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Permafrost-thaw-induced land-cover change in the Canadian subarctic: implications for water resources

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Abstract

Climate warming and human disturbance in north-western Canada have been accompanied by degradation of permafrost, which introduces considerable uncertainty to the future availability of northern freshwater resources. This study demonstrates the rate and spatial pattern of permafrost loss in a region that typifies the southern boundary of permafrost. Remote-sensing analysis of a 1·0 km^2 area indicates that permafrost occupied 0·70 km^2 in 1947 and decreased with time to 0·43 km^2 by 2008. Ground-based measurements demonstrate the importance of horizontal heat flows in thawing discontinuous permafrost, and show that such thaw produces dramatic land-cover changes that can alter basin runoff production in this region. A major challenge to northern water resources management in the twenty-first century therefore lies in predicting stream flows dynamically in the context of widely occurring permafrost thaw. The need for appropriate water resource planning, mitigation, and adaptation strategies is explained. Copyright © 2010 John Wiley & Sons, Ltd.

Key Words permafrost thaw; land-cover change; peatlands; northern water resources

Introduction

The Northwest Territories of Canada are one of the most rapidly warming jurisdictions on earth (Johannessen *et al*., 2004). There is mounting evidence that this warming is affecting the water resources of northern regions. For example, the frequency of mid-winter melt and rain-on-snow events has increased (Putkonen *et al*., 2009); end-of-winter melt occurs earlier (Pachauri and Reisinger, 2007); and key hydrological and climatic variables such as snowpack depth (Hinzman *et al*., 2005), river discharge (St. Jacques and Sauchyn, 2009), and seasonal precipitation (Putkonen *et al*., 2009) have deviated from long-term means. These system-wide changes in hydroclimatology (Hinzman *et al*., 2005) are part of a region-wide response to climate warming that includes land-cover changes resulting from permafrost thaw (Rowland *et al*., 2010) such as increased occurrence of active layer detachments slides (Lantz and Kokelj, 2008), drainage of permafrost-impounded lakes (Pohl *et al*., 2009), and changes in the cover of vegetation (Sturm *et al*., 2001) and surface water (Smith *et al*., 2005).

Land-cover change induced by permafrost thaw introduces considerable uncertainty to the future availability of northern freshwater resources. For example, permafrost often controls water storage and drainage processes by limiting the amount of water infiltration to that which can be stored in the active layer. Permafrost also severely restricts hydrological interaction between near-surface supra-permafrost water and deep sub-permafrost groundwater. Along the wetland-dominated southern boundary of permafrost, permafrost typically occurs in the form of tree-covered plateaus that rise above the surrounding treeless and permafrost-free terrain. As such, permafrost plateaus obstruct and redirect surface and near-surface drainage in the surrounding terrains. Thawing and subsidence of permafrost plateaus has led to increasing interconnectivity of drainage networks (Beilman and

Robinson, 2003), and to changes in the local hydrological cycle due to changes in soil thermal and moisture regimes (Hayashi *et al.*, 2007), surface energy balances, and snow accumulation and melt rates, and patterns (Wright *et al.*, 2009).

The growing uncertainty on the future of the northern freshwater resource is greatest throughout the southern boundary of permafrost, where warming is likely to change the sign of mean annual air and ground temperatures, causing widespread permafrost thaw (Camill, 2005). Recent modelling studies have predicted the disappearance of permafrost and development of supra-permafrost taliks (Zhang *et al.*, 2008), and climate-induced permafrost thaw has been compounded by that resulting from unprecedented industrial expansion, particularly in the oil and gas sector. In the past decade, the density of seismic exploration lines has steadily increased (Lee and Boutin, 2006), and new gas pipelines, electrical transmission lines, and all-weather highways are being planned. Such linear disturbances remove the tree canopy and much of the underlying vegetation, which leads to substantial changes in the ground thermal regime including permafrost thaw and loss (Smith *et al.*, 2008).

