

## The water balance of wetland-dominated permafrost basins

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**Abstract** Field studies were conducted in the wetland-dominated region of discontinuous permafrost of the lower Liard River valley in order to: (a) estimate the relative magnitudes of basin water balance components; and (b) demonstrate associations between total annual runoff and the relative proportions of flat bogs, channel fens and peat plateaus within this region. Annual runoff from the study basins is generally below 200 mm, while evapotranspiration ranges between 200 and 500 mm. The magnitude of the annual basin runoff increases with increasing coverage of channel fen, but decreases as the proportion of flat bogs increases.

**Key words** channel fens; evapotranspiration; flat bogs; peat plateaus; permafrost; runoff; water balance

### INTRODUCTION

The Mackenzie River basin in northern Canada has experienced some of the greatest warming in the world over the last few decades; the effect of this warming on the hydrological regime of the region is of major concern (Stewart *et al.*, 1998). The central part of the Mackenzie River basin, drained by the Liard River, is located in the continental high boreal wetland region of Canada (NWWG, 1988) and in the zone of discontinuous permafrost (Hegginbottom & Radburn, 1992). Over one-half of the land surface of the lower Liard River valley is covered by wet organic terrain (Hamlin *et al.*, 1998), largely composed of peat plateaus, flat bogs and channel fens (Robinson & Moore, 2000; Quinton *et al.*, 2003). Mature plateaus support shrubs and trees (*Picea mariana*), with the ground cover composed of folios lichens and *Sphagnum* mosses. Their surfaces are underlain by permafrost, and rise 1–2 m above the surrounding bogs and fens. During summer, the water drains to depths in excess of 50 cm on the peat plateaus, while in the bogs and fens, it remains sufficiently close to the ground surface so that these areas can be described as wetlands (NWWG, 1988). The fens are located along the drainage network of basins, often taking the form of broad, 50 to >100 m wide channels. The surface of these “channel fens” (NWWG, 1988) is composed of a floating mat of *S. riparium*-dominated peat, approximately 0.5–1.0 m in thickness, whose surface 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 & Vitt, 1995).

Recent studies (Hayashi *et al.*, 2005; Quinton *et al.*, 2003) have demonstrated that the peat plateaus, flat bogs and channel fens all have different hydrological functions,

and consequently, changes in the relative proportions of these organic cover types within a basin would have the potential of altering the water cycle at the basin scale. For example, the arrangement of the channel fens on the landscape, and observations of flow over their surfaces indicates their importance in surface and subsurface lateral flow conveyance. Owing to their relatively high topographic position and the very low permeability of frozen, saturated peat, the peat plateaus act as permafrost dams that impound water in flat bogs and re-direct flow along channel fens. Bogs, being internally drained, have more of a storage than a flow conveyance function (NWWG, 1988). It is therefore reasonable to assume that basins with a higher proportion of bogs would produce less runoff per unit input (Quinton *et al.*, 2003).

