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The Influence of Mineral Earth Hummocks on Subsurface Drainage in the Continuous Permafrost Zone

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ABSTRACT

Mineral earth hummocks are one of the most widely distributed forms of patterned ground in the permafrost areas of the world, yet little is known of their hydrological role in the drainage of hillslopes. The impact of earth hummocks on subsurface drainage was studied at three hillslope plots during the snow-free periods of 1993 and 1994 at a small hummock-covered Arctic tundra watershed (Siksik Creek) in north-western Canada. Subsurface drainage occurs preferentially through the unfrozen saturated layer of the inter-hummock area, owing to its relatively high permeability and connected nature. The inter-hummock area is composed of primary channels, oriented in the downslope direction, and secondary channels, obstructed from conducting water directly downslope. Because of their very low hydraulic conductivity, earth hummocks obstruct hillslope drainage. As a result, the spatial distribution of earth hummocks on a hillslope influences the average tortuosity of the individual inter-hummock channels that comprise the hillslope drainage network. The time required for runoff water to reach the streambank increases with increasing tortuosity of inter-hummock channels. Earth hummocks attenuate subsurface flows owing to seepage between the hummocks and the inter-hummock area. Hummocks also displace the water table in the inter-hummock area upward into a zone where the hydraulic conductivity can be orders of magnitude higher. © 1998 John Wiley & Sons, Ltd.

RÉSUMÉ

Les sols à buttes constituent une des formes de sols structurés les plus répandues de la zone du pergélisol quoique leur rôle hydrologique dans le drainage des versants reste toujours peu connu. L'impact des sols à buttes sur le drainage subsuperficiel a été étudié en trois endroits de la toundra pendant les périodes sans neige de 1993 et de 1994 sur une ligne secondaire de partage des eaux du Siksik Creek dans le Canada du nord-ouest. Un drainage souterrain se produit préférentiellement à travers la couche non gelée saturée des dépressions localisées entre les buttes en relation avec leur perméabilité relativement élevée et leur nature interconnectée. La zone entre les buttes est composée de chenaux primaires orientés dans la direction de la pente et de chenaux secondaires ne conduisant pas directement l'eau au bas du versant. En conséquence, la distribution spatiale des buttes sur la pente influence la tortuosité moyenne des chenaux individuels qui serpentent entre les buttes en formant le réseau de drainage du versant. Le temps

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requis pour que les eaux s'écoulant atteignent la berge d'un cours d'eau augmente avec la tortuosité des chenaux inter-buttes. Les buttes de terre atténuent les écoulements subsuperficiels dus à l'infiltration entre les buttes et dans la zone inter-buttes. Les buttes déplacent aussi la nappe aquifère vers une zone inter-buttes où la conductivité hydraulique peut être de plusieurs ordres de grandeur plus élevée. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: Arctic; tundra; subsurface drainage; hummocks; inter-hummock channels

INTRODUCTION

Mineral earth hummocks (Figure 1) are one of the most widely distributed forms of patterned ground in the permafrost areas of the world (Mackay, 1980). Hummocks are a type of non-sorted circle that develop in materials high in silt and clay and/or high ice content (ACGR, 1988). They develop from an upward displacement of material caused by freeze–thaw of ice lenses at the top and bottom of the active layer (Mackay, 1980). Freezing and thawing of this type produces a cell circulation driven by gravity, with downward and radially inward movement of saturated mud along the permafrost table, and upward and radially outward movement in the centre and at the surface.

In the Arctic tundra, the impact of a wide variety of landscape features on hillslope drainage has been investigated, including aspect (Landals and Gill, 1972; Young *et al*., 1997), slope length (Dunne *et al*., 1976), slope gradient (Price *et al*., 1977), vegetation cover (FitzGibbon and Dunne, 1983), snow depth and density (Dunne *et al*., 1976; Marsh and Pomeroy, 1996), soil pipes (Dyke and Eggington, 1990), organic soils (Slaughter and Kane, 1979; Hinzman *et al*., 1993; Quinton, 1997), late-lying snow drifts (Lewkowicz and Young, 1990), local decreases in frost table depth (Soulis and Reid, 1978) and active layer thaw (Wright, 1979; Woo and Steer, 1983). However, the hydrological impact of earth hummocks has not been addressed, and, as a result, prediction of hillslope runoff responses in Arctic tundra environments is limited.

Earth hummocks segregate hillslope surfaces into two areas: the area occupied by hummocks, and the inter-hummock area, composed of organic material, and arranged into a network of connected

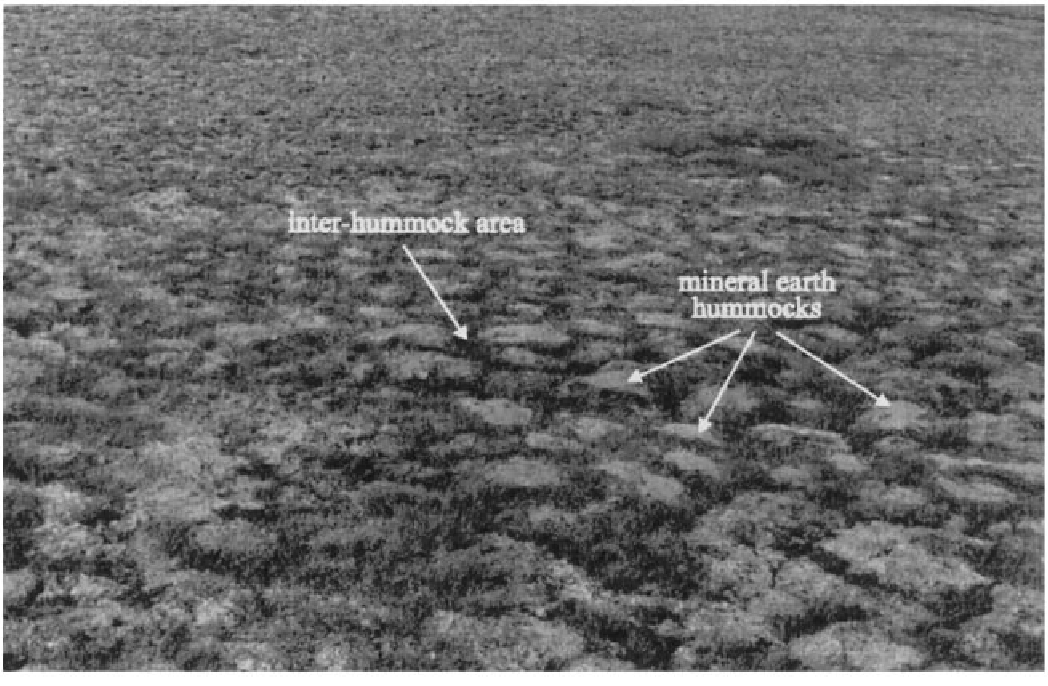

Figure 1 Mineral earth hummocks and the inter-hummock area at Siksik Creek.

inter-hummock channels (Quinton, 1997). Pump tests revealed that the horizontal hydraulic conductivity integrated over the depth of the saturated layer is three orders of magnitude higher in the inter-hummock area (10^0 m d^{-1}) than in the hummocks (10^{-3} m d^{-1}) (Quinton and Marsh, 1995). The near-surface material in the inter-hummock area is composed of living vegetation and lightly decomposed peat. The saturated hydraulic conductivity of this material can be six orders of magnitude higher than the hummock soils.

