Characterization of Hillslope Thermal and Hydrologic Processes at the Sleepers River Research Watershed

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ABSTRACT

Measurements for the characterization of thermal and hydrologic processes at the hillslope scale were made within the W-9 subwatershed at the Sleepers River Research Watershed during the 1991–92 winter season. Three soil pits were instrumented on a predominantly south-facing slope with a deciduous cover type. Soil and snow temperature sensors, soil moisture sensors, and soil water lysimeters were installed at each pit. Meteorologic data (air temperature, relative humidity, wind speed and direction, incoming and reflected short- and long-wave radiation) and snowpack characteristics were also measured throughout the study period. Streamwater and streambed temperatures were measured at the toe of the slope. These data are being used to study hillslope-scale thermal and hydrologic processes as an intermediate scale between point and basin modeling. Results of this study suggest that source areas are best defined by a field accounting of the thermal mechanisms in the snow/soil/stream system. These observed thermal mechanisms have a large effect on the internal snowmelt processes, the relative flow paths of surface, subsurface and ground water and the total outflow to the stream channel.

INTRODUCTION

The study of hillslope hydrology has been primarily concerned with flow processes within the soil and over the soil surface (Anderson and Burt, 1990). Relationships between precipitation and hillslope discharge have been derived, considering the relative flow paths of surface, subsurface, and ground water, as well as rapid through flow of "new" water and displacement of "old" water (Burt, 1989). Kirkby (1985) stated that the greatest challenge to hydrologists is to relate knowledge of flow processes to the hillslope/catchment scale without losing the potential for direct measurement of catchment processes in the field. However, as Anderson and Rogers (1987) have found, even in studies where the complete characterization of hillslope processes by measurement and observation are available, distributed models of catchment hillslope input (SHE, IDHM, VASA2) do not do an efficient analysis of the internal mechanisms even when matching catchment outflows. This problem of accounting for the internal mechanisms of hillslope flow processes is further compounded by the effects of cold regions phenomena including snow cover, freeze/thaw and the increased spatial variability of available runoff water and flow channels induced by these parameters. Considerable prior work has been conducted on hydrologic and chemical aspects of hillslope snowmelt hydrology (Beven and Dunne, 1981; Dunne and Black, 1971; Stephenson and Freeze, 1974; Jones and Stein; 1990, Jones et al., 1991). However, the internal runoff processes of the snow/soil/hillslope system have received relatively little empirical study (Dunne, 1983).

The goal of the present study is to conduct field and modeling experiments to develop a framework for a physically based, basin scale, mass and energy modeling scheme that will serve to produce the thermal and hydrologic response of a basin in snowmelt regimes. The applicability of field studies of distributed mass and energy processes has become more critical with the use of geographic information systems and remote sensing technology in water resources. Initial field experimental findings on the thermal regime of the snow/soil/stream system at the hillslope scale are presented in this paper. The objective is to identify the scale at which the heat and mass transfer mechanisms, important to the overall basin response, operate and to devise a method for appropriately modeling these mechanisms at the hillslope scale, so that the predicted timing and the temperature of outflow, for example, have a physical basis.

METHODS

Study site

The hillslope site for this study was selected within the W-9 subwatershed (0.469 km^2, 44°29'26"N, 72°09'48"W) of the Sleepers River Research Watershed (SRRW, 113 km^2, Fig. 1) near Danville, Vermont. The hillslope for intensive monitoring is located on a predominantly south-facing concave 15% slope with a deciduous cover type. The soils are primarily of the Buckland, very stony, and Woodstock–Paxton, very stony, soils series. The surficial geology is thin till 2–3 m thick underlain by the Waits River formation of quartz mica schist and minor micaceous quartzite. The climate of the Sleepers River Basin is continental and strongly influenced by Canadian air masses from the north and Gulf Stream air masses from the south. The mean annual temperature is about 4°C and the mean annual precipitation is about 1080 mm. January temperatures average about −8°C with about 40 to 60 days in the winter with minimum temperatures of −20°C or lower. Snowfall average is 2540 mm with a maximum water equivalent of the snow cover normally about 225 to 300 mm. A complete description of the SRRW is given in Anderson et al. (1977). It is noted that definitive studies of saturated overland flow and "partial area" contributions were conducted in the SRRW (Dunne and Black, 1970a, 1970b, 1971).

