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# Image analysis and water tracing methods for examining runoff pathways, soil properties and residence times in the continuous permafrost zone

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**Abstract** This paper integrates remote sensing and a tracer technique with existing information obtained from hydrometric measurements in order to improve the understanding of soil properties, runoff pathways and residence times on arctic tundra hillslopes in the continuous permafrost zone. Low altitude aerial photographs were analysed in order to quantify physical attributes of earth hummocks. These images were also used in a particle tracking procedure to determine the average tortuosity of inter-hummock channels. Image analysis was also conducted at a much smaller scale on thin sections extracted from soil cores to determine changes in physical properties with depth. Tracer experiments were repeated several times to determine the residence times for different saturated layer elevations. The subsurface drainage efficiency depends upon the physical attributes of the hummock cover, due to the influence of these attributes on the tortuosity of inter-hummock channels. The variations of the total and active porosity, and pore size with depth in the peat are important variables governing residence times, due to their impact on the hydraulic conductivity. Average residence times increased from ~0.3–0.5 day to as high as ~38 days, as the saturated layer subsided into increasingly decomposed peat.

## INTRODUCTION

Mineral earth hummocks, the most widely occurring form of patterned ground in the permafrost areas of the world (MacKay, 1980), segregate hillsides into areas where mineral soil is at or close (<5 cm) to the ground surface, and inter-hummock areas where the mineral soil is overlain by ~15 to 50 cm of peat. Since the rate of infiltration into the unfrozen organic material far exceeds that of the underlying (often frozen) mineral soil, the organic layer remains saturated during most of the year (Slaughter & Kane, 1979). Subsurface flow is the dominant mechanism of runoff to the stream channel (Quinton & Marsh, 1998) and this flow is conveyed predominantly through the peat in the inter-hummock area due to its relatively high hydraulic conductivity (Quinton & Marsh, 1998). In the inter-hummock area, the hydraulic conductivity decreases abruptly with depth as the degree of decomposition increases (Quinton & Marsh, 1998). Yet little is known about spatial and temporal variations of hillslope drainage rates in this environment. This paper combines the use of image analysis and tracers in order to determine the residence time of subsurface drainage on arctic tundra hillslopes, and how this varies with different hummock cover characteristics, and over time as the elevation of the saturated layer changes. An improved understanding of the spatial and temporal variation of residence time would improve water balance estimates, and improve our ability to determine the impact of the hillslope runoff process on stream-water chemistry, based on the time available for geochemical interaction on hillslopes.

## STUDY SITE

Data were collected from Siksik Creek (68°44'N, 133°28'W), located approximately 55 km north-northeast of Inuvik, NWT, Canada, on the Mackenzie River. Siksik Creek is in the zone of continuous permafrost (Heginbottom & Radburn, 1992), and at the northern fringe of the forest–tundra transition zone (Bliss & Matveyeva, 1992). Siksik Creek has a drainage area of ~95.5 ha, with elevations ranging between approximately 60 and 100 m a.s.l. The climate is characterized by short, cool summers and long cold winters, with an eight-month snow-covered season (Environment Canada, 1982). The mean annual air temperature is –9.8°C at Inuvik and –10.9°C at Tuktoyaktuk. In this region, the mean daily temperature rises above 0°C in June, and falls below 0°C in October. The mean total annual precipitation is 266 mm (Inuvik) and 138 mm (Tuktoyaktuk), with the proportion of the total annual precipitation that falls as snow being approximately 60% (Inuvik) and 40% (Tuktoyaktuk). Maximum observed active layer depths range between 0.4 and 0.8 m depending on aspect and soil type. The ground surface at Siksik Creek is dominated by mineral earth hummocks, composed of fine-grained material, with the clay content often exceeding 50% (Quinton & Marsh, 1998). Their surfaces which are bare or support a thin layer of lichen, are between 40 and 100 cm in diameter, and have crests rising between 10 and 40 cm above the surrounding inter-hummock surface.

## METHODS

Field data were collected between May and early August in 1993 and 1994 on the west side of Siksik Creek at three small (~1000–2000 m$^2$) study plots: the North, Middle and South plots.

### Image analysis

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. *PCI* software was used to quantify attributes of the hummock cover on each image.

