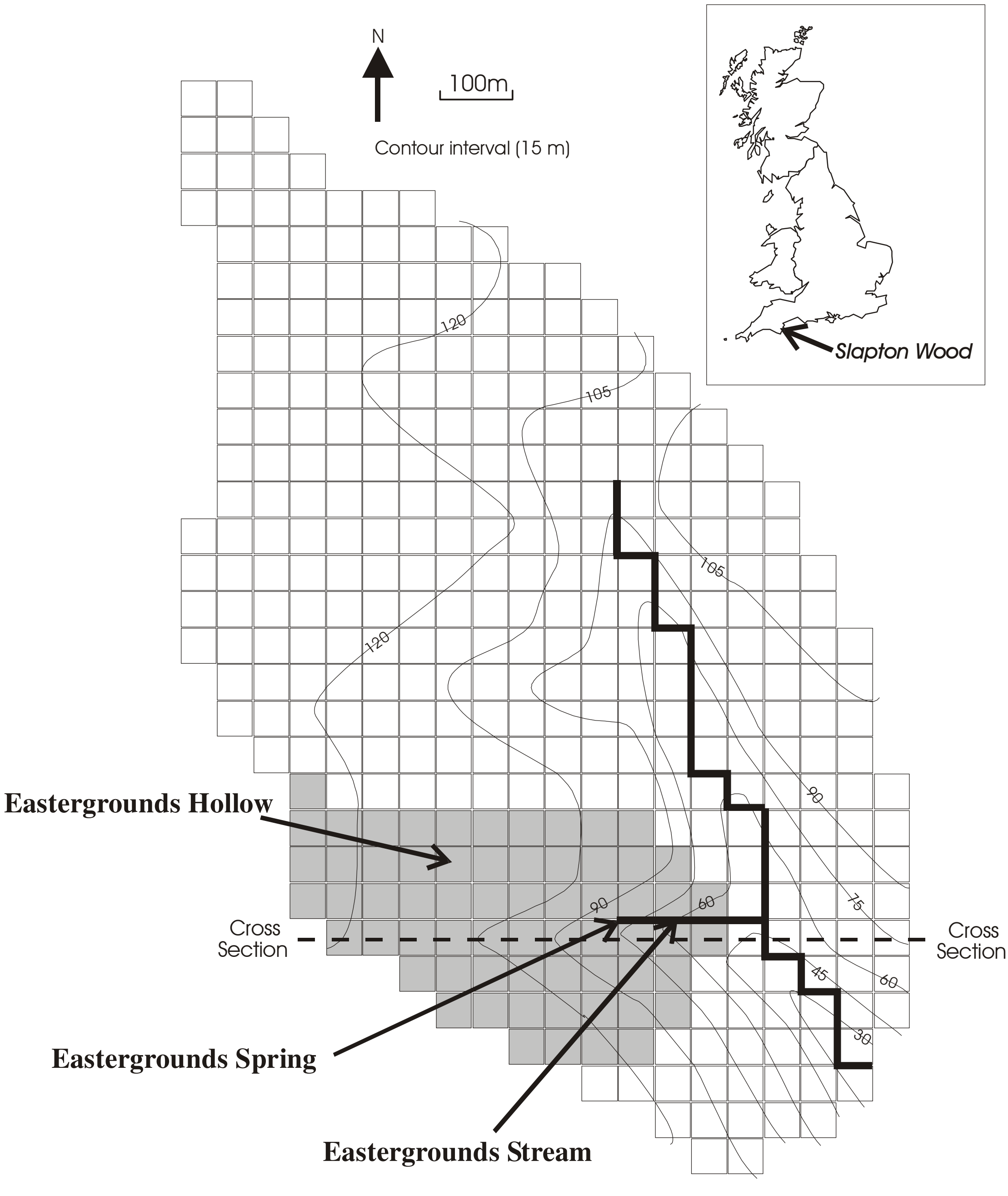

Figure 1. Location map and SHETRAN mesh for the Slapton Wood catchment. The SHETRAN mesh shows the channel network in bold. The Eastergrounds hollow sub-catchment is highlighted