Description of data collection

During the winter of 1991–92 three soil pits (Fig. 1) were instrumented on the hillslope. Platinum resistive temperature devices (RTDs), accurate to ± 0.1°C, were installed in each pit at levels of the approximate midpoints of the mineral soil horizons. These levels were 15, 45 and 90 cm for pits A and B and 9 and 36 cm in pit C. The snow above each pit was instrumented with a 1-D array of copper-constantan thermocouples, accurate to ± 0.5°C, at 8-cm spacing from the ground surface to a level of 72 cm for snow temperature measurements. A meteorological station was installed on 6 February at approximately the midpoint of the hillslope. Measured parameters at the hillslope meteorological station include air temperature, relative humidity, wind speed and direction, snow depth and four components of radiation, incoming shortwave, reflected shortwave, incoming long-wave and outgoing long-wave. All data from the automated weather station and the soil and snow temperature

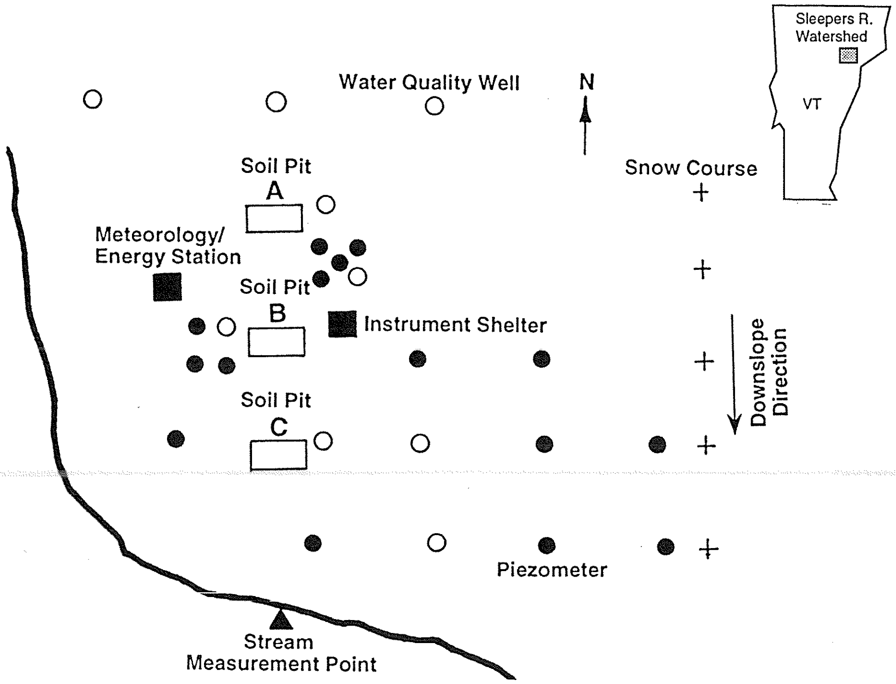

Figure 1. Hillslope research area within the W-9 subwatershed of the SRRW.

sensors on the hillslope were recorded hourly on a Campbell CR10 micrologger and retrieved approximately every two weeks. During periods of snowfall, the upright radiometers often became snow capped until someone was able to clear them of snow. Unfortunately, snow-capped radiometers resulted in a significant loss of incoming radiation data. Additionally, weekly snow course measurements were made during the 1991–92 winter at five points on the hillslope. At the toe (Fig. 2) of the hillslope, streamwater and bed temperature measurements were made. Precision thermistors were used with a Grant 1200 series Squirrel data logger. Steel temperature probes were driven into the stream bed with the thermistors at a depth of 20 cm in the streambed and in the water column 8 cm above the streambed. These thermistors, accurate to ± 0.02°C, were measured at a half-hour time interval. The water temperature system was installed on 12 February 1992.