For each plot, a single rasterized image composed of cells representing an area of approximately 3 cm × 3 cm on the ground surface, was used in a particle tracking procedure to estimate the average tortuosity of the inter-hummock channels from:

$$T_X = \frac{L_F}{L_S} \qquad (1)$$

where the tortuosity ($T_X$) is the ratio of the length of the flowpath ($L_F$) followed by runoff water from any point on the hillslope to the stream bank, to the length of the straight line route from the same starting and ending points ($L_S$). $L_F$ is determined by summing the number of cells encountered during a particle tracking run. This 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 size and distribution of their hummocks. Particle tracking runs were repeated 50 times for each image, from which average values of $T_X$ were obtained.

During each particle tracking run, a hypothetical water particle was moved cell by cell through the inter-hummock area, in the downslope or lateral directions (i.e. not upslope or diagonally). The cells along the uppermost row were numbered, and the starting cell was determined by random number generation. If the starting cell was not within the inter-hummock area, random numbers were drawn until one was. When a hummock cell was encountered (either immediately below the starting cell or following downslope movement), a lateral flow direction was determined by the generation of a random number between 0 and 1: >0.5 = left turn, <0.5 = right turn. Lateral flow continued until the active cell was above a cell in the inter-hummock area, at which time downslope flow resumed. If lateral flow resulted in exit from the image, the particle tracking run was terminated, and a new simulation begun. The simulation was completed once downslope flow resulted in exit from the image.

An image analysis technique was also applied at a smaller scale to determine changes in physical properties of peat with depth. Thin sections (~100 microns thick) sampled from peat cores were prepared and photographed for measurement of active porosity (the proportion of the total peat pore volume that actively transmits water: Romanov, 1968) and pore diameters were measured using *Mocha* image analysis software. This involved determining the percentage void space (interparticle pores) on five representative 1 $cm^2$ windows at each sampling depth. An average active porosity value for each depth was then calculated. *Mocha* was also used to measure the diameter of interparticle pores that were intersected by a transect consisting of a single row of pixels. The diameters of between 100 and 150 pores were measured along five evenly-spaced transects at each depth. The resolution of the images prevented detection of pores with diameters less than approximately 16 μm for both the active porosity and pore diameter measurements.

## Tracer tests

Tracer tests were conducted at the Middle Plot in 1993, and the North and South plots in 1994. Approximately 80 litres of KCl solution (~100 mg $l^{-1}$ of $Cl^{-1}$) were poured onto the peat surface along a line which crossed the plots ~10 m upslope of the stream bank. Tracer concentrations were monitored with chloride-sensing micro electrodes (Fig. 1) (Farrell *et al.,* 1991), placed between 5 and 10 m downslope of the tracer application line, and connected to a *Campbell Scientific* 21X data logger for continuous measurement. The electrodes were relatively inexpensive to produce (<$10.00 Canadian, per electrode), and as a result, the number of electrodes deployed at each plot (a maximum of eight) was limited only by the number of electrical ports on the dataloggers. The tracer tests were repeated as the saturated layer lowered in