In the inter-hummock area, the physical properties of the peat change abruptly with depth owing to the increasing degree of decomposition and humification. Analyses of physical properties on ~30 cm deep peat cores showed that over this depth range, bulk density increased nearly fourfold. Although the total porosity decreased only slightly, the active (i.e. inter-particle) porosity decreased from ~0.85 near the surface to ~0.50 in the basal peat, suggesting an increasing proportion of closed and dead-end pores with depth. Measurement of the frequency distribution of pore diameters also shows that the proportion of small pores increases with depth (Quinton, 1997). In contrast, media properties do not change significantly with depth in the hummocks.

Changes in peat physical properties with depth in the inter-hummock area have a dramatic effect on the hydraulic conductivity profiles. Quinton and Marsh (1995) demonstrated that the horizontal hydraulic conductivity in the inter-hummock area typically decreases by two to three orders of magnitude over a 20 cm increase in depth. The horizontal hydraulic conductivity ranges from approximately 1000 m d^{-1} near the surface to <1 m d^{-1} in the 30 to 35 cm depth range (Quinton, 1997).

Surface topography influences hillslope drainage through its effect on the spatial distribution of soil moisture, and on the channelling of flow. Where the surface is dominated by hummocks, the active layer thickness is highly variable over the hillslope. In the inter-hummock area, the thermal properties of the peat reduce the downward penetration of energy so that the frost table depth in the inter-hummock area can be half that of the hummocks (Mackay, 1981; Quinton and Marsh, 1995). Consequently, the saturated layer in the inter-hummock area is maintained close to the surface, often entirely within the peat accumulation. The organic layer remains at least partially saturated during most of the year, since the rate of infiltration into the unfrozen organic layer far exceeds the infiltration rate into the underlying, and often frozen, mineral soil (Slaughter and Kane, 1979).

The specific mechanisms, processes and pathways of hillslope drainage resulting from the presence of hummocks on the terrain need to be understood to improve prediction of the runoff response of tundra hillslopes. The objectives of this paper are to identify (i) the major ways in which subsurface drainage from hillslopes is influenced by the presence of earth hummocks, and (ii) the relative importance of these factors, and (iii) how this relative importance varies among hillslopes with different hummock cover characteristics.

THE STUDY SITE

Data were collected from Siksik Creek (68° 44′ N, 133° 28′ W), located approximately 55 km north–north-east of Inuvik, NWT on the Mackenzie River Delta, and 80 km south of the Tuktoyaktuk, NWT on the Arctic Ocean (Figure 2). Siksik Creek is in the zone of continuous permafrost (Heginbottom and Radburn, 1992), at the northern fringe of the forest–tundra transition zone (Bliss and Matveyeva, 1992), and is biophysically representative of small Arctic tundra basins. The surficial geology of the middle and upper basin components is composed of rolling moraines of early Wisconsinan origin with sediment (glacial till, gravel, sand) thicknesses of between 4 and 12 m, and a topography severely affected by thermokarst (Rampton, 1987). The lower basin component contains 0.5–3.0 m of colluvial clay, silt, sand and rubble originating from channel, flood basin, overbank and debris flow deposits during the Holocene (Rampton, 1987). Underlying the organic cover throughout the basin are fine-grained, frost-susceptible soils.

Siksik Creek flows southward into Trail Valley Creek approximately 500 m downstream of a Water Survey of Canada gauging station. The catchment is 95.5 ha in area with elevations ranging between approximately 60 and 100 m ASL. Maximum observed active layer depths range between 0.4 and 0.8 m depending on aspect and soil type. The maximum permafrost thickness ranges from 350 to >575 m (Natural Resources Canada, 1995). The climate is characterized by short, cool summers and long cold winters, with an eight month snow-covered season (Environment Canada, 1982). The mean daily temperature rises above 0 °C in June, and falls below 0 °C in October.

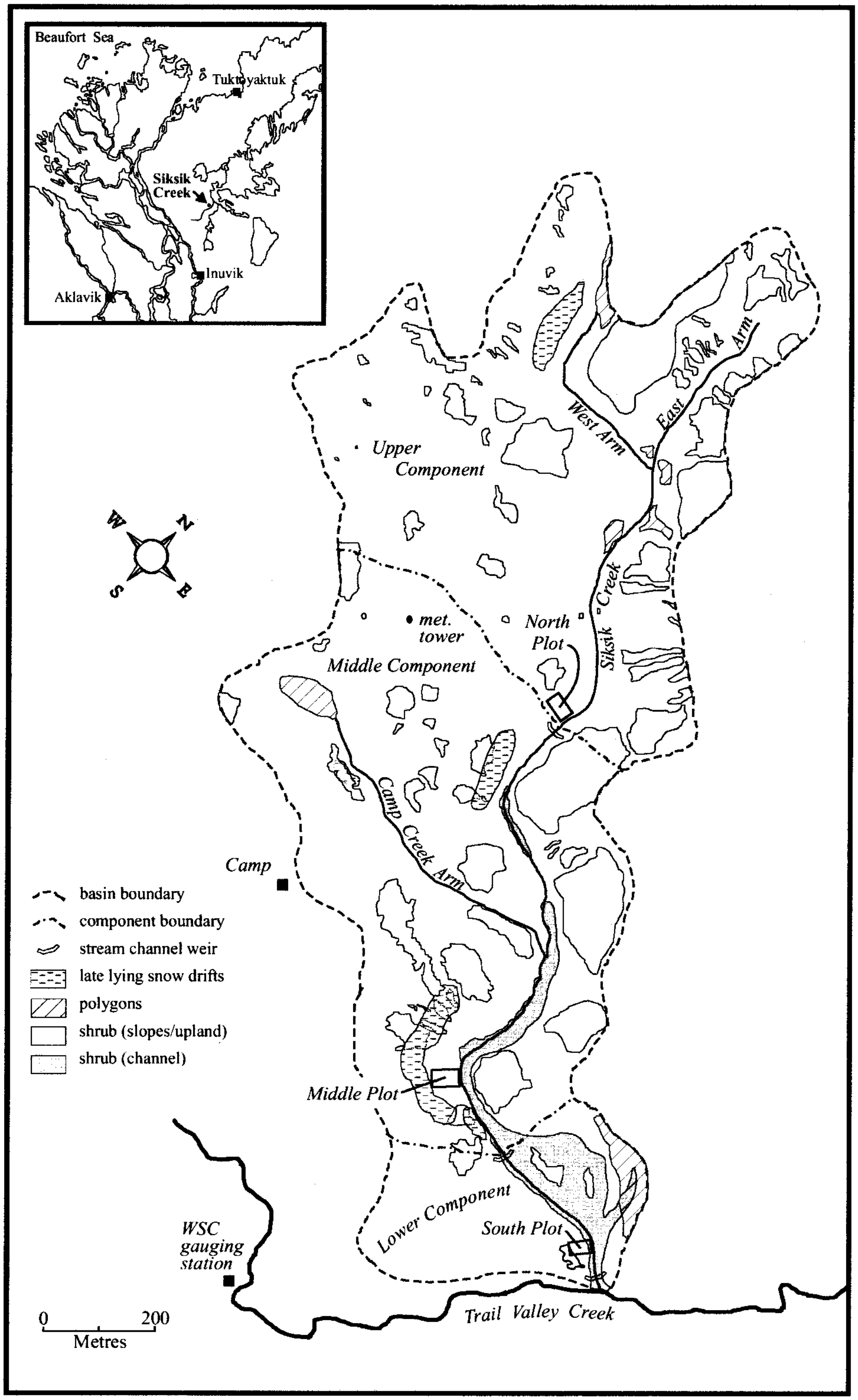

Figure 2 The Siksik Creek catchment. The hillslope plots are identified, as are the locations of other instrumented sites within the catchment. The prominent natural surface features are also identified.

