

Changing surface water systems in the discontinuous permafrost zone: implications for streamflow

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Abstract This study was conducted in the wetland-dominated, southern margin of continental permafrost at Scotty Creek, NWT, Canada over the period 2001–2010. In this region permafrost is discontinuous and occurs predominately below tree-covered peat plateaus. The southern margin of continental permafrost is experiencing unprecedented rates of permafrost thaw, yet the effect of this thaw and the resulting ecosystem changes on northern water resources is poorly understood. A distinction between primary and secondary runoff pathways that supply basin drainage networks was identified and incorporated into a new conceptual model that describes the flow and storage of water in the wetland-dominated terrains that dominate the southern margin of permafrost. The objectives of this study were to: (a) estimate primary runoff from the plateaus using the Cold Regions Hydrological Model and relate to basin runoff; and (b) evaluate the impact of changing primary runoff on basin discharge. A strong, positive correlation between primary runoff from plateaus and basin discharge was demonstrated, indicating that with the representation of other flow and storage processes, such as secondary runoff and the routing of water through connected bogs and channel fens, hydrograph simulation for basins with thawing permafrost plateaus is attainable.

Key words permafrost thaw; land-cover change; runoff simulation; northern water resources

BACKGROUND

The present ability to account for rising river flows in the southern margin of permafrost (St. Louis & Sauchyn, 2009) and the capacity to predict flow variations in that region is severely restricted by the limited understanding of water flow and storage processes in the wetland-dominated terrains that predominate throughout much of the southern margin of discontinuous permafrost. This is compounded by a poor understanding of how the warming climate in this region (IPCC, 2007) affects hydrological processes, including feedbacks, with changing ecological conditions. However, remotely-sensed data and ground-based observations provide important insights into the water flow and storage processes along the southern boundary of permafrost. For example, each of the major peatland-cover types in this region appears to have a specific hydrological function. Fens route water toward the basin outlet, as their primary function is lateral flow conveyance along their broad (~50–100 m) and hydraulically rough channels (Quinton *et al.*, 2003). Plateaus have a limited capacity to store water, a relatively large snowmelt water supply and hydraulic gradients that direct excess water into adjacent permafrost-free wetlands (Wright *et al.*, 2009). As such, plateaus function primarily as runoff generators, with runoff occurring predominately through the saturated layer between the water table and the relatively impermeable frost table (i.e. cryofront) below. Plateaus also obstruct and redirect water movement in adjacent wetlands since the open water surfaces of the latter occupy an elevation below the permafrost table. Bogs are primarily water storage features, since most are entirely surrounded by permafrost and therefore unable to exchange surface or near-surface water with the basin drainage network. Given the contrasting hydrological functions of bogs, fens and plateaus, the permafrost thaw-induced changes in the relative proportion of a drainage basin occupied by each cover type has potential consequences to the basin hydrograph (Quinton *et al.*, 2003).

There are some exceptions to the conceptual model of peatland-specific hydrological functions described above. For example, some bogs are able to exchange surface and near-surface water with an adjacent channel fen if during periods of high moisture supply (e.g. spring freshet) the bog or fen water level exceeds the elevation of the intervening permafrost embankment. Other bogs that may appear hydrologically-isolated are, on closer inspection, connected by ephemeral rills that are active during periods of high moisture supply. This observation has led to a distinction between primary and secondary runoff pathways, where the primary runoff refers to

water draining from the sloped edges of the plateaus directly into the basin drainage network (i.e. a channel fen or a bog that is perennially connected to a fen). Secondary runoff from plateaus arrives at the basin drainage network indirectly through a bog or a sequence of bogs ephemerally connected to the latter.

This study investigates the impact of permafrost thaw on the production of primary runoff from peat plateaus to the basin drainage network. This is accomplished by the following specific objectives: (a) estimate primary runoff from the plateaus using the Cold Regions Hydrological Model and relate to basin runoff; (b) evaluate the impact of changing primary runoff on basin discharge. These objectives draw upon conceptual and numerical modelling, field measurements and satellite remote sensing in order to take a critical first step toward understanding and eventually simulating basin hydrographs in a region experiencing widespread permafrost thaw with unknown consequences to water resources.

