Recent Advances Toward Physically-based Runoff Modeling of the Wetland-dominated, Central Mackenzie River Basin

W.L. Quinton[1] and M. Hayashi[2]

[1]Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON, N2L 3C5
[2]Geology and Geophysics, University of Calgary, Calgary, AB, T2N 1N4

Corresponding author: W.L. Quinton
Tel. 519-884-0710 (ext.3281)
Fax. 519-725-1342
Email: wquinton@wlu.ca

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Abstract

Field studies were initiated in 1999 at Scotty Creek in central Mackenzie River Basin to improve understanding and model-representation of the major water flux and storage processes within a wetland-dominated zone of the discontinuous permafrost region. Four main topics were covered: (1) the major peatland types and their influence on basin runoff, (2) the physical processes governing runoff generation, (3) how runoff processes observed at the hillslope scale relate to basin-scale runoff, and (4) the water balance of Scotty Creek and its adjacent basins. A conceptual model of runoff generation was developed that recognizes distinct hydrologic roles among the major peatland types of flat bog, channel fen and peat plateau. This model contributes to resolving some of the difficult issues in the hydrologic modeling in this region, especially in relation to the storage and routing functions of wetlands-dominated basins underlain by discontinuous permafrost.

1. Introduction

Wetland-dominated terrain underlain by discontinuous permafrost covers extensive parts of northern North America and Eurasia. The hydrologic response of these areas is poorly understood, in large part due to the lack of study on the hydrologic functioning of the major wetland types, and the interaction among them. Near the center of the Mackenzie River Basin is an extensive area (*ca*. 53,000 km^2) of flat organic terrain with a high density of open water and wetlands, in the continental boreal region and the zone of discontinuous permafrost (Hegginbottom and Radburn 1992). With a limited understanding of the processes governing the cycling and storage of water in this region, attempts to model basin runoff have been met with limited success (Stewart et al. 1998). Discontinuous permafrost terrain is particularly sensitive to the effects of climatic warming, and pronounced changes in water storage and runoff pathways are expected with only small additional ground heating (Rouse 2000). Improved process understanding and description will reduce the uncertainty regarding future runoff production from wetland-dominated basins in the zone of discontinuous permafrost.

2. Methods

2.1. Field studies

Wetlands occupy approximately 125×10^3 km^2 or 7% of the Mackenzie River Basin and are concentrated mainly in the Peace-Athebasca lowlands, the Mackenzie River delta and the lower Liard River valley. Scotty Creek (61° 18'N; 121°, 18'W) lies in the lower Liard River valley, 50 km south of Fort Simpson (Fig. 1a) in discontinuous permafrost. The wetlands of Scotty Creek are typical of the ‘continental high boreal’ wetland region (NWWG 1988).

The Fort Simpson region is characterised by a dry continental climate, with short summers, and long cold winters. It has an average (1971–2000) annual air temperature of -3.2° C, and receives 369 mm of precipitation annually, of which 46% is snow (MSC 2002). Snowmelt usually commences in the second half of March and continues throughout most of April so that by May, only small amounts of snow remain (Hamlin et al. 1998). Field measurements were taken at four gauged basins (Fig. 1b). At the Jean-Marie, Blackstone and Birch Rivers, measurements were limited to discharge at the basin outlets, aerial reconnaissance and ground verification surveys. Most fieldwork was conducted at Scotty Creek because it contains the major ground cover types found in the region, and was logistically manageable given its relatively small (152 km^2) size and proximity to Fort Simpson.

The stratigraphy in this region includes an organic layer of up to 8 m in thickness overlying a silt-sand layer, below which lies a thick clay to silt-clay deposit of low permeability (Aylesworth and Kettles 2000). Field reconnaissance at Scotty Creek revealed three major peatland types: peat plateaus, ombrotrophic flat bogs and channel fens (Quinton et al. 2003; Robinson and Moore 2000). These peatlands support a diverse vegetation community that includes four tree species (*Picea mariana, Larix laricina, Pinus contorta, Betula papyrifera*), fifteen shrub species (predominantly *Betula, Ledum, Kalmia and Salix*), sixteen species of lichen (predominantly *Cladina*), thirteen species of bryophytes (predominantly *Sphagnum*), in addition to species of vine, club-moss, fungi, liverwort, sedges, grasses, aquatic plants, horsetails and wild flowers. Peat plateaus are underlain by permafrost, and their surfaces rise 1 to 2 m above the surrounding bogs and fens. *Picea mariana* is the principal tree species, but *Pinus contorta* and *Betula papyrifera* are also present. Shrubs are most abundant on peat plateaus; and lichen species dominate the ground cover, although patches of bryophytes also occur. Underlying the vegetation is sylvic peat containing dark, woody material, and the remains of lichen, rootlets and needles. The water table on peat plateaus drops to a depth of 0.5 m or more during summer, but remains relatively close to the ground surface in the channel fens and flat bogs.

Channel fens take the form of broad, 50 to >100 m wide channels. Their surface is composed of a floating peat mat of sedge (*Carex* sp.) origin, approximately 0.5 to 1.0 m in thickness that supports sedges, grasses, herbs, shrubs, aquatic and plants including *Typha latifolia*, *Equisetum fluviatile* and *Menyanthes trifoliate*. Dense patches of Tamarack (*Larix laricina*) also occur in the fens. Flat bog surfaces are relatively fixed, and are covered with *Sphagnum sp*. overlying yellowish peat with well-defined sphagnum remains (Zoltai and Vitt 1995). The club-moss, fungi and liverwort species are most prevalent in the bogs. Most flat bogs are small features that occur within peat plateaus. As a result, they appear to be internally drained and hydrologically-isolated from the basin drainage system. However, other flat bogs are connected to channel fens. These are relatively large bog complexes that often contain numerous peat plateaus. Surface drainage from connected flat bogs to channel fens has been observed during the spring freshet, and in response to large, late-summer rain events.

2.2. Satellite image analysis

Two multi-spectral images were acquired for ground cover analyses, including (1) a 4×4 m resolution IKONOS image covering 90 km^2 of the 150 km^2 Scotty Creek basin, and (2) a 30×30 m resolution Landsat image covering a 32,400 km^2 area of the lower Liard River valley that includes four study basins (viz., Birch, Blackstone, Jean-Marie and Scotty). Both images were classified using the maximum likelihood method (Arai 1992; Richards 1984; Yamagata 1997) with training sites (Lillesand and Kiefer 1994) obtained from homogeneous areas, including flat bogs, channel fens and peat plateaus. The three major peatland types were readily identified on the basis of their contrast in surface characteristics. For example, because saturated surfaces absorb infra red light, the channel fens appear relatively dark compared with the surrounding bogs and peat plateaus (Fig. 2). This contrast is enhanced by the relatively high photosynthetic activity of the drier surfaces away from the channel fens. Since the reflection of red light increases with decreasing photosynthesis (Lillesand and Kiefer 1994) these drier areas are represented by bright surfaces on the image. Additional data layers containing topographic information, the location of drainage networks and basin boundaries, were included and used for computations of drainage area, drainage density, and average slope. The average slope was computed from the difference between the maximum elevation and elevation of the basin outlet, divided by the distance measured along the drainage way between these two points.

From the IKONOS image, a 22 km^2 area of interest that includes the main locations where field measurements were made, was chosen for the purpose of obtaining a detailed and accurate ground-cover classification from field knowledge. All peat plateaus, channel fen and flat bogs within the area of interest were digitised. Image analysis software was used to compute the proportion of this area occupied by each cover type, as well as the area and perimeter of individual peat plateaus, channel fens and flat bogs. Peat plateaus occupy the largest proportion (43%) of the target area (Table 1). Since permafrost occurs only beneath the peat plateaus, the analysis suggests permafrost occupies less than half of the area shown in Fig. 3. Despite the large number of isolated flat bogs, they account for less than 5% of the area, but the area covered by connected flat bogs is more than five times larger that of the isolated flat bogs, with a total area roughly equivalent to the area occupied by channel fens (Table 1). It is difficult to differentiate among individual connected flat bogs. The channel fens appear to separate much of the remaining landscape into distinct bog-peat plateau complexes, the size of which depends largely on the spacing of the channel fens. There also appears to be separation of connected flat bogs by large peat plateaus that extend between adjacent channel fens.

3. Influence of Peat Bogs and Channel Fens on Basin Runoff

The arrangement of channel fens on the landscape, and observations of flow over their surfaces suggests that their hydrologic function is primarily one of lateral flow conveyance. Bogs are either surrounded by peat plateaus and therefore internally drained, as in the case of the isolated flat bogs, or have only ephemeral, tortuous surface flow routes to the channel fens, as in the case of the connected flat bogs. Flat bogs primarily serve the function of water storage rather than conveyance. This contrast between the channel fens and flat bogs suggests that the relative proportion of these two peatland types has implications for basin runoff. For example, a basin with a relatively high proportion of flat bogs should generate less runoff than a basin with a lower coverage of flat bogs. Figure 4 indicates that annual runoff was positively correlated with the percentage cover of channel fens, and negatively correlated with the percentage cover of flat bogs. The associations between channel fen coverage and runoff, and between bog coverage and runoff, are correlated in opposite directions because of the difference in the main hydrologic function of these two wetland types. Annual runoff correlates positively with both drainage density and the square root of basin slope, suggesting that the basins with more efficient drainage mechanisms have higher annual runoff.

The Scotty and Jean-Marie basins have relatively low average annual runoff values (Table 2), as these basins posses the characteristics that would diminish and delay runoff production: a relatively low average slope and drainage density, a low proportion of channel fens, but high coverage of flat bogs. The hydrographs of these basins are more delayed and have lower peaks than those of the Blackstone and Birch River basins (Fig. 5). However, Scotty and Jean-Marie differ in the timing of their runoff. On average, by the beginning of June, 41% of the annual runoff had drained from Scotty Creek, while at Jean-Marie, only 29% of the annual runoff had occurred. The greater basin lag of Jean-Marie reflects the fact that this river drains an area approximately 8.5 times larger than that of Scotty Creek, and as a result, the average flow distance to the basin outlet and the residence time are both longer at Jean-Marie.