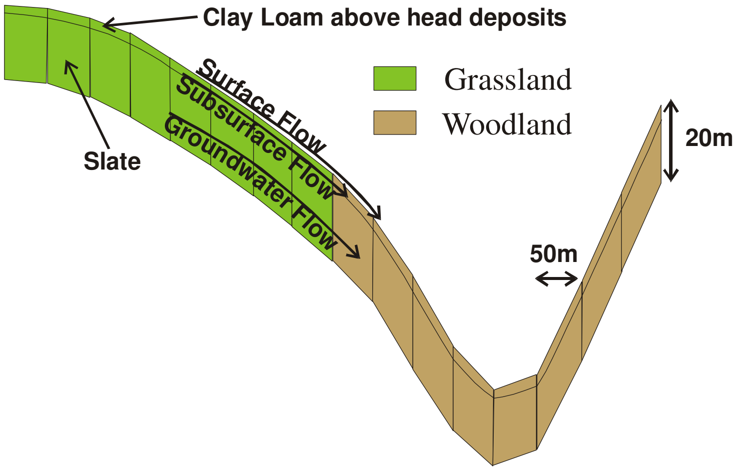

Figure 2. Slapton Wood Cross-section (location of the cross-section can be seen in Figure 1)

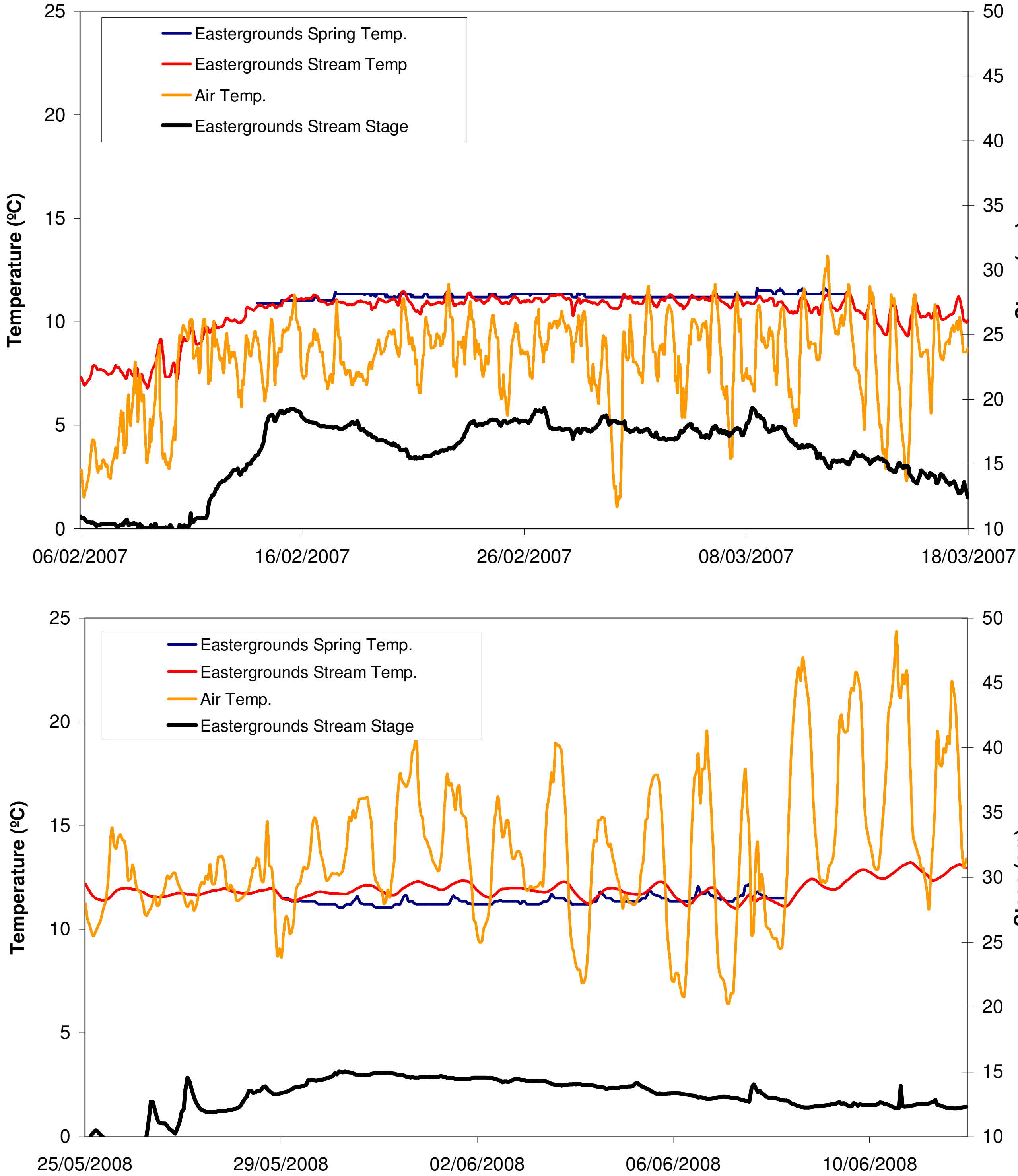

Figure 3 Measured temperatures in Eastergrounds Hollow during periods of high subsurface flows

