THE FLOW AND STORAGE OF WATER IN THE WETLAND-DOMINATED CENTRAL MACKENZIE RIVER BASIN: RECENT ADVANCES AND FUTURE DIRECTIONS

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ABSTRACT

Field studies were initiated in 1999 at Scotty Creek, Northwest Territories, Canada in order to improve the understanding and model-representation of the major water flux and storage processes within a wetland-dominated region of the discontinuous permafrost zone. This paper contributes to this end by presenting selected results on: 1) the physical and hydraulic properties of the active layer soils in this region; 2) the hydrological functioning of the major peatland forms; and 3) the water balance of selected drainage basins. A discussion of how basin water balances might be altered by climate warming is also presented. From this study, a conceptual model of runoff generation for this region has begun to develop that recognises distinct hydrological roles among the major peatland types of flat bog, channel fen and peat plateau. This conceptual model contributes to resolving some of the difficult issues in the hydrological modelling in this region, especially in relation to the storage and routing functions of wetland-dominated basins with discontinuous permafrost.

RÉSUMÉ

Des études sur le terrain ont été entreprises en 1999 à Scotty Creek, Territoires du Nord-Ouest, Canada, dans le but d'améliorer la compréhension et la représentation à l'aide de modèles des principaux processus d'écoulement et de stockage d'eau à l'intérieur d'une région dominée par des milieux humides de la zone à pergélisol discontinu. Ce document contribue à cet objectif en présentant des résultats choisis sur : 1) les propriétés physiques et hydrauliques des couches actives du sol dans cette région; 2) le fonctionnement hydrologique des principaux types de tourbières; et 3) le bilan hydrique de bassins de drainage choisis. Une discussion sur la façon dont les bilans hydriques des bassins peuvent être modifiés par le réchauffement climatique est également présentée. À partir de cette étude, on a commencé à élaborer un modèle conceptuel de la production du ruissellement pour cette région qui reconnaît les rôles hydrologiques distincts au sein des principaux types de tourbières oligotrophes plates, de tourbières minérotrophes de chenal et de tourbières à plateau palsique. Ce modèle conceptuel contribue à résoudre certains des problèmes complexes de la modélisation hydrologique dans cette région, particulièrement en rapport avec les fonctions de stockage et d'acheminement des bassins dominés par les milieux humides au pergélisol discontinu.

INTRODUCTION

The Mackenzie River basin in northern Canada has experienced some of the greatest warming in the world over the last few decades, and the effect of this warming on the hydro-climatology of this region is of major concern (Stewart *et al*., 1998). The Mackenzie River, with a drainage area of 1.8 x 10^6 km^2, is a major source of fresh water to the Arctic Ocean, and therefore contributes to the thermohaline circulation of the world's oceans, which regulates the global climate (Carmack, 2000). At the centre of the Mackenzie River basin, near the confluence with the Liard River, is an extensive flat headwater region with a high density of open water and wetlands that occupies the continental northern boreal region and the zone of discontinuous permafrost (Hegginbottom and Radburn, 1992). Discontinuous permafrost terrain is believed to be particularly sensitive to the effects of climatic warming, because pronounced changes in water storage and runoff pathways could occur with small additional ground heating (Rouse, 2000).

Over half the land surface of the lower Liard River valley is covered by wet organic terrain (Hamlin *et al*., 1998) that includes peat plateaus, channel fens and ombrotrophic flat bogs (Robinson and Moore, 2000; Quinton *et al*., 2003). Peat plateaus are underlain by permafrost, and their surfaces rise 1 to 2 m above the surrounding bogs and fens. Mature plateaus support shrubs and trees (*Picea mariana*), with the ground cover composed of lichens and mosses overlying 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 50 cm or more during summer, but it remains relatively close to the ground surface in the channel fens and flat bogs. Channel fens occupy the drainage network of basins, often taking the form of broad 50 to >100 m wide channels. Their surface is composed of a floating mat of *Sphagnum riparium*-dominated peat, approximately 0.5 to 1.0 m in thickness that supports sedges and various herbs and shrubs. Bog surfaces are relatively fixed and are covered with Sphagnum species, overlying yellowish peat with well-defined *Sphagnum* remains (Zoltai and Vitt, 1995). The arrangement of the channel fens on the landscape, and observation of flow over their surfaces, suggests that their hydrological function is primarily one of lateral-flow conveyance. The relatively high topographic position of the peat plateaus, in combination with the very low permeability of frozen, saturated peat, suggests that these features may act as 'permafrost dams' that obstruct and re-direct drainage in the surrounding wetlands. A major hydrological difference between fens and bogs is that fens convey flow from upstream to downstream areas, while bogs, being internally drained, have more of a storage than a flow-conveyance function (NWWG, 1988).

OBJECTIVE

Recognising that improved prediction of flows from ungauged basins is best achieved by an improved understanding of the governing processes, the objective of this paper is to examine the major water flux and storage processes within wetland-dominated basins of the discontinuous permafrost zone. This will be accomplished by discussing a selection of published and unpublished results on: 1) the physical and hydraulic properties of the active layer soils; 2) the hydrological functioning of the major peatland forms; 3) the water balance of selected basins in the region; and 4) a consideration of how basin water balances might be altered by climate warming.

THE STUDY REGION

Field studies were conducted in the lower Liard River valley, near Fort Simpson, Northwest Territories, Canada (Figure 1a), a zone of high wetland coverage (Hamlin *et al*., 1998; Robinson and Moore, 2000), in the 'continental high boreal' wetland region of Canada (NWWG, 1988) and in the zone of discontinuous permafrost (Hegginbottom and Radburn, 1992). 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). The Fort Simpson region is characterised by a dry continental climate with short, dry 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).