Annual total precipitation is low (~200 mm) and over half of it occurs as snow. Heavy rains occur in August and September, and snowfall is heaviest in October. The mean annual air temperature is −9.8 °C at Inuvik and −10.9 °C at Tuktoyaktuk. The mean total annual precipitation is 266 mm (Inuvik) and 138 mm (Tuktoyaktuk). The total mean annual rainfall and snowfall is 115 mm and 177 mm respectively for Inuvik, and 72 mm and 65 mm respectively for Tuktoyaktuk.

The ground surface at Siksik Creek is dominated by mineral earth hummocks. Hummock surfaces are bare or support a thin layer of lichen. Hummock diameters range between 40 and 100 cm, with their crests rising between 10 and 40 cm above the surrounding inter-hummock surface. Hummocks are composed of fine-grained material, with the clay content often exceeding 50% (Quinton and Marsh, 1995). Inter-hummock areas consist of organic soils, approximately 20 to 50 cm in depth, supporting mainly bryophytes, but also graminoid and herbaceous species.

METHODOLOGY

Research at Siksik Creek was conducted between the middle of May and early August in 1993 and 1994. During this time, data were collected on the west side of Siksik Creek at three small (~1000 m^2) hillside plots: the North, Middle and South Plots (Figure 2).

A 35 mm camera was used to take plan view aerial photographs from a helicopter while it hovered approximately 40 m above each hillslope plot. From this height, the average surface area encompassed by the photographs was approximately 410 m^2. The photographs were scanned at 300 dpi to generate 8-bit grey scale images, with the average pixel dimension representing approximately a 1.5 × 1.5 cm area of the ground surface. *PCI* software was used to quantify several attributes of the hummock cover on each image, including the total area occupied by hummocks, the number of hummocks per unit area (hummock density), and the frequency distribution of the areas and perimeters of the hummocks.

A particle tracking technique (Quinton, 1997) was applied to a single rasterized image of each plot in order to estimate the tortuosity of flow through the inter-hummock area from

$$T_X = L_F/L_S \tag{1}$$

where the tortuosity T_X is the ratio of the length L_F of the flowpath followed by runoff water from any point on the hillslope to the streambank, to the length L_S of a straight line route from the same starting and ending points. L_F is determined by summing the number of cells encountered during a particle tracking run. The particle tracking procedure assumed that all other hillslope features (slope gradient, media properties, etc.) are equal among the plots, and that hillslopes differ only with respect to the physical attributes of their hummock covers. Particle tracking runs were repeated 50 times for each image (total runs = 150), from which average values of T_X for each plot were obtained.

Each plot had a network of six observation wells arranged into two rows oriented parallel to the hillslope. Water table depths in both hummock and inter-hummock areas were also measured continuously at the Middle Plot with chart recorders. Near-surface liquid soil moisture was measured *in situ* using time domain reflectometry (TDR) in 1993 at the Middle Plot. Shortly following the disappearance of the snow cover, 29 soil moisture TDR wave guides (20 cm length) were inserted into the 0 to 5 cm depth layer at selected hummock and inter-hummock locations, and left there until the end of the study period. Most (24) were located in the inter-hummock area. Sampling frequency varied between daily and weekly, depending upon location and season. For organic soils, the approach of Pepin *et al.* (1992) was used to estimate soil moisture content from the measured dielectric constant. Wave guides were also inserted at 15, 22 and 38 cm below the surface at a location in the inter-hummock area.

Thermistors were installed at 8, 20, 30 and 45 cm below the surface at a location in the inter-hummock area to monitor soil temperature changes at these depths over time. A total of ten peat cores, including cores from each plot, were extracted from the inter-hummock area in order to calculate the specific yield following the procedure of Boelter (1976).

RESULTS

Mineral earth hummocks influence hillslope drainage by (i) concentrating flow through the inter-hummock area; (ii) obstructing flow from following a direct path to the streambank; (iii) attenuating flow by interacting with the saturated layer of the inter-hummock area; and (iv) increasing the water table elevation in the inter-hummock area by displacement. The following sections consider these influences in detail.

Preferential Flow through the Inter-Hummock Area

Hillslope runoff is channelled preferentially through the inter-hummock area since, as noted earlier, the hydraulic conductivity in this area can be three to six orders of magnitude higher than in the hummocks. While the hummock cover is composed of individual, disconnected elements, the inter-hummock area is a continuum of connected channels (Figure 3). This enables the inter-hummock area to function as the hillslope drainage network. While both inter-hummock and hummock areas receive meltwater percolation and rainfall, the connected nature of the former, its lower microtopographic position and higher hydraulic conductivity enable it to receive lateral inflow as well. Lateral flow reaches hummocks only indirectly from inter-hummock areas.

The inter-hummock area contains primary and secondary channel types (Figure 3). Primary channels are oriented parallel to the slope, and conduct water to the streambank with little obstruction by hummocks. Secondary channels are obstructed from conducting water directly downslope owing to the presence of hummocks on their downslope sides. Secondary channels include the narrow pathways forming lateral connection between primary channels (e.g. Figure 3b) as well as larger portions of the inter-hummock area that are obstructed by hummocks from conveying water directly downslope (e.g. Figure 3a). The arrangement of the hillslope drainage network varies among the plots. For example, at the Middle Plot, where hummocks occur in elongated clusters oriented parallel to the slope, the distinction between primary and secondary channels is easily made (Figure 3). The downslope orientation of inter-hummock channels is greater on hillsides of higher slope (e.g. Middle Plot) (Table 1). Where there is very little inclination (e.g. South Plot), there is little preferential orientation of inter-hummock channels (Figure 3).

The liquid soil moisture is generally higher in the primary channels owing to their relatively low microtopographic position within the inter-hummock area. The liquid water content in the inter-hummock area (Figure 4a) is initially high owing to *in situ* meltwater infiltration. At several primary channels, the moisture level remained high for an extended period since the lateral input of meltwater from the late-lying drift upslope continued until approximately 20 June. Following the snowmelt runoff period, the average soil moisture of most primary channels remained close to 0.5. On secondary channels, soil moisture decreases relatively quickly to approximately 0.3, which is similar to the soil moisture of the hummocks (Figure 4b). Hummock soil moisture values had decreased from the high values of the melt runoff period prior to the soil moisture monitoring programme, and remained within the 0.2 to 0.3 range throughout the study (Figure 4b). The relatively high microtopographic position of the hummocks, and their low hydraulic conductivity, limit the amount of lateral runoff to these areas. At primary channels occurring further upslope, soil moisture decreased to the levels characteristic of the secondary channels and the hummocks (Figure 4a). These locations may have primary channel characteristics (with respect to their soil

Table 1 Hillslope and hummock coverage characteristics at the North, Middle and South Plots determined from image analysis and measurements on the ground.