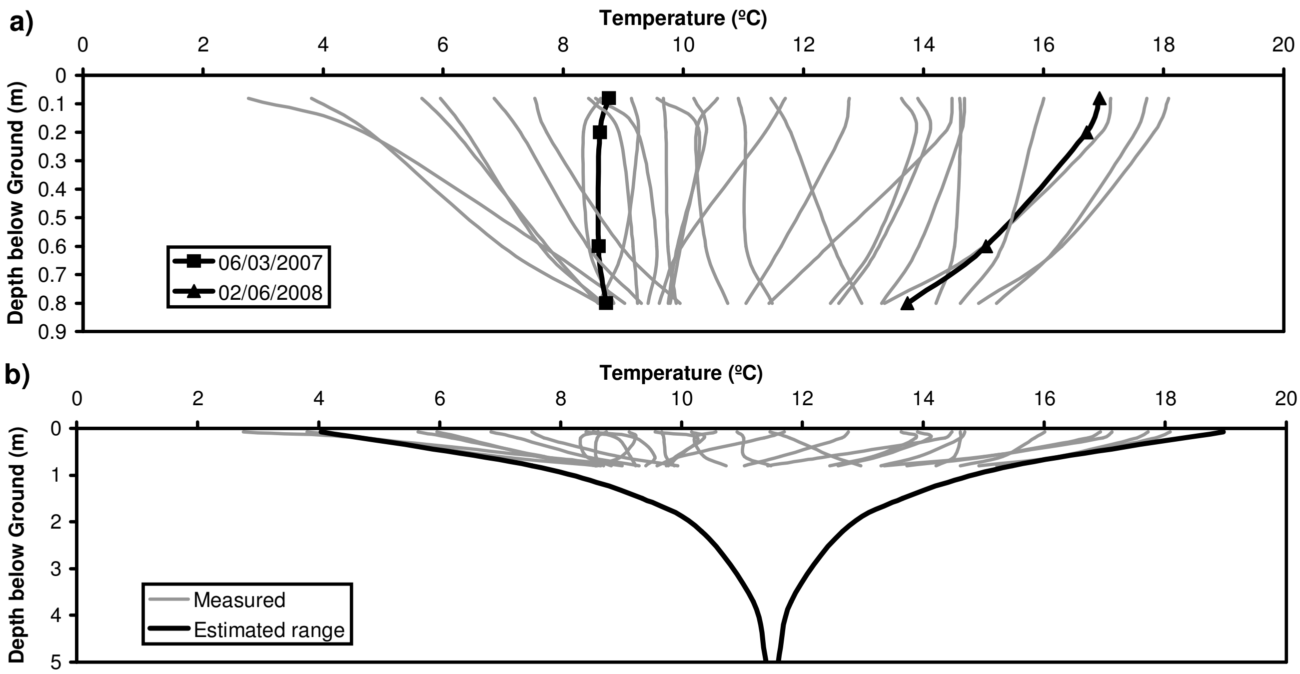

Figure 4. Soil Temperatures in the Eastergrounds hollow. a) Measured data every 10 days. b) Measured data and the estimated range in temperatures from the fitted sinusoidal curve