SITE DESCRIPTION

Scotty Creek (61°18'N, 121°18'W) is a 152 km² drainage basin that lies 50 km south of Fort Simpson in the lower Liard River valley of the Northwest Territories, Canada, where the landscape is dominated by both discontinuous permafrost (Hegginbottom & Radburn, 1992) and peatland complexes typical of the “continental high boreal” wetland region (NWWG, 1988). As such, Scotty Creek is also typical of the southern extent of permafrost where the large thermal offset created by dry, insulating peat preserves isolated patches of permafrost in the form of raised peat plateaus (Robinson & Moore, 2000; Smith & Riseborough, 2002). The Fort Simpson region has 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, 2011). 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). The Scotty Creek drainage basin is covered by 3–4 m of peat overlying a thick clay to silt-clay deposit of low permeability (Aylesworth & Kettles, 2000). The peat plateaus at Scotty are tree-covered (predominantly *Picea mariana*), underlain by permafrost, and their surfaces rise 1–2 m above the surrounding bogs and fens (Fig. 1(a)) which are permafrost free and largely treeless. The active (i.e. seasonally-thawed) layer contains an upper layer of living vegetation and fibric peat, underlain by a darker, sylvic layer in a more advanced state of decomposition. The thickness of the upper layer is highly variable, but typically between 0.15 and 0.2 m. The water table lowers to ~0.5 m or more by late summer. This is in contrast to the bogs and fens where the water table remains close to the ground surface throughout the thaw season.

The Scotty Creek watershed is undergoing rapid and widespread permafrost thaw. The proportion of a 1 km² area of interest (Fig. 1(b)) underlain by permafrost decreased from 70% to 43% between 1947 and 2008 (Quinton *et al.*, 2011). Electrical resistivity imaging across the width of plateaus at Scotty Creek indicated that the permafrost is of the order of 10 m thick with edges that are vertical, or nearly so, and that the transition from permafrost to non-permafrost terrain is abrupt (McClymont *et al.*, 2010). Permafrost thaw involves both the recession of these vertical permafrost edges as well as thickening of the active layer. The average end of summer thaw depth measured at 1-m intervals across the plateau presented in Fig. 1(a) increased by approximately 0.36 m between 1999 and 2010. Over the same period, the plateau width decreased by over 18 m. The surface elevation at the 1-m interval points decreased on average by 0.13 cm (SD = 0.12 cm) between 2006 and 2009 (Quinton *et al.*, 2011).

METHODOLOGY

Model simulation of primary runoff

Earlier studies at this study site indicated remarkable spatial uniformity among peat plateaus in terms of their rate of active layer thaw (Hayashi *et al.*, 2007) and with depth below the ground surface (Quinton *et al.*, 2008). There also appears to be very little variation of slope angles on the