Blackstone and Birch River basins both possess characteristics associated with higher runoff production, namely a relatively high average slope and drainage density, a high proportion of channel fens and a low coverage of flat bogs (Table 2). Consequently these two basins had the highest average annual runoff production (Fig. 4). The Birch River has a relatively small drainage area, and therefore would also have a relatively small average stream flow distance to the basin outlet. This could account for the slightly larger average runoff from this basin compared with the Blackstone during the April-May period (Table 2). Among the four basins studied, the Birch River basin was the first to commence runoff in each of the four study years. In three of these years, Scotty Creek, the other relatively small basin, was the second to respond.

4. Influence of Peat Plateaus on Basin Runoff

Several physical attributes suggest that peat plateaus perform an important role in basin runoff generation. Annual late winter snow surveys over the period 1993–2005 indicated that a large amount of snow was stored beneath the tree canopy by late winter. The relatively high topographic position of peat plateaus produces a hydraulic gradient that is an order of magnitude larger than the adjacent flat bogs and channel fens. In addition, the presence of frozen, saturated soil close to the peat plateau surface severely restricts their capacity to store snowmelt and rainfall inputs so that much of the water received is shed laterally through their active layer (Fig. 6). However, the rate of subsurface drainage from peat plateaus to their adjacent bogs and fens strongly depends on the depth of ground thaw, as the frozen soil is relatively impermeable.

Horizontal transmission also depends on properties of the active layer which vary sharply with depth (Quinton et al. 2000).

4.1 Soil Conductance and Hydraulic Response

Similar to many other northern organic-covered terrains, such as arctic and alpine tundra, the soil profile on a peat plateau contains an upper, lightly decomposed layer, underlain by a darker layer in a more advanced state of decomposition (Fig. 7a), though the thickness of the upper layer can be highly variable over short (<1 m) distances. Because the degree of decomposition increases with depth below ground, the bulk density generally increases with increasing depth (Fig. 7b), while the porosity generally decreases (Fig. 7c). Peat development on the peat plateaus is derived mainly from sphagnum moss which, under similar environmental conditions, can produce organic soils with a similar range of inter-particle pore diameters, regardless of the geographic setting. This is important hydrologically since pore size controls both the flux and the storage of water in the active layer. Detailed microscopic analysis (Quinton et al. 2000) of soils sampled from arctic tundra (Fig. 8a) indicates that the lower layer contains a larger proportion of small-diameter pores, with the consequence that both the hydraulic conductivity (Fig. 8b) and drainable porosity (Fig. 8c) are substantially reduced in the lower peat layer (Quinton and Gray 2003). Here, drainable porosity refers to the amount of water drained from a unit volume of sample, when a 0.4 m long core was placed vertically and allowed to drain freely for a period of 24 hours.

For a peat plateau in Scotty Creek basin, Fig. 9 illustrates the sequence of events that produced a rapid runoff response to 23 mm rainfall. Prior to this rain, the water table was 0.43 m below the ground surface. The relatively large hydraulic conductivity near the surface (Fig. 8b) allowed the infiltrating rainwater reach to reach quickly the zone of high moisture content above the water table, thereby inducing an abrupt 0.13 m water table rise. The magnitude of this rise indicated a field-based drainable porosity of 18 %, which is consistent with the drainable porosity measured in the laboratory (Fig. 8c) on soils sampled from 0.3-0.4 m below the surface. Figure 8b indicates that this water table would rise into a zone where the hydraulic conductivity is one to two orders of magnitude higher, thereby allowing efficient lateral drainage of subsurface water.

4.2 Soil water storage

When saturated, the volumetric moisture content of the organic soil typically exceeds 80% (Fig. 10a). Laboratory data show that saturated peat from the upper layer can drain to a residual value of about 20%. Under field situations, this may occur during periods of relatively high soil tension, such as in late-summer and during soil freezing. The annual minimum unfrozen moisture content is around 20% at all depths but the annual maximum unfrozen moisture content increases with depth. The consequence is that the annual range of unfrozen moisture content changes with depth. For example, at 0.3 m below the ground surface, the annual range in the daily average unfrozen volumetric moisture content is about 50% (Fig. 10b), but decreases to 40% (20% to 60%) and 15% (20% to 35%) at 0.2 m and 0.1 m depths respectively.

Regardless of the moisture content at various depths prior to freezing, the unfrozen moisture content converges to about 20% throughout the active layer during soil freezing (Fig. 11). However, this does not suggest that the total moisture content remains at a constant value throughout winter. At freeze-up, the water table is typically more than 0.5 m below ground, while at the onset of spring melt, the upper surface of the frozen, saturated soil is typically about 0.1 m below the ground surface, in the zone of high hydraulic conductivity (Fig. 8b). How this condition develops during the winter period remains unclear. Recent field investigation suggests that the amount of water supplied to the soil during the spring melt event in addition to the cumulative amount of meltwater supplied during the preceding over-winter melt events, is sufficient to saturate the ~0.4 m thick soil zone between the water table position at the time of freeze-up and the frost table position at the end of winter. This is supported by recent (2002–03) measurements of liquid moisture using water content reflectometers (Campbell Scientific, CS 615) in a soil pit, and from measurements of total soil moisture (frozen and unfrozen) in two soil cores extracted in late winter (prior to snowmelt) near the pit (Fig. 12). Between freeze-up and late-winter, the total (frozen and unfrozen) soil moisture increased throughout the core profiles but was greatest near the ground surface, particularly at the 0.1 m level. In both cores, the total soil moisture below 0.3 m was 5–10% below porosity, which was close to the saturated state. It was also indicated by the measured values in the soil pits that the unfrozen moisture content was only about 20% on the day when the two cores were extracted (Fig. 12).

5. Toward Basin Runoff Computation

The field and laboratory studies have produced an understanding of the key factors controlling subsurface runoff from a peat plateau, a critical step toward modelling the magnitude and timing of subsurface input from the peat plateaus to the basin drainage network. Depth to the frost table is a critical consideration for subsurface drainage but recent field measurements indicate that variations in the mean frost table depth and in the hydraulic gradient are small among peat plateaus, suggesting that the subsurface drainage rate would not vary appreciably among plateaus. However, individual peat plateaus vary widely in size (Fig. 3) and so would the subsurface flowpath length and therefore the timing of subsurface drainage from plateaus. The hydraulic radius R_h provides a reasonable approximation of the average flow length to the edge of a peat plateau. It can be estimated by $R_h = 2A / P$, where P is the plateau perimeter and A is its area, both easily obtainable using image analysis software. Based on 609 peat plateaus identified (Fig. 3), R_h appears to follow a log-normal distribution (Fig. 13). Current research is focussed on using the Cold Regions Hydrological Model, CRHM (Quinton et al. 2004) to compute the composite subsurface drainage hydrograph for the overall cover of peat plateaus for the range of flowpath lengths defined by the frequency distribution of R_h, using representative values of frost table depth and hydraulic gradient. This composite hydrograph represents the ‘hillslope’ input from the peat plateaus to the adjacent bogs and fens, including the basin drainage network.

Computing a composite hydrograph of drainage from the peat plateau land cover type, such as from all the peat plateaus shown in Fig. 3, is a first step toward computing the basin hydrograph for Scotty Creek and other basins in this region. The next step is to route the water from the peat plateaus, through the channel fens and connected flat bogs to the basin outlet, but there is little research on the hydrologic functioning of these two land-cover types. Water level recorded at several nodes within the Scotty Creek basin (Quinton et al. 2003) showed that following storm events, drainage water concentrates in the channel fens and moves toward the outlet at an average flood-wave velocity of 0.23 km h^{-1}. By tracking flood waves as they moved through the basin, it is evident that channel fens are an integral component of the overall drainage system, which also includes intervening lakes and open stream channels. The flood-wave velocity appears to be controlled by channel slope and hydraulic roughness in a manner consistent with the Manning formula, suggesting that a roughness-based routing algorithm might be useful. Although the apparent continuity of channel fens is clearly identified in satellite images (Fig. 2), Hayashi et al. (2004) demonstrated that the actual hydraulic connection varies over the snow-free period, and may depend on the water level in the fens. With a large supply of water such as during spring runoff, connected flat bogs often convey surface drainage along their perimeters and into channel fens. However, the spatial and temporal variation of this hydrologic connectivity and its role on basin drainage, are poorly understood. Furthermore, the possibility of deep subsurface flow below the peat plateaus cannot be ruled out. Such groundwater flow connections are well established in temperate wetlands (e.g., Siegel and Glaser 1987) but poorly documented in the discontinuous permafrost region.

6. Basin Water Balance

6.1 Evaporation

Over a four-year period (1999–2002) the cumulative precipitation was 1683 mm and only 593 mm discharged from Scotty Creek. Assuming that their difference was lost to evapotranspiration, the average annual evapotranspiration of this period was 273 mm yr^{-1}. Claassen and Halm (1996) showed that a chloride mass balance can be used to estimate the basin-scale evapotranspiration when the lithologic source of chloride is negligible. Scotty Creek basin is underlain by mineral sediments derived mainly from clay-rich glacial till with low hydraulic conductivity. Active flow of groundwater in such glacial till in western Canada is limited to a shallow (<10 m) local system (Hayashi et al., 1998a) in which the pre-Holocene chloride has been flushed out (Hayashi et al., 1998b). Scotty Creek therefore offers conditions suitable for applying the chloride method, where chloride enters the system predominantly through precipitation, and is lost mainly through stream flow. Using this method, evapotranspiration Et is given by

$$Et = P\,(Cs - Cp)\,/\,Cs, \quad (1)$$

where P is annual precipitation, and Cs and Cp are the volume-weighted average chloride concentration in stream water and precipitation, respectively. Forty-three water samples were collected at the outlet between March and December during 1999–2002 and analyzed for chloride (Hayashi et al., 2004). The volume-weighted average concentration was calculated by summing the product of the chloride concentration and the stream discharge at the time of sample collection, and dividing the total by the sum of all discharge values. The average Cs for the four-year period was 0.151 mg L^{-1}. The average Cp (0.044 mg L^{-1}) is given by the 10-year mean (1992–2001) of chloride in precipitation reported in the NatChem database (MSC 2002) at Snare Rapids, located 400-km northeast of Scotty Creek. This value is similar to the NatChem data from other stations in the interior western Canada (0.04 mg L^{-1}) presented by Hayashi et al. (1998b). The average precipitation for the water years 1999–2002 was 421 mm yr^{-1} (Table 3). Therefore, Eq. (1) gives Et = 298 mm yr^{-1}, which agrees with the hydrometric estimate of 273 mm yr^{-1}. A simple arithmetic average concentration of the 43 samples was 0.133 mg L^{-1}. Using this value for Cs in Eq. (1) gives Et = 282 mm yr^{-1}, which is also in agreement with the hydrometric estimate. These results suggest that the chloride method has a great potential as a tool for estimating the basin-scale evapotranspiration in ungauged basins.