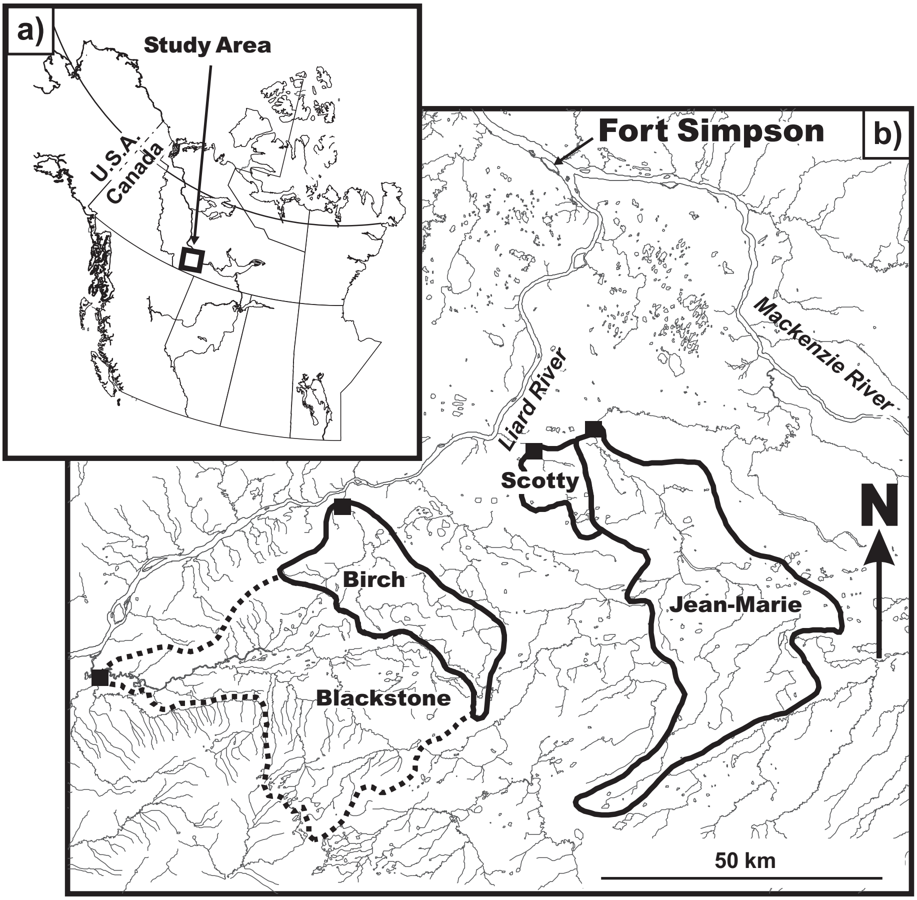

Figure 1. *a) The location of the lower Liard River valley within northwestern Canada. b) The Birch, Blackstone and Jean-Marie Rivers, and Scotty Creek study basins in the lower Liard River valley, near Fort Simpson, Northwest Territories, Canada. The gauging stations operated by the Water Survey of Canada are identified with solid black boxes. The catchment area of the Blackstone River has recently been revised by the WSC, and this most recent value (1910 km2) was used for all calculations in this paper. However, since the location of the basin boundary has not yet been published by the WSC, Figure 1b presents the former published estimate with a dashed line.*

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 drainage basins ranging in area from 150 to 2000 km^2 (Figure 1b). At the Jean-Marie, Blackstone and Birch Rivers, measurements were limited to discharge at the basin outlets, and to aerial reconnaissance and ground verification surveys. Most

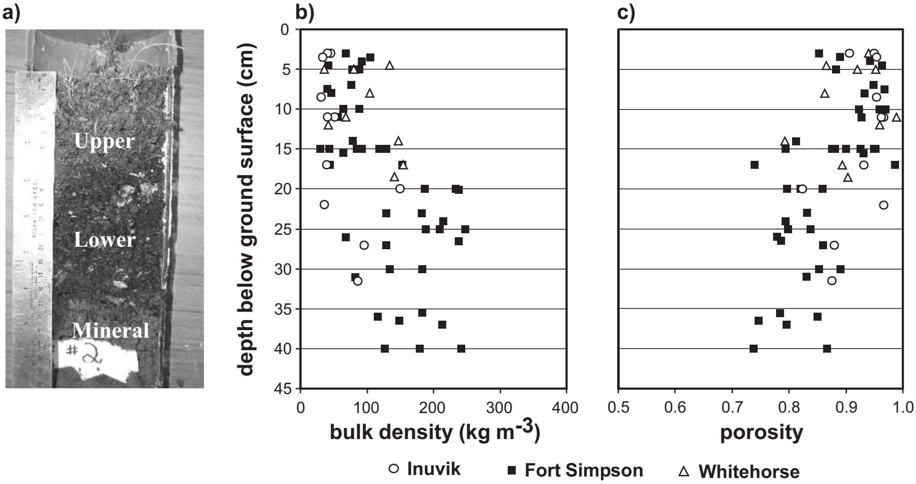

Figure 2. *a) photograph of typical organic soil profile in the study region showing upper and lower organic layers; variation in b) bulk density and c) total porosity with depth below the ground surface of a peat plateau at Scotty Creek. In b) and c), comparison is made with other organic cover types in northwestern Canada.*

fieldwork was conducted at Scotty Creek (61°18'N; 121°, 18'W), as it contained the major ground cover types within the region (i.e. channel fens, flat bogs, peat plateaus, and other wooded uplands) and was logistically manageable given its relatively small (152 km^2) size and close proximity to Fort Simpson.

SOIL PROPERTIES

Organic soils cover extensive portions of northwestern Canada, in the form of boreal forest, arctic and alpine tundra, taiga and wetland ecotones (Quinton and Gray, 2003). Despite the biophysical differences among these regions, the physical and hydraulic properties of their organic soils have a high degree of similarity. For example, soil profiles typically contain an upper, lightly decomposed layer, underlain by a darker layer in a more advanced state of decomposition (Figure 2a), although the thickness of the layers is highly variable at all site types. Because the degree of decomposition increases with depth below the ground surface, the bulk density generally increases with increasing depth (Figure 2b), while the porosity generally decreases (Figure 2c). Within these regions, peat is formed predominantly by Sphagnum species. Under similar conditions, a common botanical origin, such as a common suite of sphagnum species, could enable the process of decomposition to produce organic soils with a similar range of particle and inter-particle pore diameters.

