Connectivity and storage functions of channel fens and flat bogs in northern basins

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Abstract:

The hydrological response of low relief, wetland-dominated zones of discontinuous permafrost is poorly understood. This poses a major obstacle to the development of a physically meaningful meso-scale hydrological model for the Mackenzie basin, one of the world's largest northern basins. The present study examines the runoff response of five representative study basins (Scotty Creek, and the Jean-Marie, Birch, Blackstone and Martin Rivers) in the lower Liard River valley as a function of their major biophysical characteristics. High-resolution (4 m × 4 m) IKONOS satellite imagery was used in combination with aerial and ground verification surveys to classify the land cover, and to delineate the wetland area connected to the drainage system. Analysis of the annual hydrographs of each basin for the 4 year period 1997 to 2000, demonstrated that runoff was positively correlated with the drainage density, basin slope, and the percentage of the basin covered by channel fens, and was negatively correlated with the percentage of the basin covered by flat bogs. The detailed analysis of the water-level response to summer rainstorms at several nodes along the main drainage network in the Scotty Creek basin showed that the storm water was slowly routed through channel fens with an average flood-wave velocity of 0·23 km h^{-1}. 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. Copyright © 2003 Crown in the right of Canada. Published by John Wiley & Sons, Ltd.

KEY WORDS   fens; bogs; runoff; connectivity; discontinuous permafrost; hydrological modelling

INTRODUCTION

Northern wetland complexes cover extensive areas of North America, Europe, and Asia. The hydrological response of this wet organic terrain is poorly understood, in large part due to the lack of understanding of the hydrological function of the different types of organic terrain occurring in these regions. The lower Liard River valley in northwestern Canada (Figure 1a) is composed mainly of channel fens, ombrotrophic flat bogs and peat plateaus, which vary greatly in their biophysical properties (Aylesworth and Kettles, 2000). For example, peat plateaus are underlain by permafrost, and their surfaces rise 1 to 2 m above the surrounding flat 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. Peat plateaus develop from a process that begins in flat bogs with the vertical growth of the peat surface to an elevation high enough above the water table to allow the establishment of *Sphagnum fuscum* (Robinson and Moore, 2000). This rapidly growing species further increases the elevation of the ground surface, leading to decreased ground temperatures, followed by the formation of frost bulbs that further raise the ground surface (Robinson and Moore, 2000).

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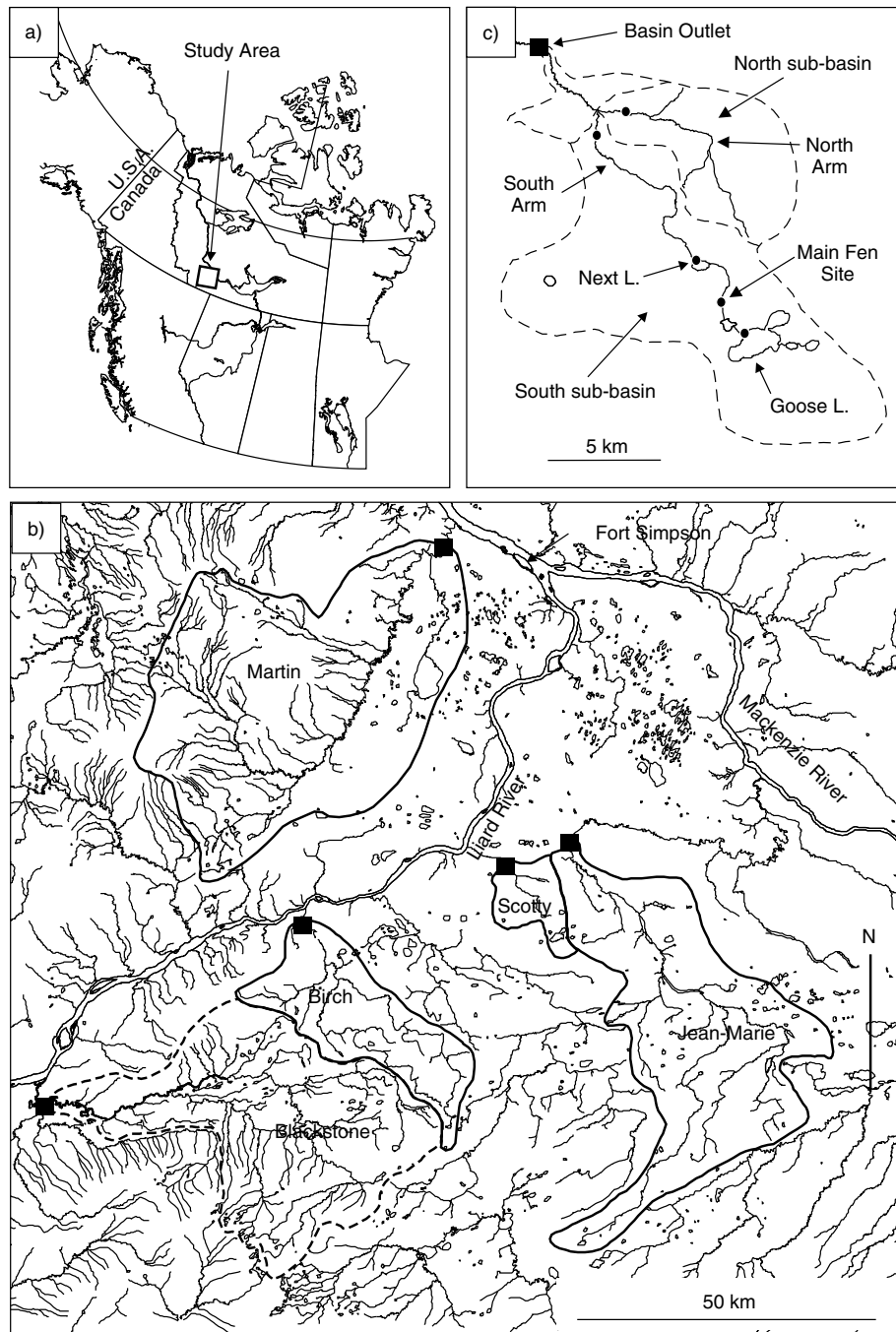E-mail: bquinton@sfu.ca

Figure 1. (a) The location of the lower Liard River valley within northwestern Canada. (b) The Martin, 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 WSC 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^2) was used for all calculations in this paper. However, since the location of the basin boundary has not yet been published by the WSC, (b) presents the former published estimate with a dashed line. (c) The Scotty Creek drainage basin, including its north and south sub-basins. The major drainage system of the basin is shown, as are the water-level recording stations (solid black circles) along this system. Water level was also recorded at the basin outlet by the WSC

In contrast to the peat plateaus, both the flat bogs, hereinafter referred to as 'bogs', and fens occupy a relatively low topographic elevation. As a result, the bogs and fens receive drainage water from the peat plateaus. The water table in the fens and bogs remains sufficiently close to the ground surface throughout the year to satisfy the definition of a 'wetland' (NWWG, 1988). By this criterion, peat plateaus are not wetlands, since the water table in these areas can subside to a depth of 50 cm or more. Furthermore, the peat plateaus of this region overly permafrost, whereas the wetlands do not. The two major wetland types also have contrasting characteristics. The fens are located along the drainage network of basins, often taking the form of broad, 50 to >100 m wide channels. These 'channel fens' (NWWG, 1988) are composed of a 0·5 to 1·0 m thick mat of *Sphagnum riparium*-dominated peat. The surface of this peat mat is typically 10 to 20 cm below the water surface, and supports sedges, the dominant vegetation of the fens, as well as various herbs and shrubs. The peat mat is also buoyant, and its elevation therefore, adjusts with the water level fluctuations in the fen (Roulet, 1991). Unlike the raised bogs described for temperate regions (e.g. Glaser *et al*., 1981; Siegel and Glaser, 1987), which, owing to their elevated position, are able to shed water, but receive only meteoric inputs, the bogs in the present study are flat, featureless surfaces that occupy broadly defined depressions (Aylesworth and Kettles, 2000). As such, they are able to receive drainage water from surrounding terrains in addition to meteoric inputs, but appear unable to shed water to surrounding areas. In contrast to the fens, the bog surfaces are relatively fixed, and are covered with *Sphagnum* species, overlying yellowish peat with well-defined *Sphagnum* remains (Zoltai and Vitt, 1995). Fens and bogs are relatively easily distinguished on satellite images, owing to the abrupt change in the vegetation cover at their margins. Also, the fens have a linear form, whereas the bogs appear as 'patches' on the landscape.