6.2 Precipitation and Runoff

For long term water balance estimation, the discharge record for the Birch (1974–2000), Blackstone (1991–2000), Jean-Marie (1972–2000) and Scotty (1995–2000) Creeks (Fig. 1b) were compiled. Annual runoff from these basins was generally below 200 mm (Fig. 14). The average annual runoff ratio (annual runoff expressed as a percentage of the annual precipitation) ranged between 21% (Scotty) and 35% (Birch), indicating that ET is the dominant mechanism of water loss, with annual average rates of 297 mm (Scotty), 271 mm (Jean-Marie), 245 mm (Blackstone) and 241 mm (Birch).

7. Discussion

In the wetland-dominated central Mackenzie River Basin, peat plateaus are areas of saturated permafrost that support a tree canopy and rise above the surrounding terrain. This enables them to effectively retain water in isolated flat bogs, while re-directing runoff produced by snow melt and rainfall to the channel fens and connected flat bogs. Water entering channel fens is conveyed directly to the basin outlet, whereas water entering connected flat bog reaches the basin outlet via a channel fen. Runoff-generation algorithms in hydrologic models must account for the storage capacity of the isolated and flat bogs. Similarly, routing algorithms in distributed hydrologic models need to incorporate the network of connected flat bogs and channel fens. Preliminary studies indicate that surface roughness and channel slope may be the essential factors controlling the surface flow in channel fens.

Some major challenges remain before the conceptual model can be successfully implemented numerically. The apparent continuity of channel fens is clearly identified in satellite images, but their actual hydraulic connection likely depends on the water level. Further development of conceptual and numerical models requires the understanding of these subsurface and surface processes and their temporal and spatial variability. Likewise, the surface and subsurface hydrologic connection of flat bogs to channel fens has not been investigated. The exchange of mass and energy among the major peatland forms, and between them and the overlying atmosphere is poorly understood. Upon melt, large volumes of water are released, dramatically altering the heat exchanges (Marsh et al. 2007) and creates a mosaic of snow, bare ground and standing water for several weeks (Bowling et al. 2003). The infiltration, storage and redistribution of water within the active layer in organic terrain is exceptionally complex due to phase changes, abrupt depth-variations in soil transmission properties, and spatial and temporal configuration of the frost frost table. An improved understanding of the mass and energy exchanges among the peatland types, as well as the subsurface–surface–vegetation–atmosphere exchanges within each form, will permit proper modeling of the wetland-dominated drainage system in the subarctic region.

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Table 1: Selected results of detailed ground cover classification of sub-section of the IKONOS image of Scotty Creek, representing an area of *ca.* 22 km^2 on the ground. N is the number of samples of each cover type. Deriving the number of connected flat bogs was not attempted.

Cover type	N	Area (km^2)	Area (%)
Peat Plateaus	609	9.52	43.0
Flat bogs (isolated)	999	0.89	4.0
Flat bogs (connected)	-	5.03	22.7
Channel fens	2	4.65	21.0
Lakes	4	2.06	9.3

Table 2: Size and percentage cover of major terrain types of the four study basins, derived from Landsat imagery. For each basin, the drainage density, average slope, and the average annual, spring (April–May) and summer (June–August) runoff for the four years (1997–2000) of observation are shown. The bog class refers to the sum of both isolated and connected flat bogs. The wooded class includes peat plateaus and wooded uplands in the northern parts of each basin.

basin	area	Average annual runoff	average spring runoff	average summer runoff	wooded	fens	bogs	drainage density	avg. slope
	km^2	mm	mm	mm	% of basin	% of basin	% of basin	km/km^2	m/m
Blackstone	1910	161.8	56.8	105.0	66.8	33.5	3.4	0.378	0.0055
Jean-Marie	1310	127.4	34.5	92.9	65.6	27.4	7.6	0.237	0.0034
Birch	542	155.0	59.9	95.0	64.9	30.7	6.5	0.373	0.0063
Scotty	152	108.8	43.3	65.5	63.2	19.6	10.2	0.161	0.0032

Table 3: Fort Simpson annual and summer (May-September) precipitation (P) for each water year (October 1 to September 30), average snow water equivalent (SWE) in late March from snow survey data, and total annual runoff of Scotty Creek. All values in mm; n/a indicates the data not available.

	Normal	1999	2000	2001	2002
Period	1971-00	10/98-09/99	10/99-09/00	10/00-09/01	10/01-09/02
Total P	369	409	431	431	412
May-Sep P	221	238	296	316	269
SWE	n/a	90	101	n/a	142
Total runoff	n/a	96	139	161	197

List of Figures:

measurements on the same day. Soil porosity was obtained from samples taken from the soil pit in August 2001 when sensors were installed. Crosses indicate soil moisture immediately before freeze-up, at 10, 20 and 30 cm depth increments.

Fig. 13: Cumulative probability of the logarithmically-transformed values of the hydraulic radius (R_h) of the 609 peat plateaus identified in Fig. 3. Dashed line indicates the lognormal distribution computed from the mean and standard deviation of the R_h values.

Fig. 14: Annual runoff measured at the outlets of: (a) Scotty Creek, (b) Blackstone River, (c) Jean-Marie River and (d) Birch River for the entire gauging period at these stations. Total Annual precipitation (rain and snow) measured at Fort Simpson is plotted for the same period.

Figure 1

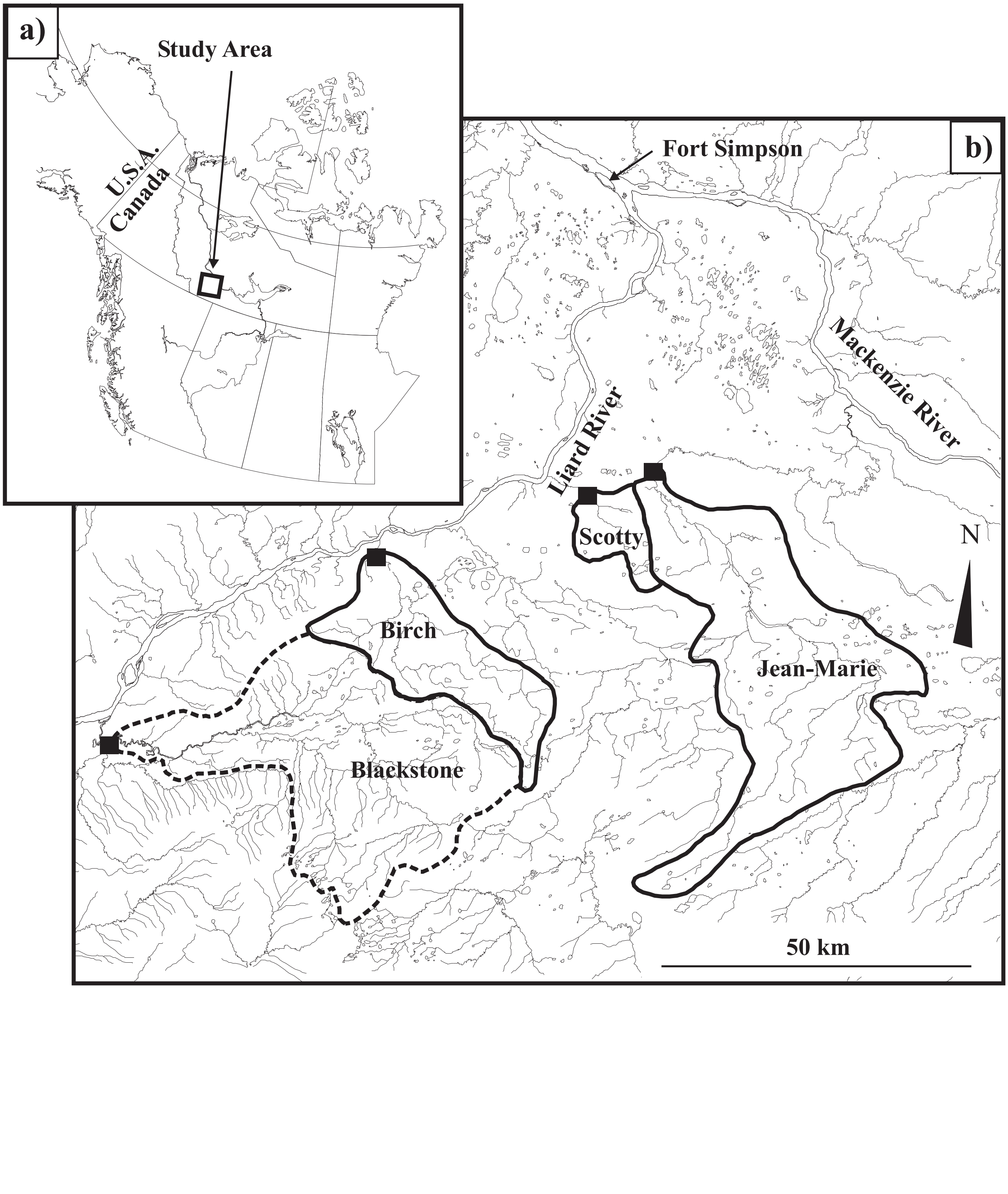

a)
Study Area
U.S.A.
Canada
b)
Fort Simpson
Mackenzie River
Liard River
Scotty
Birch
Jean-Marie
Blackstone
N
50 km