RESULTS

The key hydrologic events were two rain-on-snow events in January (12–15 and 23–24), two midwinter snowmelt events in February and March (18–22 February and 4–12 March), and the final snow melt period during 18–28 April. Data from January through April of the 1991–92 winter season are presented (Fig. 2 and 3). Air temperature on the hillslope

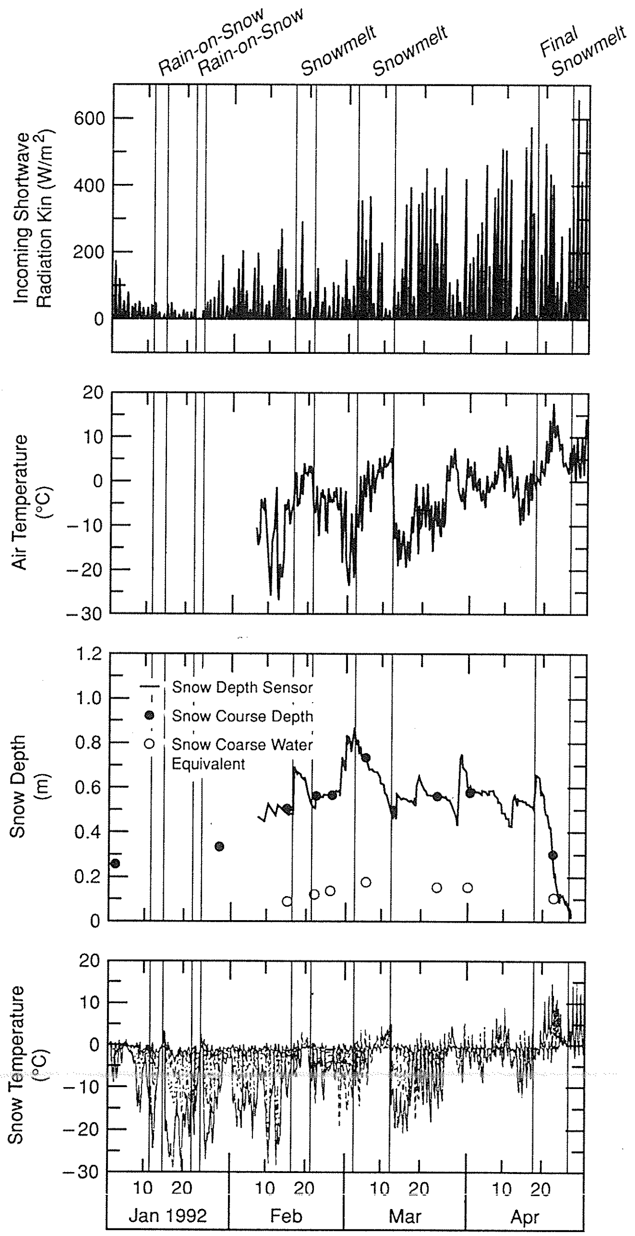

Figure 2. Meteorologic and snow temperature data, 1 January–3 April 1992.