The contrast in biophysical properties among the three major organic cover types (channel fen, flat bog, and peat plateau) implies that their hydrological functions vary as well. Channel fens are arranged in a dendritic-like pattern and have water flowing over their surfaces, suggesting that their hydrological function is primarily one of lateral flow conveyance. The hydrological function of the peat plateaus and bogs is less clear. The relatively high topographic position of the peat plateaus in combination with the very low permeability of frozen, saturated peat suggest that these features may act as 'permafrost dams' that obstruct and redirect surface drainage in the surrounding wetlands.

The water table in bogs is usually below the ground surface (NWWG, 1988), and subsurface flow is, therefore, the predominant lateral flowpath (Quinton and Marsh, 1999). Under conditions of high water supply or limited storage availability, such as during snowmelt when the ground is still largely frozen, or during heavy summer storms when the water storage capacity is exceeded, bogs may drain into channel fens, and thereby contribute as a source of basin runoff. However, the spatial and temporal extent of such a hydrological connection between the bogs and channel fens, and the impact of this on basin discharge, remain poorly understood.

Previous studies on the runoff response of northern peatland-dominated basins have shown that the areal extent of organic terrain greatly influences the basin runoff response. For example, in several northern sites, snowmelt and summer-period hydrographs of basins containing a large proportion of wet organic terrain, produce larger peaks (Roulet and Woo, 1988) and longer recessions (Anderson, 1974; Ryden, 1977; Roulet, 1986; Chapman, 1987) than non-wetland basins. Compared with wetland basins of the temperate zone, those at high latitudes have much shorter lag times (Likes, 1966; Dingman, 1973) and recessions that can be as much as 10 000 times longer (Ford and Bedford, 1987).

Uncertainty in the hydrological functioning of the organic terrains of the lower Liard River valley has prevented successful modelling of the hydrograph response of the basins in this region. For example, recent attempts to simulate the hydrograph response of selected basins in the lower Liard River valley using the WATFLOOD model (Kouwan *et al*., 1993) failed to replicate the volume and timing of the observed hydrographs (Pietroniro *et al*., 1996a). They attributed this shortcoming to inadequate representation of (i) snowmelt, (ii) subsurface drainage, and (iii) wetland storage and routing processes. Some recent studies have improved the modelling accuracy in this region by specifically addressing the representation of the snowmelt (e.g. Hamlin *et al*., 1998) and subsurface flow (e.g. Quinton *et al*., 2000; Soulis *et al*., 2000)

routines. However, little progress has been made towards understanding and representing the storage and routing processes in this environment. In addition to the need for improved process representation, basin runoff modelling in this environment has also been hampered by the lack of detailed ground cover information (Pietroniro *et al.*, 1996a).

The objective of this study is to increase the level of understanding of the factors that control the runoff response of drainage basins in the lower Liard region. Specifically, this will be accomplished by: (1) developing methods to quantify the spatial distribution of the ground cover types that influence basin runoff; (2) determining the relation between the abundance of these ground cover types, namely fens and bogs, and the amount of runoff discharged from drainage basins; (3) evaluating the storage and transmission characteristics of channel fens; and (4) proposing simple wetland routing schemes that can be easily incorporated into existing hydrological models.

STUDY SITE

Field studies were conducted in the lower Liard River valley, near Fort Simpson, Northwest Territories, Canada (Figure 1a), a zone of high coverage of wetlands (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 (Heginbottom 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 characterized by a dry continental climate, with short dry summers and long cold winters. It has an average (1971–2000) annual air temperature of $-3.2\,°C$, 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 five gauged drainage basins ranging in area from 150 to 2000 km^2 (Figure 1b). At the Jean-Marie, Martin, 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°18′N; 121°18′W), as it contained the major ground-cover types within the region (i.e. channel fens, 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. The major drainage system of Scotty Creek (Figure 1c) is composed of channel fens, open stream channels, and intervening lakes. Open stream flow predominates over the lower one-third of both the North and South Arms, as well as between the confluence and the basin outlet. The remaining, upstream portions of both arms are composed of channel fens and lakes.

METHODS

Image analyses

Two multi-spectral images of the study region were acquired: (i) a 4 m × 4 m resolution IKONOS image covering 90 km^2 of the 150 km^2 Scotty Creek basin, and (ii) a 30 m × 30 m resolution Landsat image covering a 32 400 km^2 area of the lower Liard River valley that includes the five study basins. Prior to analysis of the images, the contrast among individual spectral bands was enhanced following the procedure of Wakelyn (1990). Redundancy in the image data was reduced using a principal component analysis (Richards, 1984) in which each principal component was treated as a single band, and then combined into a colour composite image. The optimal combination of bands was then selected and enhanced using an iterative process (Hoffbeck and Landgrebe, 1996; Pietroniro *et al.*, 1996b). Both images were classified using the maximum likelihood method (Richards, 1984; Arai, 1992; Yamagata, 1997) with training sites (Lillesand and Kiefer, 1994) obtained from homogeneous areas where the cover type was known from site visits.

In September 1999 and June 2000, oblique colour photographs were taken of the Scotty Creek basin from a helicopter at altitudes ranging from 200 to 1500 m above the ground surface. The areas photographed included examples of the major cover types, many of which were pre-determined from inspection of the satellite images, and all sites where hydrometric experimental measurements were made. The geographical coordinates of each area that was photographed was recorded with a global positioning system. In addition, ground-based photographs were taken at all study sites, as well as at selected sites where further inspection of the cover type was required. In order to assist in the classification of the Landsat image, the IKONOS data were superimposed onto the latter so as to provide a zone of increased resolution on the relatively course Landsat image (Hopkins, 2001)

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. Except for the Martin River basin, 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. Because the Martin River basin contains an upland component with a high average slope (0·0141), and a relatively flat (0·0016) lowland component, the average slope for this basin was taken to be the root-mean-square of two slopes. This method was used because stream discharge is commonly related to the square root of channel slope (e.g. Chezy formula).

An estimate of the portion of the total wetland area that could potentially convey water to the basin outlet was obtained through further analysis of the 90 km^2 subarea within Scotty Creek using both IKONOS and Landsat images, and to the entire Scotty Creek basin area using the Landsat image. To evaluate the connectivity of wetlands, all pixels classified as fen, bog or open water were grouped in a single class of pixels representing those that are connected to the main drainage system of channel fens, open stream channels and intervening lakes (Figure 1c), either directly (i.e. adjacent to) or indirectly via other pixels of this class. The lake and stream-channel pixels were then removed from this class, leaving only the fen and bog pixels that are connected to the main drainage system. This enabled an estimate of the wetland area that has the potential to become a connected body of surface water and, therefore, the potential to convey water to the outlet. Wetland pixels not included in the connected group were assumed to be physically separated from the basin drainage network by the peat plateaus and, therefore, unable to convey runoff to the outlet.