Figure 2

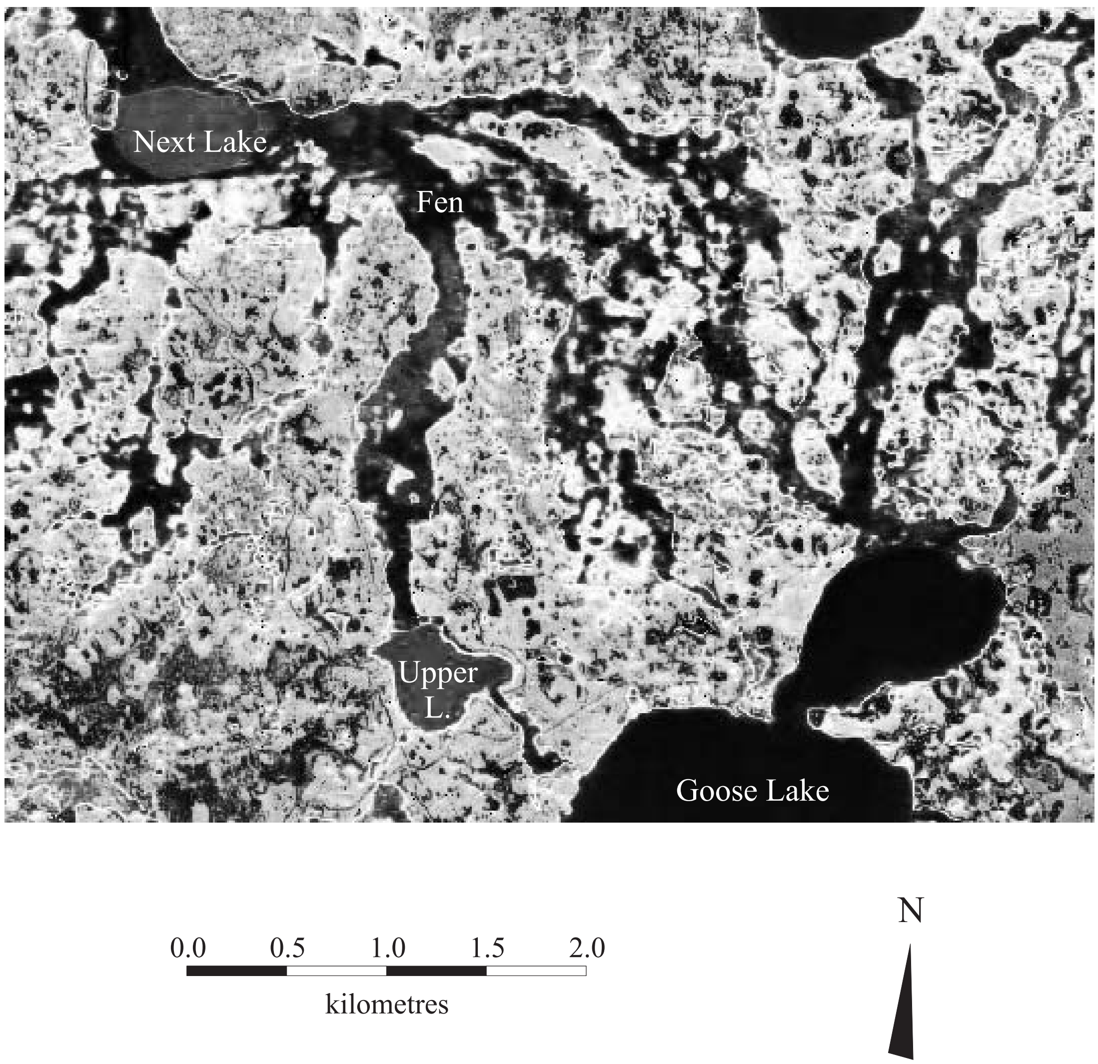


Figure 3

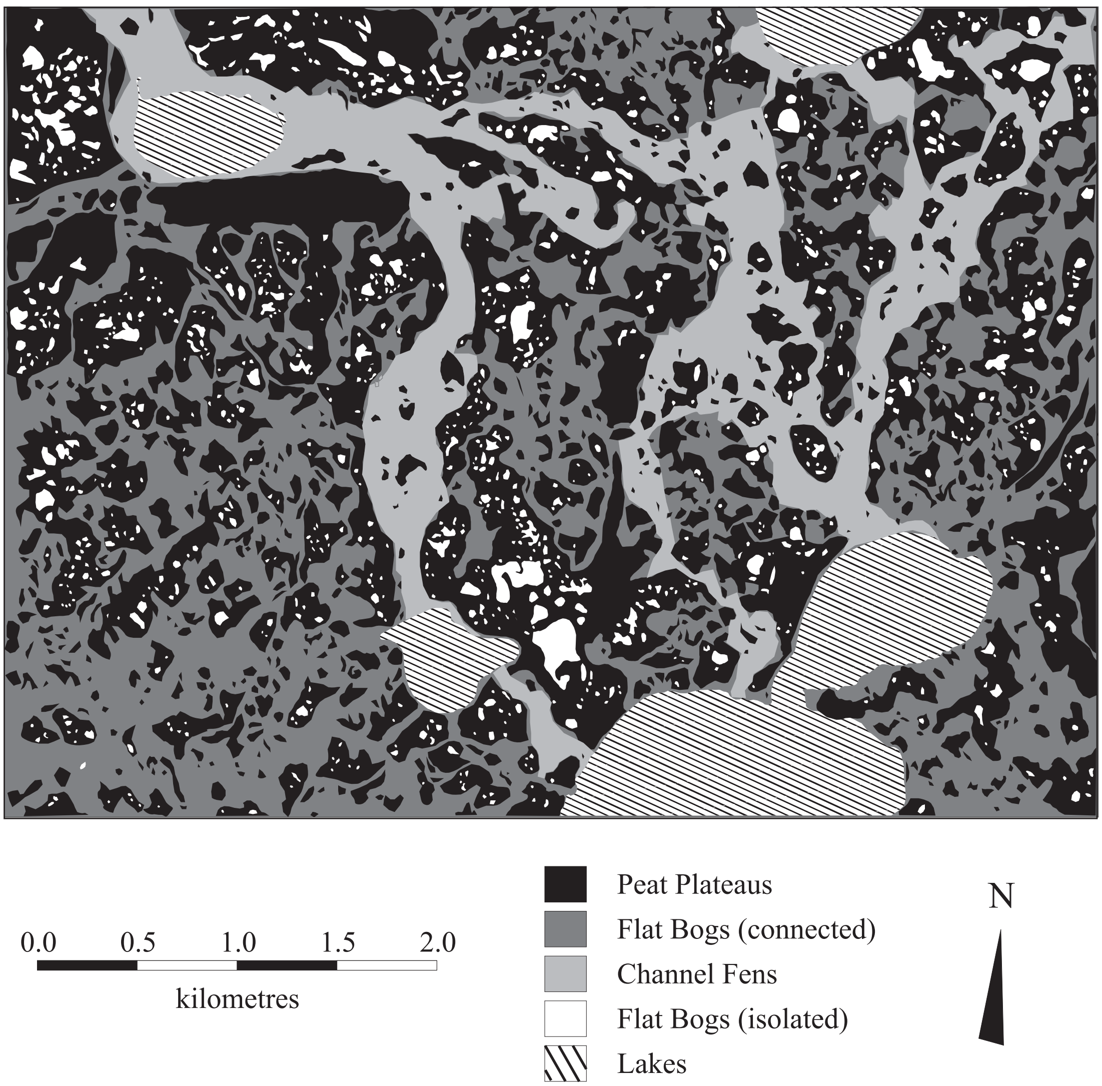

0.0 0.5 1.0 1.5 2.0
kilometres
Peat Plateaus
Flat Bogs (connected)
Channel Fens
Flat Bogs (isolated)
Lakes
N