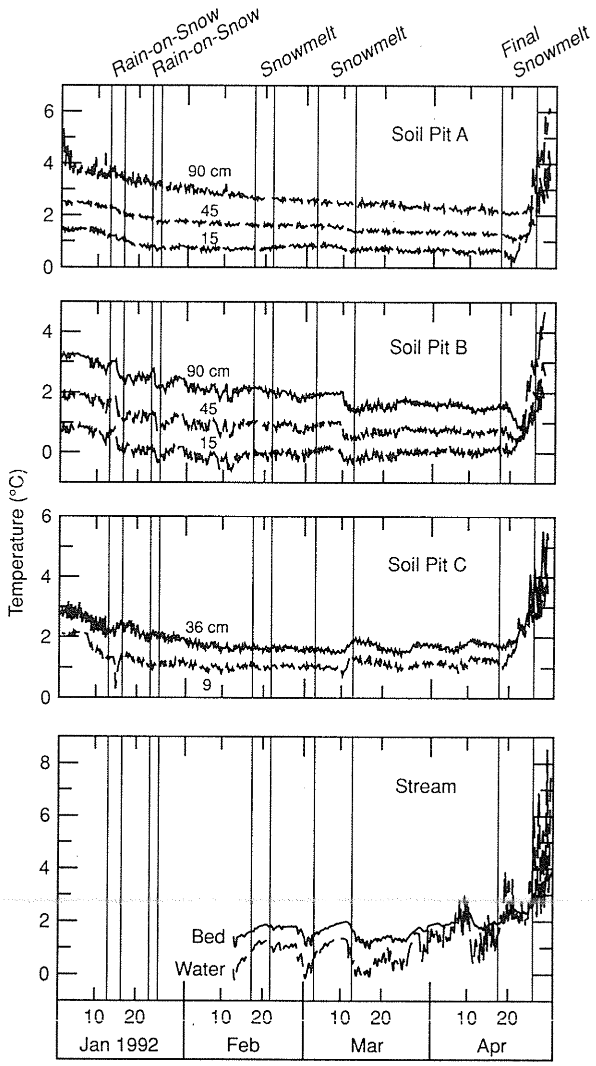

Figure 3. Soil temperature and streamwater and bed temperature data, 1 January–30 April 1992.

ranged from a minimum of –26.8°C on 12 February to a maximum of 17.8°C on 21 April. Snow depth reached a maximum of 87 cm on 1 March and the hillslope was snowfree on 26 April.

Rain-on-snow events

The two rain-on-snow events (Fig. 2) showed similar responses in snow temperature. All snow temperatures reached isothermal conditions within 72 hours of onset of the rain-on-snow event. This has a pronounced effect on grain size distribution, ice layer formation and chemical constituents in the snowpack. Both events are followed by severe cold periods. Observations after these events showed formation of ice layers at the ground/snow interface and surface crusts. All snow thermocouples in the vertical array are presented in the figures; however, at times throughout the study period some of the snow thermocouples are exposed to air, depending on the snow depth, and therefore give higher readings than can be expected for snow temperature.

The soil temperature response in the three pits varied dramatically based on their position on the hillslope (Fig. 3). Pit A at the top of the hillslope showed relatively little response to these rain-on-snow events, where pit B showed a sharp initial decrease in ground temperature and then a warming during the event. Pit C at the toe of the slope exhibited a drastic decrease in temperature at 9 cm during the first rain-on-snow event, with a less pronounced decrease in the second rain-on-snow event. The response in pit C is indicative of the observed saturated soil conditions at the toe of the hillslope. Zero-degree water effectively flowed directly through the snow-soil system in pit C, while in pits A and B the available rain and meltwater were absorbed by the soil matrix. During these periods daily incoming short-wave radiation peaked at approximately 50 W/m^2 (Fig. 2) with the snow depth being approximately 28 cm (based on snow course observations).

Prior to the two midwinter melt events, there was a very cold period from 25 January until 18 February, with air temperatures seldom reaching a maximum of zero, and with the seasonal minimum of –26.8°C occurring on 12 February. During this period the first subzero Celsius readings were made of streamwater temperature and soil temperature (in pit B at the 9-cm depth). Throughout the period pit B had the most dynamic soil temperature fluctuations. Lower initial water contents in the sandy, well-drained pit B soil led to frost formation in the upper 9 cm and caused more dramatic temperature fluctuations due to upward water flow from layers beneath the freezing zone. On the coldest night of the measurement period, 12 February, all soil temperatures showed an increase due to upward flow of warmer water from lower soil water layers. The streamwater measurement of subzero temperatures during this period is an interesting phenomenon. The stream was completely covered with a cold snowpack nearly 50 cm thick; nonetheless, both the streamwater and streambed temperatures showed drastic decreases, to –0.31 and 0.96°C respectively, in response to the low air temperature.