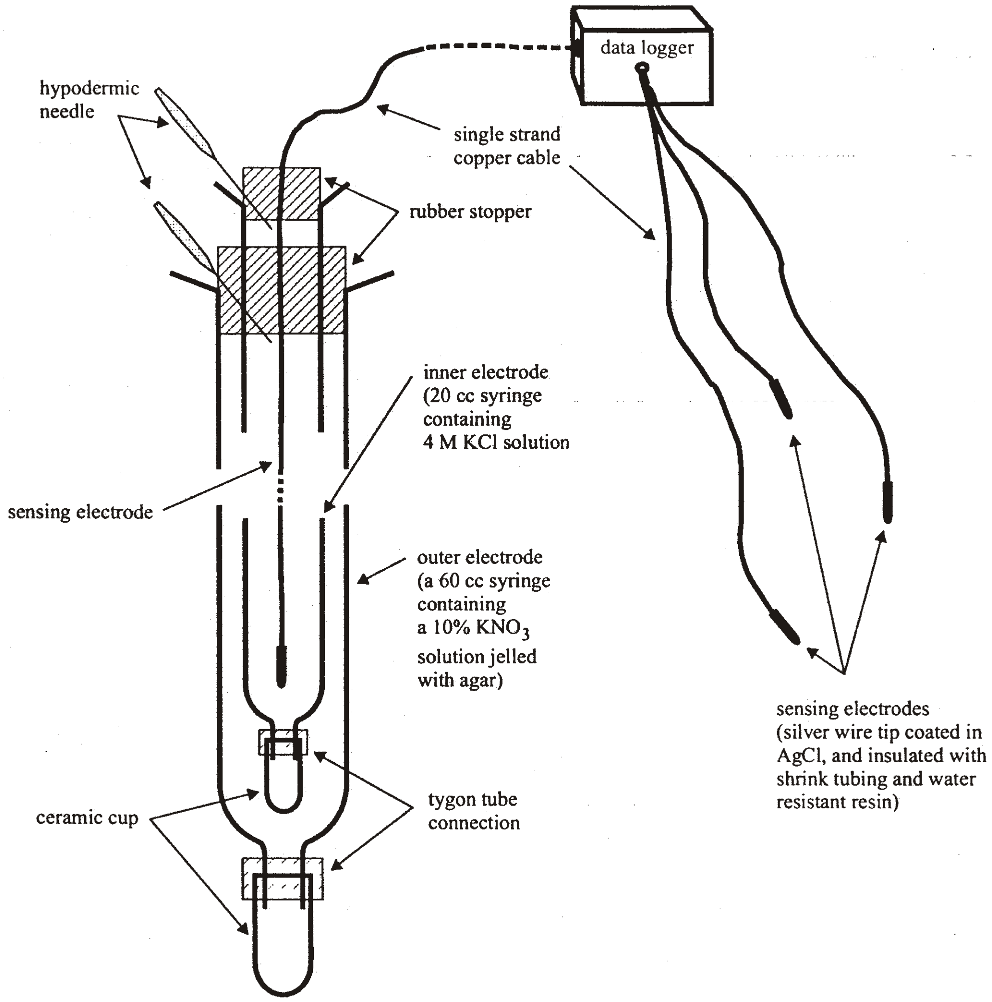



**Fig. 1** A schematic diagram showing the major components of the electrodes used to sense tracer concentrations on the hillslope plots.

response to drainage and thaw layer deepening. This enabled estimates of the residence time of the water draining through the inter-hummock channels for different saturated layer elevations. Prior to each test, therefore, the depth of each sensor was adjusted to the middle of the saturated layer.

## RESULTS AND DISCUSSION

### Image analysis of hillslope surfaces

The efficiency of the inter-hummock drainage network depends upon the physical attributes of the hummock cover (Table 1). Although the North and South plots have approximately the same proportion of their surface covered by hummocks (~50%), the hummocks at the North Plot are relatively few in number, and relatively large, resulting in a low hummock density. By contrast, the South Plot has a large number of small hummocks, and a relatively dense hummock cover. On average, the hummocks at the Middle Plot are similar in size to those at the South Plot, but since only ~38% of the Middle Plot surface is occupied by hummocks, the hummock density is relatively low. The average tortuosity is lowest at the Middle Plot, where the percentage of the surface covered by hummocks, the average hummock size, and the hummock density are relatively small.

**Table 1** Hillslope and hummock cover characteristics at the North, Middle and South plots determined from analysis of low altitude aerial photographs.

| Variable | North Plot | Middle Plot | South Plot |
|---|---|---|---|
| Image area ($m^2$) | 489.22 | 455.07 | 388.49 |
| Average hummock area ($m^2$) | 0.74 | 0.50 | 0.40 |
| Hummock cover (%) | 48.3 | 38.1 | 51.2 |
| Hummock density ($m^{-2}$) | 0.65 | 0.77 | 1.29 |
| Slope angle ($m\ m^{-1}$) | 0.042 | 0.085 | 0.035 |
| Average tortuosity ($T_X$) | 1.28 | 1.22 | 1.33 |
| Maximum, minimum $T_X$ | 1.43, 1.09 | 1.33, 1.04 | 1.45, 1.13 |

## Image analysis of soil samples

Figure 2(a) shows total porosity for three inter-hummock area peat profiles, and the active porosity for two of them. The active porosity near the surface approaches 0.8, but decreases to as low as 0.5, while total porosity decreased only slightly with depth. The more abrupt decrease in the active than total porosity, suggests an increased proportion of closed and dead end pores at depth. The cumulative distribution of pore diameters for selected depths (Fig. 2(b)) shows that the proportion of small pores increases with depth. The decrease in the geometric mean pore diameter with depth results from the increasing state of decomposition and compaction. These variations in