Hydrometric studies

Stream discharge from the five study basins was monitored continuously by the Water Survey of Canada (WSC) at established gauging stations (Figure 1b). Because of the logistical constraints and the high cost of maintaining a field programme in this remote region, fieldwork was limited to the Scotty Creek drainage basin for the June to September periods of 1999 and 2000. In addition to the water level recorded at the outlet of Scotty Creek by the WSC, water level was also monitored along the drainage system at five nodes: Goose Lake, the Main Fen site, Next Lake, and near the outlets of the South and North Arms of Scotty Creek. (Figure 1c). The Goose Lake and Next Lake stations recorded the water level fluctuations of these lakes, and the Main Fen station recorded the water level fluctuations of the intervening channel fen. The South and North Arm stations recorded water levels in open stream channels. These measurements were made with pressure transducers (Druck PDCR 950) installed in a slotted 5 cm diameter PVC stilling well and connected to data loggers (Campbell Scientific 21X) for continuous measurement. Readings were taken every 60 s and averaged and recorded every 30 min. The stilling wells were driven 20–30 cm into mineral soil at each node. Only the South Arm (Figure 1c) site was suitable for discharge measurement by the velocity–area method. Velocity was measured using a Price AA current meter, and a rating curve was developed for this site from which a continuous discharge hydrograph was obtained. A continuous hydrograph for the outlet of the North Arm was obtained by subtracting the South Arm hydrograph from the Scotty Creek hydrograph provided by the WSC.

On a peat plateau adjacent to the Main Fen site, water table elevation was continuously monitored at slotted 5 cm PVC wells located 2·7 and 14·2 m from the edge of the channel fen with pressure transducers connected

to a data logger with measurements made, averaged and recorded using the same intervals as used at the water-level recording stations. The elevation of the tops of well casings was determined using an optical surveyor's level. A tipping bucket rain gauge was installed in a clearing to measure the depth and intensity of rainfall. Rainfall was also recorded at the Jean-Marie (1999) and Blackstone (1999 and 2000) gauging stations by the WSC (Figure 1b).

RESULTS AND DISCUSSION

The ground cover of the lower Liard River valley

Because saturated surfaces absorb infrared light, the channel fens appear relatively dark on the satellite imagery compared with the surrounding bogs and peat plateaus (Figure 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. The detailed classification of land cover types for the 90 km^2 area of Scotty Creek covered by the IKONOS image (Table I) shows a high degree of correspondence between the IKONOS- and Landsat-based analyses. Both analyses produced the same ranking of the land covers in terms of their relative occurrence on the landscape and, other than for the sparse coniferous forest class, the difference between the Landsat- and IKONOS-based estimates is less than 5% for all classes. This finding suggests that the Landsat image, classified using IKONOS data and ground surveys, will provide a reasonable land-cover classification for the remainder of the Scotty Creek basin, as well as for the remaining study basins for which only Landsat imagery is available.

The land-cover classification scheme used for the 90 km^2 area of Scotty Creek (Table I) was applied to the five study basins on the Landsat image. Combining the woodland areas into a single class, and removing the relatively minor classes (shrubs, lakes, barren land and ponds), resulted in a simplified land-cover classification (Table II). In Table II, the percentage coverage of the major cover types for Scotty Creek varies slightly from the values in Table I since this analysis was conducted using the full basin area rather than the 90 km^2 sub-area of IKONOS coverage. The combined classes suggest that all of the basins are composed roughly of one-quarter to one-third wetland (channel fens and bogs) and two-thirds woodland (peat plateaus and other wooded upland areas). Further analysis was conducted on the north and south sub-basins of Scotty Creek. Both of their surfaces are covered by approximately the same percentage of channel fens; however, bogs occupy approximately 15% of the south sub-basin, compared with only about 2% in the north sub-basin. In addition, only about one-half of the south sub-basin is composed of wooded areas (peat plateaus and larger

Table I. A detailed land-cover classification for the 90 km^2 area of the Scotty Creek basin covered by the IKONOS image as determined from IKONOS data and Landsat data. Land-cover classes are presented in order of descending coverage

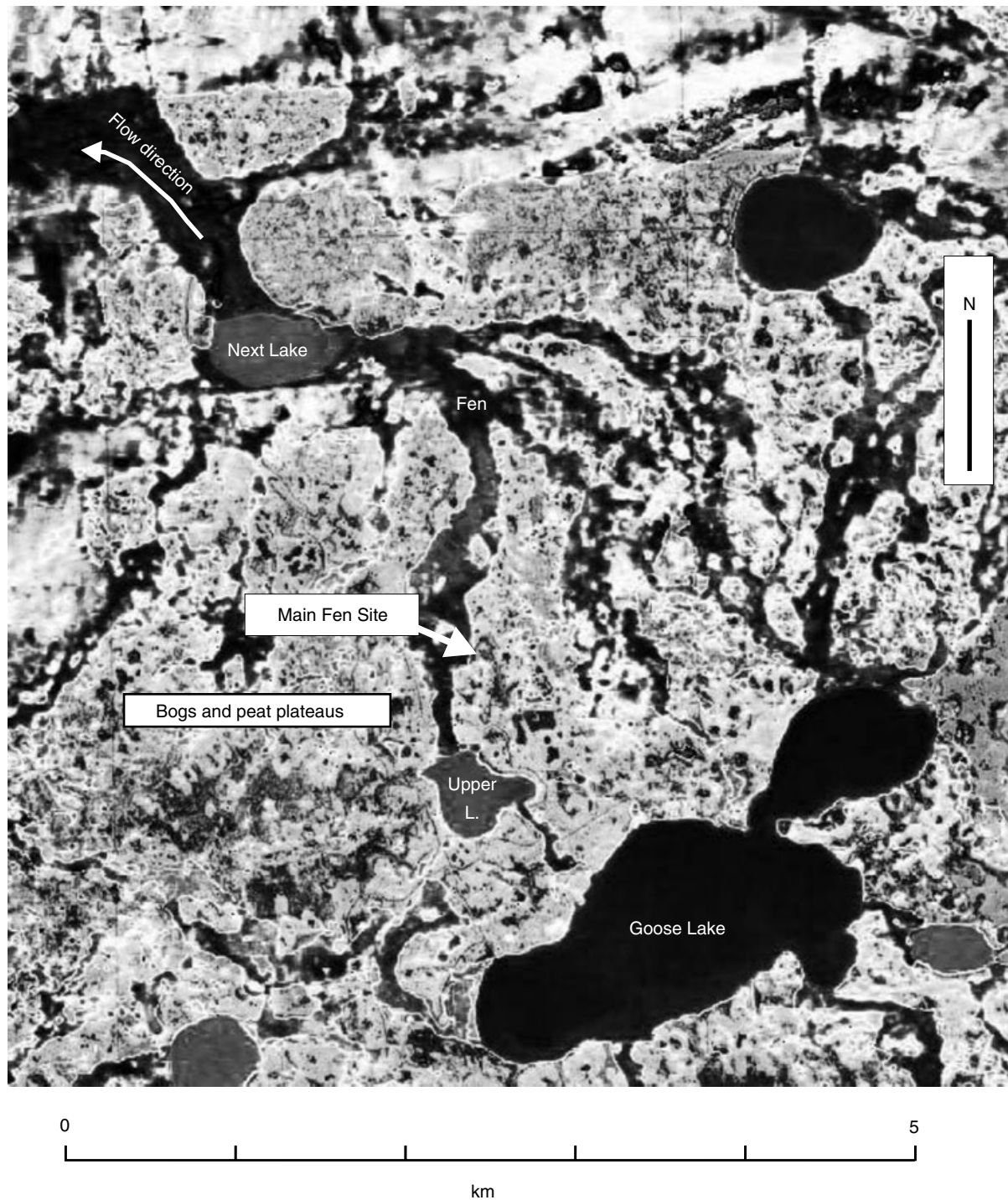| Cover type	Area analysed (%)		Difference (%)
	IKONOS	Landsat	
Coniferous forest (sparse)	28·7	39·2	10·5
Channel fens	28·0	25·7	2·3
Coniferous forest (dense)	16·0	14·0	2·0
Bogs	14·4	11·2	3·2
Shrubs/transitional	6·2	4·2	2·0
Lakes/rivers	3·5	3·7	0·2
Deciduous forest	3·2	1·8	1·4
Barren land	0·0	0·1	0·1
Ponds/shallow water	0·0	0·0	0·0

Figure 2. 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. The locations of Goose Lake, the Main Fen Site, and Next Lake are also shown

wooded uplands) compared with approximately two-thirds woodland coverage in the north sub-basin. The ground-cover classification system presented in this study gives detailed information on the distribution of the major cover types with contrasting water flux and storage characteristics. As such, its development removes one of the impediments identified by Pietroniro *et al*. (1996a) to improving the understanding of and ability to model the storage and routing processes in this environment.