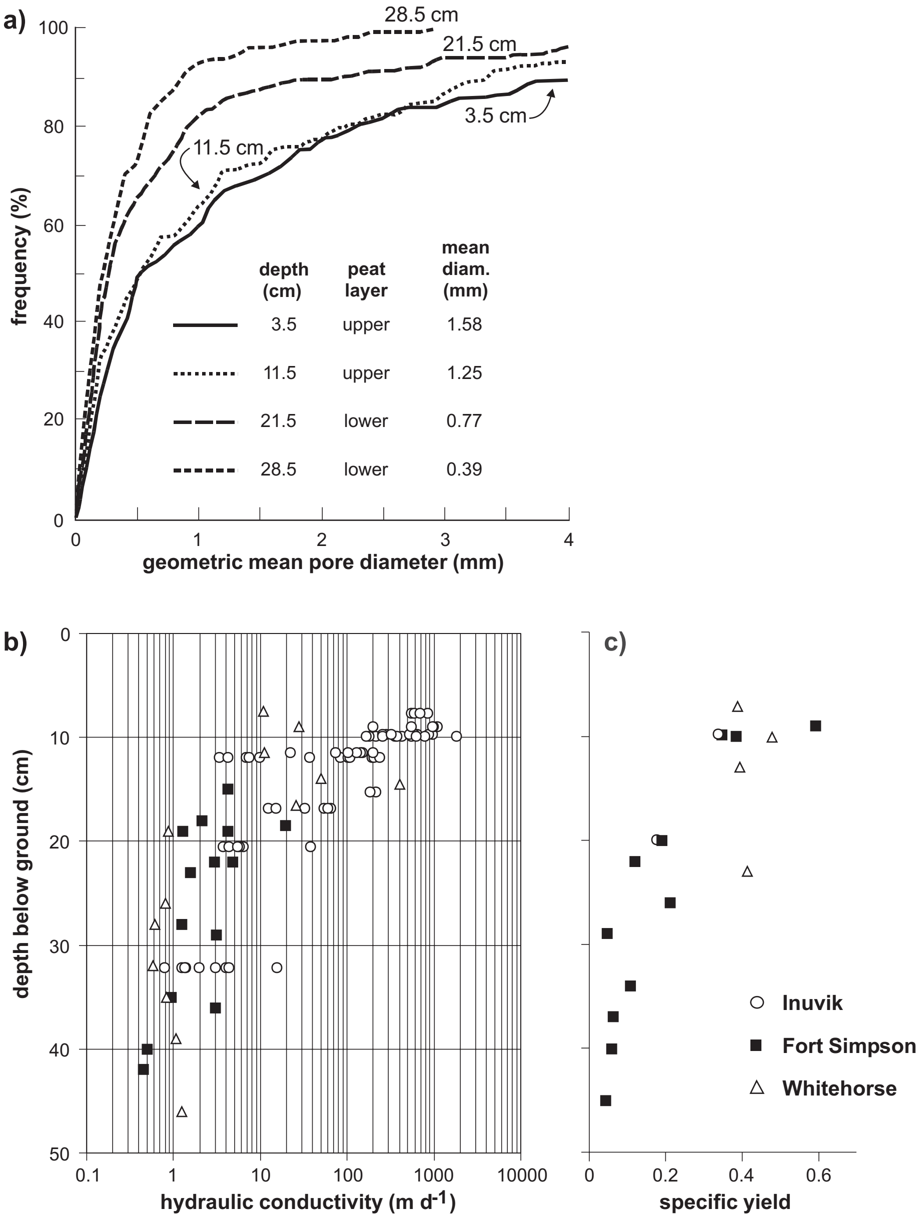

Figure 3. *a) The cumulative frequency distribution of pore diameters for pores less than 4 mm diameter at four depths below the ground surface. The upper two depths (3.5 and 11.5 cm) are in the upper peat layer, and the lower two (21.5 and 28.5 cm) are in the lower peat layer; variation in b) hydraulic conductivity and c) specific yield with depth below the ground surface of a peat plateau at Scotty Creek. In b) and c), comparison is made with other organic cover types in northwestern Canada.*

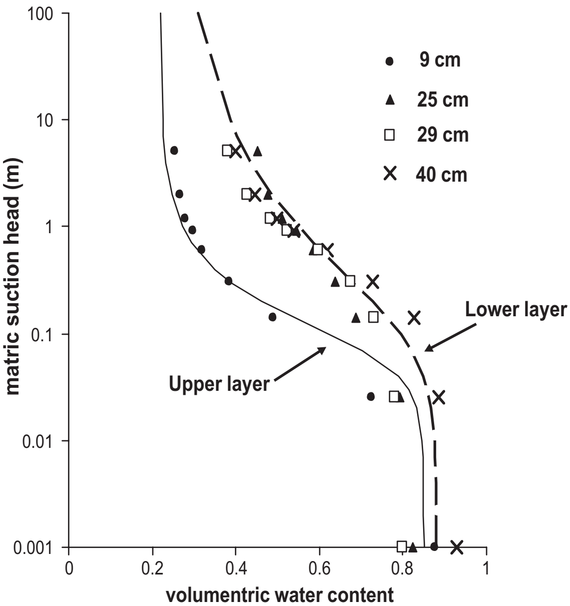

Figure 4. *The variation in soil moisture with soil tension for samples representing different depth positions in a soil pit on a peat plateau at Scotty Creek.*

This is important hydrologically since pore size controls both the flux and the storage of water in the active layer. The results of detailed microscopic analysis (Quinton *et al*., 2000) on soils sampled from the arctic tundra (Figure 3a) indicate that the lower layer contains a larger proportion of small-diameter pores. As a result, the hydraulic conductivity (Figure 3b) and 'specific yield' (Figure 3c) are substantially higher in the upper layer, compared to the lower layer (Quinton and Gray, 2000). Specific yield in the context of this paper 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 overnight. When saturated, the volumetric moisture content of the organic soils exceeds 80% (Figure 4). The moisture content of the relatively easily drained upper layer declines to a residual value of ca. 20% during periods of relatively high soil tension, such as in the late-summer period, and during soil freezing (Quinton *et al*., submitted).

RUNOFF GENERATION

Annual late winter snow surveys over the period 1993-2003 indicate that the peat plateaus accumulate a relatively large amount of snow. Because of their relatively high elevation and the presence of permafrost below their surfaces, much of the snowmelt and rainfall input to the plateaus drains laterally through the active layer to adjacent bogs and fens (Figure 5). The rate of subsurface drainage from peat plateaus strongly depends on the extent of soil thaw. As the soil thaws, the relatively impermeable frost table and the liquid-saturated layer immediately above it descend through peat of decreasing permeability (Figure 3b).