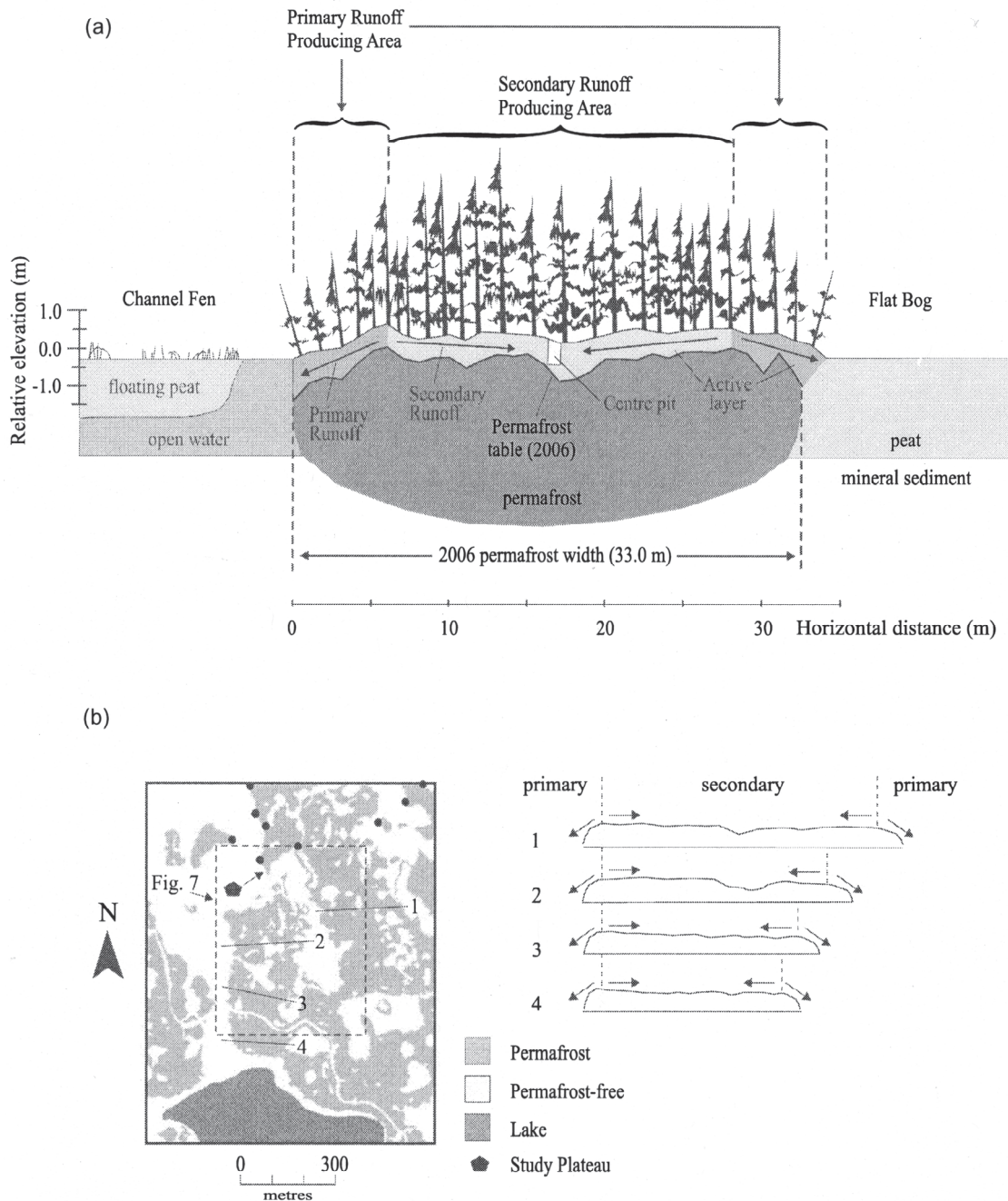


Fig. 1 (a) A schematic cross-section of the study plateau depicting the position of the ground surface and upper surface of the permafrost as measured in September 2006. The primary and secondary runoff producing areas are also illustrated. (b) A 1 km² area of Scotty Creek maps the distribution of permafrost for 2008. Also plotted is the location of the Study Plateau, and the locations where the plateau slope angles were measured. The four transects shown on the 1 km² area are schematically illustrated in cross-section to the right of the map.

flanks of plateaus where primary runoff occurs (Fig. 1(a)). To confirm this, the slope angles of nine plateau edges were measured (rise/run) with a hand-held clinometer over the distance between the plateau edge and the approximate break in slope that separates the primary and secondary runoff producing areas (Fig. 1(b)).

Subsurface runoff from the study plateau was simulated using the Cold Regions Hydrological Model (CRHM) platform, a flexible object-oriented modelling system devised for purposes of

simulating the cold regions hydrological cycle from hillslopes to medium sized basins. CRHM has no provision for calibration. Instead, parameters and model structure are selected based on the understanding of the hydrological system. As such the model can be used both for prediction and for diagnosis of the adequacy of hydrological understanding. A full description of CRHM is provided in Pomeroy *et al.* (2007). Details on the field measurements in support of the model runs presented here are provided in Quinton & Baltzer (2013).