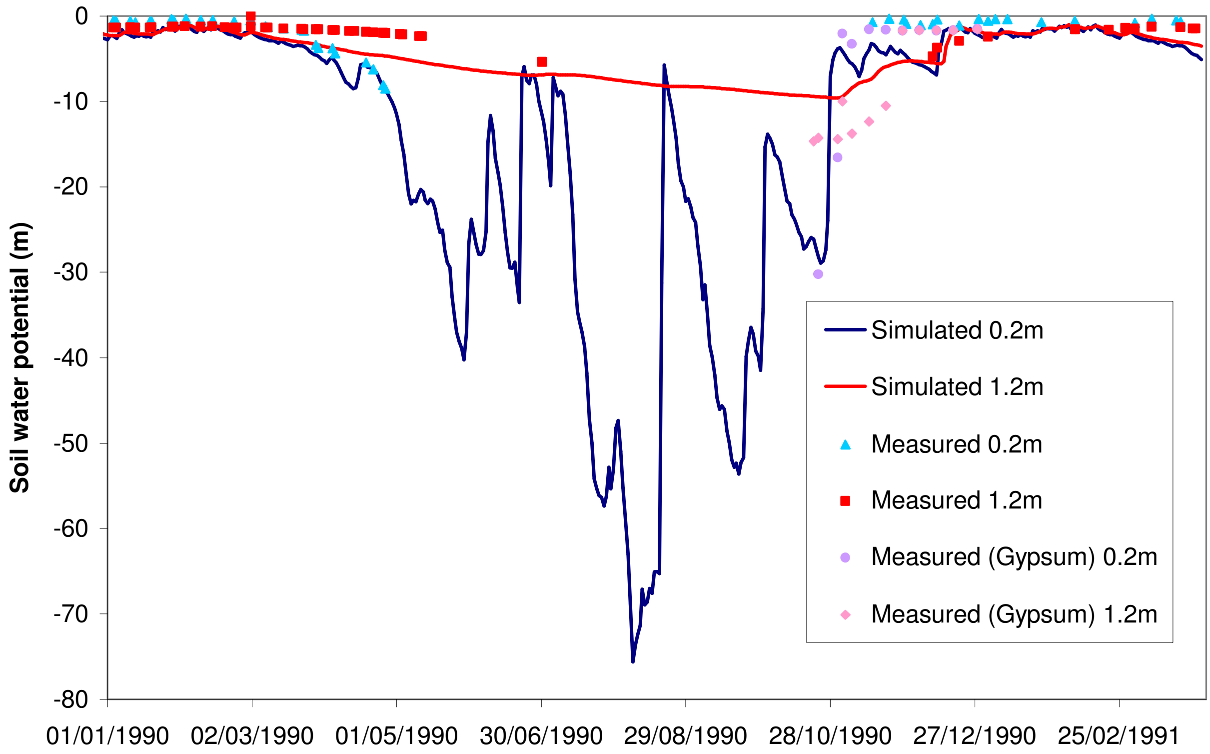

Figure 5. Simulated and measured soil water potentials for the grass site

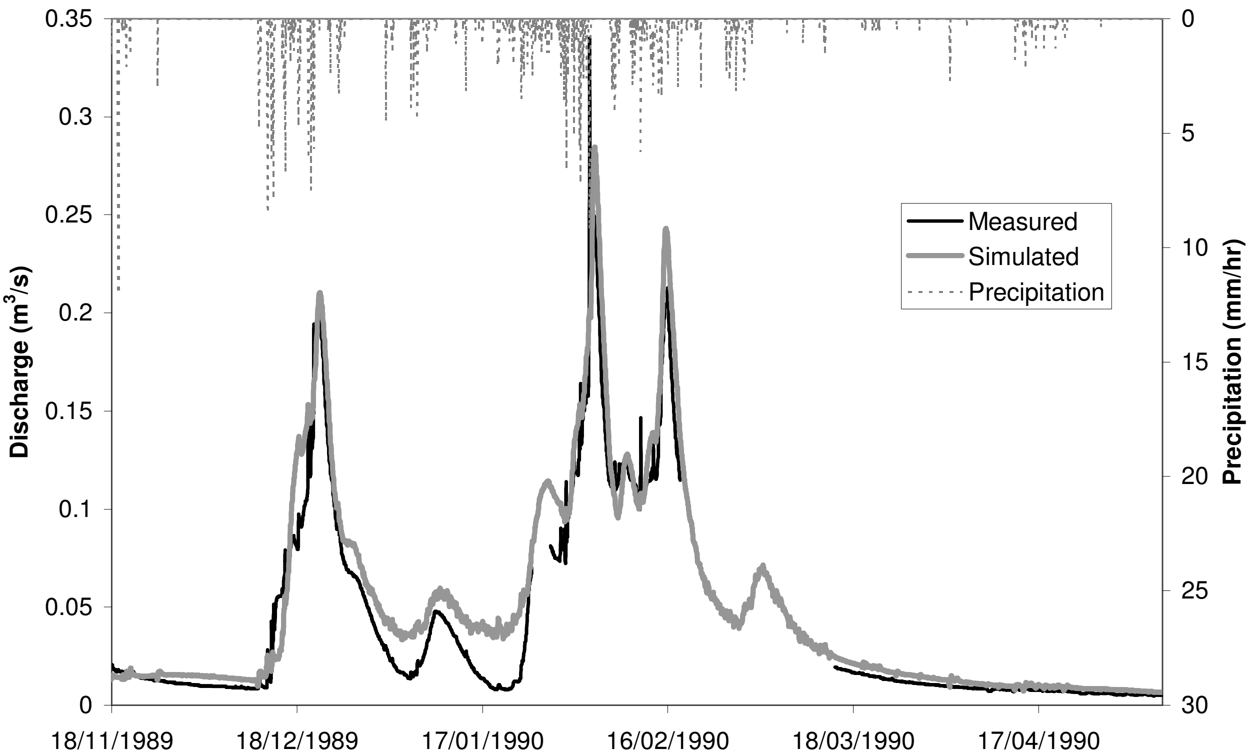

Figure 6. Measured and simulated (deeper soils) discharge at the Slapton Wood catchment outlet (the measurement flume was blocked by sediment from 15/2/1990 to 10/3/1990)