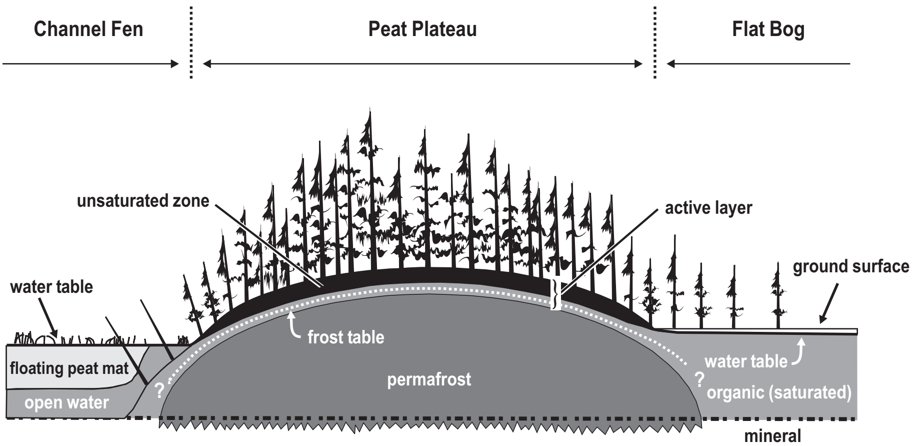

Figure 5. *A schematic cross-section of a peat plateau flanked by a channel fen on one side, and a flat bog on the other.*

For a peat plateau at Scotty Creek, the sequence of events producing the rapid runoff response to a 23 mm rainfall event is illustrated in Figure 6. Prior to this event, the water table was approximately 0.43 m below the ground surface. The relatively high hydraulic conductivity near the surface (Figure 3b) allows a rapid vertical delivery of infiltrating water to the zone of high water content above the water table, thereby causing a rapid rise of the water table. The water table responded to the 23 mm input by rising approximately 0.13 m, indicating a field-based specific yield of 18%, which is consistent with laboratory-based specific yield (Figure 3c) corresponding to the depth of 0.3-0.4 m. Figure 3b indicates that a rise of this magnitude can put the saturated layer into a zone where the hydraulic conductivity is one to two orders of magnitude higher, allowing efficient lateral drainage of subsurface water.

At the onset of the spring melt runoff period, the relatively impermeable frost table is typically *ca*. 0.1 m below the ground surface, and therefore in a zone of high hydraulic conductivity. How this condition develops during the winter period is not clear, since at the time of freeze-up, the water table is typically more than 0.5 m below the ground. Recent field studies (Quinton *et al*., submitted) suggest 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 measurements of liquid moisture using water content reflectometers (Campbell Scientific, CS 615) in a soil pit during the winter of

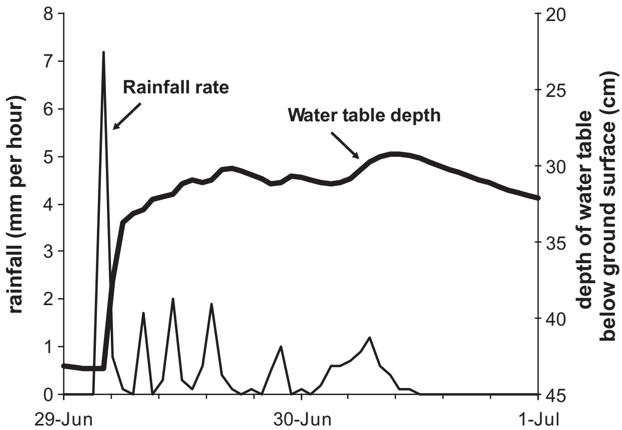

Figure 6. *The water table response on a peat plateau at Scotty Creek to a 23 mm rain event that occurred between 04:00 on 29 June and 11:00 on 30 June in 1999.*

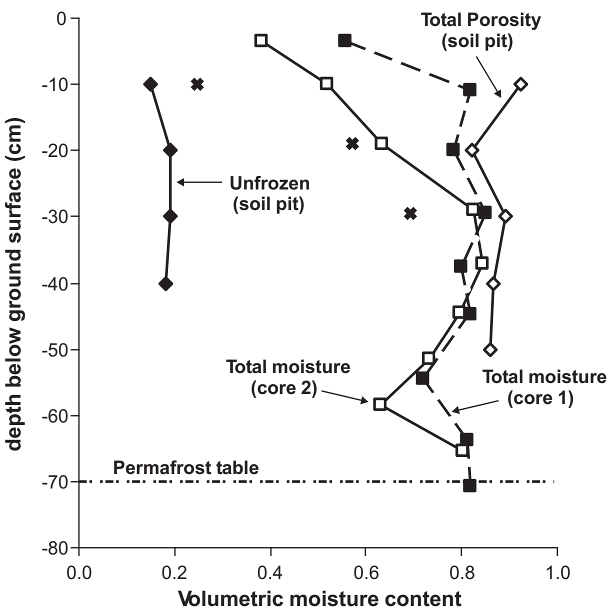

Figure 7. *The unfrozen and total (unfrozen + frozen) soil moisture content at Scotty Creek in the late winter period. The total soil moisture is derived from gravimetric measurements on two soil cores extracted from below the snow cover on 6 April, 2003. The unfrozen moisture was taken from the soil pit measurements on the same day. Soil porosity was measured on samples taken from the soil pit in August, 2001 when the sensors were installed. The crosses indicate the soil moisture just prior to freeze-up, at 10-, 20- and 30-cm depth increments.*