Hydrological connection among wetlands

For the 90·0 km^2 subarea of Scotty Creek covered by both IKONOS and Landsat images, approximately three-quarters of all wetland pixels (bog and fen) are connected, either directly or indirectly, to the main drainage system. This fraction of the total wetland cover represents the continuous wetland area connected to the basin outlet, via lakes and/or open stream channels (Table III). When applied to the whole of the Scotty basin, covered by the Landsat image alone, this method estimates that roughly 62% of all wetland pixels are connected to the basin drainage system. This value is similar to the percentage of total wetland area composed of channel fens (i.e. 66%), based on the values presented in Table II. In addition, the area occupied by the class of 'connected' wetland pixels in Scotty Creek (Figure 3) closely corresponds with the distribution of the channel fens within the basin (e.g. Figure 2). Likewise, the distribution of the remaining wetland area corresponds closely with the distribution of the bogs. It is suggested, therefore, that the percentage of a basin occupied by channel fens (Table II), easily obtainable from the ground-cover classification presented above, serves as a useful index of the contiguous wetland area that is connected to the main drainage system.

It is possible that the Landsat-based connectivity analysis may underestimate the actual connectivity, since connections smaller than the resolution of the Landsat image would be undetected. However, as discussed above, the connectivity analysis on the 90·0 km^2 subarea of Scotty Creek showed that increasing the image resolution from 30 m × 30 m (Landsat) to 4 m × 4 m (IKONOS) did not appreciably change the estimate of the connected portion of the overall wetland coverage (Table III).

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

Basin	Area (km^2)	Average runoff (mm)			Percentage of basin (%)			Drainage density (km km^{-2})	Average slope (m m^{-1})
		Annual	Spring	Summer	Wooded	Fens	Bogs		
Martin	2050	129·9	49·7	80·2	66·5	10·4	13·2	0·424	0·0063
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 III. The percentage of the total wetland area (bogs and fens) that is connected to the basin outlet, as estimated from analysis of satellite images for the 90 km^2 subarea of the Scotty Creek, as well as for the entire basin

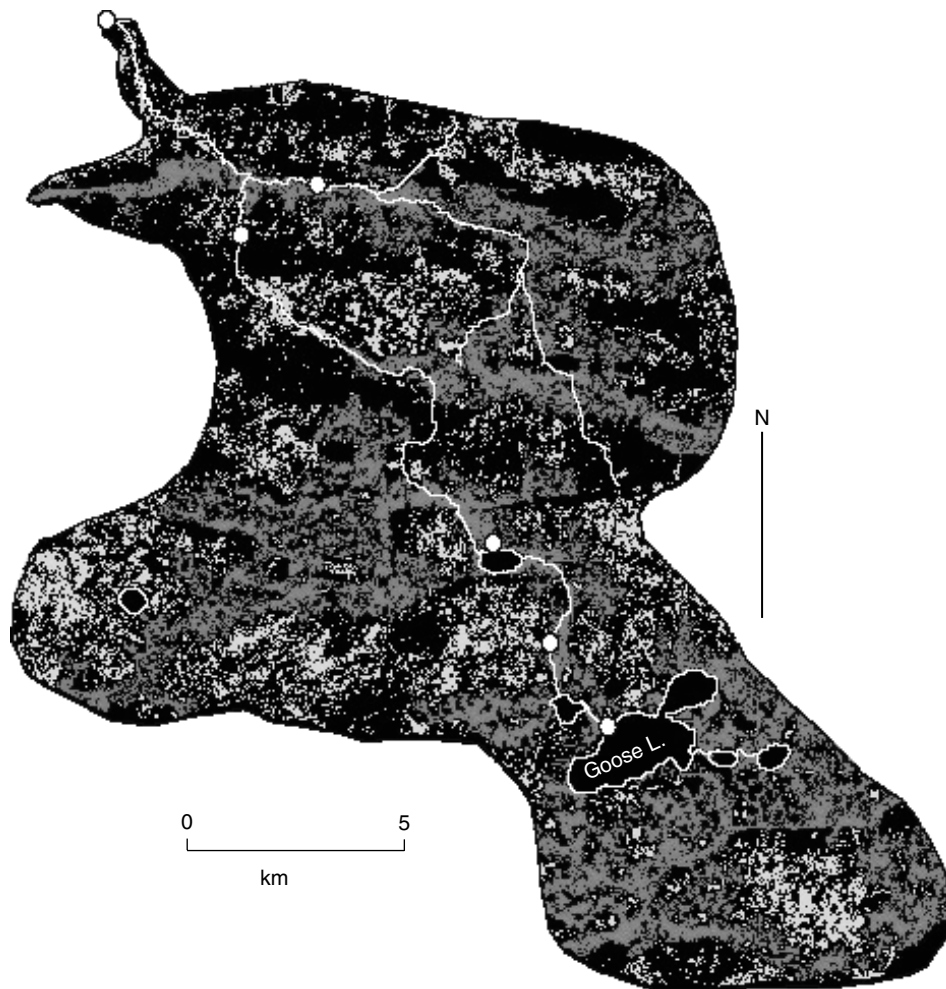|	90 km^2 subarea of Scotty Creek		Entire basin (Landsat)
	Landsat	IKONOS	
Wetland area (%)	73·2	77·8	61·8

Figure 3. A Landsat image of Scotty Creek with the non-wetland surfaces, including lakes shown in black. The wetland surfaces are divided into areas that are connected to the basin drainage system (dark grey) and those wetland areas that are not connected to it (light grey). The water level recording stations along the channel fen-lake-open stream drainage system are also identified (circles)

By identifying the wetland pixels that are connected to the basin outlet, Figure 3 reveals the major flow routes of the Scotty Creek drainage system, and shows that water is conducted laterally along broad wetland tributaries to the central drainage system before proceeding toward the basin outlet. The type of spatial information should be accounted for in hydrological models when routing water through the drainage basins in this region. Failure to do so will result in errors in predicting the timing of the basin hydrograph response.

Basin biophysical characteristics related to runoff

Table II includes two groups of parameters that may be relevant to the amount of runoff from basins. The first group describes the ground cover in terms of the aerial coverage of fens and bogs. The second group consists of basin drainage density and average slope. The percentage cover of fens had a strong negative correlation with that of bogs ($r = 0.98$, $p = 0.005$; where r is the correlation coefficient and p is the observed significance level), as would be expected given that while the percentage of bogs and fens varies

among the basins, the variation in the total wetland coverage among the basins is relatively small. Drainage density had a strong positive correlation with basin slope ($r = 0.96$, $p = 0.010$), as expected.

As shown in Figure 4, the amount of annual runoff had some degree of correlation with the percentage cover of channel fens and bogs, even though the statistical level of significance (Table IV) is not very high due to the small sample size. 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, whereas 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 (Table IV), indicating that the basins with more efficient drainage mechanisms have higher annual runoff.

The Scotty, Jean-Marie, and Martin basins have relatively low average annual runoff values (Table II), 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 5). 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, whereas 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 associations plotted in Figure 4 were considerably strengthened when the Martin River basin was excluded from the analysis, suggesting that additional factors unaccounted for in the present analysis influence the runoff response of that basin. The Martin River drainage basin is more heterogeneous than the Scotty and Jean-Marie drainage areas. The upland areas north of the main channel have a relatively high slope (0.0141), a high drainage density, and very few wetlands. By contrast, on the south side of the main river channel, the terrain is relatively flat (average slope: 0.0016), has a low drainage density, and numerous bogs and fens. The lateness of the spring hydrograph response may be related to the delay in the melt of the snowpack in the basin uplands. However, the relatively low cumulative runoff by year's end (i.e. a characteristic observed at Scotty and Jean-Marie) suggests that the relatively flat, lowland terrain also influences the runoff response of this basin. Within this portion of the basin, the drainage density and fen coverage are similar to Scotty and Jean-Marie, whereas the bog coverage is higher. For the 4 year study period, the annual runoff from the Martin River basin was more variable than that from the other basins. For example, in 1997 it was relatively high, and approximately the same as for the Birch River, whereas in 2000 it was as low as the Scotty Creek runoff.