Variable	North	Middle	South
Image area (m^2)	489.22	455.07	388.49
Total hummock area (m^2)	236.16	173.44	198.79
Total hummock perimeter (m)	1059.55	957.69	1238.29
Average hummock area (m^2)	0.74	0.50	0.40
Average hummock perimeter (m)	3.32	2.74	2.47
Inter-hummock:hummock edge per unit area (m m^{-2})	2.17	2.10	3.19
Hummock cover (%)	48.3	38.1	51.2
Number of hummocks	319	350	501
Hummock density (m^{-2})	0.65	0.77	1.29
Average tortuosity T_x	1.28	1.22	1.33
Hillslope gradient (m m^{-1})	0.042	0.085	0.035

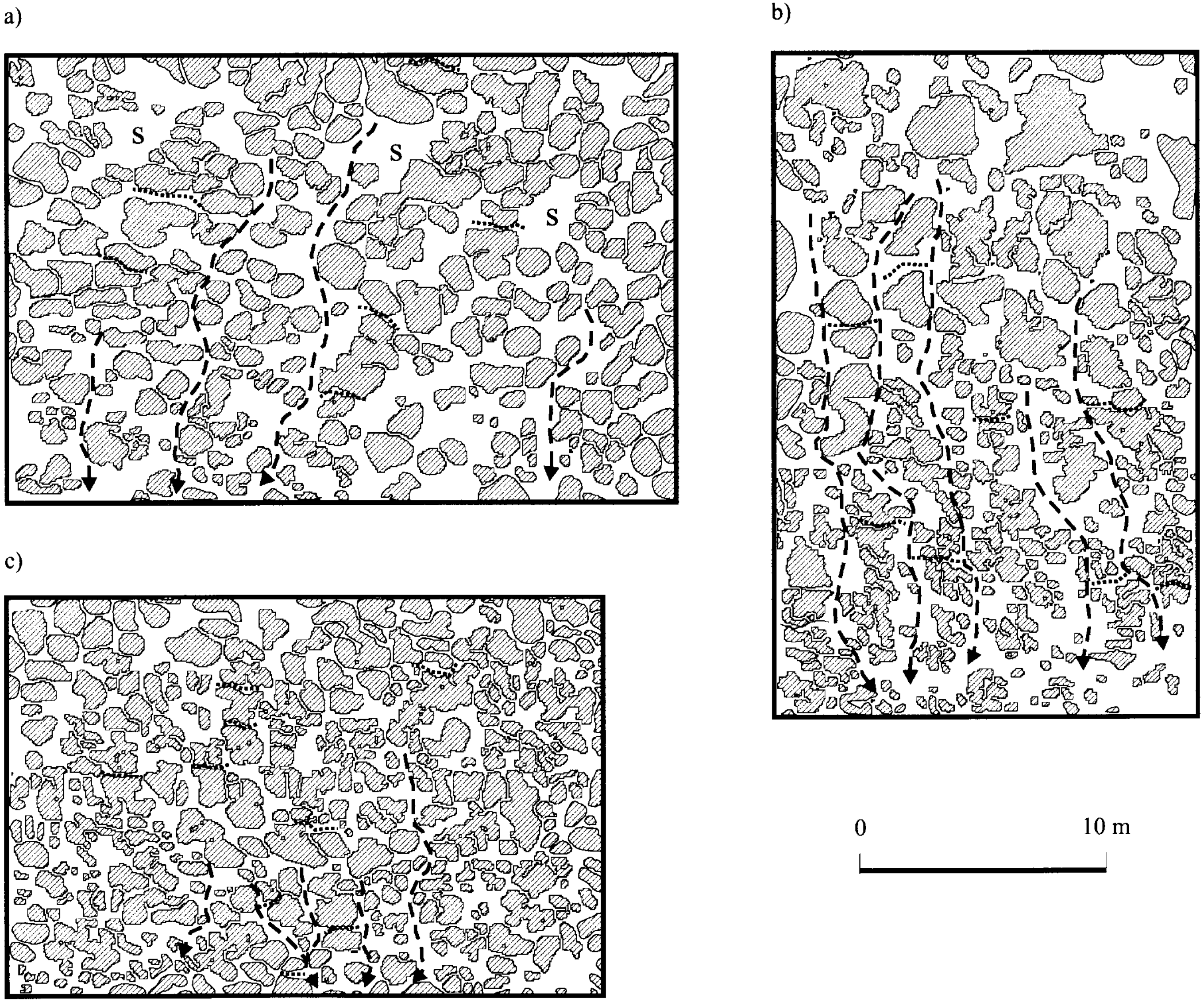

Figure 3 Classified images distinguishing the hummocks (striped) from the inter-hummock area for the (a) North, (b) Middle and (c) South Plots. The streambank is at the bottom of each image. Examples of primary (long dashes) and secondary (short dashes) channels are shown on each image. The letter S in (a) shows examples of large open areas, a type of secondary channel.

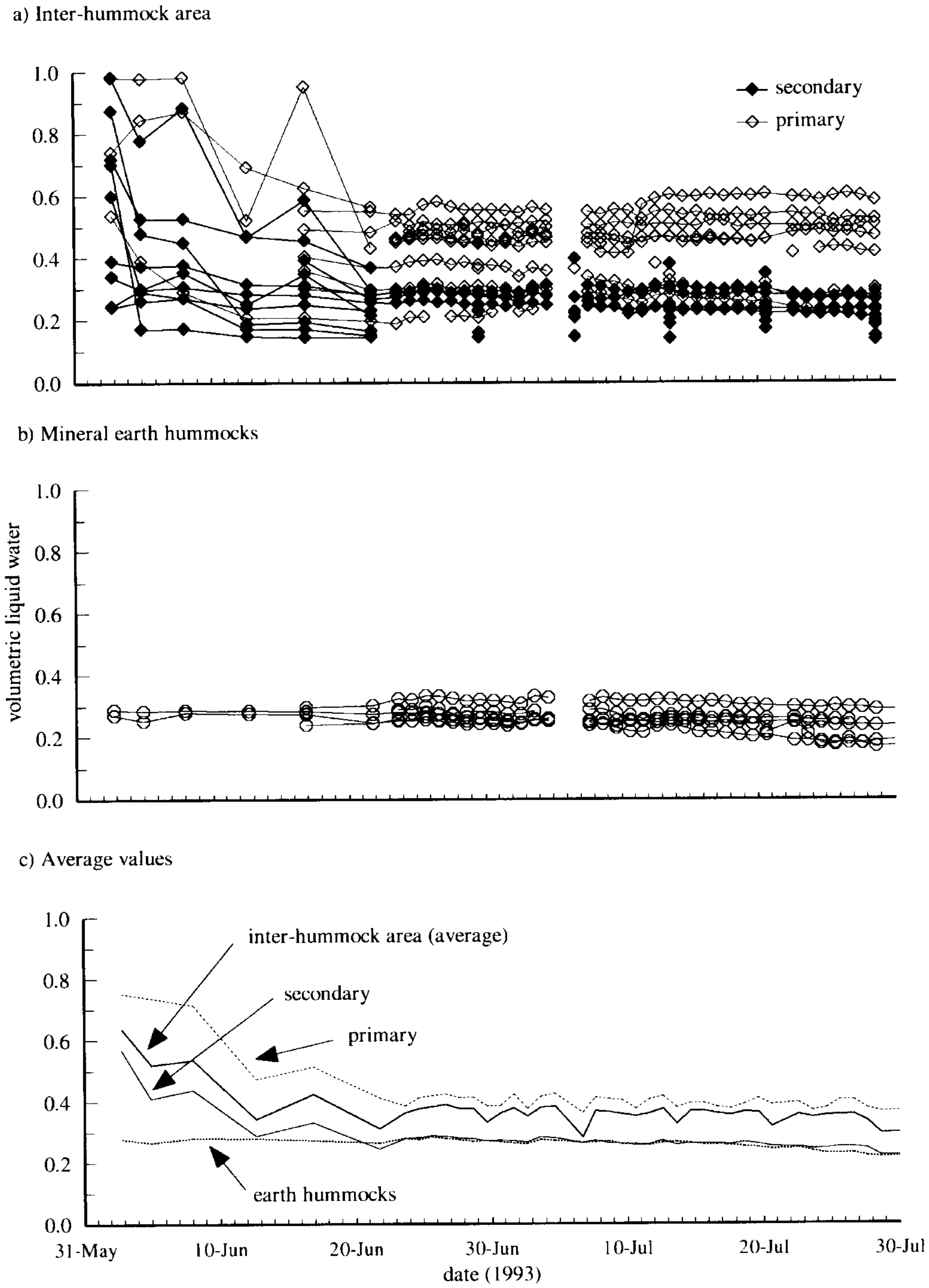

Figure 4 Variations in the liquid volumetric soil moisture with time in the 0 to 5 cm depth layer at fixed locations at the Middle Plot in 1993.