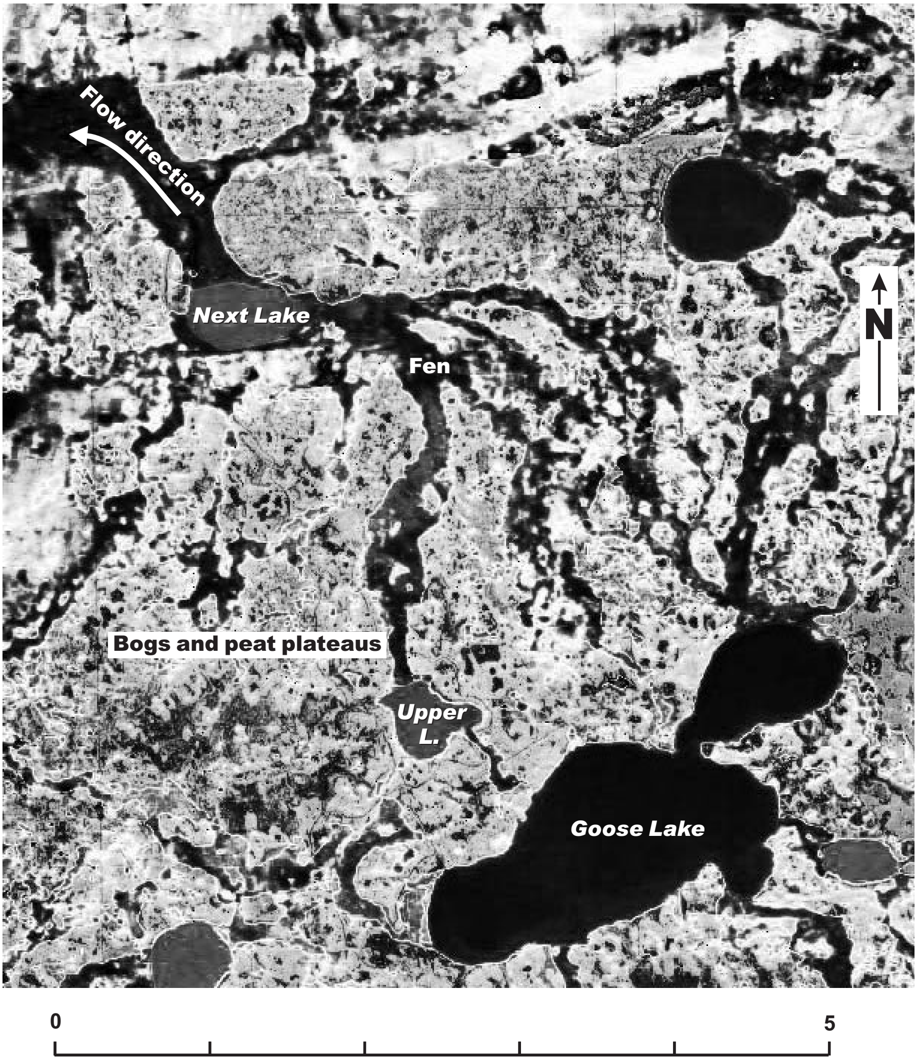

Figure 8. *A sample of the high-resolution (4 m × 4 m) IKONOS image showing the southern portion of the Scotty Creek basin. The image is unclassified and was converted from false-colour to a grey scale. The channel fens appear relatively dark compared with the surrounding areas composed of bogs and peat plateaus.*

2002-2003, and from measurements of total soil moisture (frozen and unfrozen) on two soil cores extracted in late winter (prior to snowmelt) near the pit (Figure 7). Analysis of the soil cores indicated that between freeze-up and late winter, the total (frozen and unfrozen) soil moisture increased throughout the profile, and that this increase was greatest close to the ground surface, particularly at the 0.1 m depth position. In both cores, the total soil moisture below 0.3 m was 5-10% below porosity, and was therefore close to a saturated state. In both cores, the unfrozen moisture content indicated by the measured values in the soil pit on the day the cores were sampled (Figure 7) was close to the minimum moisture value of 20% indicated by the fitted curves presented in Figure 4.

Considerably less research has been conducted on the hydrological functioning of the channel fens and flat bogs. Water level data 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 slowly 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 Scotty Creek basin, it is evident that channel fens are an integral component of the overall basin 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 in large-scale hydrological models. The apparent continuity of channel fens is clearly identified in satellite images (e.g. Figure 8), but the actual hydraulic connection likely depends on the water level. Flat bogs appear to be isolated from the drainage system on the surface. However, recent field observations suggest that under conditions of high water supply, such as during spring runoff, some bogs and channel fens become hydrologically connected, although the spatial and temporal variation of such connections, and its role on basin drainage, are poorly understood. Furthermore, the possibility that bogs are drained by subsurface flow has not been ruled out. Subsurface flow connections have been well established in temperate wetlands (e.g. Siegel and Glaser, 1987), but they are poorly documented in the discontinuous permafrost region.

PEATLAND FORM AND BASIN RUNOFF

Two multi-spectral images were recently acquired for the purpose of conducting a ground cover analysis of the study region: i) a 4 x 4 m resolution IKONOS image covering 90 km^2 of the 150 km^2 Scotty Creek basin, and ii) a 30 m x 30 m resolution Landsat image covering a 32,400 km^2 area of the lower Liard River valley that includes the four study basins. Both images were classified using the maximum likelihood method (Arai, 1992; Yamagata, 1997; Richards, 1984) 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 satellite images owing to the contrast in their

Table 1. *The size and aerial coverage of the major terrain types of the four study basins in the lower Liard River valley. The drainage density, average slope, and average annual, spring (i.e. April - May) and summer (i.e. June - August) runoff for the four years (1997 to 2000) of observation are shown for each basin.*

Basin	Area	Average annual runoff	Average spring runoff	Average summer runoff	Wooded	Fens	Bogs	drain. den.	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

surface characteristics. For example, because saturated surfaces absorb infrared light, the channel fens appear relatively dark compared with the surrounding bogs and peat plateaus (Figure 8). 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, and 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 simply from the difference between the maximum elevation and the elevation at the basin outlet, divided by the distance measured along the drainage way between these two points.

The biophysical attributes of the study basins derived from image analyses are presented in Table 1. The annual runoff had some degree of correlation with the percentage cover of channel fens and bogs (Figure 9). It is suggested that 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 hydrological function of these two wetland types. The majority of fens are connected to the drainage system and efficiently convey runoff water, while bogs are mostly disconnected from the main drainage system. Therefore, runoff is expected to increase with the cover of channel fens and decrease with increasing bog coverage. Annual runoff had positive correlations with both drainage density and the square root of basin slope, indicating that the basins with more efficient drainage mechanisms have higher annual runoff.

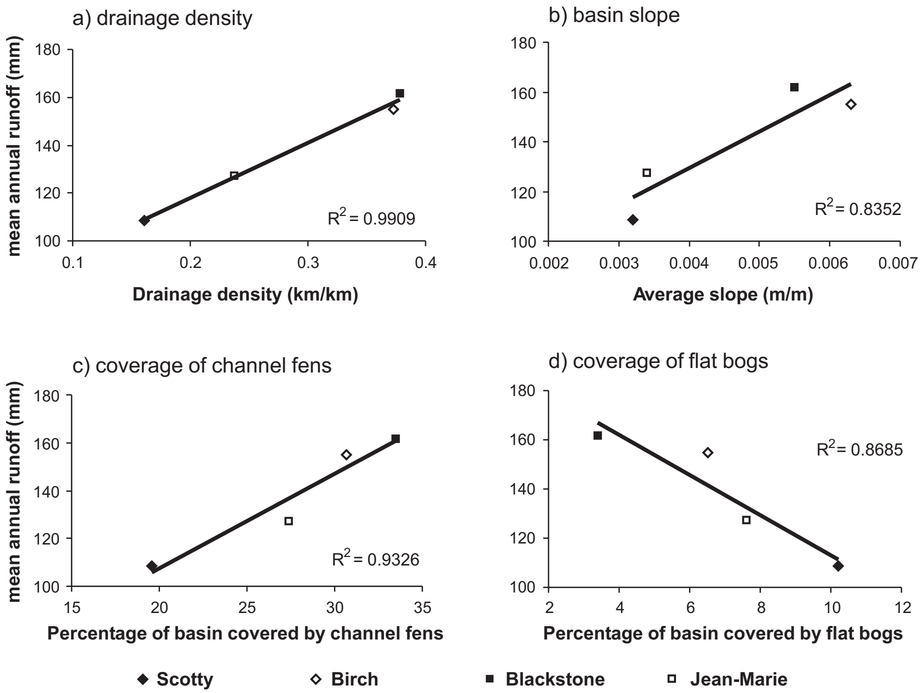

Figure 9. *The average runoff of the four-year period 1997 - 2000 is plotted with: a) drainage density; b) square root of the average basin slope; and the percentage of the basin covered by c) channel fens and d) flat bogs.*