The lack of knowledge on the mechanisms and rates of land-cover change, induced by permafrost thaw, their impact on water drainage and storage patterns and processes, and appropriate mitigation strategies, underscores the need for sound scientific research to provide the knowledge base required for informed and sustainable water resource management. As a preliminary step, this article (1) demonstrates the rate and spatial pattern of permafrost loss over the last 60 years in a wetland-dominated drainage basin near the southern boundary of permafrost in the Northwest Territories and (2) explains key hydrological and water resource implications of this change in the land-cover resulting from widespread permafrost thaw.

Study Site

This study was conducted in the 152-km^2 Scotty Creek basin (61°18′N, 121°18′W; 285 m above sea level), which lies within the 140 000-km^2 Hay River Lowland of the Northwest Territories, Canada. Scotty Creek typifies the southern extent of permafrost in much of Canada where a high density of peatlands helps preserve discontinuous permafrost due to the large thermal offset created by the dry, insulating peat covering the ground surface (GS) (Robinson and Moore, 2000; Smith and Riseborough, 2002). The peatlands of the Scotty Creek basin and much of the Hay River Lowland are dominated by a mosaic of permafrost plateaus, channel fens, and ombrotrophic flat bogs (Quinton *et al.*, 2009). Unlike bogs and fens, the permafrost plateaus support a tree cover (*Picea mariana*) and are underlain by ~5–10-m-thick permafrost (Burgess and Smith, 2000). Their crests rise 1–2 m above the surfaces of the surrounding bogs and fens (Robinson and Moore, 2000). Channel fens take the form of broad, 50- to >100-m-wide channels. Unlike the floating peat mat characterizing the surface of fens, flat bog surfaces are relatively fixed. Most flat bogs are small features that occur within permafrost plateaus, while others are relatively large, contain numerous permafrost plateaus, and are connected to channel fens.

Detailed field measurements and analysis of high-resolution aerial and satellite imagery indicate that the plateaus, fens, and bogs have contrasting functions with respect to basin hydrology (Quinton *et al.*, 2003; Hayashi *et al.*, 2004). Plateaus function as runoff generators, given their relatively large snowmelt water supply, limited capacity to store water, and their relatively large hydraulic gradient that directs excess water into the adjacent permafrost-free wetlands: i.e. the channel fens and bogs (Quinton *et al.*, 2009). Because the elevation of the ice-rich permafrost table (PT) below the plateau GS is greater than the surface elevation of the permafrost-free wetlands, the plateaus also obstruct and redirect the drainage of water in the wetlands. Bogs that are completely surrounded by plateaus are therefore hydrologically isolated from other wetlands with respect to surface and near-surface drainage. As such, water entering isolated bogs is stored until it is removed by evaporation or groundwater recharge (Wright *et al.*, 2008). During most of the year, water entering connected bogs (i.e. those with a surface connection to channel fens) is stored as in the case of the isolated bogs; however, surface runoff into channel fens can occur during the annual snowmelt period and in response to large, late-summer rain events (Wright *et al.*, 2008). The water chemistry of bogs indicates that they recharge groundwater systems, consistent with the general conceptual model of bog–fen complexes (Hayashi *et al.*, 2004). Water entering channel fens from plateaus or bogs is routed toward the basin outlet, as the primary hydrological function of the fens is lateral flow conveyance along their broad, hydraulically rough channels (Quinton *et al.*, 2003). In contrast to the bogs, analysis of fen water samples and of the vertical hydraulic gradient in fens indicates that fens receive groundwater discharge (Hayashi *et al.*, 2004).

Methodology

Remote sensing

The forest cover distribution in the study area mirrors that of the permafrost, as the forest occurs only on the permafrost plateaus. This offers a unique opportunity to monitor permafrost thaw rates as such thaw transforms permafrost plateaus into treeless wetlands (i.e. bogs or fens), a change easily detected on the ground and from aerial and satellite imagery (Jorgenson *et al.*, 2001). Field observations at Scotty Creek (Quinton *et al.*, 2009) and elsewhere in the Hay River Lowland (Robinson and Moore, 2000) indicate that permafrost thaw leads to local inundation and water logging, causing death of the tree cover within 1 or 2 years.