moisture and their role in hillslope drainage) only during periods of high hydrological input (i.e. snowmelt and large rain events).

The average soil moisture values of primary and secondary channels, the overall inter-hummock area and the hummocks are shown in Figure 4c.

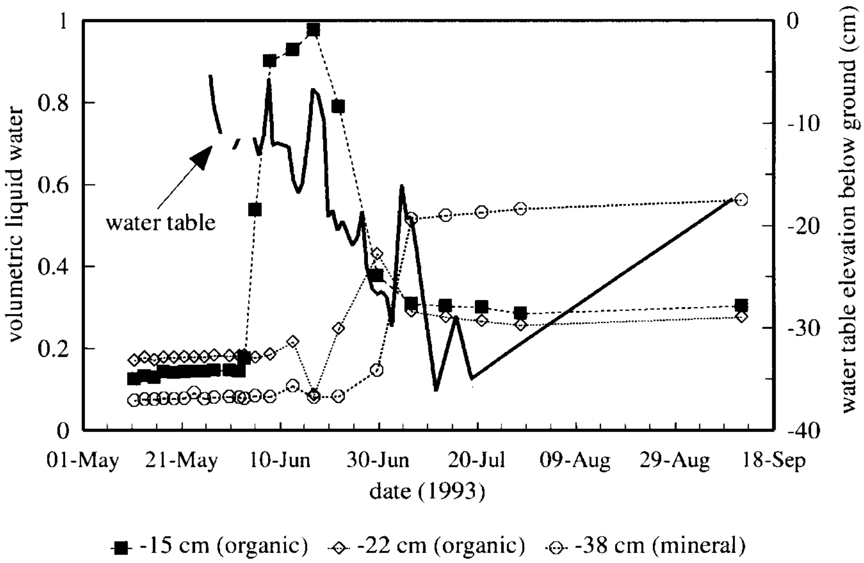

Figure 5 Variations in water table elevation and volumetric liquid soil moisture with time at 15, 22 and 38 cm below the surface at a point in the inter-hummock area of the Middle Plot in 1993.

Following the snowmelt runoff period, the average value of the secondary channels decreased to close to that of the hummocks, with a similar lack of fluctuation. The average soil moisture of the primary channels, however, remained relatively high, and continued to fluctuate, suggesting that primary channels maintain their viability as runoff-conducting channels throughout the thaw period. The soil moisture fluctuations in the primary channels are responsible for the fluctuations in the average soil moisture in the inter-hummock area after the snowmelt runoff period.

Figure 5 shows the fluctuations in the water table and in the liquid soil moisture at several depths below the ground surface of a secondary channel at the Middle Plot in 1993. The upper two measurement points were located in the organic accumulation at 15 and 22 cm depths. The 15 cm point was at the interface between the upper organic layer, composed of living and weakly decomposed peat, and the more humified subsurface organic layer. The 38 cm depth point was in the mineral substrate, just below the interface with the subsurface organic layer. The soil temperature at 15 cm below the ground rose above 0 °C by 1 June (Quinton, 1997). Figure 5 shows that the liquid soil moisture content at this depth responded to thawing by abruptly rising to near saturation within two days. By the time of the initial soil moisture rise at 15 cm, the area downslope of the drift had been snow-free for over a week, and the inter-hummock area was now receiving lateral inflows from the melting snow drift. By 30 June, both organic depths were above the water table. The convergence of soil moisture values for these two depths from this time onward suggests that the liquid soil moisture in the inter-hummock area does not change substantially with depth in the unsaturated layer. The soil moisture at 15 cm and 22 cm below the surface adjusted to ~0.3, the summer period value typical of secondary channels (Figure 4a). Shortly after 30 June, the frost table depth reached 38 cm. The measurement point at this depth responded by increasing to near-saturation, where it remained.

Obstruction to Drainage

Because of their low hydraulic conductivity, mineral earth hummocks obstruct drainage from hillslopes. Water is therefore forced to follow tortuous rather than direct routes to the streambank, which increases the travel time. The travel time to the streambank increases with the degree of channel tortuosity. For example, water flowing along an inter-hummock channel with a tortuosity of 1.5 would reach the streambank 1.5 times later than runoff water following a direct route. Increased travel time results in an increase in the lag between the time of hydrological input and the time of arrival at the streambank.