The Scotty and Jean-Marie basins have relatively low average annual runoff values (Table 1), as these basins possess 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 bogs. The hydrographs of these basins are more delayed and have lower peaks than those of the Blackstone and Birch River basins (Figure 10). However, Scotty Creek and the Jean-Marie River differ greatly with respect to 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 River only 29% of the annual runoff had occurred. The greater basin lag of Jean-Marie River reflects the fact that this river drains an area approximately 8.5 times larger than the drainage area of Scotty Creek, and as a result, the average flow distance to the basin outlet is larger at Jean-Marie River.

The Blackstone and Birch River basins both possess the characteristics associated with high runoff production; namely, a relatively high average slope and drainage density, a high proportion of channel fens and a low coverage of

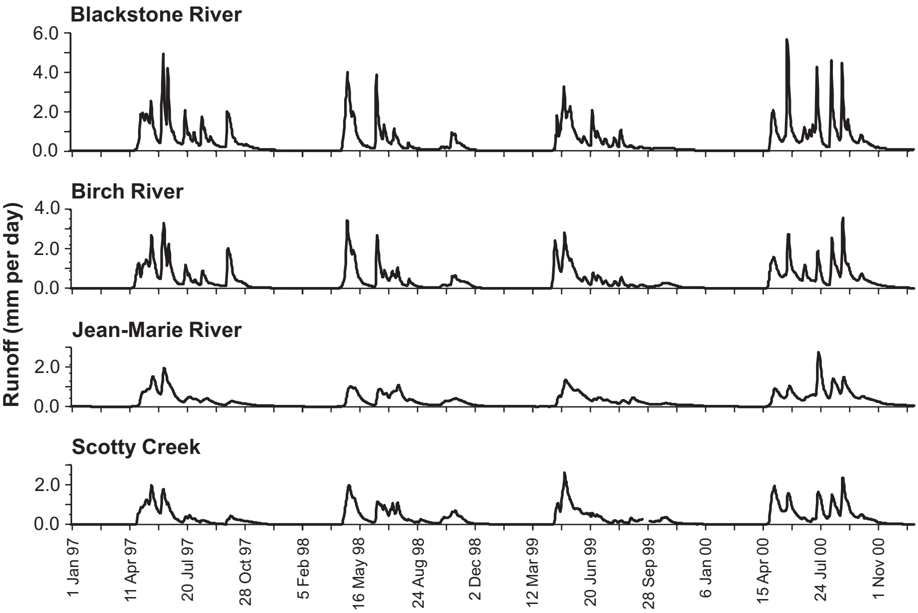

Figure 10. *The hydrographs measured at the outlets of the four study basins for the four-year period 1997 to 2000.*

bogs (Table 1). Consequently the average annual runoff production from these two adjacent basins was the highest among the four basins studied (Figure 9). 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 would account for the slightly larger average runoff from this basin compared with the Blackstone River during the April - May period (Table 1). Among the five basins studied, the Birch River basin was also 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.

BASIN WATER BALANCE

Evaporation

Over the four-year period, 1999-2002, while the cumulative precipitation was 1683 mm, only 593 mm discharged from Scotty Creek. Assuming that the difference was lost to evapotranspiration, the average annual evapotranspiration of this four-year period was 273 mm/yr. Claassen and Halm (1996) showed that a chloride mass balance can be used to estimate the basin-scale evapotranspiration when the lithological source of chloride is negligible. The underlying mineral soil is mainly derived from clay-rich glacial till having low hydraulic conductivity. The extensive literature on the hydrogeology of clay-rich glacial till in western Canada suggests that active flow of groundwater is limited to a relatively shallow (< 10 m) local system (Hayashi *et al*., 1998a) and that pre–Holocene chloride within the active flow system has been flushed out (Hayashi *et al*., 1998b). Therefore, Scotty Creek provides favourable conditions for applying the chloride method, where chloride enters the system predominantly through precipitation, and is lost predominantly through stream flow. Using the chloride method, evapotranspiration *Et* is given by

$$Et = P\ (C_s - C_p)\ /\ C_s \tag{1}$$

where P is annual precipitation, and C_s and C_p 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 C_s for the four-year period was 0.151 mg/L. The average C_p (= 0.044 mg/L) 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) presented by Hayashi *et al*. (1998b). The average precipitation for the hydrological years 1999-2002 was 421 mm/yr (Table 2). Therefore, Eq. (1) gives *Et* = 298 mm/yr, which agrees with the hydrometric estimate of 273 mm/yr. A simple arithmetic average

Table 2. *Fort Simpson annual and summer (May-September) precipitation for each hydrological 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 reported in mm. n/a indicates the data not available. Normal precipitation is for 1971-2000.*

	Normal	1999	2000	2001	2002
Period		**10/98-09/99**	**10/99-09/00**	**10/00-09/01**	**10/01-09/02**
Total pcp.	369	409	431	431	412
May-Sep pcp.	21	238	296	316	269
SWE	n/a	90	101	n/a	142
Total runoff	n/a	96	139	161	197