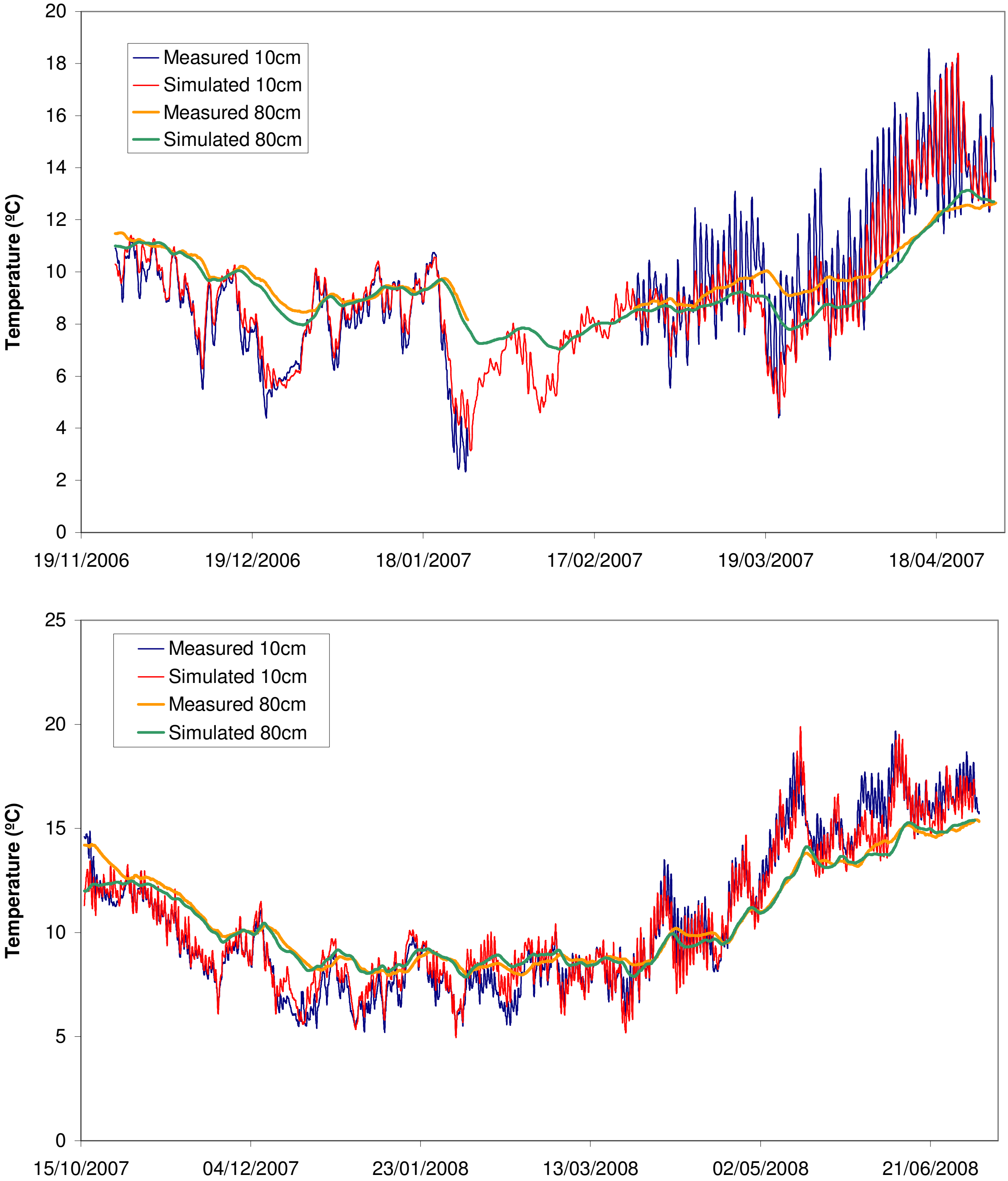

Figure 7. Measured and simulated soil temperatures in the Eastergrounds Hollow