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 II). Consequently, the average annual runoff production from these two adjacent basins was the highest among the five basins studied (Figure 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 would account for the slightly larger average runoff from this basin compared with the

Table IV. The correlation coefficient r and the observed level of significance p between the average annual runoff and the four basin biophysical parameters

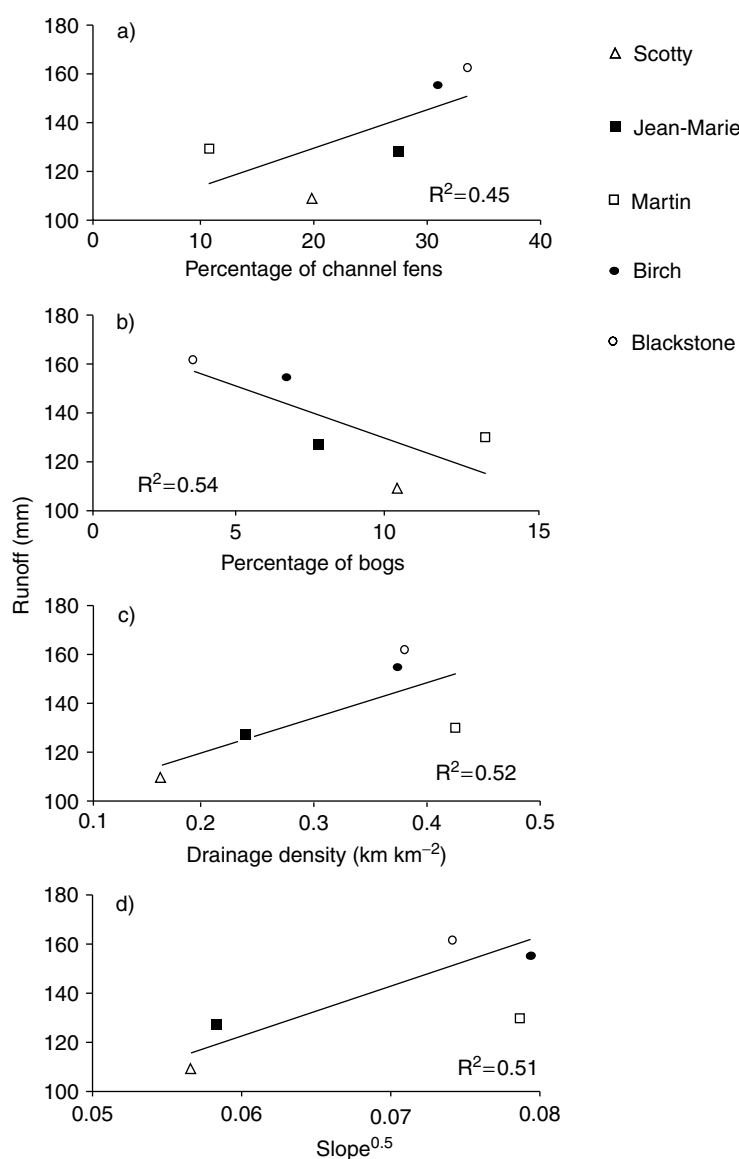|	Percentage of basin (%)		Drainage density (km km^{-2})	Average slope (m m^{-1})
	Fens	Bogs		
r	0.67	−0.73	0.72	0.71
p	0.21	0.16	0.17	0.18

Figure 4. For each of the five study basins, the average runoff of the 4 year period 1997–2000 is plotted with the percentage of the basin covered by channel fens (a) and bogs (b), with the drainage density (c), and the square root of the average basin slope (d)

Blackstone during the April–May period (Table II). 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.

Runoff response to precipitation

The rainfall record is composed of numerous groups of separate but closely spaced rainfall events (Figure 6). The Scotty Creek and Jean-Marie rainfall data presented in Table V are strongly correlated ($r = 0.93$, $p = 0.022$), suggesting that the rainfall data from Jean-Marie can be used as a substitute when rainfall
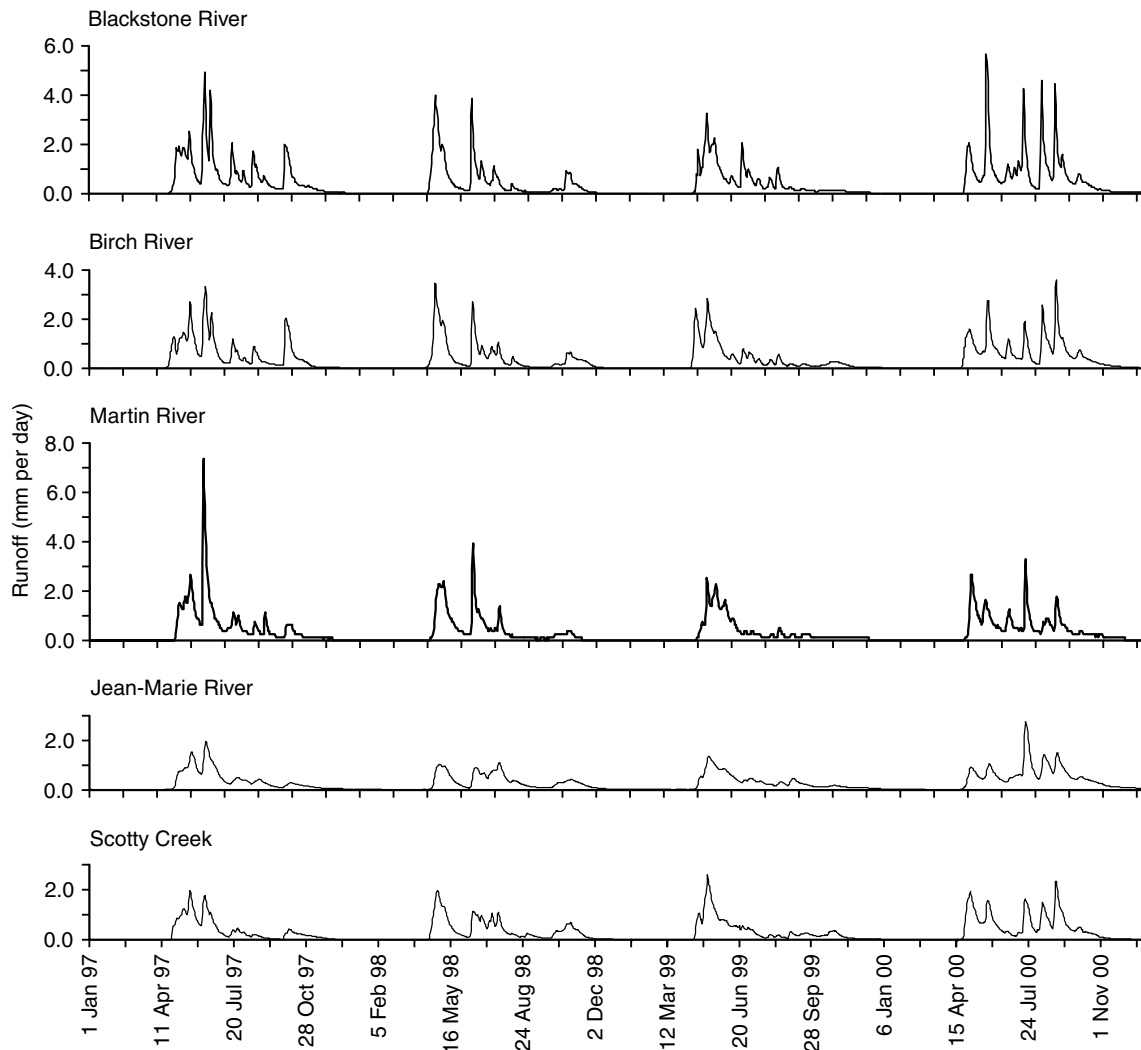
Figure 5. The hydrographs measured at the outlets of the five study basins for the 4 year period 1997 to 2000

data from Scotty Creek are not available. Runoff ratios were computed by first separating storm flow from baseflow, assuming that baseflow was equal to pre-storm discharge, and then dividing the storm discharge corresponding to each group of rainfall events by the total amount of rainfall on the basin (Table V). Scotty Creek rainfall data were used when available, otherwise the Jean-Marie rainfall data were used.