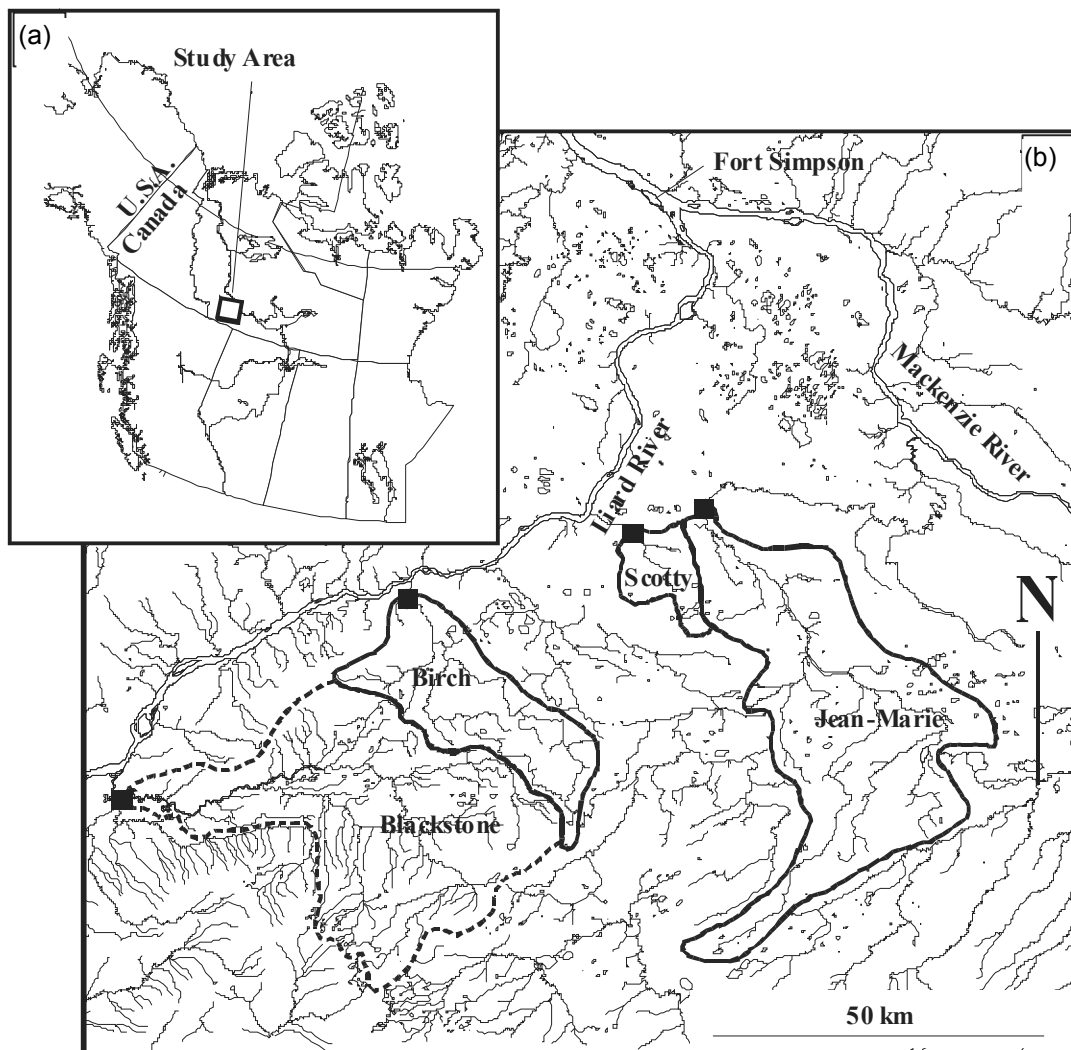
The objective of this paper is to present a selection of published and unpublished results that demonstrate: (a) the relative magnitudes of the total annual precipitation (rain and snow), runoff and evaporation terms in the water balance of wetland-dominated basins in a zone of discontinuous permafrost; and (b) associations between total annual runoff and the relative proportions of flat bogs, channel fens and peat plateaus within drainage basins of this zone.

## STUDY SITE

Field studies were conducted in the lower Liard River valley, near Fort Simpson, Northwest Territories, Canada (Fig. 1), a zone of high wetlands coverage (Hamlin *et al.*, 1998; Robinson & Moore, 2000), in the “continental high boreal” wetland region of Canada (NWWG, 1988) and in the zone of discontinuous permafrost (Hegginbottom & 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 & Kettles, 2000). The Fort Simpson region is characterized by a dry continental climate, with short, dry summers, and long cold winters. It has an average (1971–2000) annual air temperature of  $-3.2^{\circ}\text{C}$ , and receives 369 mm of precipitation annually, of which 46% is snow (MSC, 2002). Field measurements were taken at four gauged drainage basins ranging in area from 152 to 2000 km<sup>2</sup>. 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 fieldwork was conducted at Scotty Creek ( $61^{\circ}18'N$ ,  $121^{\circ}18'W$ ), as it contained the major ground cover types within the region and was logistically manageable given its relatively small (152 km<sup>2</sup>) size.