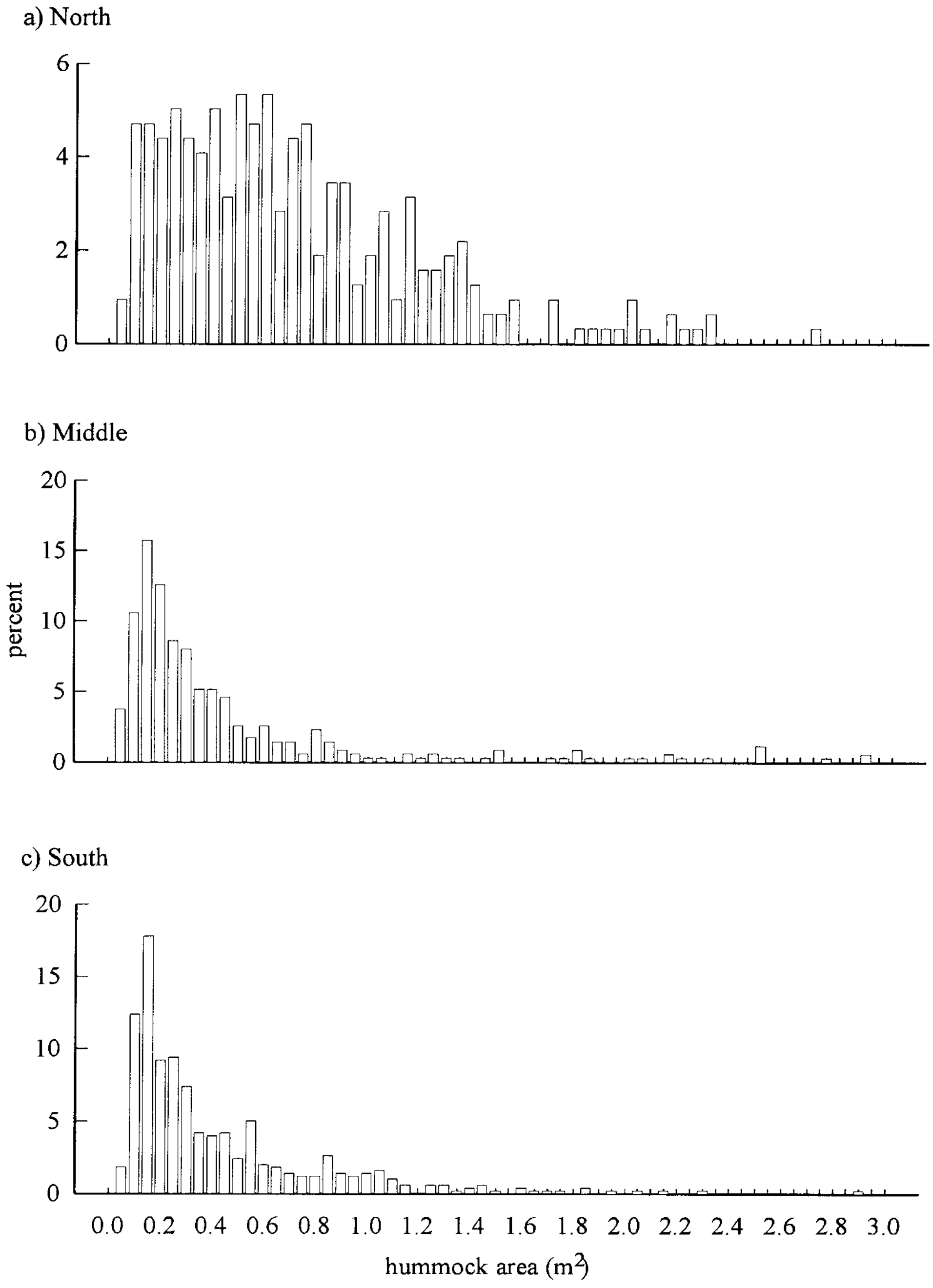

Figure 6 Frequency distribution of hummock areas determined from image analyses for the (a) North, (b) Middle and (c) South Plots.

The South Plot has the largest average tortuosity, and the Middle Plot the lowest (Table 1). Tortuosity is affected by hummock density (Table 1), the hummock size distribution (Figure 6) and the spatial arrangement of the hummock cover (Figure 3). Compared with the Middle Plot, the North Plot hummocks are on average larger and more widely spaced (Table 1). The distribution of hummock sizes at the North Plot (Figure 6a) is characterized by a broad range of well represented classes, rather than being dominated by relatively small hummocks, as at the other plots. At the Middle Plot, the hummocks occur in clusters oriented parallel to the slope, with intervening large primary channels that conduct runoff to the streambank with little obstruction by hummocks. Therefore, although the average hummock size is closer to the South than the North Plot value, tortuosity at the Middle Plot is the lowest among the plots. The North and South Plots have approximately the same percentage of their surfaces covered by hummocks (~50%), but the North Plot is characterized by a small number of large hummocks, and the South Plot by a large number of small hummocks (Table 1). Obstruction to flow resulting from the tortuosity of inter-hummock channels is therefore greater at the South Plot, where the hummock density is approximately twice that of the other plots. For hillslopes with roughly equally sized hummocks (e.g. Middle and South Plots), the hillslope with the greater hummock density (i.e. South Plot) would have greater channel tortuosity. Hillslope gradient appeared to affect the arrangement of hummocks in a way that influences the tortuosity of the inter-hummock channels. Tortuosity is relatively low at the Middle Plot, where the hillslope gradient is relatively high (Table 1). At the North Plot, the slope of the hillside and the channel tortuosity are intermediate (Table 1). The South Plot with the shallowest slope has the highest tortuosity (Table 1).

Attenuation

Hummocks attenuate hillslope drainage as a result of the hydraulic gradient between the hummocks and the inter-hummock area. Specifically, water flows into the hummocks during periods of high flow when the direction of the hydraulic gradient is toward the hummocks, and released back into the inter-hummock area during periods of low flow, when the direction of the hydraulic gradient is reversed. The process of attenuation reduces peak flows and increases low flows. If attenuation is large relative to the total amount of hillslope drainage, then the shape of subsurface discharge hydrographs observed at the streambank can be substantially altered.

Figure 7 shows water table depths measured at adjacent wells at the Middle Plot – one in an earth hummock, and the other approximately 1 m away in the inter-hummock area. The difference in hydraulic head between the two locations often exceeds 10 cm which, over the lateral distance between the two wells, gives a hydraulic gradient of >0.1. The overall decrease in the elevation of the water tables is due to drainage and active layer development. The snowmelt period is characterized by large fluctuations of the inter-hummock water table in response to the daily pulses of meltwater input from the late-lying drift upslope. For a period of approximately one week, immediately following snowmelt runoff, water drains from the hummocks back into the inter-hummock area. During

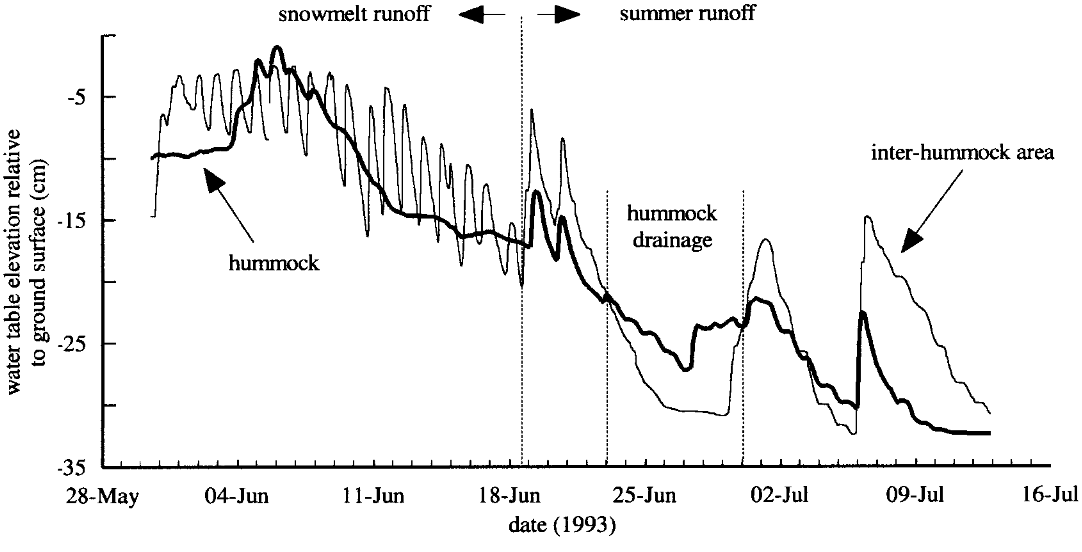

Figure 7 Continuous water table depth measurements at a hummock and inter-hummock site in 1994. The two records are referenced to a common elevation datum. Also shown is the approximate separation between the snowmelt runoff period and summer, when water table rises are generated by rainfall.

summer, the water tables often rise in response to large rain events.

Assuming that the hydraulic gradient between the hummocks and the inter-hummock area is equal among hillslopes, the potential for hydrological interaction between the two areas would be greater at hillslopes where the overall interface between the hummocks and inter-hummock areas is greater. The North Plot has the largest average hummock perimeter length (Table 1). However, the low number of hummocks at this plot reduces the total hummock perimeter, and as a result, the inter-hummock:hummock edge per unit area is low. Although the South Plot has the lowest average hummock perimeter, the large number of small hummocks and large total hummock perimeter at this plot result in a relatively large inter-hummock:hummock edge per unit area. As a result, the potential for flow attenuation by the hummocks is greatest at the South Plot.