Midwinter melt events

The first snow melt period of 18–22 February had a limited effect on soil and stream temperatures. Although the snow depth decreased by 19 cm, the snow water equivalent stayed fairly consistent through this melt period. Thus the effect of the warm period was to consolidate the snowpack, and most of the meltwater refroze in the snowpack during diurnal temperature depressions. Slight temperature depressions were observed at the onset of the melt event in the unfrozen pits A and C; however, in pit B the meltwater (assumed to be at 0°C) delivered heat to the frozen layer and the latent heat effect damped out the pit B temperature depression. Streamwater and bed temperatures increased during this period, indicating that no significant quantity of zero-degree meltwater was delivered to the stream channel.

After another cold period a major snowmelt event occurred between 4 and 12 March, accounting for a loss of 44 cm from the snowpack. With three sunny days and air temperatures above freezing, the snowpack became nearly isothermal on 7 March and began to deliver meltwater to the soil column and stream channel on 11 March. Soil pit B thawed during this period and all three pits showed a lagged temperature depression with depth from the inflowing 0°C meltwater. At the end (12–13 March) of this snowmelt period, pit C, at the lowest point on the hillslope, exhibited an increase in soil temperatures. This may be attributed to downslope displacement of warmer soil water from deeper soil horizons. Contrary to this is the response of the streamwater and bed temperatures during 12–13 March, which showed a considerable depression after initial warming. Lateral inflow of meltwater arrived at the stream channel from pipeflow or other source areas, effectively bypassing the near-channel saturated zone environment of pit C.

On 13 March another cold period resumed with 12 days of subfreezing temperatures. After this period all soil temperatures exhibited a fairly stable period (26 March–18 April) of positive temperature values. The 15-cm depth in pit B remained near zero degrees. The snowpack experienced several small melt and accumulation events varying between snow depths of 40 and 70 cm during this period. The snowpack ripened and began to collapse above the stream channel, opening the channel to solar radiation input. This can be seen beginning approximately on 6 April when the water temperature data started to exhibit more distinct diurnal temperature fluctuations. The streambed temperatures also showed a lagged response to this solar radiation input.

Final melt period

On 18 April the final snowmelt period began with a snow depth of 64 cm. Air temperatures increased until reaching a period maximum of 17.8°C on 21 April. Figures 4 and 5 show the expanded data for the 18–28 April period. In the first three days of this period maximum incoming short-wave radiation averaged approximately 375 W/m^2 with a continuous above-freezing warming trend during which the snowpack depth decreased to 30 cm. The lower 24 cm of the snowpack demonstrated a very unusual behavior early in this melt period (18–21 April). Snow temperatures in this zone dropped gradually during the night and then rapidly during the morning hours, reaching a minimum of –2° to –4°C by midday. This behavior was measured at all three thermo-