## METHODS

The entire daily discharge record for the Birch (1974–2000), Blackstone (1991–2000), Jean-Marie (1972–2000) and Scotty (1995–2000), measured at the Water Survey of Canada (WSC) gauging stations, were compiled. The daily total rainfall and snowfall measured at Fort Simpson was also compiled for these periods. Two multi-spectral images of the study region were acquired: (i) a  $4 \times 4$  m resolution IKONOS image covering 90 km<sup>2</sup> of the 150 km<sup>2</sup> Scotty Creek basin, and (ii) a  $30 \times 30$  m resolution Landsat image covering a 32 400 km<sup>2</sup> area of the lower Liard River valley that



**Fig. 1** (a) 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 km<sup>2</sup>) was used for all calculations in this paper. However, since the location of the basin boundary has not yet been published by the WSC, Fig. 1(b) presents the former published estimate with a dashed line.

includes the four study basins. Both images were classified using the maximum likelihood method (Richards, 1984; Arai, 1992; Yamagata, 1997) with training sites (Lillesand & Kiefer, 1994) obtained from homogeneous areas, including flat bogs, channel fens and peat plateaus. 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 channel 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 (including channel fens and open stream channels) between these two points.

Field measurements were conducted at Scotty Creek over the 4-year period between 1999 and 2002. Surface water was sampled from the basin outlet at an interval that varied from weekly during spring runoff to monthly during summer. Over the same period, subsurface water was collected from the active layer at monitoring wells, and rainwater was sampled from a bulk raingauge at the Environment Canada office in Fort Simpson. The rain samples were transferred to sample bottles on the same day or the next day following each rain event to minimize the effects of evaporation. Depth-integrated samples of the snowpack were collected during the annual snow survey in March of each year. The concentration of major ions was analysed using atomic absorption spectroscopy and ion chromatography. The samples for chemical analysis were filtered using 0.45- $\mu\text{m}$  membrane filters.

## SUMMARY OF MAJOR FINDINGS

### Measured and computed fluxes

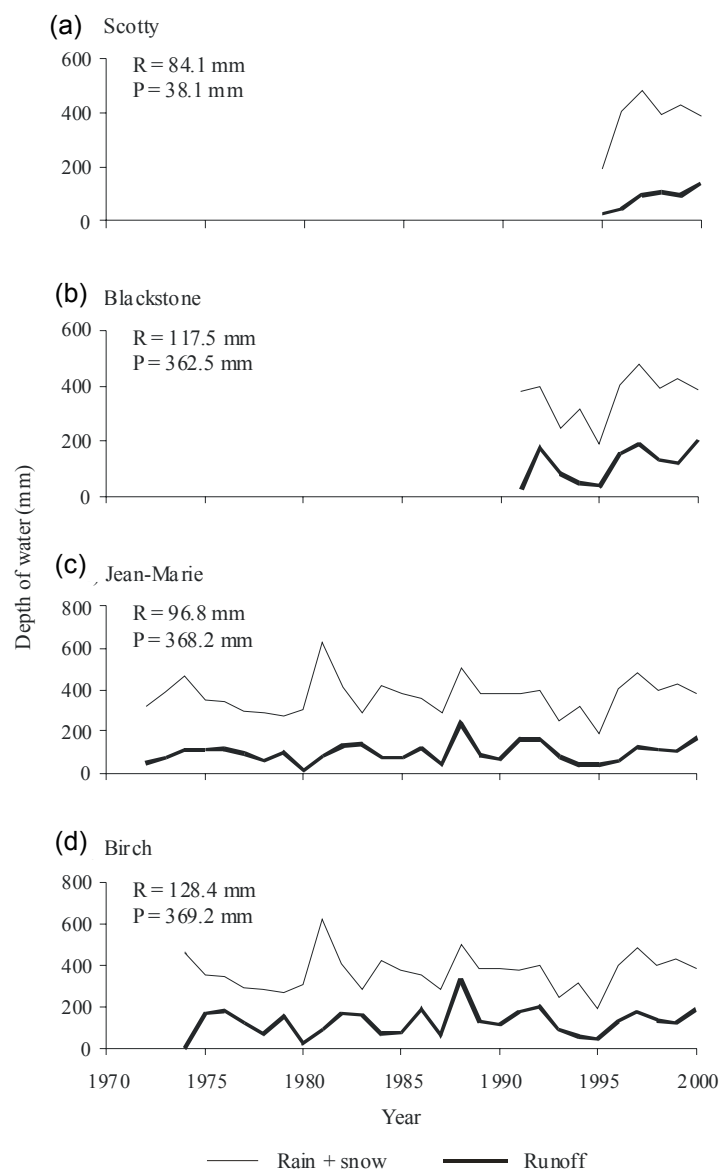
Over the 4-year period 1999–2002, while the cumulative precipitation was 1683 mm, only 593 mm discharged from Scotty Creek. Assuming that the difference was lost to evapotranspiration, the average annual evapotranspiration of this 4-year period was 273 mm year<sup>-1</sup>. Claassen & Halm (1996) showed 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:

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

where  $P$  is annual precipitation, and  $Cs$  and  $Cp$  are the volume-weighted average chloride concentration in stream water and precipitation, respectively. A total of 43 water samples were collected at the outlet between March and December during 1999–2002 and analysed for chloride. 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 4-year period was 0.151 mg l<sup>-1</sup>. The average  $Cp$  (= 0.044 mg l<sup>-1</sup>) 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<sup>-1</sup>) presented by Hayashi *et al.* (1998b). The average precipitation for the hydrological years 1999–2002 was 421 mm year<sup>-1</sup> (Table 1). Therefore, equation (1) gives  $Et = 298$  mm year<sup>-1</sup>, which agrees with

**Table 1** Fort Simpson annual and summer (May–September) precipitation for each hydrologic year (1 October to 30 September), 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 is not available. Normal precipitation is for 1971–2000.

	Normal	1999	2000	2001	2002
Period		Oct 1998–Sep 1999	Oct 1999–Sep 2000	Oct 2000–Sep 2001	Oct 2001–Sep 2002
Total precip.	369	409	431	431	412
May–Sep precip.	221	238	296	316	269
SWE	n/a	90	101	n/a	142
Total runoff	n/a	96	139	161	197



**Fig. 2** 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) measured at Fort Simpson is plotted for the same period. For each basin, the average annual precipitation (measured at Fort Simpson) and average annual runoff for the period of record are also given.

the hydrometric estimate of 273 mm year<sup>-1</sup>. A simple arithmetic average concentration of the 43 samples was 0.133 mg l<sup>-1</sup>. Using this value for  $C_s$  in equation (1) gives  $Et = 282$  mm year<sup>-1</sup>, 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. Annual runoff from the study basins is generally below 200 mm (Fig. 2). 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 (Fig. 1) suggests annual average  $Et$  rates of 297 mm (Scotty), 271 mm (Jean-Marie), 245 mm (Blackstone), and 241 mm (Birch). The basins with the high  $ET$  rates (Scotty and Jean-Marie) had relatively low average annual runoff rates (Fig. 2).