IKONOS multispectral satellite imagery (4-m resolution) from August 2000 and four sets of aerial photographs taken between 1947 and 2008 were obtained for Scotty Creek. The aerial photographs include high-resolution (0·55–1·22 m) historic black and white (visible) aerial photography (acquired from July to September 1947, 1970, 1977) and mosaicked near-infrared aerial photography (0·18 m resolution) acquired in August 2008 coincident with an airborne survey using light detection and ranging (LiDAR). The historical aerial photographs were ortho-rectified using the 2008 aerial photography and a LiDAR-derived digital elevation model (DEM) (resolution = 1 m) (Chasmer *et al.*, in press). A 1 km × 1 km subset area was chosen, corresponding to the area covered by the LiDAR survey and also containing linear disturbances visible in all images (requirement of aerial triangulation and ortho-rectification processes). The three cover types [permafrost plateaus, wetlands (i.e. bogs and channel fens) and open water] were classified on the basis of land-cover spectral properties (Chasmer *et al.*, in press). Using the time series of images, sequential maps were developed that show changes in the spatial distribution of the tree-covered area and, by proxy, the area underlain by permafrost. Owing to the mismatch in pixel resolution, the accuracy of aerial triangulation and ortho-rectification, the ability to detect plateau features within aerial photographs, and forest/plateau edge delineation, the uncertainty in the delineation of the boundaries between different land-covers results in errors that range between 8% and 12% in the land-cover area estimates from the air photos and up to 26% from the IKONOS imagery (Chasmer *et al.*, in press). All linear disturbances were digitized using the IKONOS image to obtain an estimate of their total length within the Scotty Creek basin.

Field studies

Field measurements were initiated at Scotty Creek in June 1999 to assist with the interpretation of aerial and satellite imagery. These included measurements of water table elevation, soil temperature (ten depths between 0·05 and 0·7 m), water content (four depths between 0·05 and 0·4 m) and thaw rate, and surface energy balance measurements at selected bogs, fens, and permafrost plateaus. A main study site was established that included instrumentation on a permafrost plateau and its adjacent bog and channel fen. On the plateau, soil pits were excavated to the frost table on 20 August 2001 and instrumented with thermistor and water content sensor arrays (Wright *et al.*, 2009). A meteorological station was erected on the plateau crest in August 2003 and instrumented for GS radiation and energy balance measurement (Wright *et al.*, 2008). Water table elevations were monitored in 5-cm-diameter monitoring wells (Hayashi *et al.*, 2004) using pressure transducers. To assess the inter-annual variation of water levels, a common datum was used from June 2003 onwards, which was well anchored into the deep (>3 m) mineral sediment in the fen. All sensors were connected to data loggers programmed to measure every minute and to record half-hourly averaged values.

A transect extending between the edges of the channel fen and bog on opposite sides of the instrumented plateau was established in June 1999 to measure the width of the permafrost below the plateau, and to monitor soil thaw above the permafrost. The width of the permafrost was measured at the end of each summer thaw period as the distance between the points on either side of the plateau where permafrost was undetectable by the 1·3-m probe. Electrical resistivity imaging along the measurement transect as well as across other plateaus at the study site indicate that the permafrost edges are typically vertical or nearly so, and the transition from permafrost to non-permafrost is abrupt (McClymont *et al.*, 2010). The thaw depth was measured at 1-m intervals along the transect by probing the ground with a graduated steel rod, which readily detected the top of the frozen peat (Wright *et al.*, 2008). Thaw depths were measured every 2 days during the 2004, 2005, and 2006 field seasons, weekly in 2007 and 2008, and at the beginning and end of the summer field seasons in the other years. In 2006 and 2009, a total station was used to obtain the surface elevation of the transect points relative to a common datum in the channel fen.

Results

Analysis of remotely sensed images

Remote sensing analysis of the 1·0-km^2 subset area (Figure 1) indicates that permafrost occupied 0·70 ± 0·06 km^2 in 1947 and decreased with time to 0·43 ± 0·03 km^2 by 2008, as evidenced by the expansion and merger of wetlands (i.e. bogs and fens) and the shrinkage and disappearance of the forest cover (i.e. permafrost plateaus). This corresponds to a 38% loss (±8%) of the permafrost present in 1947 by 2008, which is similar in magnitude to that reported by Bielman and Robinson (2003) over the same period for other sites in the region. The 2008 imagery indicates 133 km of linear disturbance (i.e. winter roads and seismic cutlines) within the 152-km^2 basin. Thus, compared to the basin's natural drainage density (0·161 km^{-1}) (Quinton *et al.*, 2003), the density of linear disturbance within the Scotty Creek drainage basin (0·875 km^{-1}) is about five times greater.