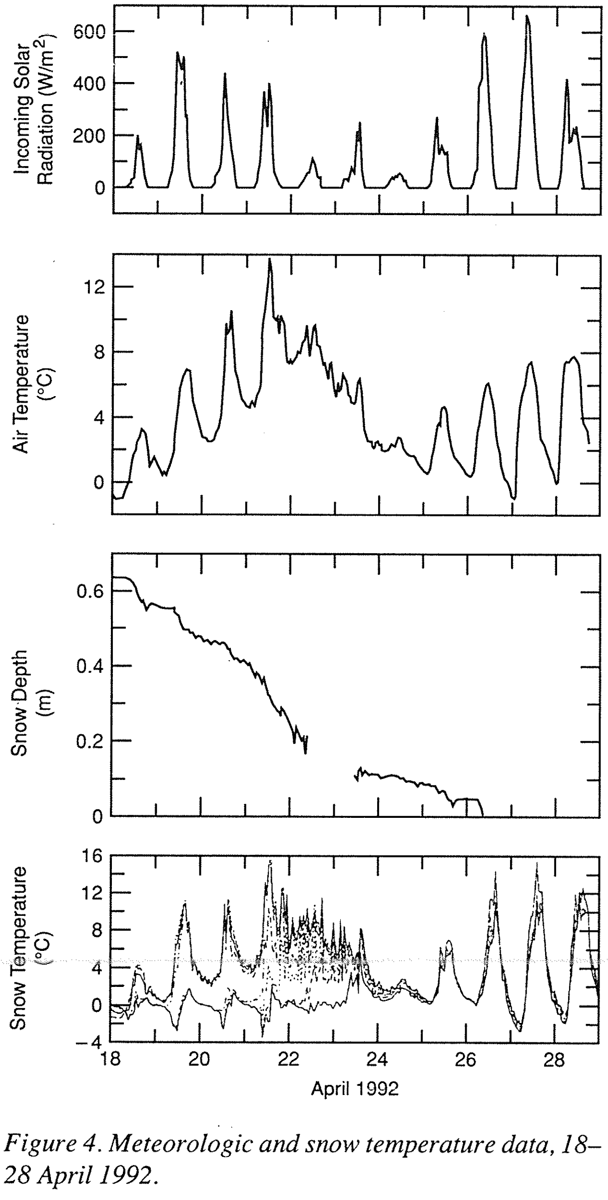

Figure 4. Meteorologic and snow temperature data, 18–28 April 1992.

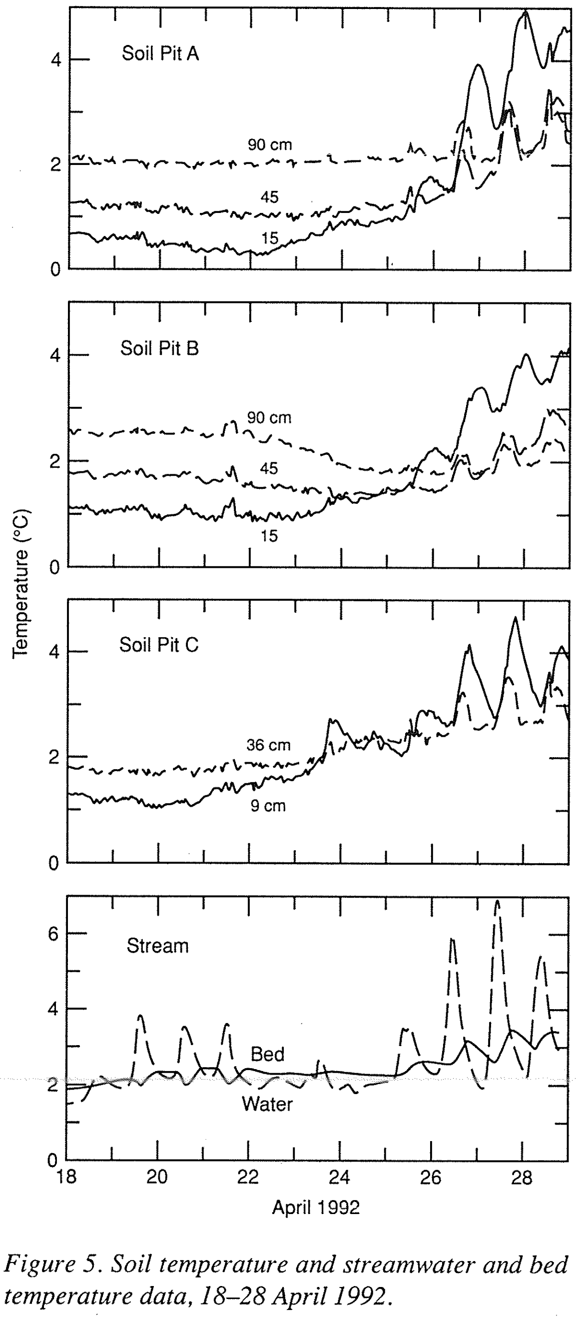

Figure 5. Soil temperature and streamwater and bed temperature data, 18–28 April 1992.