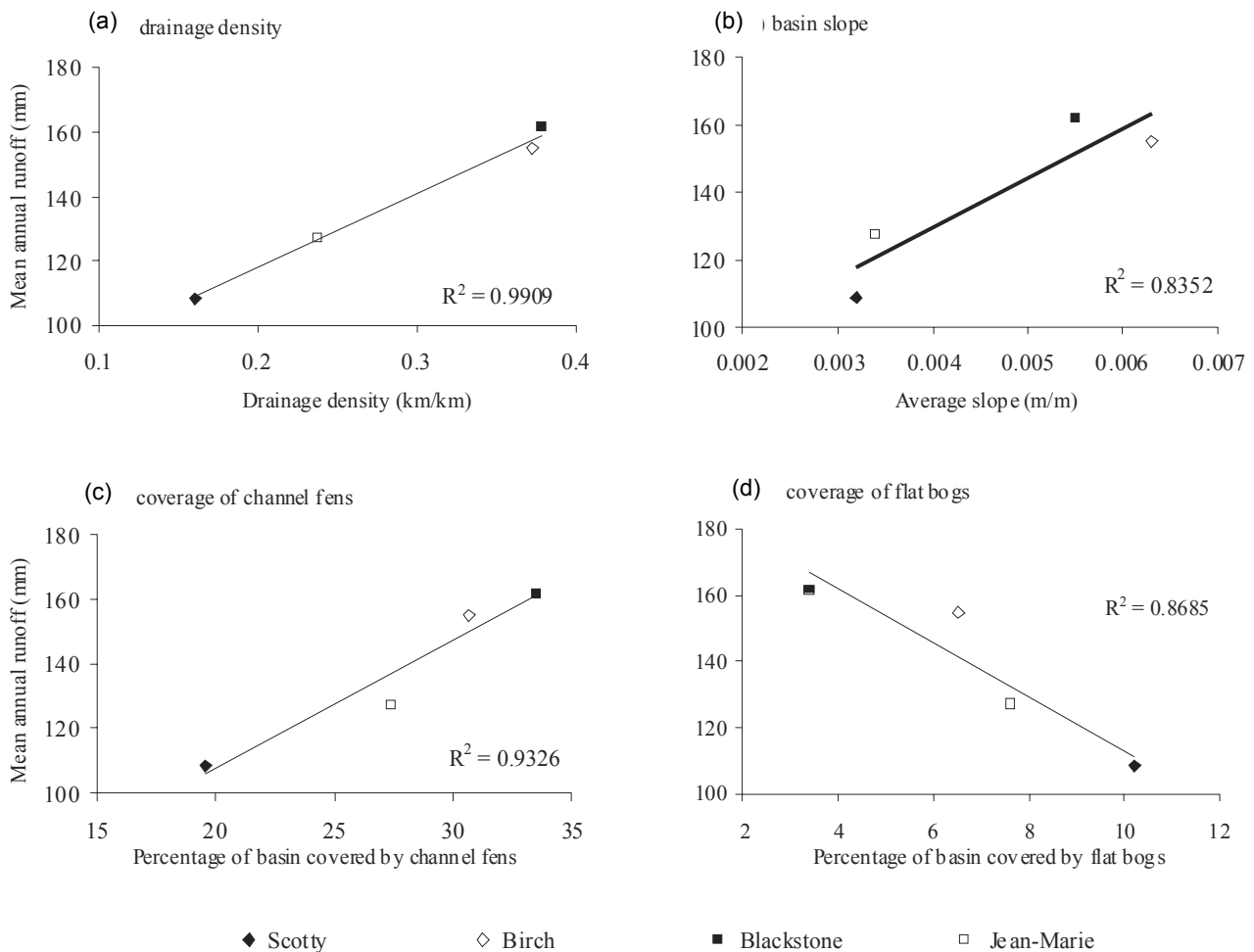
### Runoff related to drainage basin characteristic

The biophysical attributes of the study basins derived from image analyses are presented in Table 2. The annual runoff had some degree of correlation with the percentage cover of channel fens and bogs (Fig. 3). 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.

The Scotty and Jean-Marie basins have relatively low average annual runoff values (Table 2), 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

**Table 2** Size and aerial coverage of the major terrain types of the four study basins in the lower Liard River valley. For each basin, drainage density, average slope, and average annual, spring (i.e. April–May) and summer (i.e. June–August) runoff for the 4 years (1997–2000) of observation are shown.