Ground-based observations

The remotely sensed observations of permafrost loss are supported by ground-based observations of the same within the subset area. During the course of the field studies since 1999, stark changes were noted on the permafrost plateaus, including subsidence, active layer thickening, and paludification and flooding of their margins,

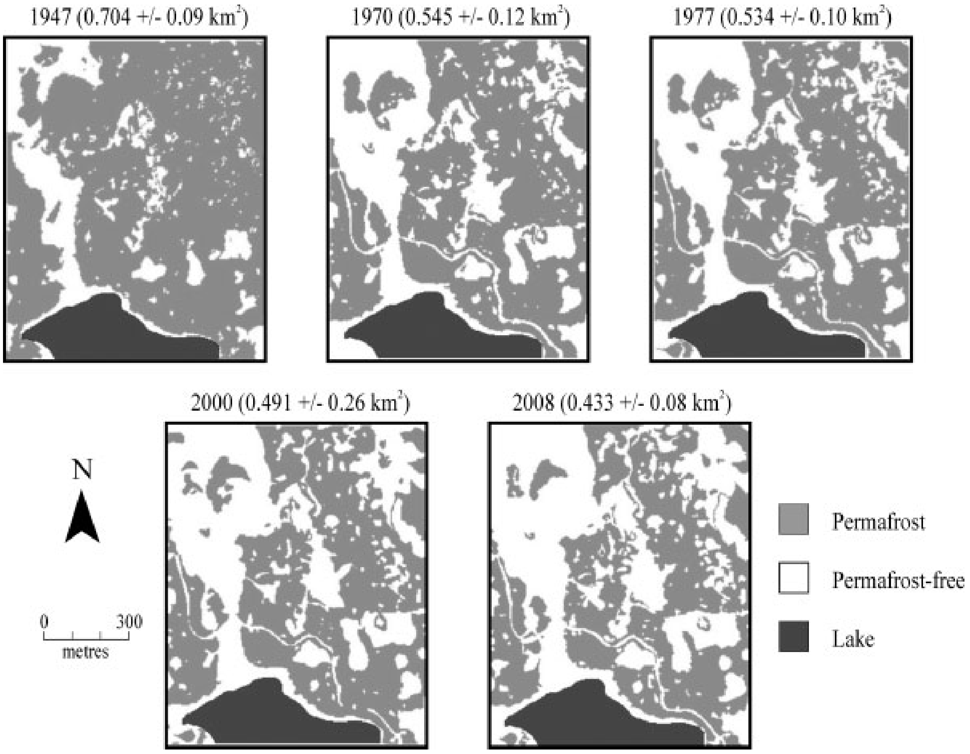

Figure 1. The area of the 1-km^2 subset area of Scotty Creek, Northwest Territories, Canada underlain by permafrost in 1947, 1970, 1977, 2000, and 2008

all of which appear to be due to widespread permafrost thaw. For example, in August 2002, an instrumented soil pit was 8 m from the edge of the channel fen and 0·6 m above it. By August 2008, the same pit was at the edge of the fen and had subsided to the fen's elevation. Such changes were not the result of rising water levels in the surrounding wetlands, as the variations in water level around the plateau were relatively minor throughout the 1999–2009 observation period. For instance, for the period since June 2003, while a common elevation datum was used, the difference between the lowest and highest water level in the fen was only 0·36 m.

Following the initial measurement of 41·6 m in June 1999 (Figure 2a), the permafrost plateau width steadily declined over the 1999–2009 period. By September 2009, it had decreased to 24·2 m (Figure 2b). Of the 17·4 m decrease, the majority (11·8 m) thawed on the side of the plateau bordering the channel fen. Over the 1999–2009 period, the average depth of thaw of the transect points at the end of the summer (late August to early September) increased by over 0·3 m (Figure 2b). These observations indicate that the permafrost thaw in this terrain is driven by both horizontal and vertical heat flows. Over the last 3 years (2006–2009), the end-of-summer thaw depth increased on average by 0·34 m (SD = 0·20 m), and the GS subsided on average by 0·13 cm (SD = 0·12 cm) (Figure 3).