couple arrays, pits A, B and C, but only temperature data from pit A are presented. The authors are unaware of snow temperature measurements of this kind in other studies of snowmelt runoff. One possible explanation of this behavior is that the increase in thermal conductivity, due to snowpack ripening and available meltwater, and the very high gradient (greater than 63°C/m) may induce freezing due to near-surface frozen soil zones. Further analysis and measurements will be conducted in the near future to investigate this phenomenon. By 22 April, the thermocouple temperatures warmed and this phenomenon ceased to occur. Eventually by 25 April, with the complete disappearance of the snowpack, the thermocouples all became exposed and were tracking air temperature.

The soil pit temperature response (Fig. 5) to this final snowmelt was very dependent on their position on the hillslope. At the onset of the melt period (18–20 April) all three pits exhibited slight fluctuations of temperatures in response to the diurnal melt events. However, on the 21st of April there appeared to be a meltwater breakthrough in response to the maximum air temperatures. All three pits exhibited a more pronounced warming at each level. At this point the differences between the soil pits became more pronounced. At the head of the slope, pit A temperatures remained fairly stable at the 45- and 90-cm depths, whereas the 15-cm temperature began a consistent increase until the snowpack completed its melt and all levels increased due to the diurnal temperature and radiation fluxes. At the middle of the hillslope, the deeper pit B soil layers exhibited a decrease in temperatures after the warming on 22 April until the snowpack melted and all levels again followed diurnal warming trends. At the toe of the slope, pit C temperatures immediately began to increase after the 22nd and began to track diurnal fluctuations much earlier on the 24th. These differences may be explained by the following progression: 1) at pit A meltwater flowed downslope laterally through the snowpack and the upper soil horizons, 2) some of this meltwater was transported downslope to pit B, and 3) with the additional available meltwater in situ to pit B there was a storage in the sandier hollow of lower soil horizons of this hillslope position. This increase in soil water content at pit B caused a downslope flow of warmer water to pit C which induced its more rapid temperature increases. The earlier temperature increases at pit C were also a function of its observed thinner snowpack due to its relatively consistent warmer ground temperatures.

During this melt period the streamwater temperatures followed diurnal temperature fluctuations enhanced by radiative fluxes to the water column. These water temperature fluctuations are damped somewhat by the input of snowmelt water. By comparing the water temperature fluctuations for similar energy inputs, i.e., 19–20 April and 27–28 April, for snow-covered and non-snow-covered periods, this damping is apparent. The streambed temperatures showed a more pronounced difference for snow-covered melt events. During the extreme melt period, 19–21 April, the streambed temperature exhibited a depression with a minimum in temperature at peak melt times (1300 hours). This corresponds to the component of the snowmelt that is entering the streambed through preferential flow channels. After this extreme melt period the streambed temperatures stabilized until they exhibited a lagged response to input fluxes after the snowpack had disappeared. The stable period during the final melt is consistent with the warming of the near-channel saturated zone of the pit C environment.

CONCLUSIONS

Initial field observations of the thermal and hydrologic processes at the hillslope scale have been presented. The preliminary results of this study were consistent with the findings of Dunne and Black (1971) that significant snowmelt runoff is produced on small "partial" areas of the hillslope. The significance of the findings of the present study is that these areas were best defined by a field accounting of the thermal mechanisms in the snow/soil/stream system. The observed thermal mechanisms have a large effect on the internal snowmelt processes, the relative flow paths of surface, subsurface and ground water and the total outflow to the stream channel. This information will be used to determine the level of complexity required by mass and energy transport models at this hillslope scale. In the future, more field experiments will be conducted at other relatively homogeneous hillslope units, with a final goal that, for each basin subdivision of the overall basin model, the simplest appropriate model that adequately provides a physical basis for the heat and mass transfer of that subdivision is determined.

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