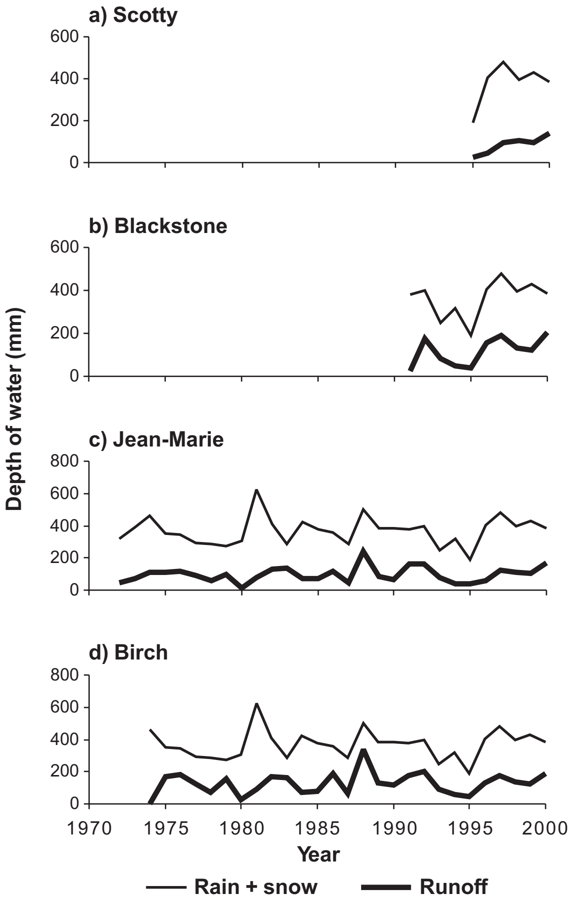

Figure 11. *The total annual runoff R, measured at the outlet of the a) Scotty Creek, b) Blackstone River, c) Jean-Marie River and d) Birch River basins for the entire gauging period at these stations. Total Annual precipitation P, (rain and snow), was measured at Fort Simpson and is plotted for the same period.*

concentration of the 43 samples was 0.133 mg/L. Using this value for C_s in Eq. (1) gives Et = 282 mm/yr, 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.

Precipitation and Runoff

The entire daily discharge record for the Birch (1974-2000), Blackstone (1991-2000), and Jean-Marie (1972-2000) rivers, and Scotty Creek (1995-2000) measured at the Water Survey of Canada (WSC) gauging stations (Figure 1b) was compiled. Annual runoff from the study basins is generally below 200 mm

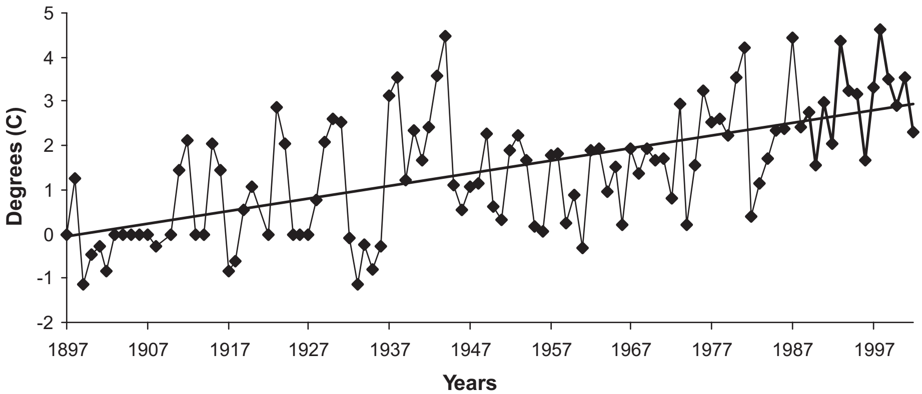

Figure 12. *The average maximum daily temperature for each year for the period 1897 - 2000 measured at Fort Simpson.*

(Figure 11). 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 means of water loss from basins in this region, accounting for approximately two-thirds to three-quarters of the annual precipitation input. Dividing the difference between the cumulative runoff and cumulative precipitation by the number of years of record shown in Figure 11 suggests annual average *Et* rates of 297 mm (Scotty), 271 mm (Jean-Marie), 245 mm (Blackstone) and 241 mm (Birch).

WATER BALANCE-CLIMATE INTERACTION

Daily temperatures (mean, minimum and maximum) at Fort Simpson were obtained from the Meteorological Service of Canada for the period 1895-2003. For the same period, the daily total rainfall and snowfall was also compiled. The long-term record of air temperatures (1897 - 2000) suggests that Fort Simpson warmed slightly throughout the 20th century. This is especially noticeable with the record of the time series of the average annual daily maximum temperatures (Figure 12). This measure of temperature was usually below 0°C in the first half of the 20th century, but was below 0°C only once in the second half of that century. Aerial photographic documentation over the Fort Simpson region for the period 1947 - 2000 has shown that the flat bogs, peat plateaus and channel fens are highly dynamic; as peat plateaus degrade into bogs, new plateaus form, and channel fens laterally shift their position. Robinson (2002) determined that over this period, the permafrost coverage of a ca. 0.25 km^2 wetland area 40 km west of Fort Simpson decreased from ca. 45% to 22%. A reduction in the coverage of peat plateaus would be expected with a warming climate, since it is the peat plateaus that are underlain by permafrost. Given the different hydrological functions of bogs, fens and peat plateaus, a change in the relative proportions of these cover types will have implication for the flux and storage of water within the drainage basins of this region.

SUMMARY AND FUTURE DIRECTIONS

From the results of recent studies (e.g. Hayashi *et al*., 2004; Quinton *et al*., 2003), a conceptual model of runoff generation for the wetland-dominated basins of the lower Liard River valley has begun to develop. Peat plateaus represent areas of saturated permafrost that rise above the surrounding terrain. This enables them to effectively impound water in the bogs, while re-directing flow in the fens. Owing to their relatively high topographic position and the limited water storage capacity within their active layer, peat plateaus also shed water to the surrounding wetlands. The flowpath then followed by this drainage water depends upon the type of wetland that receives it. Water entering channel fens is more likely to be conveyed toward the basin outlet, than water entering bogs. This conceptual model contributes to resolving some of the difficult issues in the hydrological modelling of northern basins, especially in relation to the storage and routing functions of wetlands. Runoff-generation algorithms in hydrological models must account for the storage capacity of the bogs. Similarly, routing algorithms in distributed hydrological models need to incorporate the network of channel fens. Preliminary studies suggest that surface roughness and channel slope may be the essential factors controlling the flow of surface water in channel fens.

There are still some major challenges before the conceptual model can be successfully implemented in numerical algorithms. Although flat bogs appear to be isolated from the drainage system on the surface, the possibility of hydrological connection to the fens via ground water systems has not been investigated. Likewise, 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 the temporal and spatial variability.

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 direction and magnitude of turbulent heat exchanges and subsurface heat flux (Pomeroy *et al*. 2003). This meltwater release also changes the character of the land-surface, creating a mosaic of snow, bare ground (with or without vegetation) and water-covered lands (temporary standing water) for several weeks (Bowling *et al*. 2003). The infiltration, storage and redistribution of water within the active layer is exceptionally complex due to phase changes, abrupt depth variations in soil transmission properties, and spatial and temporal variations in the elevation of the relatively impermeable frost table (Gray *et al*. 2001). Additionally, soil moisture variability also effects summer evaporation and therefore the recycling of water within drainage basins.