Data from the instrumented soil pits indicate that the temperature of the active layer has steadily increased since monitoring began in 2001. For instance, the maximum annual temperature at the depth of the deepest sensor (0·7 m) increased with each successive year between 2001 (2·0 °C) and 2009 (8·1 °C). The thaw depth transect measurements also indicated the development of several preferential thaw zones that persisted from year to year. Since 2006, the maximum thaw depth exceeded the length of the graduated rod (i.e. 1·3 m). Such observations have helped in guiding initial studies on permafrost thaw mechanisms, which in turn have led to a new conceptual model of preferential thaw leading to permafrost thaw. Key processes include tree canopy thinning, which increases radiation loading to the GS, leads to a local thaw depression toward which subsurface water drains, and therefore an area of increased soil moisture content with concomitant increased bulk thermal conductivity. More thermal energy is then transferred into the ground, further deepening and broadening the thaw depression, leading to surface saturation, loss of tree canopy, more energy loading at the GS, and eventually to a local loss of permafrost (Quinton *et al*., 2009). Ground observations suggest that this conceptual model also applies to linear disturbances. Where these features traversed permafrost plateaus, the black spruce canopy was felled and the ground has since thawed and subsided, resulting in a grid of linear, permafrost-degraded or permafrost-free corridors, which potentially allow isolated bogs to drain and hydrological connections among bogs, fens, and permafrost plateaus to form.

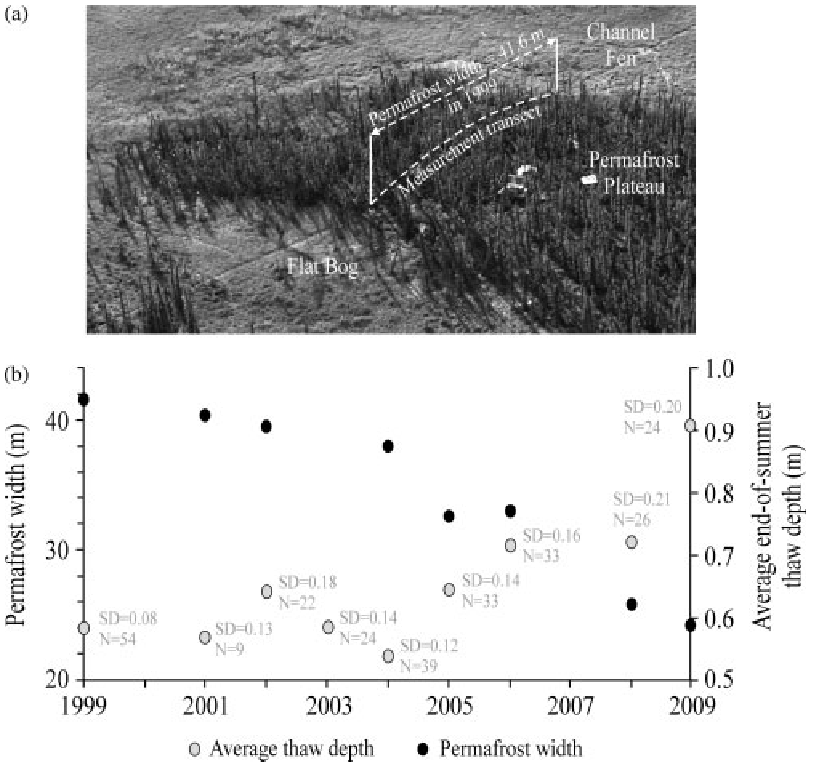

Figure 2. (a) Oblique aerial photograph of the study plateau showing the location of the measurement transect and the initial width of permafrost of 41·6 m measured in June, 1999 (photograph taken in September, 2006) and (b) change in permafrost width and the average end-of-summer thaw depth for the period 1999–2009. SD is the standard deviation and *N* is the number of observations