Figure 4

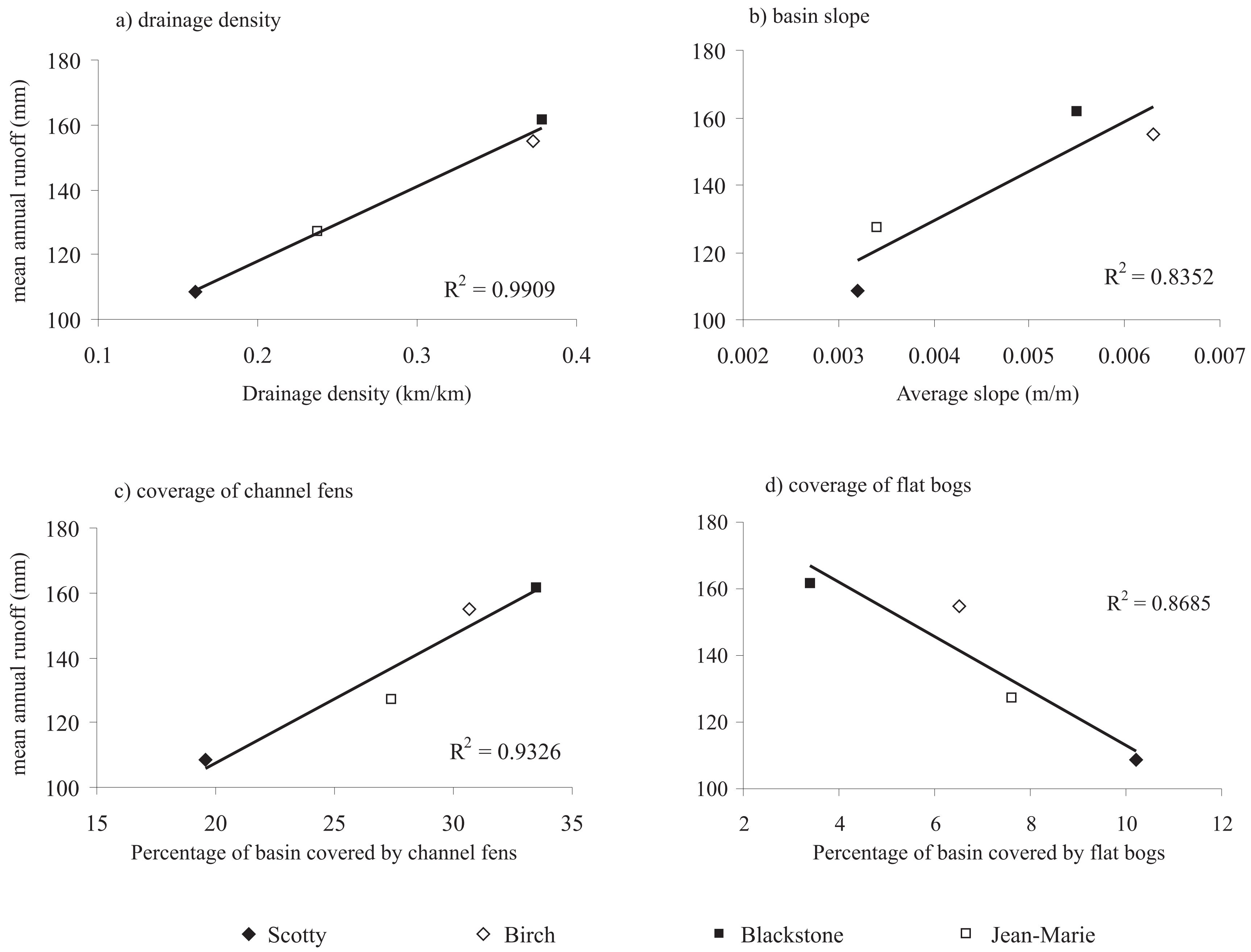
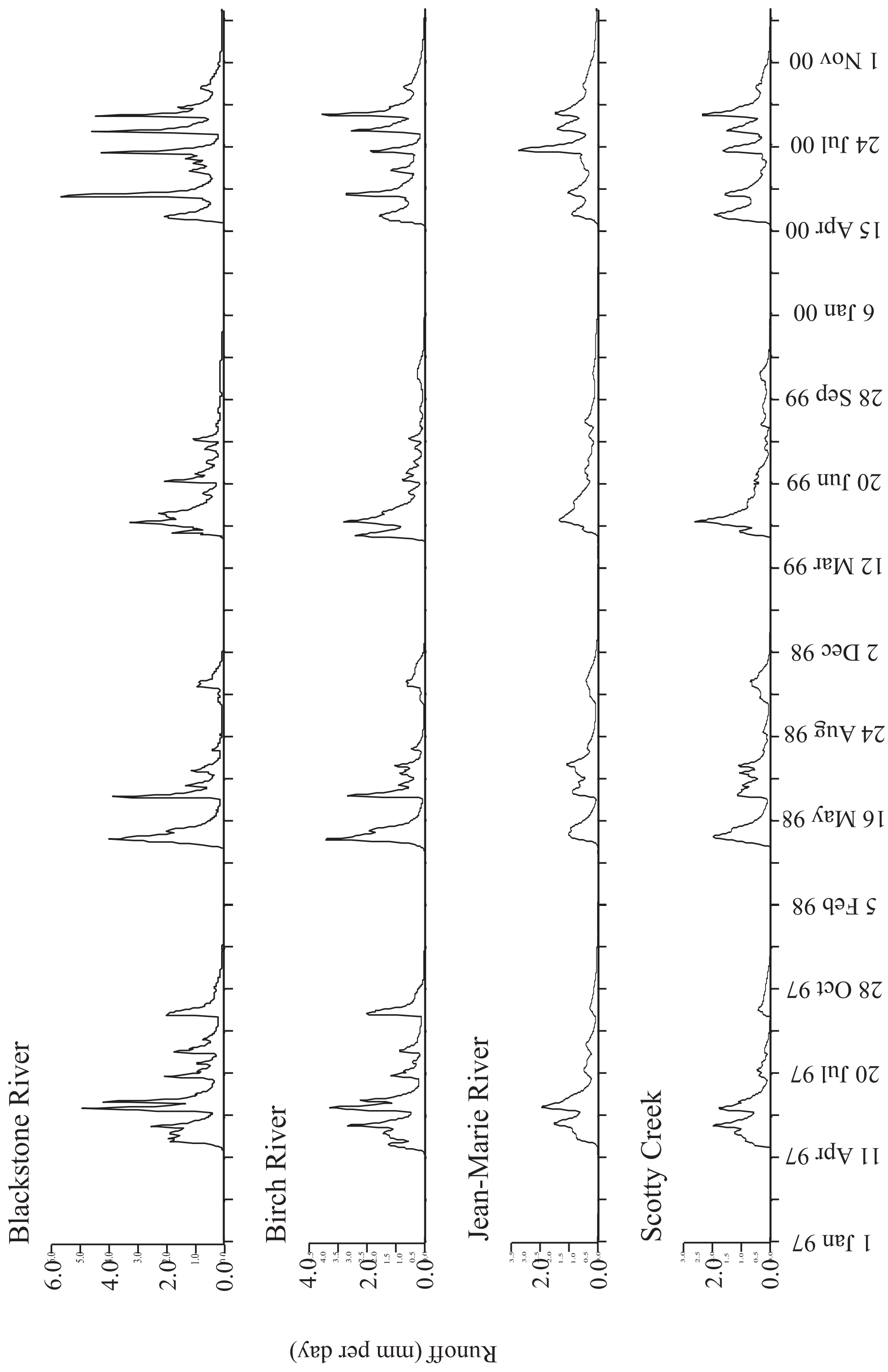
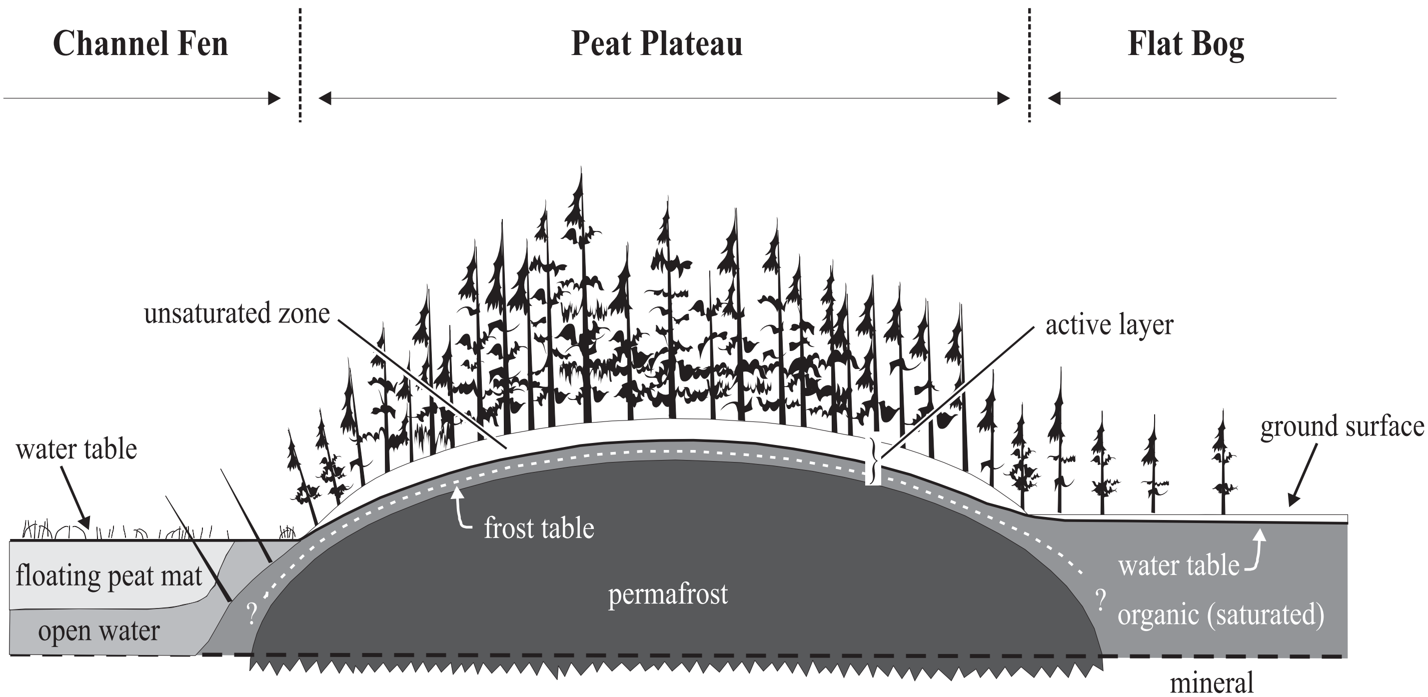

a) drainage density
mean annual runoff (mm)
180
160
140
120
100
0.1
0.2
0.3
0.4
Drainage density (km/km)
R^2 = 0.9909
b) basin slope
0.002
0.003
0.004
0.005
0.006
0.007
Average slope (m/m)
R^2 = 0.8352
c) coverage of channel fens
15
20
25
30
35
Percentage of basin covered by channel fens
R^2 = 0.9326
d) coverage of flat bogs
2
4
6
8
10
12
Percentage of basin covered by flat bogs
R^2 = 0.8685
Scotty
Birch
Blackstone
Jean-Marie

Figure 5



Blackstone River
Birch River
Jean-Marie River
Scotty Creek
Runoff (mm per day)
1 Jan 97
11 Apr 97
20 Jul 97
28 Oct 97
5 Feb 98
16 May 98
24 Aug 98
2 Dec 98
12 Mar 99
20 Jun 99
28 Sep 99
6 Jan 00
15 Apr 00
24 Jul 00
1 Nov 00

Figure 6


Channel Fen
Peat Plateau
Flat Bog
unsaturated zone
active layer
ground surface
water table
frost table
floating peat mat
open water
permafrost
water table
organic (saturated)
?
?
mineral