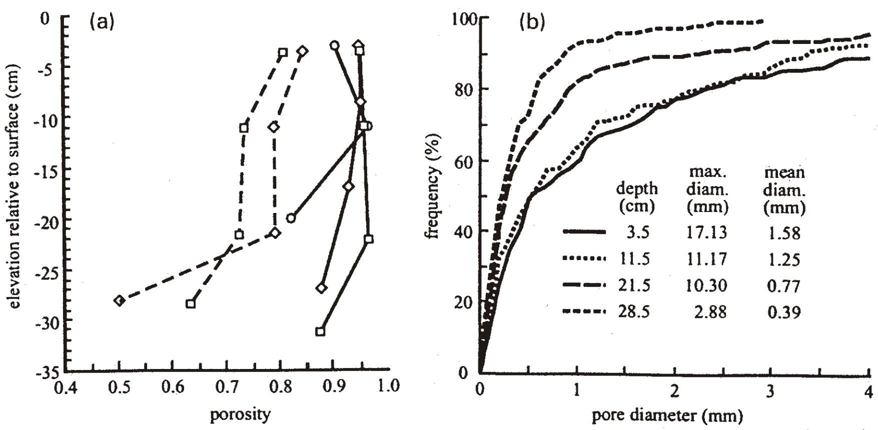



**Fig. 2** (a) Changes in total (solid lines) and active (dashed lines) porosity for peat cores: 1 (circles), 2 (diamonds) and 3 (squares). (b) Cumulative frequency distribution of pore diameters at 3.5, 11.0, 21.5 and 28.5 cm below the surface for pores less than 4 mm diameter.

physical properties are likely very important to the residence times of water in the inter-hummock channels, due to the impact of these properties on the hydraulic conductivity. For example, Quinton & Marsh (1998) reported that the saturated hydraulic conductivity of the peat at the study site decreases by two to three orders over a ~20 cm increase in depth.

### Tracer tests on hillslope plots

The average residence time of water draining through inter-hummock channels was calculated from:

$$T_R = \frac{t_C}{L_X \cdot T_X} \tag{2}$$

where $t_C$ is the length of time between the application of the tracer and the time when the centre of mass of the tracer plume reached the sensing location, and $L_X$ is the straight line distance between the tracer application and sensing locations. This yields an expression with units T $L^{-1}$, which when multiplied by the distance between the application line and the stream-bank yields an estimate of the residence time for individual inter-hummock channels.

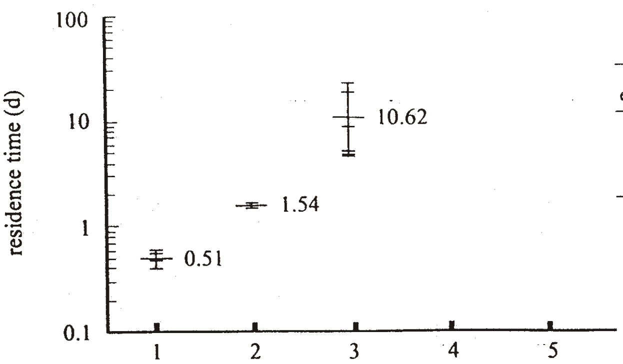
Figure 3 shows the range in residence times for different saturated layer positions at each plot. The residence time on hillslopes increased as the saturated layer subsided with time into peat of lower hydraulic conductivity. At each plot, the average residence time for the initial saturated layer position was in the range ~0.3–0.5 day. At the Middle Plot, the average residence time increased by 2 orders of magnitude between the highest and lowest saturated layer elevation. The higher rate at which residence times increased at the North and South plots resulted from the more abrupt decrease in the water table elevation. The water table remained high at the Middle Plot for an extended period due to the presence of a melting, late-lying drift upslope of that plot.

Spatial variations in residence time among hillsides result from differences in their slope angles and the tortuosity of their inter-hummock channels. Residence times increase with increasing tortuosity since water is forced to follow more tortuous, and therefore longer flow routes to the stream bank. For example, water flowing along an inter-hummock channel with a tortuosity of 1.5 would reach the stream bank 1.5 times later than runoff following a direct route. For similar saturated layer positions among the plots, residence time is lowest at the Middle Plot where the slope angle is highest and the average tortuosity is lowest (Table 1). Although for the initial saturated layer position, the average residence times were similar among the plots, by the second position, the average residence time was highest at the South Plot where the tortuosity is highest and the slope angle is lowest.