Discussion and Recommendations

A major challenge to northern water resources management in the coming decades lies in predicting runoff dynamically by considering widely occurring permafrost thaw and the resulting change in land-cover. Meeting this challenge requires new research on the mechanisms and rates of permafrost thaw, the influence of permafrost thaw on water drainage and storage patterns and processes, and appropriate planning, mitigation, and adaptation strategies. Numerous studies indicate that the subarctic is responding to climate warming, as indicated by changes in permafrost, land-cover, hydro-climatology, and river flow, as referenced above. However, the causal linkages and feedbacks among these factors are poorly understood, in part because individual studies typically focus on a single factor, and the results of studies are difficult to compare as they are often based on different time and space scales. For example, the discharge from subarctic rivers in both Eurasia (Smith *et al*., 2007) and Canada (St. Jacques and Sauchyn, 2009) have increased in recent decades, particularly during low-flow periods, and this increase is expected to continue throughout the subarctic due to climate warming (Milly *et al*., 2005). However, these studies were mainly focussed on long-term trends of monthly or daily discharge data, and as such provide little information on linkages to permafrost thaw, land-cover change, or other possible causes.

The present study in the wetland-dominated southern boundary of permafrost has shown that permafrost thaw transforms plateaus into permafrost-free wetlands, i.e. bogs or channel fens (Robinson and Moore, 2000). At the drainage basin scale, this land-cover change alters the relative proportions of the three main cover types. As each of the cover types is known to have a distinct hydrological function, a change in their relative coverage has the potential to affect the basin hydrograph (Quinton *et al*., 2009). This is supported by a recent study (Quinton *et al*., 2009) that compared a 4-year average annual runoff of wetland-dominated, discontinuous permafrost basins with different relative proportions of permafrost plateau, flat bog, and channel fen, and found that the average annual basin runoff is negatively correlated with the percentage of the basin covered by bogs, and positively correlated with the percentage covered by channel fens (Figure 4). In recent years, changes have been reported in runoff production from wetland-dominated basins with discontinuous permafrost. For instance, the total annual runoff from Scotty Creek and several other gauged rivers in the Hay River Lowland appears to be increasing since the mid-1990s (St. Jacques and Sauchyn, 2009; Quinton *et al*., 2009).

An important first step towards understanding the linkages between land-cover change and river flow in wetland-dominated discontinuous permafrost is to develop a numerical model to accurately simulate the