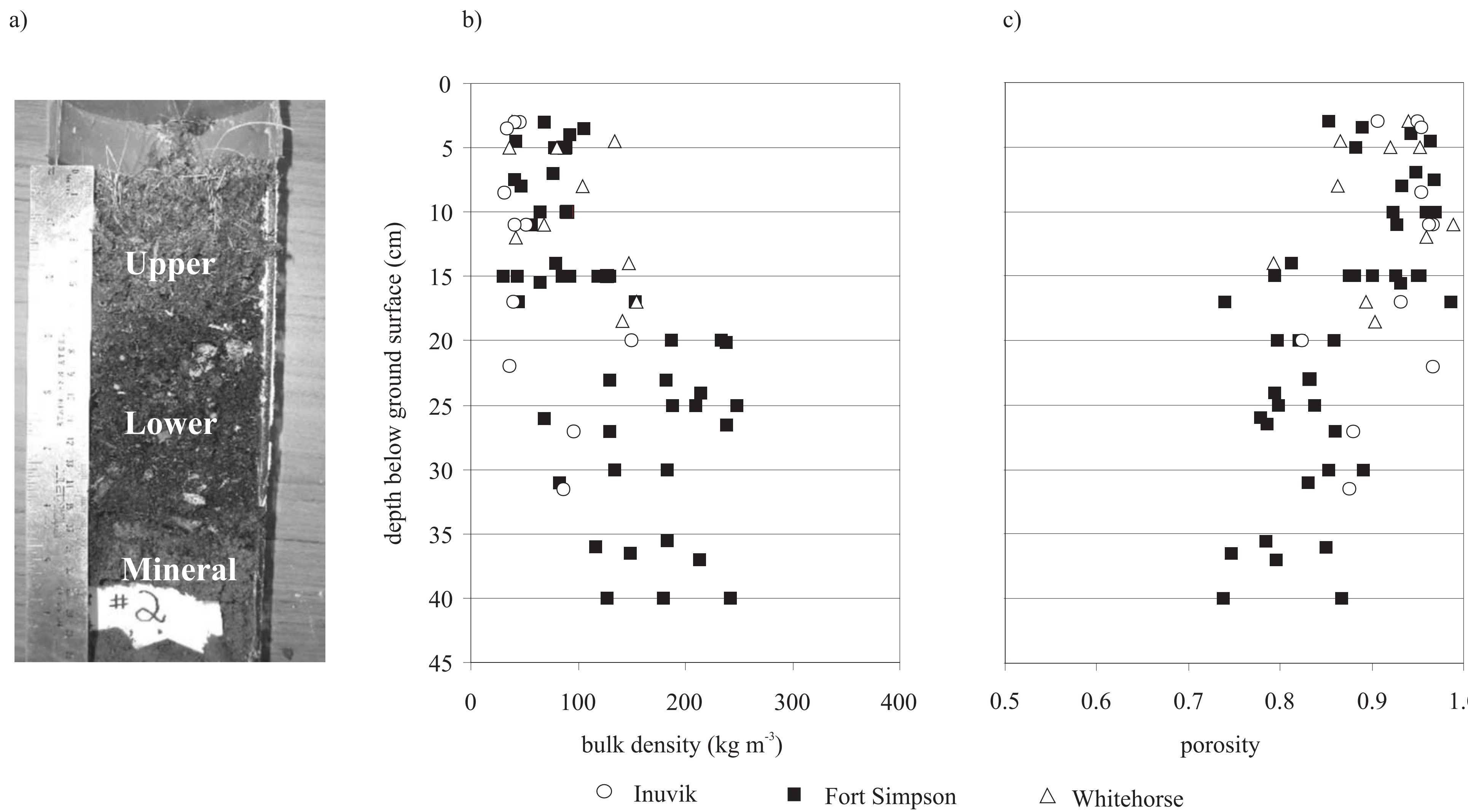
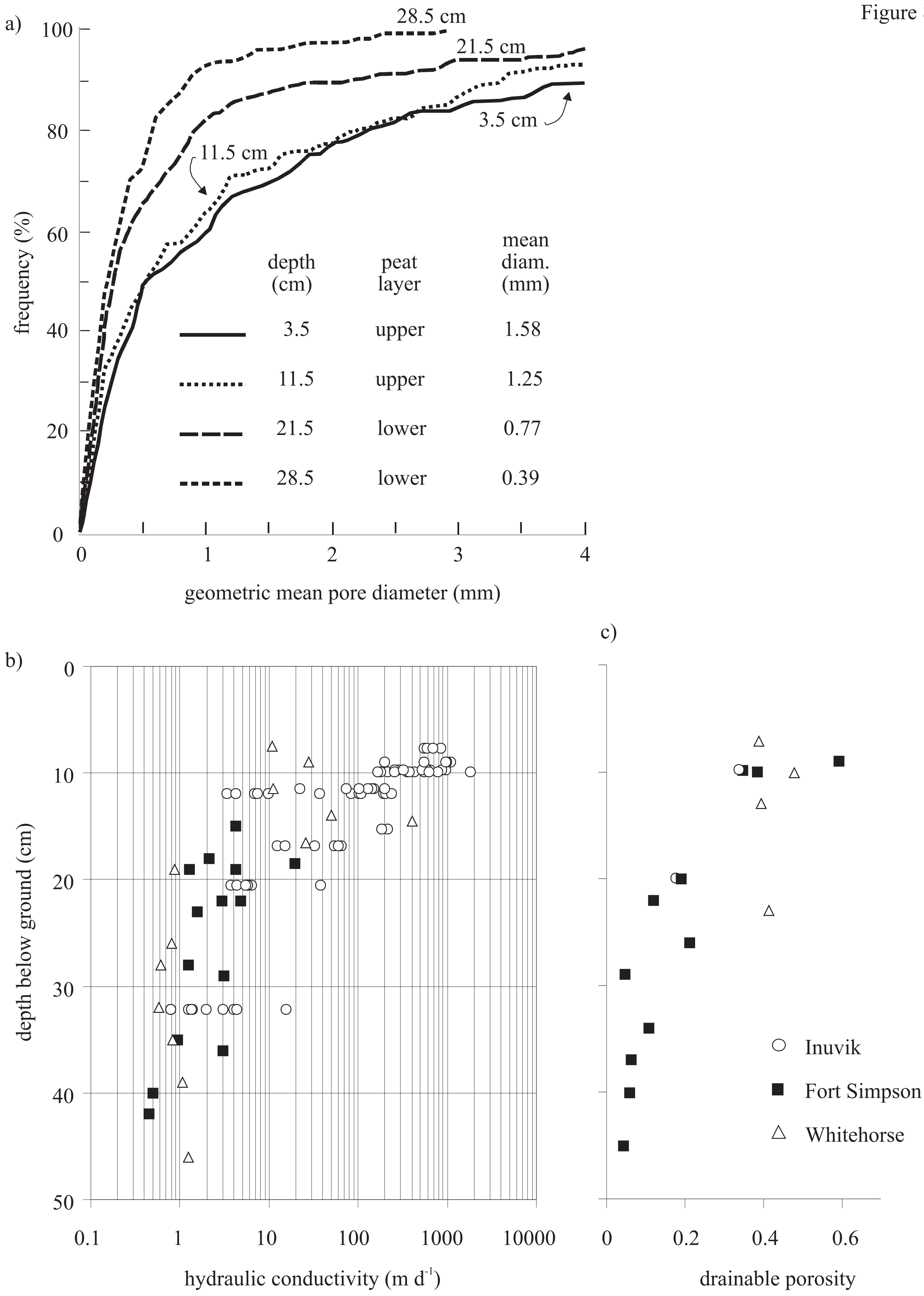

a)
Upper
Lower
Mineral
#2
b)
depth below ground surface (cm)
bulk density (kg m-3)
c)
porosity
Inuvik
Fort Simpson
Whitehorse