The importance of runoff abstraction by the earth hummocks can be estimated by calculating the amount of water flowing into the hummocks, and comparing this flux to the amount of subsurface flow from the plot over the same period. The total amount of water Q_{H} entering the hummocks of the Middle Plot is estimated from the water table rise ΔH_{H}, the specific yield S_{Y} and the fractional area of the plot occupied by hummocks F_{H}:

$$Q_{\mathrm{H}} = \Delta H_{\mathrm{H}} S_{\mathrm{Y}} F_{\mathrm{H}}. \qquad (2)$$

Using the ΔH_{H} of 5 mm observed on 9 June (a value typical of the daily water table rises during the snowmelt period), a specific yield of 10% for material high in silt and clay (Dunne and Leopold, 1978) and the F_{H} of 0.38 for the Middle Plot (Table 1) gives a Q_{H} of 0.19 mm per unit slope area. With the total subsurface flow Q_{S} from the Middle Plot for this day of approximately 26 mm, Q_{H} is less than 1% of Q_{S}. Recalculation based on the few relatively large daily water table rises (e.g. 10–15 mm of 5–8 June) yields an abstracted amount that is less than 5% of the total subsurface drainage from the plot.

Although large gradients between hummock and inter-hummock areas can develop, hydrological interaction between hummocks and inter-hummock areas is limited by the very low hydraulic conductivity of the former. The amount of water entering hummocks as a percentage of the amount of water exiting the plot through subsurface channels would likely increase as the thaw season progresses, since the hydraulic gradient remains directed toward the hummocks for longer periods during summer (Figure 7). Moreover, in the summer period, the saturated layer in the inter-hummock area occupies a deeper position, where the hydraulic conductivity of the peat is orders of magnitude lower. The flow velocity through inter-hummock channels is therefore far lower than during the snowmelt runoff period, and as a result, the time available for seepage into the hummocks is lengthened.

Displacement of the Water Table in the Inter-Hummock Area

The much higher hydraulic conductivity of the inter-hummocks area enables lateral inputs (e.g. from the drift above the Middle Plot) to flow through the inter-hummock area at a rate much higher than the rate of seepage into the hummocks. Since only a small percentage of the lateral flow entering a plot seeps into the hummocks, the water table in the inter-hummock area is displaced upward. Water table displacement not only increases the hydraulic gradient between the hillslope and the stream channel, but also elevates the inter-hummock saturated layer into a zone where, depending upon the height of displacement, the hydraulic conductivity of the peat may be orders of magnitude higher. Water table displacement increases the flow velocity through inter-hummock channels, and as a result the subsurface discharge hydrographs observed at the streambank would have higher peaks and shorter lag times. The displacement height is a function of the proportion of the hillslope saturated layer occupied by the earth hummocks. For example, the water table at the North and South Plots, where hummocks occupy ~50% of the hillslope surface, would be displaced further than at the Middle Plot, where hummocks occupy only ~38% of the surface (Table 1).

The increase in the water table elevation in the inter-hummock area $\Delta H_{\mathrm{I\text{-}H}}$ produced by a unit input of runoff water to a plot can be calculated from

$$\Delta H_{\mathrm{I\text{-}H}} = \frac{1}{(1 - F_{\mathrm{H}})S_{\mathrm{Y}}}. \qquad (3)$$

F_{H} is the volume fraction of the saturated layer of the plot occupied by hummocks (assumed to be equal to the percentage of the surface area occupied by hummocks: Table 1), and S_{Y} is the specific yield of the peat over the depth of the water

Table 2 Changes in the elevation of the water table in the inter-hummock area $\Delta H_{\text{I-H}}$ in response to a unit input of runoff water, calculated for different values of F_{H}.

F_{H}	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
$\Delta H_{\text{I-H}}$	3.7	4.1	4.6	5.3	6.2	7.4	9.25	12.3	18.5

table rise. Equation (3) assumes that flow between the hummocks and the inter-hummock area is negligible, a valid assumption for short periods, such as the daily runoff cycles of the spring melt period (Figure 7).

In calculating $\Delta H_{\text{I-H}}$ for a range of values of F_{H} (Table 2), a constant S_{Y} of 0.27 was used, the average of the depth-integrated S_{Y} values of the ten peat cores ($\sigma = 0.05$). For a hillside with no hummocks, $(1 - F_{\text{H}}) = 0$, the height of the water table rise is equal to the inverse of the specific yield. Using the F_{H} value of 0.38 for the Middle Plot (Table 1) and a water input of 1 cm, $\Delta H_{\text{I-H}}$ is 5.9 cm. Recalculating with $F_{\text{H}} = 0.5$, a value characteristic of the North and South Plots, increases $\Delta H_{\text{I-H}}$ to 7.4 cm, suggesting that an increase in the hummock cover of 12% would displace the water table in the inter-hummock area an additional 1.5 cm. The proportion of hillslope surfaces occupied by hummocks ranges approximately between 30% and 70% at Siksik Creek. This suggests that water table displacement as a function of the percentage of the surface covered by hummocks ranges approximately between 5.3 cm ($F_{\text{H}} = 0.3$) and 12.3 cm ($F_{\text{H}} = 0.7$) for a 1 cm input of water. It is recognized that using a single value of S_{Y} for the entire peat depth is a simplification, since it has been demonstrated that S_{Y} can be as much as four times higher near the surface than in the basal peat (Verry and Boelter, 1978). Therefore, by using the constant value for S_{Y} in equation (3), $\Delta H_{\text{I-H}}$ would be underestimated when the water table is deep in the profile, and overestimated when it is near the surface.

The impact of a water table rise on the subsurface flow velocity through inter-hummock channels depends upon the water table elevation prior to displacement, owing to the increasingly abrupt rise in hydraulic conductivity with elevation in the peat profile. When the water table is close to the surface (i.e. within ~15 cm), a water table rise of 1.5 cm can be sufficient to increase the hydraulic conductivity at the top of the saturated layer by an order of magnitude. When the water table is deeper (e.g. during summer), the impact of a 1.5 cm rise in water table on the hydraulic conductivity would be relatively small.

THE OVERALL INFLUENCE OF HUMMOCKS ON HILLSLOPE DRAINAGE

The tortuosity coefficient T_{X}, the inter-hummock: hummock edge per unit area, and the percentage of the hillslope surface covered by hummocks are qualitative indices of obstruction, attenuation, and water table displacement respectively. The variation among the plots in the values of each index is shown in Table 3. The importance of obstruction of flow by hummocks is relatively minor since obstruction effectively increases channel length by a factor proportional to T_{X}, which is usually less than 1.5. Consequently, the lag time of runoff reaching the streambank would increase by a factor of < 1.5. As demonstrated above, during high flow periods, the amount of water seeping into hummocks is low compared with the amount of subsurface flow from the hillside. However, the importance of flow attenuation by hummocks increases during periods of low flow, when the saturated layer in the inter-hummock area is deeper. Water table displacement is important when the water table is close to the surface (0–15 cm) since the rate of subsurface flow to the stream could increase substantially (depending on the magnitude of the displacement) owing to

Table 3 Comparison of the impacts of water table displacement, obstruction and attenuation of flow by hillslope hummocks using indices representing these factors.