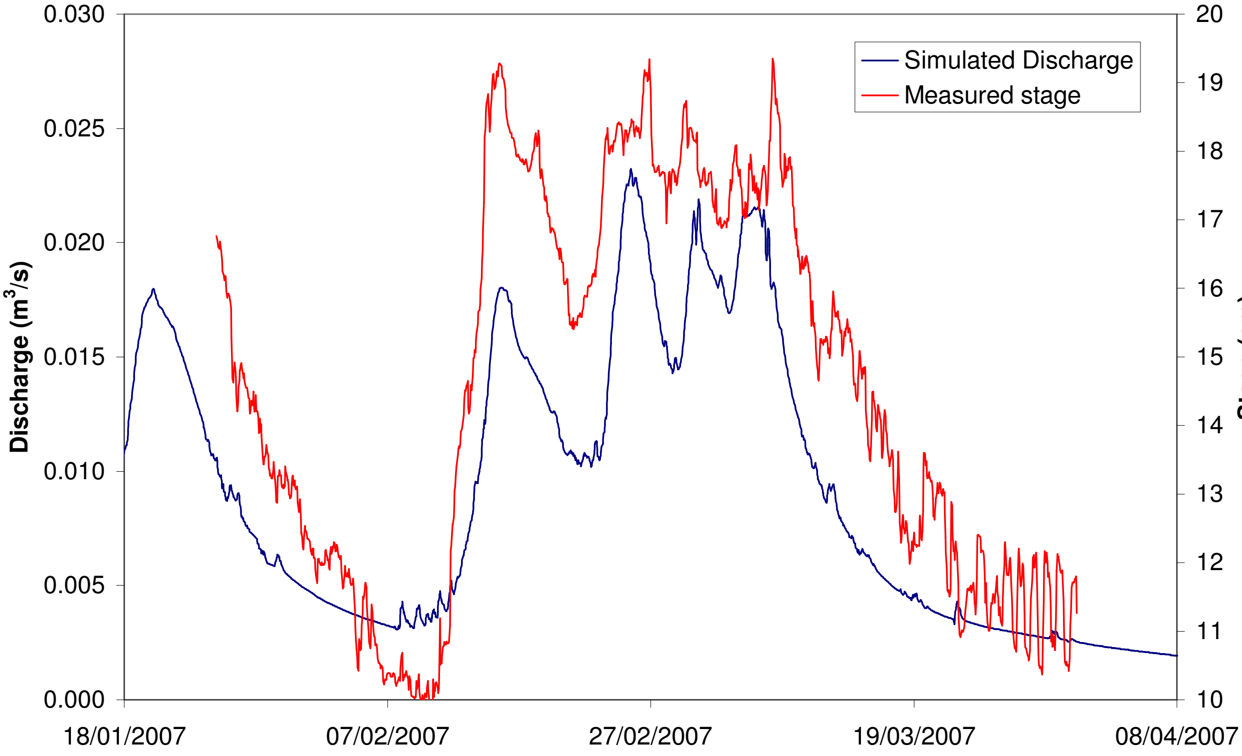

Figure 8 Simulated discharge (deep soils) and measured stage for the Eastergrounds hollow