## EVALUATION OF TECHNIQUES

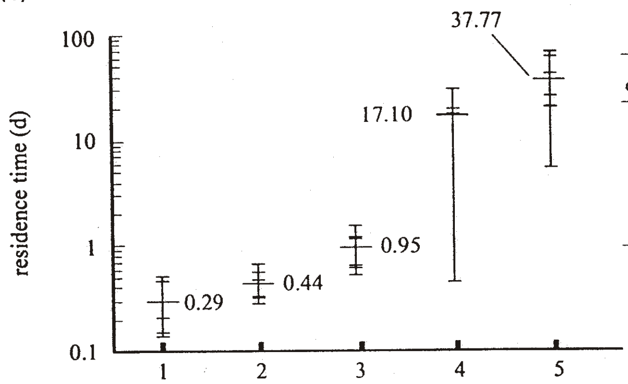
Through the combined use of image analysis and tracing, this paper defined residence times of subsurface drainage for arctic tundra hillslopes with different hummock cover characteristics, and how these values change with time for different saturated layer elevations.

(a) North Plot



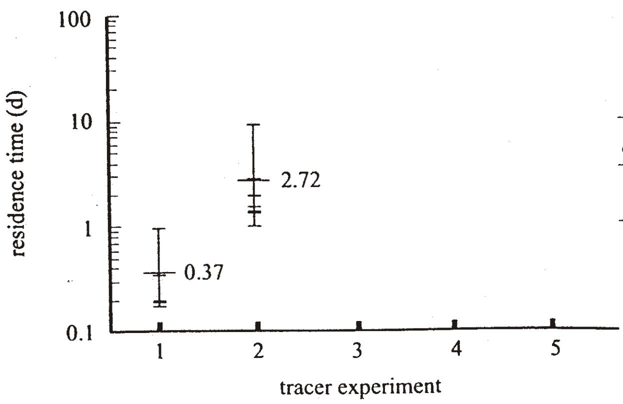

| tracer experiment | date | water table depth (cm) | frost table depth (cm) |
|---|---|---|---|
| 1 | 23 May/94 | 6.7 | 8.7 |
| 2 | 02 Jun/94 | 13.8 | 16.8 |
| 3 | 09 Jun/94 | 15.1 | 18.6 |

(b) Middle Plot




| tracer experiment | date | water table depth (cm) | frost table depth (cm) |
|---|---|---|---|
| 1 | 02 Jun/93 | 7.7 | 11.7 |
| 2 | 09 Jun/93 | 6.5 | 13.3 |
| 3 | 18 Jun/93 | 7.0 | 16.8 |
| 4 | 05 Jul/93 | 15.5 | 25.6 |
| 5 | 30 Jul/93 | 26.2 | 38.3 |

(c) South Plot




| tracer experiment | date | water table depth (cm) | frost table depth (cm) |
|---|---|---|---|
| 1 | 02 Jun/94 | 6.9 | 11.1 |
| 2 | 09 Jun/94 | 6.7 | 16.3 |

**Fig. 3** Residence times calculated for each monitored inter-hummock channel at the North (a), Middle (b) and South (c) plots. The average residence times (days) are given. The position of the saturated layer for each tracer experiment as defined by the depth of the water table and frost table below the ground surface is shown on the tables to the right of each graph.

Image analysis was used at the scale of the hillslope plots to quantify surface characteristics including the tortuosity of inter-hummock channels from a particle tracking procedure. Image analysis was also used at the scale of soil thin sections for analysis of porous media properties that control subsurface flow rates.

The relatively low cost of producing the chloride-sensing micro electrodes enabled the deployment of a large number of them on the hillslopes. Since they provide continuous measurements, water sampling and subsequent analysis was not necessary. During the study periods, neither the reference nor the sensing electrodes required maintenance, and by the end of the study, the electrodes showed very little drift from their initial calibrations. Under certain conditions however, the electrodes did not perform well. For example, erroneous readings occurred when the electrodes were exposed to sunlight (since their tips are coated with silver chloride), frozen into the ground, or when the soil around the sensor fell below saturation for an extended period (hours). The limited occurrence of these conditions resulted in only minimal disruption to the tracer monitoring programme.

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