The runoff from the group 1 rain events was augmented by snowmelt runoff, which resulted in the relatively high runoff ratio of 0·4 (Table V). All subsequent runoff ratios computed for 1999 represent the snow-free period. During this period, runoff ratios are all below 0·1, but show some variation with time. Early in the summer period, the recent large inputs of meltwater combined with limited active layer development result in high water levels and, therefore, relatively high runoff ratios. Runoff ratios were lowest in mid-summer, when low-flow conditions prevailed (Figure 6a). Runoff ratios increase in late summer, since, compared with mid-summer, there is less energy available for evaporation, and the frequency and magnitude of rainfall events is greater. The rainfall record at Scotty Creek in 2000 was of short duration and contained only a single group of rainfall events sufficient in depth for computation of a runoff ratio. However, the amount of rain in this
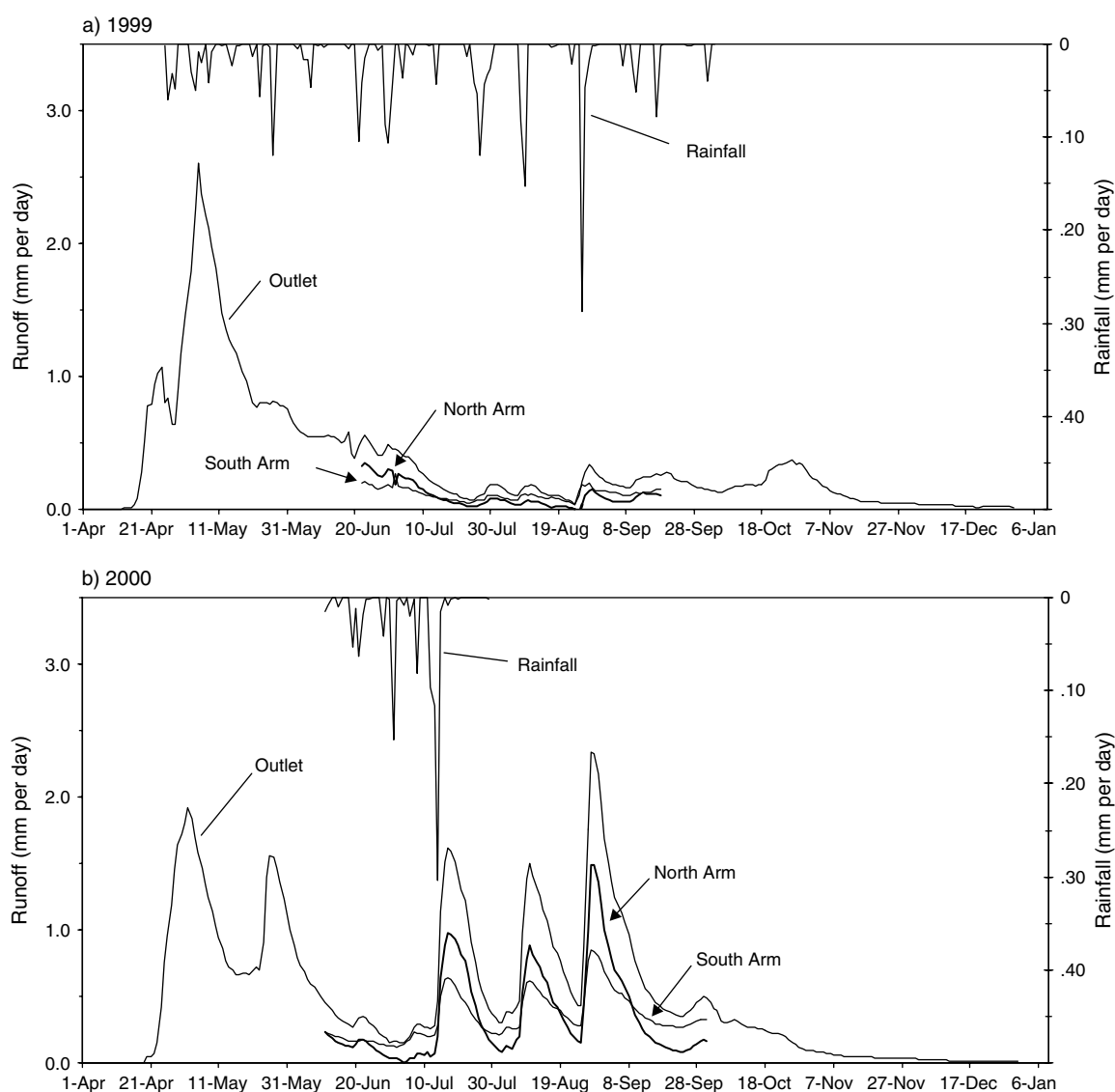
Figure 6. Runoff hydrographs for Scotty Creek for 1999 (a) and 2000 (b), with runoff from the north and south sub-basins shown for the periods while water level was recorded. The rainfall data presented was recorded at the Jean-Marie outlet (1999) and the Main Fen site (2000). Rainfall at Scotty Creek in 2000 was measured only between 10 June and 29 July

group of events was roughly 50% larger than the largest group of the preceding year. The relatively large magnitude of the input, in addition to the higher water levels in 2000 (Figure 6b), resulted in a runoff ratio nearly three times larger than the largest value computed for 1999 (Table V). These results suggest that the basin runoff in this region is relatively sensitive to variations in storage capacity and water availability.

Previous studies in other northern basins also showed that the magnitude of the runoff response from wetland areas increases as the storage capacity in the soil and in topographic depressions decreases (Boudreau and Rouse, 1995; Woo and Young, 1998), and that runoff in response to snowmelt in the spring is large following years of abundant rainfall (Metcalfe and Buttle, 1999). For a variety of wetlands types, summer storms have produced runoff ratios of between 0·01 and 0·28 in northern Quebec (Quinton, 1991), 0·02 and

Table V. Runoff ratios for the Scotty Creek basin and for its two major sub-basins for the major groups of rainfall events in 1999, and for a single group of events in 2000. Runoff ratios were computed using rainfall recorded at the Jean-Marie outlet by the WSC, and at the Main Fen site of Scotty Creek. Collection of rainfall data commenced in April at Jean-Marie, but not until late June at Scotty Creek

Group	Date	Rainfall (mm)		Runoff ratio: Scotty outlet		Runoff ratio: sub-basins	
		Jean-Marie	Scotty	Jean-Marie ppn	Scotty ppn	South	North
1	3 May 1999	12·8	—	0·400	—	—	—
2	22 May 1999	18·2	—	0·025	—	—	—
3	20 June 1999	16·7	—	0·054	—	0·030	0·143
4	28 June 1999	28·6	22·6	0·020	0·009	0·012	0·052
5	24 July 1999	31·6	33·1	0·031	0·027	0·028	0·050
6	7 August 1999	23·6	25·9	0·021	0·019	0·021	0·029
7	25 August 1999	37·5	36·2	0·064	0·081	0·058	0·103
8	9 September 1999	16·1	12·8	0·084	0·100	—	—
	12 July 2000	—	53·2	—	0·238	—	—

0·16 in central Keewatin (Roulet, 1986), 0·1 and 0·85 in northern Manitoba (Chapman, 1987), 0·14 and 0·42 in central Alaska (Dingman, 1971), and between 0·01 and 0·69 near Barrow, Alaska (Brown *et al.*, 1968). Analysis of runoff ratios also indicates large spatial variations in the runoff response, associated with variations in ground cover. For example, in comparing the runoff ratios of the north and south sub-basins of Scotty Creek, for the period 20 June to 18 September (i.e. the period over which water levels were recorded in 1999), the woodland-dominated north sub-basin, with only 2% bog coverage, discharged 42·5 mm of runoff, while the wetland-dominated south sub-basin, with 15% bog coverage, discharged only 15·0 mm. Given the cumulative rainfall of 162·2 mm for this period, the runoff ratio of the south sub-basin (0·09) is relatively small compared with that of the north sub-basin (0·26). The runoff ratios of the individual storms (Table V) for this year were consistently higher for the woodland-dominated north sub-basin, although the difference is small during mid-summer.