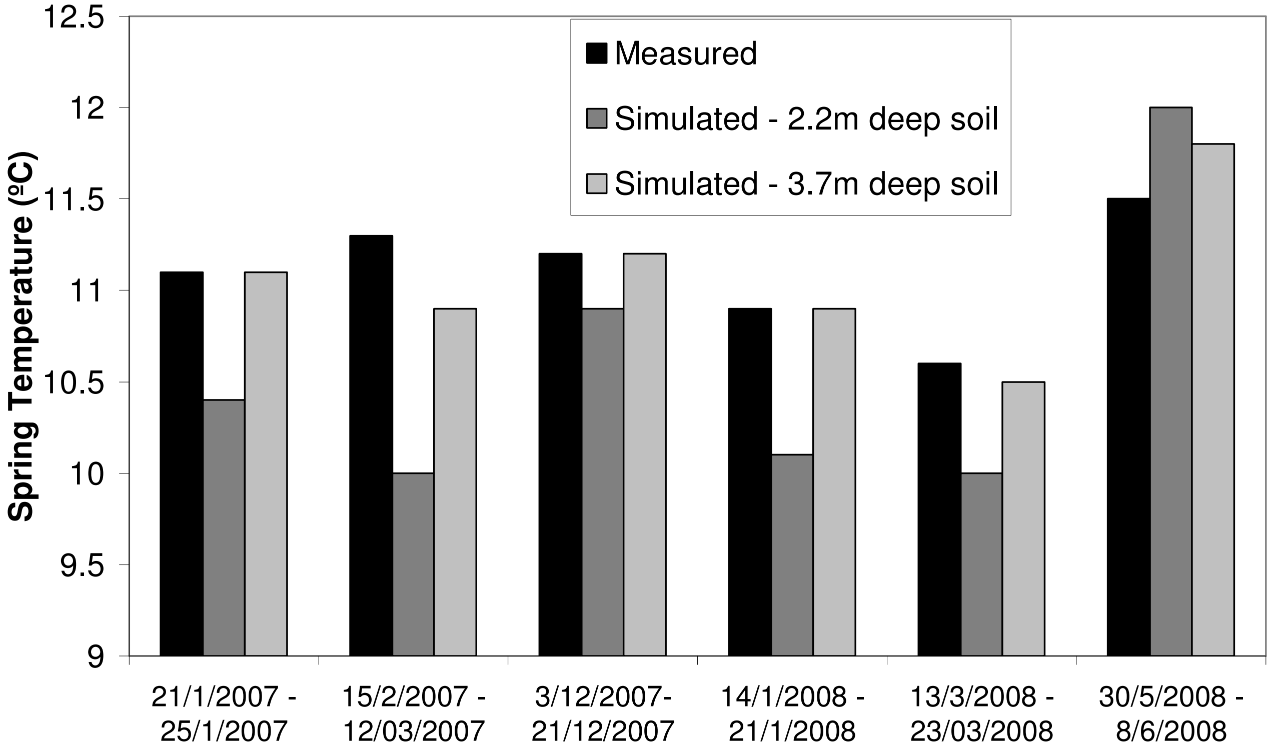

Figure 9. Measured and simulated spring temperatures in the Eastergrounds Hollow. Measured and simulated temperatures are the mean value in each of the six periods (there is little variation over each period).