Because the dominant peatland forms contrast sharply in terms of their hydrometeorological functioning, changes in their relative coverage will affect the cycling of water and energy within the drainage basins of this region. 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 improve our ability to understand and therefore predict climate-induced changes to the water cycle in this region.

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REFERENCES

Arai, K. 1992. Maximum Likelihood TM Classification-Taking the Effect of Pixel to Pixel Correlation into Account. *Geocarto International,* 7: 33-39.

Aylesworth, J.M. and I.M. Kettles. 2000. Distribution of Fen and Bog in the Mackenzie Valley, 60°N - 68°N. Natural Resources Canada, Geological Survey of Canada Bulletin, 547 pp.

Bowling, L.C., D.L. Kane, R.E. Gieck, L.D. Hinzman and D.P. Lettenmaier. 2003. The Role of Surface Storage in a Low-gradient Arctic Watershed. *Water Resources Research,* 39: 1087.

Carmack E.C.. 2000. The Arctic Ocean's Freshwater Budget: Sources, Storage and Export. In: *The Freshwater Budget of the Arctic Ocean*, Lewis, E.L., E.P. Jones, P. Lemke, T. D. Prowse, P. Wadhams. (eds). Kluwer Academic Publishers: Dordrecht, Netherlands, 91-126.

Claassen, H.C. and D.R. Halm. 1996. Estimates of Evapotranspiration or Effective Moisture in Rocky Mountain Watersheds from Chloride Ion Concentrations in Stream Baseflow. *Water Resources Research,* 32: 363-372.

Gray, D.M., B. Toth, L. Zhao, J.W. Pomeroy and R. Granger. 2001. Estimating Areal Snowmelt Infiltration into Frozen Soils. *Hydrological Processes,* 15: 3095-3111.

Hamlin, L., A. Pietroniro, T. Prowse, R. Soulis and N. Kouwen. 1998. Application of Indexed Snowmelt Algorithms in a Northern Wetland Regime. *Hydrological Processes,* 12: 1641-1657.

Hayashi, M., G. van der Kamp and D.L. Rudolph. 1998a. Water and Solute Transfer between a Prairie Wetland and Adjacent Uplands, 1. Water Balance. *Journal of Hydrology,* 207: 42-55.

Hayashi, M., G. van der Kamp, and D.L. Rudolph. 1998b. Water and Solute Transfer between a Prairie Wetland and Adjacent Uplands, 2. Chloride Cycle. *Journal of Hydrology,* 207: 56-67.

Hayashi, M., W.L. Quinton, A. Pietroniro and J. Gibson. 2004. Hydrologic Functions of Wetlands in a Discontinuous Permafrost Basin indicated by Isotopic and Chemical Signatures. *Journal of Hydrology,* 296: 81-97.

Hegginbottom, J.A. and L.K. Radburn,. 1992. Permafrost and Ground Ice Conditions of Northwestern Canada. Geological Survey of Canada, Map 1691A, scale 1:1 000 000.

Lillesand T.M. and R.W. Kiefer. 1994. *Remote Sensing and Image Interpretation*. Wiley, 319 pp.

Meteorological Service of Canada (MSC), 2002. National Climate Data Archive of Canada. Environment Canada: Dorval, Quebec, Canada.

National Wetlands Working Group (NWWG), 1988. Wetlands of Canada: Ecological Land Classification Series, no. 24. Sustainable Development Branch, Environment Canada, Ottawa, Ontario, and Polyscience Publications Inc., Montreal, Quebec, 452 pp.

Pomeroy, J.W., B. Toth, R.J. Granger, N.R. Hedstrom and R.L.H. Essery. 2003. Variation in Surface Energetics during Snowmelt in a Subarctic Mountain Catchment. *Journal of Hydrometeorology,* 4: 702-719.

Quinton, W.L., S.K. Carey and M. Hayashi. Submitted. Controls on Soil Moisture Variability and the Development of an Impermeable Frozen Layer in Organic-cover Permafrost Terrains. *Nordic Hydrology*.

Quinton, W.L., M. Hayashi and A. Pietroniro. 2003. Connectivity and Storage Functions of Channel Fens and Flat Bogs in Northern Basins. *Hydrological Processes,* 17: 3665-3684.

Quinton, W.L. and D.M. Gray. 2003. Subsurface Drainage from Organic Soils in Permafrost Terrain: The Major Factors to be Represented in a Runoff Model. Proceedings of the 8th International Conference on Permafrost, Davos, Switzerland, 6 pp.

Quinton, W.L., D.M. Gray and P. Marsh P. 2000. Subsurface Drainage from Hummock–covered Hillslopes in the Arctic–tundra. *Journal of Hydrology* 237: 113-125.

Richards, J.A. 1984. Thematic Mapping from Multitemporal Image Data using the Principal Components Transformation, *Remote Sensing of Environment*, 16: 35-46

Robinson S.D. and T.R. Moore. 2000. The Influence of Permafrost and Fire upon Carbon Accumulation in High Boreal Peatlands, Northwest Territories, Canada. *Arctic, Antarctic and Alpine Research,* 32: 155-166.

Robinson, S.D. 2002. Peatlands of the Mackenzie Valley: Permafrost, Fire, and Carbon Accumulation. In: *Long-Term Dynamics and Contemporary Carbon Budget of Northern Peatlands*, Z.C. Yu, J.S. Bhatti and M.J. Apps. (eds.). Proc. of International Workshop on Carbon Dynamics of Forested Peatlands: Knowledge Gaps, Uncertainty and Modelling Approaches. 23-24 March, 2001, Edmonton, Alberta, 21-24.

Rouse, W.R. 2000. Progress in Hydrological Research in the Mackenzie GEWEX Study. *Hydrological Processes,* 14: 1667-1685.

Siegel, D.I. and P.H. Glaser. 1987. Groundwater Flow in a Bog-fen Complex, Lost River peatland, Northern Minnesota. *Journal of Ecology,* 75: 743-754.

Stewart, R.E. *et al*. 1998. The Mackenzie GEWEX Study: The Water and Energy Cycles of a Major North American River Basin. *Bulletin of the American Meteorological Society,* 79: 2665-2683.

Yamagata, Y. 1997. Advanced Remote Sensing Techniques for Monitoring Complex Ecosystems: Spectral Indices, Unmixing, and Classification of Wetlands. Ph.D. thesis, University of Tokyo.

Zoltai, S.C. and D. Vitt. 1995. Canadian Wetlands - Environmental Gradients and Classification. *Vegetation,* 118: 131-137.