The cumulative rainfall for the period of record in 1999 (1 June to 4 October) was only 4% higher at Blackstone than at Jean-Marie; consequently, it was assumed that the total summer rainfall does not vary appreciably between these two basins, or in the intervening Scotty and Birch River basins. A summer-period runoff ratio was computed for each of these basins from the rainfall recorded at Jean-Marie and the cumulative discharge from each basin over the same period (Table VI). Unlike the runoff ratios presented in Table V, these seasonal values include baseflow. Using the values for the percentage of each basin covered by channel fens and bogs presented in Table II and the basin runoff ratios in Table VI, the runoff ratio appeared to be positively correlated ($r = 0.77$, $p = 0.23$) to fen coverage, and negatively correlated ($r = -0.83$, $p = 0.17$) to bog coverage, even though the statistical level of significance was low.

Flood-wave propagation in the Scotty Creek basin

Analysis of the water-level response to summer rain storms provided insight into the hydrological functioning of channel fens. For example, Figure 7 shows hourly precipitation at the Main Fen site and water levels at various nodes during a relatively large rain event (29 mm) of 25 August 1999. The bulk of precipitation occurred between 2:00 and 10:00 local time on 25 August (Figure 7a), to which water levels at Goose Lake and the Main Fen responded immediately (Figure 7b). Water level in Goose Lake rose 20 mm above the pre-storm level. Considering the uncertainty in the spatial distribution of precipitation, the rise in Goose Lake is about the same magnitude as the amount of precipitation. This suggest that runoff generated over the drainage basin of Goose Lake was temporarily stored in numerous fens around the lake and was slowly drained, as indicated by the gradual rise of water level after the storm (Figure 7b). Water level over

Table VI. Runoff ratios computed for 1999 using the cumulative basin runoff between 1 June and the end of the rainfall-recording period (4 October) and the rainfall recorded at the Jean-Marie station over the same period. Runoff ratios are given for all basins except for Martin River, where rainfall data were not available

Basin	Runoff ratio
Blackstone	0·30
Scotty	0·19
Jean-Marie	0·27
Birch	0·22

the surface of the Main Fen rose by 44 mm above the pre-storm level, indicating that the fen received a small input of water in addition to direct precipitation (29 mm), presumably from the upstream source and from the surrounding peat plateaus, as expected given its apparent role as a conveyor of water. The average rate of water-level recession in the Main Fen was 2·9 mm d^{-1} before the storm (Figure 7b), which is comparable to the potential evaporation in this region (Gibson *et al.*, 1993). It is likely, therefore, that evapotranspiration accounts for significant water loss from the fen.

The peak water level in the fen occurred at 20:00 on 25 August (Figure 7b) and travelled downstream to reach the South Arm node at 20:00 on 27 August (Figure 7c). Since the distance between the Main Fen and South Arm is 12 km, the estimated velocity of the flood wave, or celerity, within this fen-dominated reach (see Figure 3) was 0·25 km h^{-1}. The peak must have reached the outlet sometime during 28 August, but it is impossible to determine the exact time from the water-level record. On the peat plateau adjacent to Main Fen site, the water table was below the pressure sensor before the storm, and immediately responded to infiltration during the storm (Figure 7d). Following the storm, the water table slowly declined, indicating that storm water was slowly released into the fen as subsurface runoff.

Similar characteristics of the water-level record were observed during other major storms in 1999 and 2000 (Table VII). Flood-wave velocity between the Main Fen and South Arm sites was estimated for six storms that produced distinctive water-level peaks at each of the nodes. The flood-wave velocities of these storms ranged between 0·17 and 0·33 km h^{-1} with an average of 0·23 km h^{-1}. No significant correlation was found between flood-wave velocity and peak discharge, nor between velocity and the water level at the Main Fen site. This is probably because the surface of the peat mat rises and subsides with the fluctuations of the water surface above it, thereby keeping the effective depth of water in channel fens more or less constant. In 2000, a water-level recorder was moved from Goose Lake to the outlet of Next Lake in order to determine the flood-wave velocity in the 3000 m reach between Main Fen and Next Lake (Figure 2). For the three storms analysed in 2000, the average flood-wave velocity between the Main Fen and Next Lake sites was 0·11 km h^{-1}.

Flood-wave velocity gives a quantitative indication of the hydraulic roughness of channel fens. At the Main Fen site, on 10 June 2000, the surface flow velocity in the middle of the fen measured from the float method was, on average, approximately 0·02 m s^{-1}, while further downstream at the South Arm station the discharge was 0·4 m^3 s^{-1}. At that time, the approximate height of the water surface above the top of the peat mat was in the order of 0·05–0·1 m in the fen, which gave a Reynolds number in the 1000 to 2000 range. Therefore, it is expected that the flow regime in the fen is within the range where the concept of hydraulic roughness is valid. Channel fens have a complex geometry, but for analytical simplicity it is useful to assume that, on average, the network of channel fens (see Figure 2) is hydraulically equivalent to a wide, shallow rectangular channel. Based on this assumption, the flow velocity (v, m s^{-1}) is given by
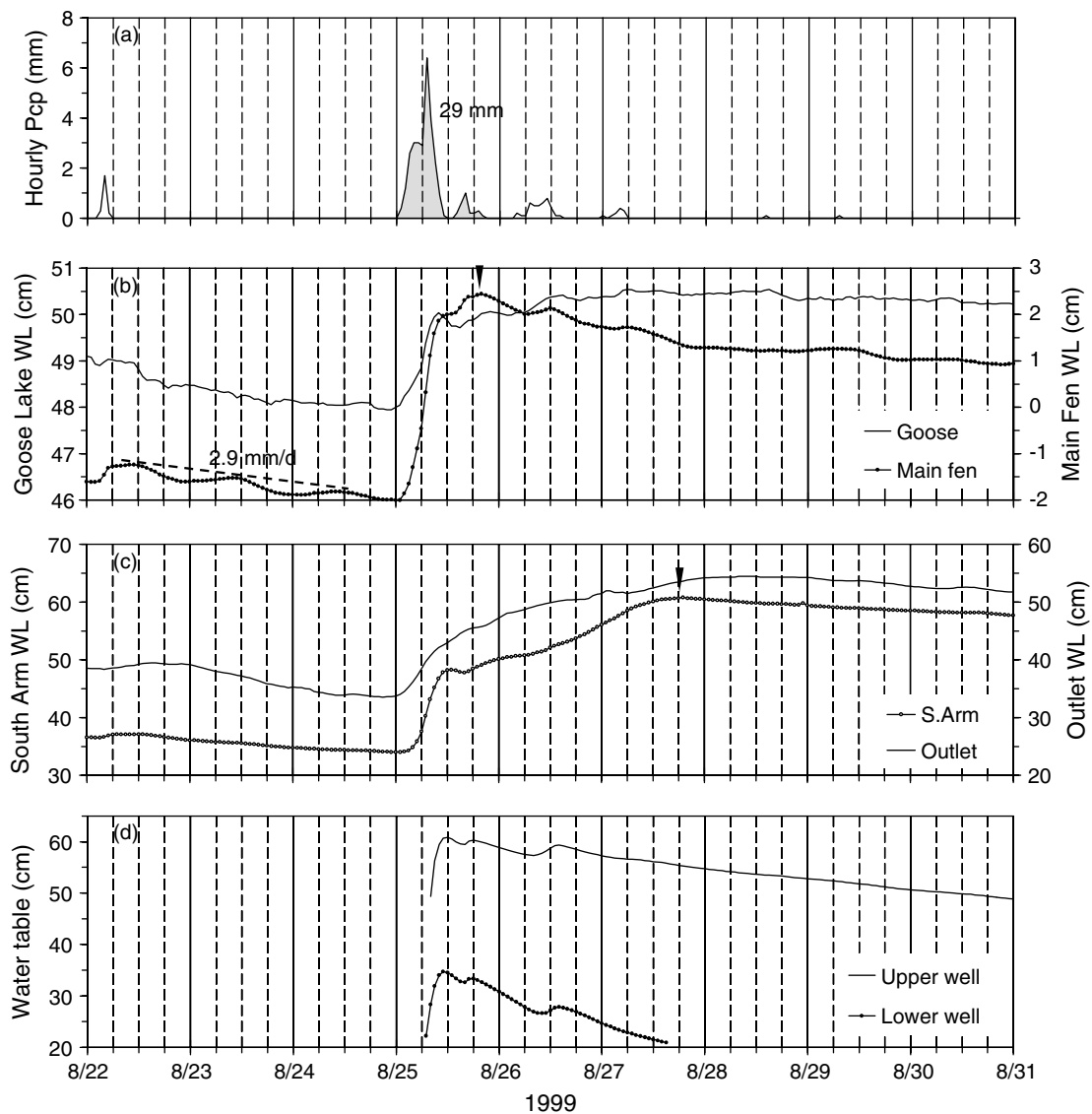
$$v = y^{2/3} S^{1/2} n^{-1} \tag{1}$$