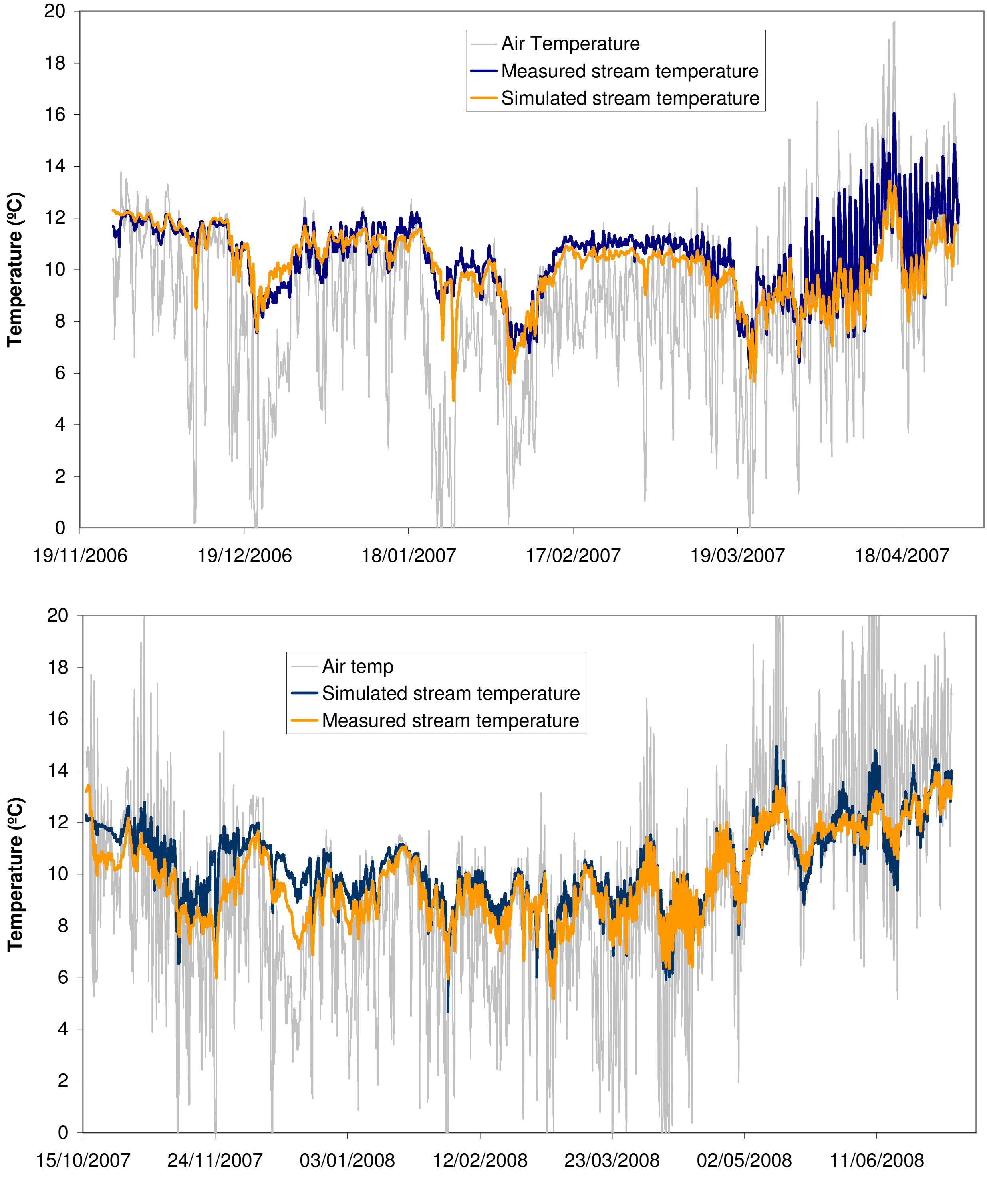

Figure 10. Measured and simulated (deep soil) stream temperatures in the Eastergrounds hollow

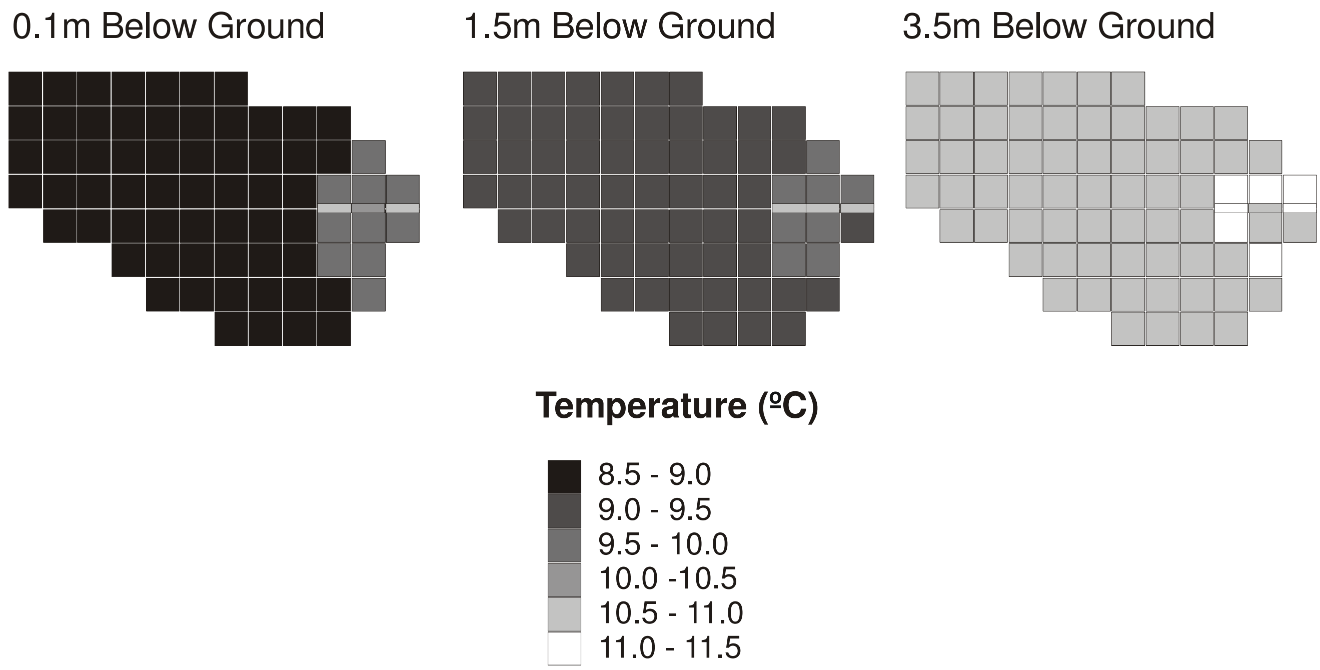

Figure 11. Simulated soil temperatures (deep soils) on 22/2/2007 in the Eastergrounds Hollow