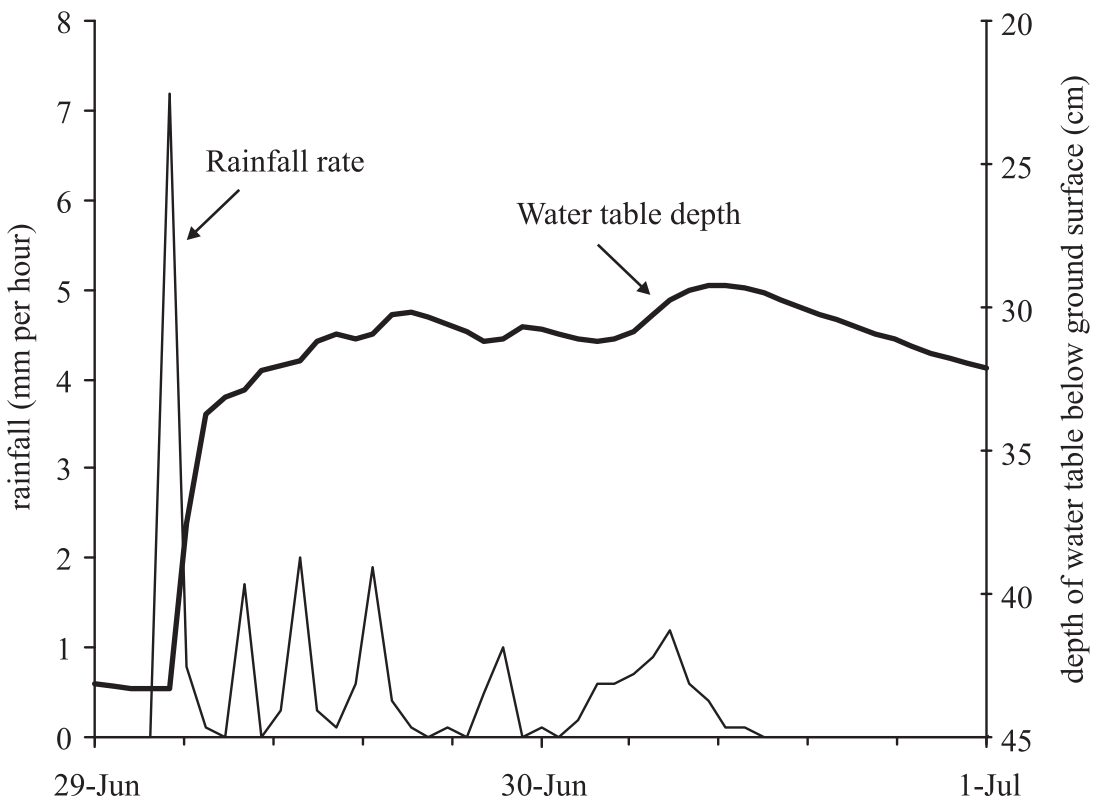
Figure 7

Figure 8



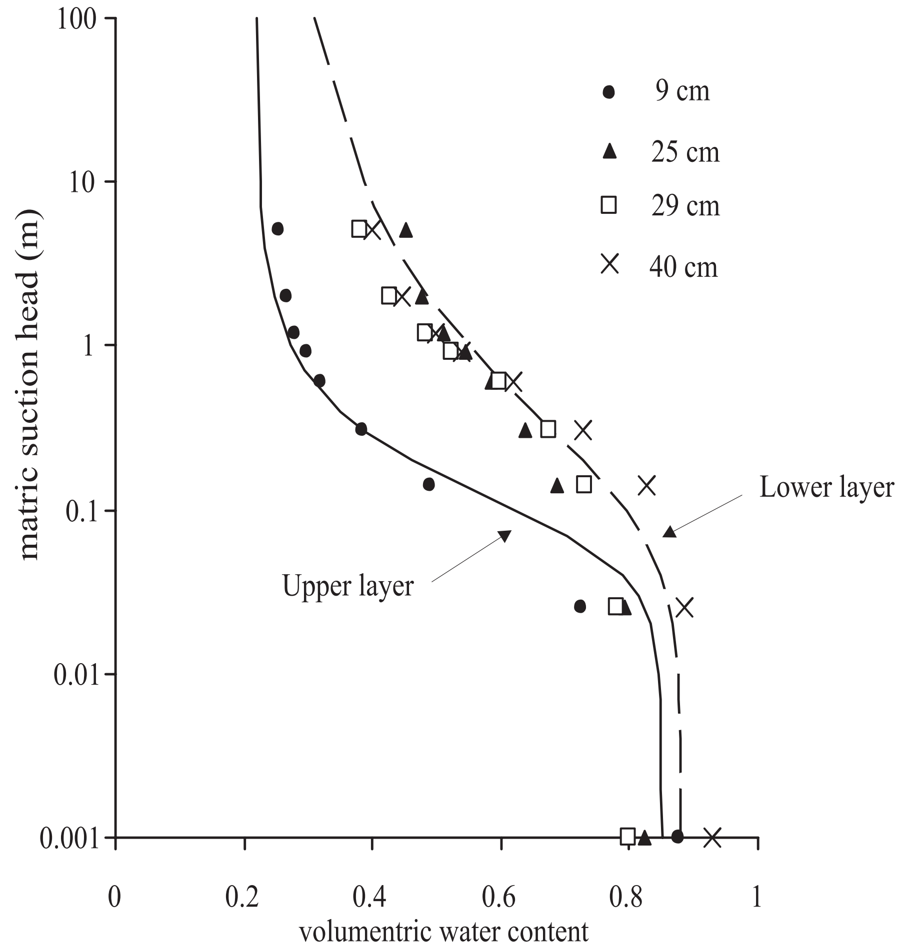
a)
frequency (%)
geometric mean pore diameter (mm)
28.5 cm
21.5 cm
11.5 cm
3.5 cm
depth (cm)
peat layer
mean diam. (mm)
3.5 upper 1.58
11.5 upper 1.25
21.5 lower 0.77
28.5 lower 0.39
b)
depth below ground (cm)
hydraulic conductivity (m d-1)
c)
drainable porosity
Inuvik
Fort Simpson
Whitehorse

Figure 9



8
7
6
5
4
3
2
1
0
rainfall (mm per hour)
Rainfall rate
Water table depth
20
25
30
35
40
45
depth of water table below ground surface (cm)
29-Jun
30-Jun
1-Jul

a)


100
10
1
0.1
0.01
0.001
matric suction head (m)
0
0.2
0.4
0.6
0.8
1
volumentric water content
9 cm
25 cm
29 cm
40 cm
Lower layer
Upper layer

b)

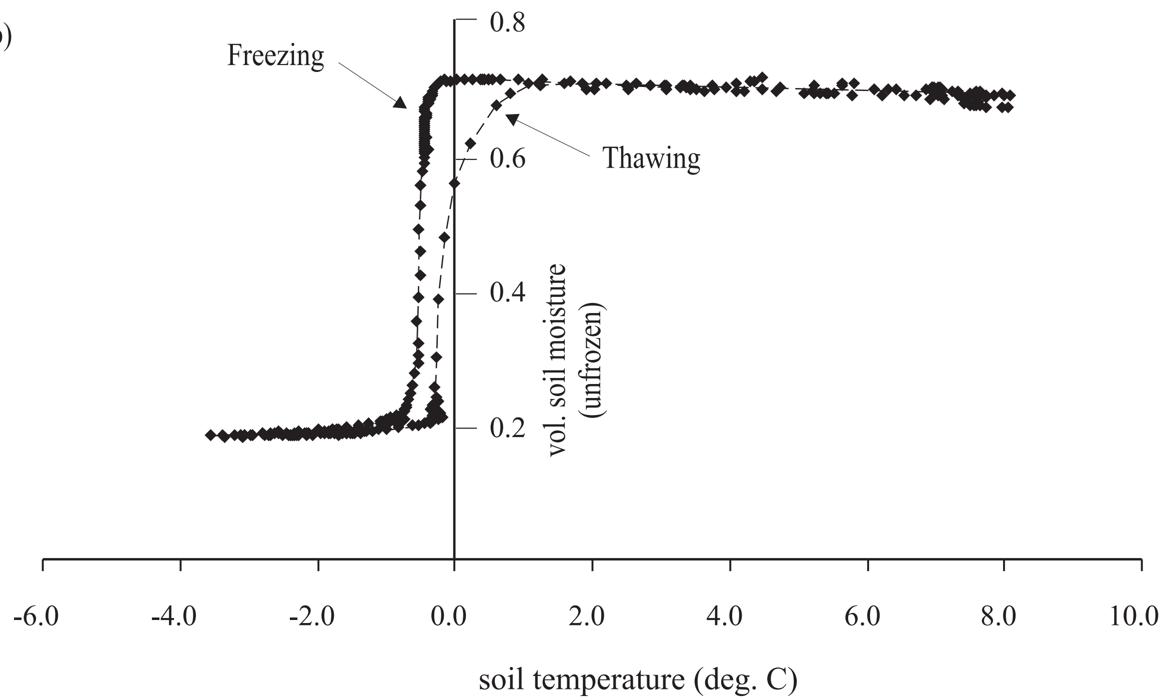
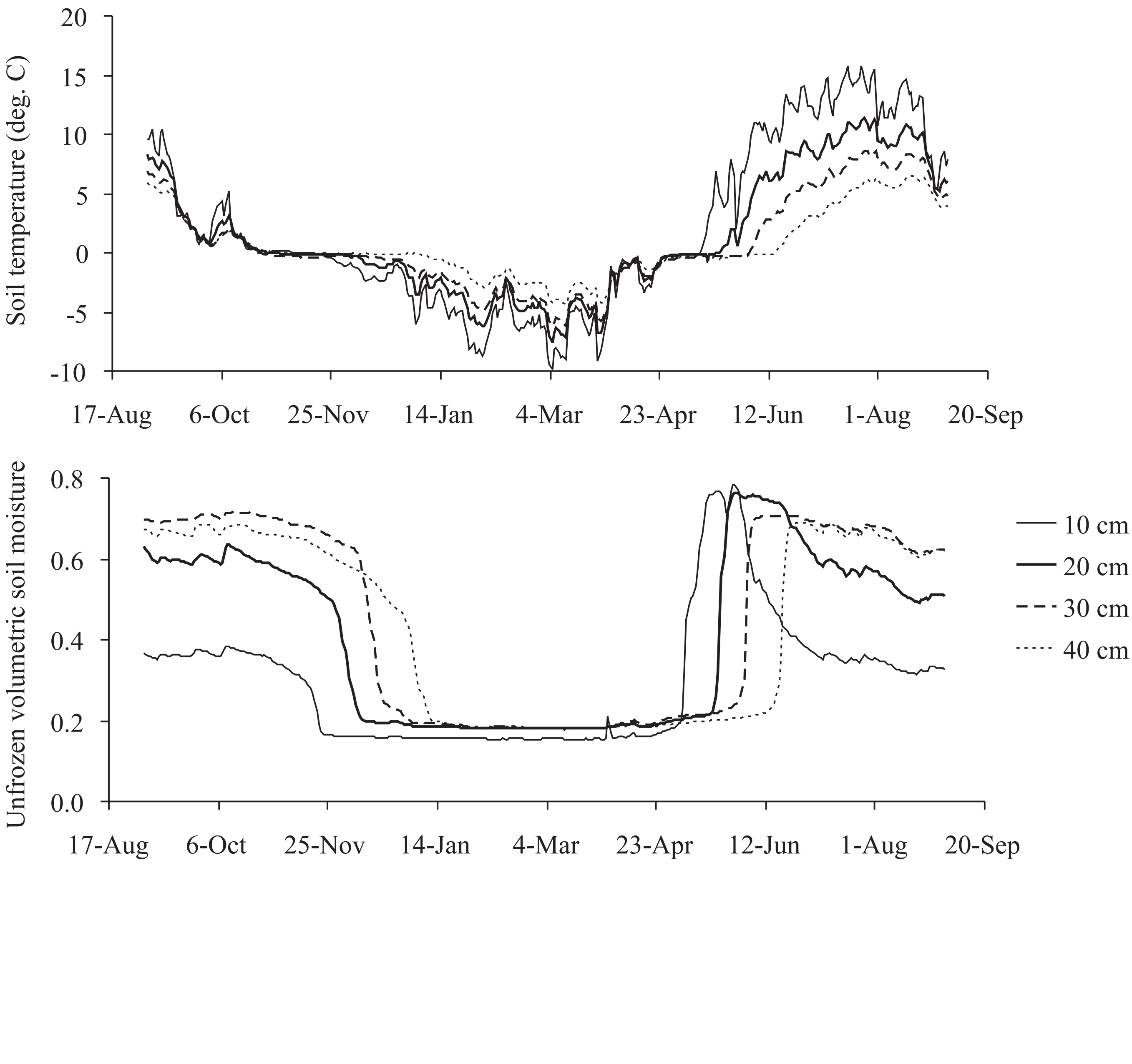
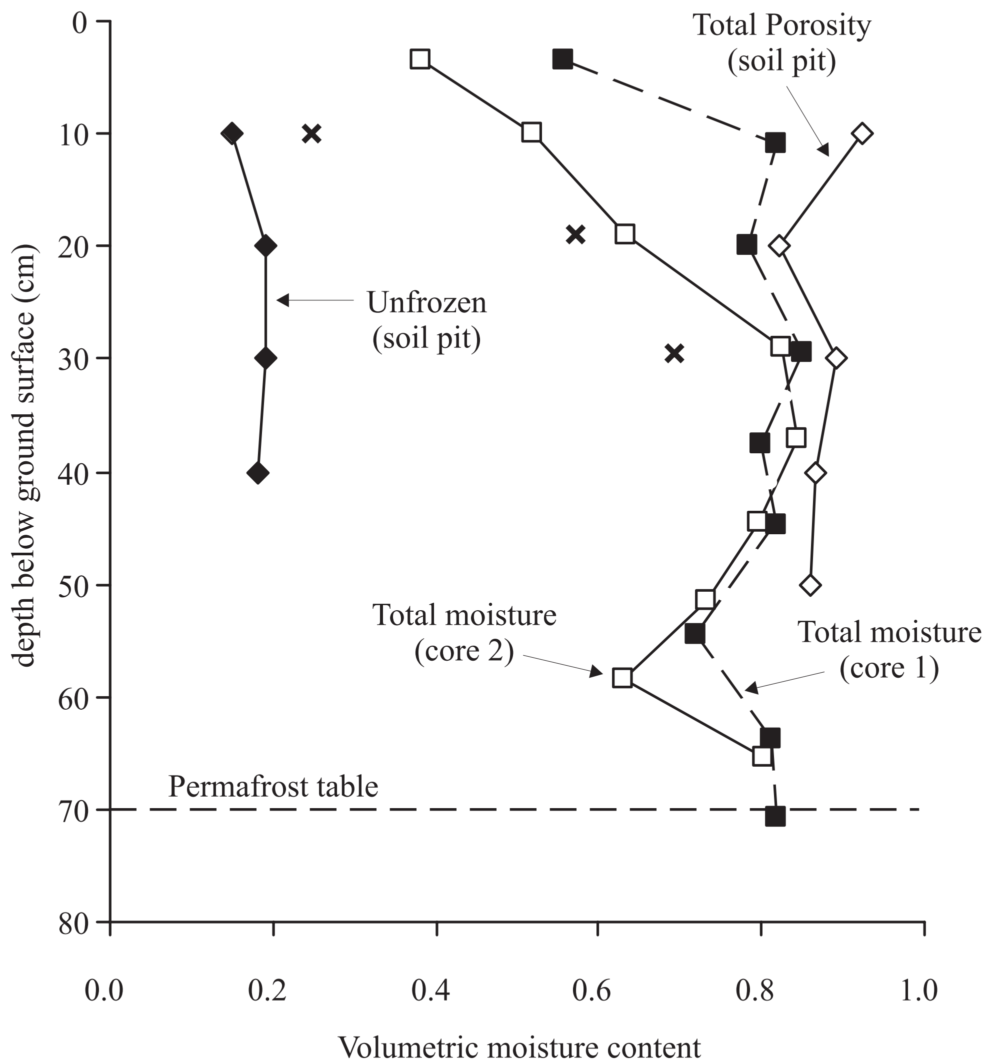