Figure 7. (a) Hourly precipitation recorded at Main Fen site, with the storm event indicated by the shade. (b) Water levels at Goose Lake and Main Fen. (c) Water level at South Arm and outlet. (d) Water table in two wells on peat plateau. The water level in the fen and water table in wells (d) are all referenced to a common datum set at 95 cm below the ground surface at the upper well. This datum corresponded roughly to the surface of the peat mat measured at the stilling well in the fen on June 2000

where y (m) is the average depth, S is the energy slope, and n is Manning's roughness coefficient. Assuming further that flow is reasonably uniform, flood-wave velocity (c, m s^{-1}) is given by

$$c = 5v/3 \qquad (2)$$

and S is approximated by the average channel slope (Bedient and Huber, 2002: 272). The model presented here is a crude approximation of the complex reality, but it serves the purpose of estimating a useful parameter from limited field data for this region.

Table VII. Analysis of water-level response to major rainfall events at Scotty Creek, including rainfall measured at the Main Fen site, water-level rise Δh in Goose Lake and the Main Fen (MF) site, peak water level h_{pk} at the Main Fen, peak discharge Q_{pk} at the South Arm (SA), and flood-wave velocity for the MF–SA reach and MF–Next Lake (NL) sub-reach. N/a indicates no data available

Date	Rainfall (mm)	Δh (mm)		h_{pk} MF (cm)	Q_{pk} SA(m^3 s^{-1})	c (km h^{-1})	
		Goose Lake	MF			MF–SA	MF–NL
29 June 1999	23	19	25	8·4	0·31	0·33	n/a
8 August 1999	17	14	23	3·0	0·21	0·22	n/a
25 August 1999	29	20	44	2·2	0·31	0·25	n/a
14 July 2000	44	n/a	41	11·8	1·12	0·17	0·09
7 August 2000	n/a	n/a	35	11·7	1·09	0·18	0·11
26 August 2000	n/a	n/a	37	14·1	1·49	0·23	0·14

The average slope of the ground surface estimated from the $1:50\,000$ map sheet is $0·000\,33$ between the Main Fen and Next Lake, and $0·0023$ between the Main Fen and the South Arm. Substituting $S = 0·0023$, $y = 0·05$ m, and $c = 0·23$ km h^{-1} gives $n = 0·17$ for the Main Ferr–South Arm reach. Substituting $S = 0·000\,33$, $y = 0·05$ m, and $c = 0·11$ km h^{-1} gives $n = 0·13$ for the Main Fen–Next Lake sub-reach. These values of n are similar to published values for short grasses (Bedient and Huber, 2002: 277). Therefore, it seems promising to incorporate roughness-based routing algorithms, such as the kinematic wave model, in large-scale hydrological models.

The low slope and high hydraulic resistance in channel fens presumably cause the slow propagation of the flood wave in Scotty Creek. The effects of low slope and high resistance are more pronounced in the larger Jean-Marie basin (see Figure 1b). For example, the peak of the same storm shown in Figure 7 arrived at the outlet of Jean-Marie on 31 August, 6 days after the storm. In contrast, the flood peak arrived at the outlet of the Blackstone basin (see Figure 1b) on 28 August, the same day as the arrival of the peak at Scotty outlet. These findings indicate the importance of taking into account basin slope and hydraulic resistance in routing algorithms.

SUMMARY AND CONCLUSIONS

The organic terrain of the lower Liard River valley consists primarily of peat plateaus, channel fens and flat bogs, each having distinct biophysical and hydrological characteristics. A detailed ground-cover classification scheme that distinguishes among these organic terrain types was developed using IKONOS and Landsat images. Classified images were then produced that show that the channel fens form a network of broad channels that are connected to the basin drainage system, whereas the bogs typically occur as isolated patches, surrounded by peat plateaus. The classified images were also used to demonstrate how the hydrological role of these channel fens differs from that of the bogs, through analysing the degree of connection between all wetland pixels and the basin drainage system. In terms of total area, and spatial distribution, a high degree of similarity was found between wetlands of the connected class and the portion of the classified images defined as 'channel fen'. Likewise, the extent and distribution of the remaining wetland pixels was a close approximation of the bog coverage on the classified images. These findings suggest that the channel fens and bogs have contrasting hydrological functions. By being part of a continuous fen–lake–stream channel pathway leading to the basin outlet, channel fens are potentially able to function as conveyors of water. By contrast, the bogs, being isolated from this drainage system, are unable to function effectively as conveyors, but instead are relatively effective water storage areas.

The hydrometric data indicated a positive correlation between annual basin runoff and fen coverage, suggesting that basins with a high coverage of channel fens would generate more runoff per unit input

than basins with a lower proportion of channel fens. By contrast, a negative correlation was found between basin runoff and bog coverage. These findings, in addition to positive correlations between annual runoff and both drainage density and basin slope, will provide a frame of reference for a hydrologically meaningful interpretation of remotely sensed ground-cover information.

The water-level data recorded at several nodes within the Scotty Creek basin showed that, following storm events, drainage water concentrates in the channel fens and moves slowly 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.

From the results of the image analyses and hydrometric studies, 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 effectively to impound water in the bogs while redirecting 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.

The conceptual model presented here contributes to resolving some of the difficult issues in the hydrological modelling of northern basins, in particular the storage and routing functions of wetlands. This study showed that channel fens and bogs have distinctively different hydrologic functions, and they must be treated accordingly in models. The two types of wetland can be easily distinguished on satellite images due to the contrast in the surface moisture regime, which gives a practical tool for a hydrologically based land classification. Since they occur in depressions, the bogs serve as storage areas that reduce runoff production, whereas channel fens, being an integral part of the basin drainage network, serve as conveyors of flow. 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. The present study suggests 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. Flat bogs appear to be isolated from the drainage system on the surface, but the possibility that they 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 are poorly documented in the discontinuous permafrost region. The apparent continuity of channel fens is clearly identified in satellite images, but the actual hydraulic connection likely depends on the water level. Further development of conceptual and numerical models requires the understanding of subsurface processes and the temporal and spatial variability of channel–fen connectivity.

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