Impact	Index	North	Middle	South
Obstruction	Average T_{X} of inter-hummock channels	1.282	1.219	1.327
Attenuation	Inter-hummock : hummock edge per m^2 (m)	2.17	2.10	3.19
Displacement	Percentage of plot surface occupied by earth hummocks	48.3	38.1	51.2

order of magnitude increases in the hydraulic conductivity of the saturated layer as the water table rises. This is not to suggest that hillslopes of equal percentage hummock coverage would necessarily have equal drainage rates. If two hillslopes of equal percentage hummock cover are compared, where one contains a large number of small hummocks (high hummock density) and the other a small number of large hummocks (low hummock density), the inter-hummock channels of the former would be more tortuous, and as a result the arrival of subsurface flow at the bottom of the slope would be delayed relative to the other hillslope.

At the North Plot, the overall influence of the hummocks is to enhance hillslope drainage, since the percentage hummock cover is relatively high, the T_x value is intermediate, and the inter-hummock : hummock edge per unit area is relatively low. This is supported by Figure 8a which shows that at the North Plot, the water table falls more abruptly than at the other plots. The Middle Plot is least affected by hummocks, since the values for hummock cover, channel tortuosity and inter-hummock:hummock edge per unit area are the lowest among the plots. The higher water table at this plot during the spring (Figure 8b) was maintained by meltwater inputs from the late-lying drift upslope. At the South Plot, where the tortuosity and inter-hummock:hummock edge per unit area are substantially higher than at the other plots, the hummock cover imposes the greatest resistance to hillslope drainage. Figure 8c demonstrates that the water table at the South Plot remained close to the surface for the longest period, in spite of the hillslope gradient being similar to the North Plot (Table 1).

SUMMARY AND CONCLUSIONS

The relatively low hydraulic conductivity of mineral earth hummocks promotes preferential flow through the inter-hummock area where subsurface flow occurs through primary and secondary channels. Primary channels maintain an elevated near-surface moisture condition, and therefore remain primed as runoff pathways. Hummocks offer resistance to hillslope drainage by obstructing flow, which results in tortuosity of inter-hummock channels, and by attenuating flow owing to hydraulic gradients between the hummocks and the inter-hummock area. Hummocks enhance hillslope drainage by displacing the water table in the inter-hummock area upward to an elevation where the hydraulic conductivity can be orders of magnitude higher.

The overall impact of mineral earth hummocks on hillslope drainage depends upon the spatial arrangements of hummocks, which varies among hillslopes, and upon hydrological conditions, which vary with time as the thaw layer deepens. Tortuosity increases with increasing hummock number and density and decreasing hummock size. However, obstruction is also affected by the arrangement of hummocks. At the Middle Plot, where the hummocks occur in clusters oriented parallel to the slope, the tortuosity of inter-hummock channels is low. Attenuation of flow by the hummock cover increases with increasing inter-hummock:hummock edge per unit area, and with increasing hydraulic gradient toward the hummocks. Increases in subsurface flow velocity resulting from displacement of the water table into peat of higher hydraulic conductivity, increases with the proportion of the plot occupied by hummocks.

At the North Plot, the hummocks enhance hillslope drainage, since the percentage hummock cover is relatively high, T_X is intermediate, and the inter-hummock:hummock edge per unit area is relatively low. The Middle Plot is least affected by hummocks, since the values for the percentage hummock cover, T_X, and the inter-hummock: hummock edge per unit area are the lowest among the plots. At the South Plot, the hummock cover resists hillslope drainage since T_X and the inter-hummock:hummock edge per unit area are substantially higher than at the other plots.

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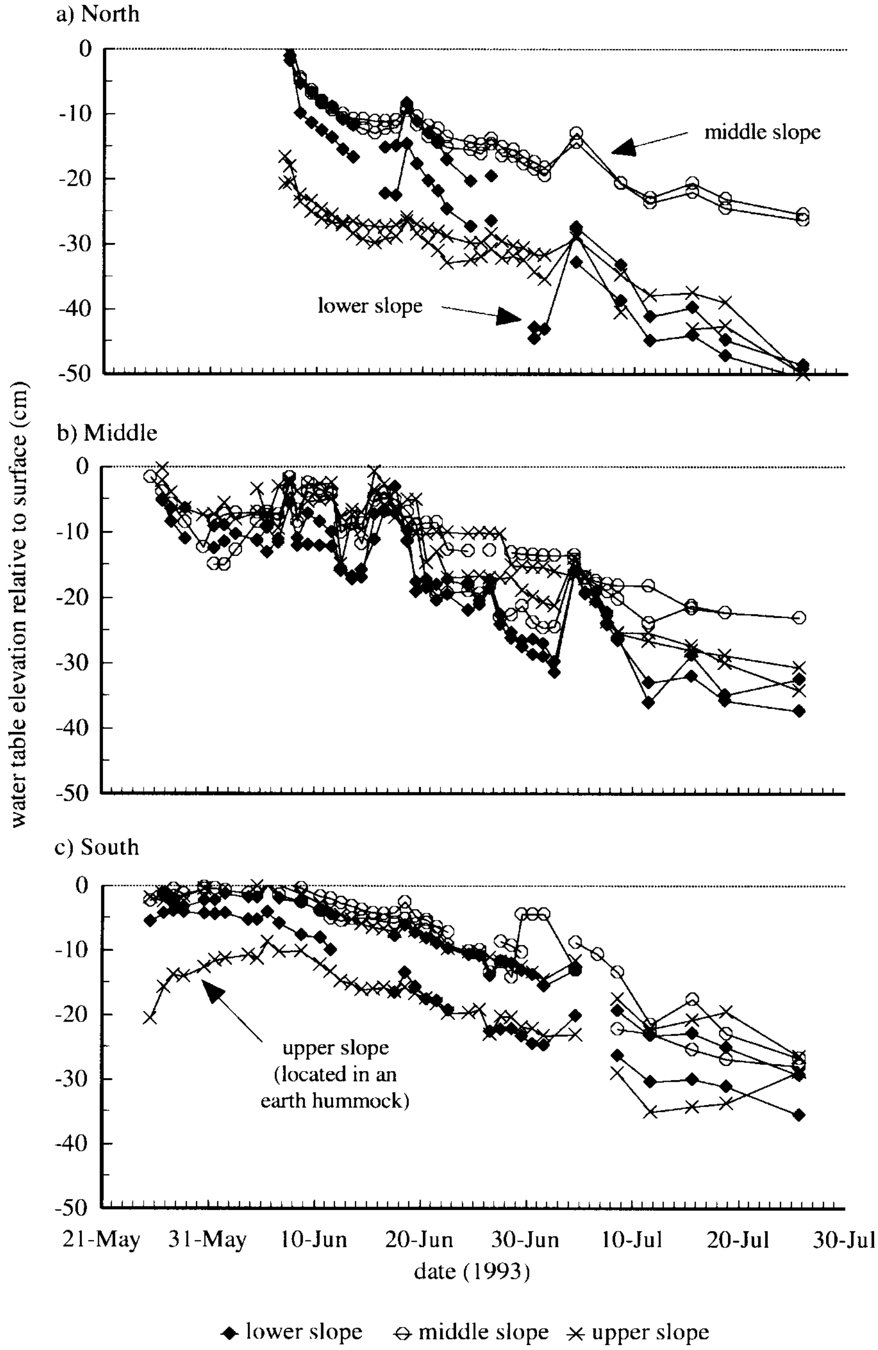

Figure 8 Water table depth below the surface at the lower, middle and upper hillslope positions at each plot in 1993.

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