0.8
0.6
0.4
0.2
vol. soil moisture (unfrozen)
Freezing
Thawing
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
soil temperature (deg. C)

Figure 11

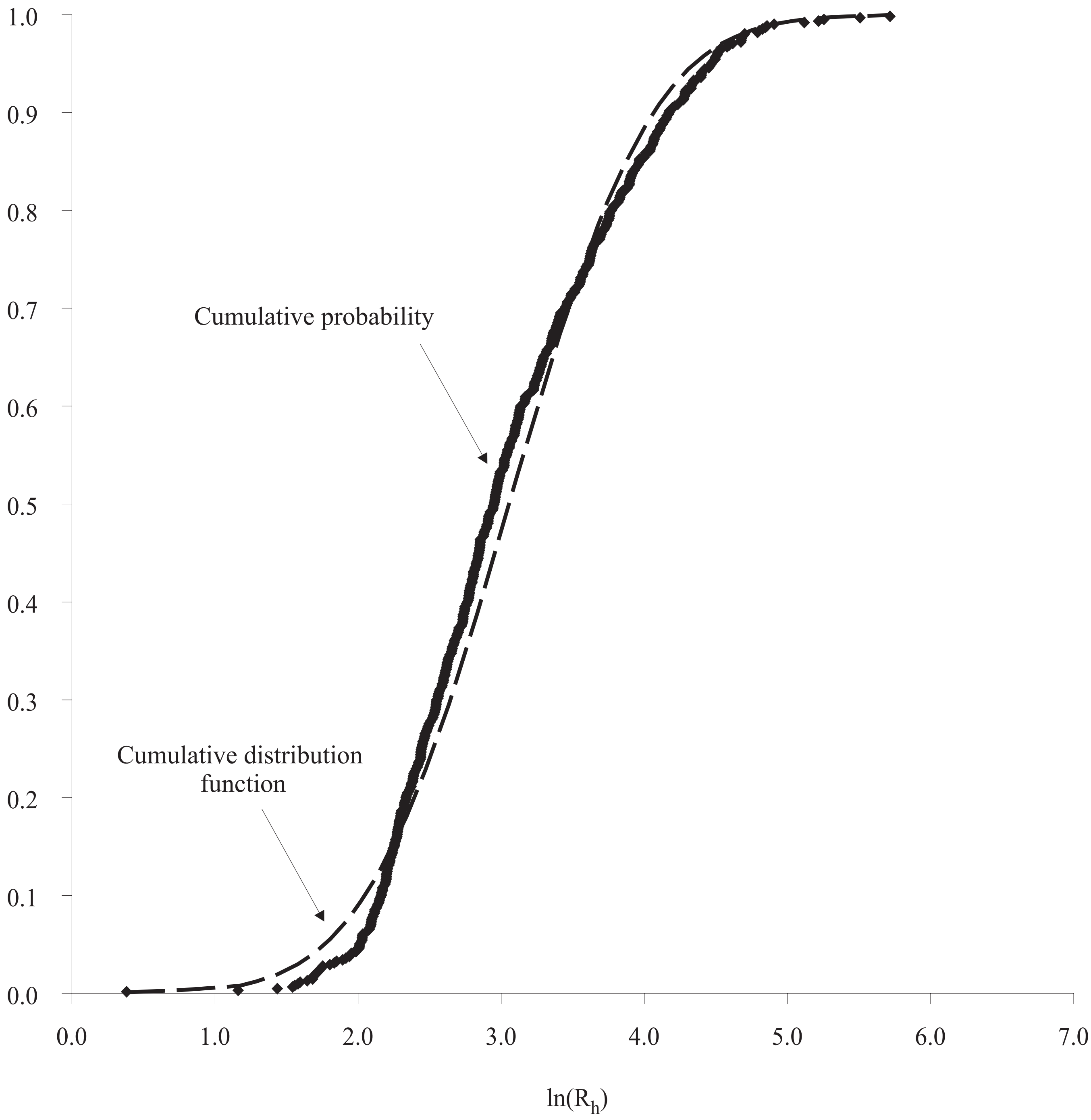


Soil temperature (deg. C)
20
15
10
5
0
-5
-10
17-Aug
6-Oct
25-Nov
14-Jan
4-Mar
23-Apr
12-Jun
1-Aug
20-Sep
Unfrozen volumetric soil moisture
0.8
0.6
0.4
0.2
0.0
17-Aug
6-Oct
25-Nov
14-Jan
4-Mar
23-Apr
12-Jun
1-Aug
20-Sep
10 cm
20 cm
30 cm
40 cm



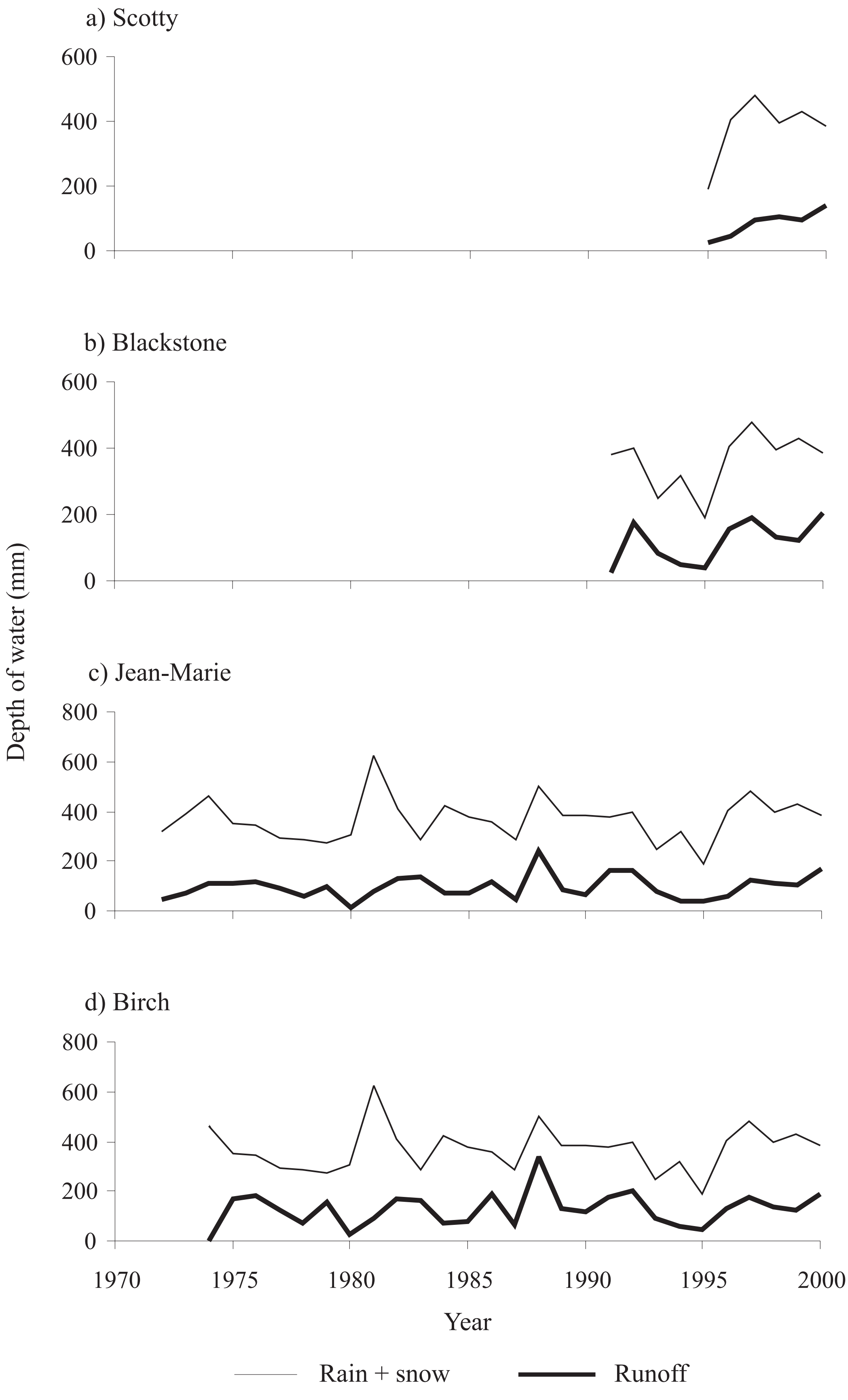
Total Porosity
(soil pit)
Unfrozen
(soil pit)
Total moisture
(core 2)
Total moisture
(core 1)
Permafrost table
depth below ground surface (cm)
0
10
20
30
40
50
60
70
80
0.0
0.2
0.4
0.6
0.8
1.0
Volumetric moisture content

Figure 13



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative probability
Cumulative distribution
function
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
ln(Rh)

Figure 14


a) Scotty
b) Blackstone
c) Jean-Marie
d) Birch
Depth of water (mm)
Year
1970
1975
1980
1985
1990
1995
2000
Rain + snow
Runoff