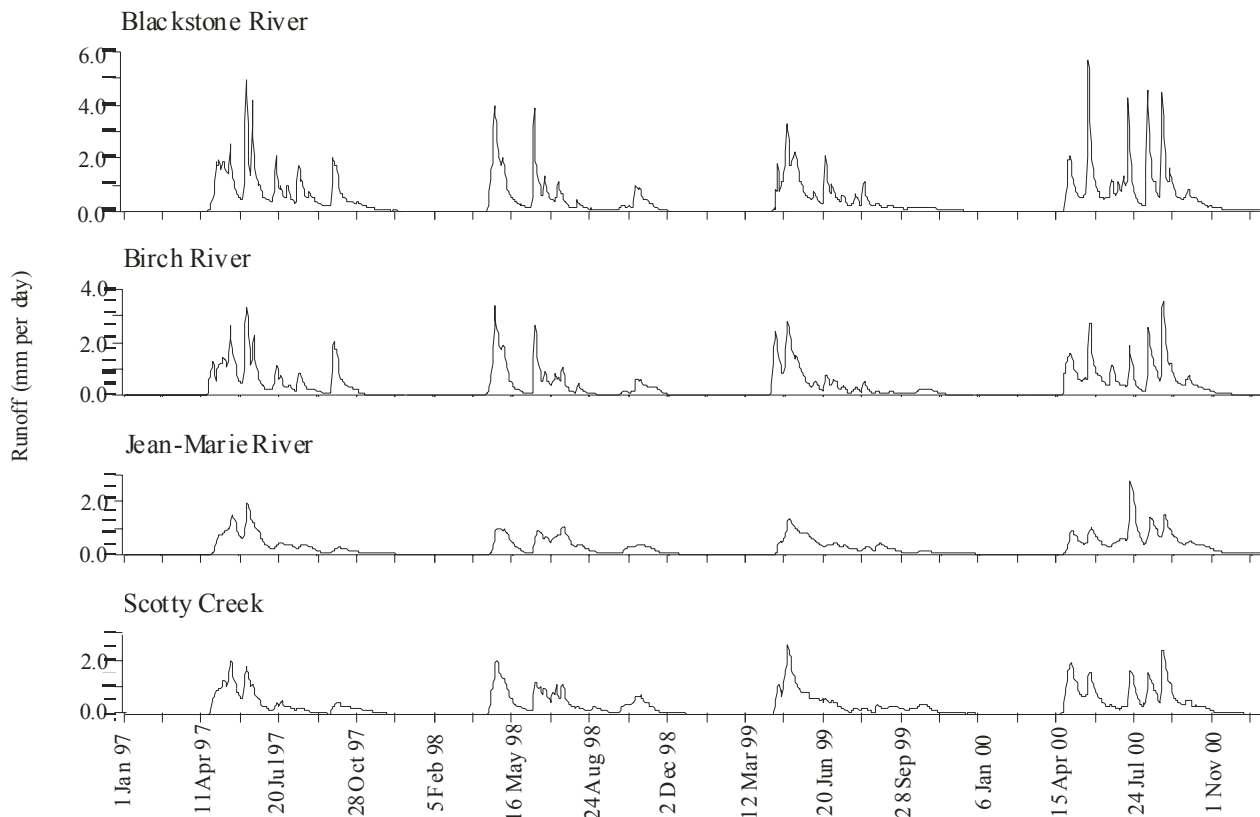
Basin	area (km <sup>2</sup> )	Average annual runoff (mm)	Average spring runoff (mm)	Average summer runoff (mm)	Wooded (% of basin)	Fens (% of basin)	Bogs (% of basin)	Drain. den. (km km <sup>-2</sup> )	Avg. slope (m m <sup>-1</sup> )
Blackstone	1910	161.8	56.8	105.0	66.8	33.5	3.4	0.378	0.0055
Jean-Marie	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



**Fig. 3** The average runoff of the 4-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.

basins (Fig. 4). However, Scotty and Jean-Marie 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, 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 the drainage area of Scotty Creek, and as a result, the average flow distance to the basin outlet is larger at Jean-Marie.

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 bogs (Table 2). Consequently the average annual runoff production from these two adjacent basins was the highest among the four basins studied (Fig. 3). 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 during the April–May period (Table 2). Among the four basins studied, the Birch River basin was also the



**Fig. 4** The hydrographs measured at the outlets of the four study basins for the 4-year period 1997–2000.

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.

**Acknowledgements** The authors wish to acknowledge the financial support of the Natural Sciences and Engineering Research Council, and the Canadian Foundation for Climate and Atmospheric Sciences. Dr A. Pietroniro of the National Water Research Institute helped to co-ordinate the field programmes. The authors also acknowledge the logistical support given by Gerry Wright and Roger Pilling of the Water Survey of Canada in Ft Simpson. The NatChem data were provided by the Meteorological Service of Canada and the Government of the Northwest Territories, Environmental Protection Service.

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