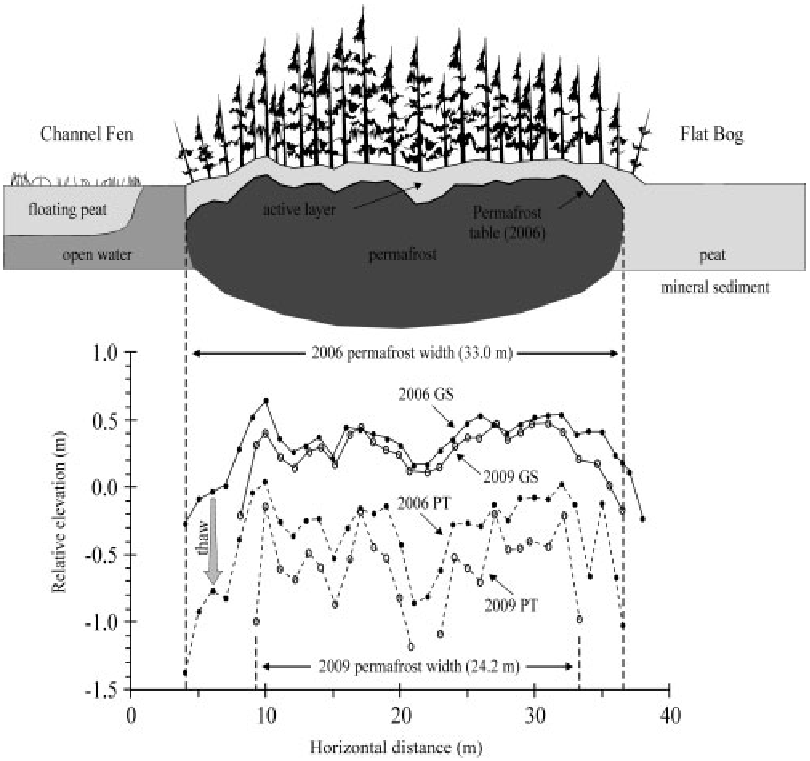

Figure 3. A schematic cross section of the study plateau along the measurement transect depicting the GS and upper surface of the permafrost (i.e. PT) as measured in September 2006. The graph indicates the elevations of the GS and PT at the end of the 2006 and 2009 soil thaw seasons. The vertical shaded arrow illustrates an example of thaw depth for the third transect point in September 2006

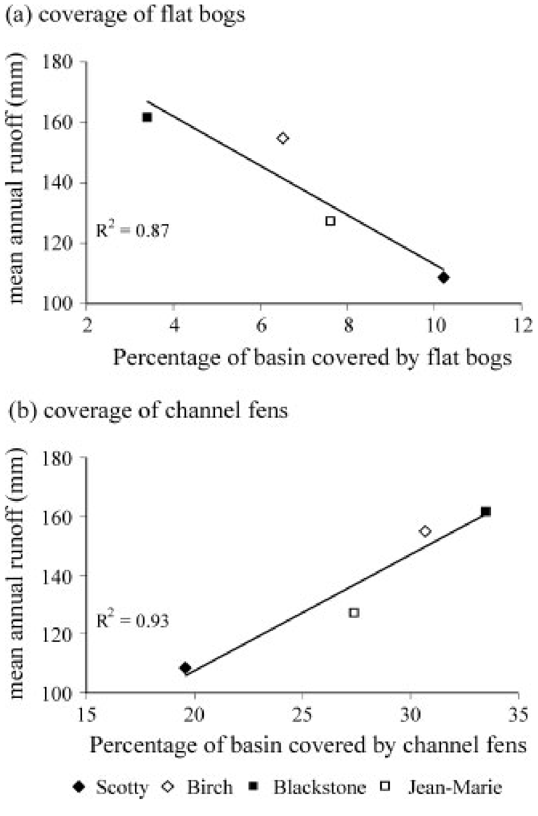

Figure 4. Mean annual runoff for a 4-year period (1997–2000) plotted against the percentage of the basin covered by (a) flat bogs and (b) channel fens. Modified after Quinton *et al*. (2003)

rates and patterns of permafrost thaw. The current suite of models (Zhang *et al*., 2008) used to predict permafrost response to warming are one-dimensional, run on large grids (e.g. 0·5° × 0·5°), and do not consider the juxtaposition of permafrost and permafrost-free terrain that characterizes discontinuous permafrost. As such, these models contribute relatively little to a mechanistic understanding of how permafrost thaw and the consequent land-cover change relate to streamflow. The new thaw model should be coupled to a hydrological model that drains water from contributing bogs and permafrost plateaus and routes it through the drainage network towards the basin outlet. In the context of widely occurring permafrost thaw, coupling basin runoff and routing to the thawing of plateaus is essential because it would produce basin runoff estimates on the basis of continually updated permafrost plateau spatial distributions. This approach also offers the possibility of estimating basin runoff for future permafrost plateau distributions projected to occur after decades of thaw. This new predictive capacity would help reduce the uncertainty of future runoff production along the southern boundary of permafrost.

Permafrost thaw resulting from tree canopy removal along linear disturbances should be included in the coupled thaw-runoff model, as the impact of linear disturbances on permafrost thaw and basin hydrology in the context of widely occurring climate-induced permafrost thaw remains poorly understood. From a hydrological point of view, linear disturbances can be viewed as permafrost-free wetlands that function analogously to channel fens by collecting water from surrounding plateaus and bogs and routing it towards the basin outlet. The relatively dense linear disturbance at Scotty Creek increases the effective drainage area of the basin by allowing the drainage of areas that were previously isolated from the drainage network, and increases the basin drainage efficiency by providing more direct drainage pathways to the basin outlet. The new thaw model would help minimize the impact of linear disturbances on permafrost and drainage by providing information on appropriate grid densities and widths and orientations of individual lines.

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