The Centre pit and meteorological station provided the values of the soil thermo-physical properties, air and ground surface temperatures, temperature and moisture content of each computational layer of soil, as well as the initial water equivalent depth of the snowpack and depth to the frost table needed to initialise CRHM. The air temperature was used to estimate the snowmelt rate and the ground surface temperature, the ground thaw rate (Quinton & Gray, 2003). Although these temperature index methods used to simulate snowmelt and frost table lowering are relatively simple, their use has several advantages, since (i) the present study is focused on improving the understanding of subsurface runoff processes, and (ii) index methods enable a close match between the measured and simulated snowmelt and frost table lowering, and as such remove the possibility that significant error in the runoff simulations are routed in the snowmelt and ground thaw routines. Running the model required air temperature, ground surface temperature and rainfall, all of which were measured at 30-minute intervals on the Study Plateau. All computations were made on a 30-minute time step for a 1-m wide strip of ground extending from plateau edge to the break in slope, thereby covering the entire length of the primary runoff producing area. The upper boundary of the strip was the ground surface, and its lower boundary the impermeable frost table.

RESULTS AND DISCUSSION

Model simulation of primary runoff

A detailed analysis of the sensitivity and uncertainty of CRHM runoff simulations at Scotty Creek is provided by Quinton & Baltzer (2013). In the present study, CRHM was run for two periods in each year for the period 2002–2010 (except 2009), one ending 1 June, and the other ending 1 September. The length of the 1-m wide modelling strip was set to 20 m, a typical length between the plateau edge and the break in slope that separate the primary and secondary runoff areas at the study site. The slope of the modelling strip was set to 0.041, the mean value of the measurement locations indicated in Fig. 1(b). The use of a mean value is reasonable given the small standard deviation among the locations ($SD = 0.006$).

Since this study is a first step toward the longer-term objective of simulating hydrographs from wetland-dominated basins with discontinuous permafrost, and because the first segment of the overall runoff pathway connecting plateaus to the basin outlet is primary runoff, the simulated total primary runoff was plotted with the peak discharge from the basin outlet arising from the annual freshet to see if any correspondence exists between primary pathway runoff drainage basin response. The reasonably strong correlation (Fig. 2) provides some encouragement that with the representation of the other flow and storage processes along the basin drainage network, such as the routing of water through connected bogs and channel fens, basin hydrograph simulation is attainable.

There is also some correspondence between the temporal patterns of plateau and basin discharge. Figure 3 plots the simulated plateau water loss for the period ending 1 September with the observed basin hydrograph for three years that represent the lowest (2004) and highest (2007) primary runoff, and a year with intermediate primary runoff (2010). In each year, the major peaks of the plateau hydrographs are followed by peaks in basin discharge. The magnitude of individual peaks in the basin hydrographs appear to be related to the hydrological condition of the plateaus. For example, the largest peak in the basin hydrograph of 2004 (Fig. 3(a)) occurred in response to the 34 mm event of 25–27 May, while the water table occupied the zone of uniformly high K suggesting a rapid runoff from the plateau flanks into the channel fens from where it is conveyed to the basin outlet. A similar condition produced the basin hydrograph peaks of 27 April 2007 (Fig. 3(b)) and 17 July 2010 (Fig. 3(c)). The 2010 peak rose in response to the 26.8 mm (15 July)

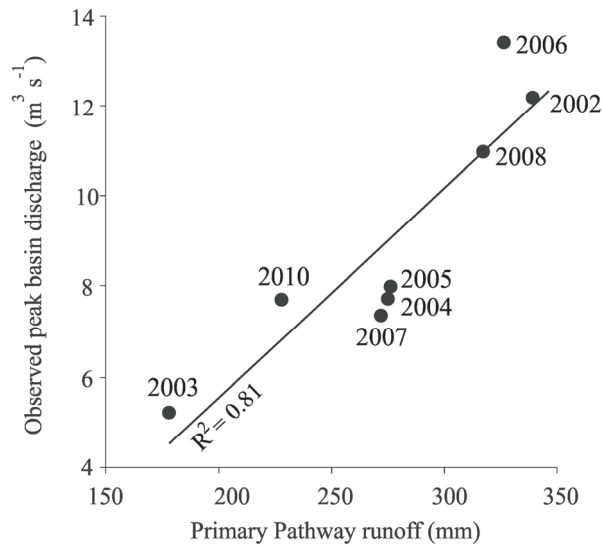


Fig. 2 Simulated primary runoff for each year of study for the period ending 1 June plotted with the peak discharge measured during the same period by the Water Survey of Canada at the outlet of Scotty Creek.

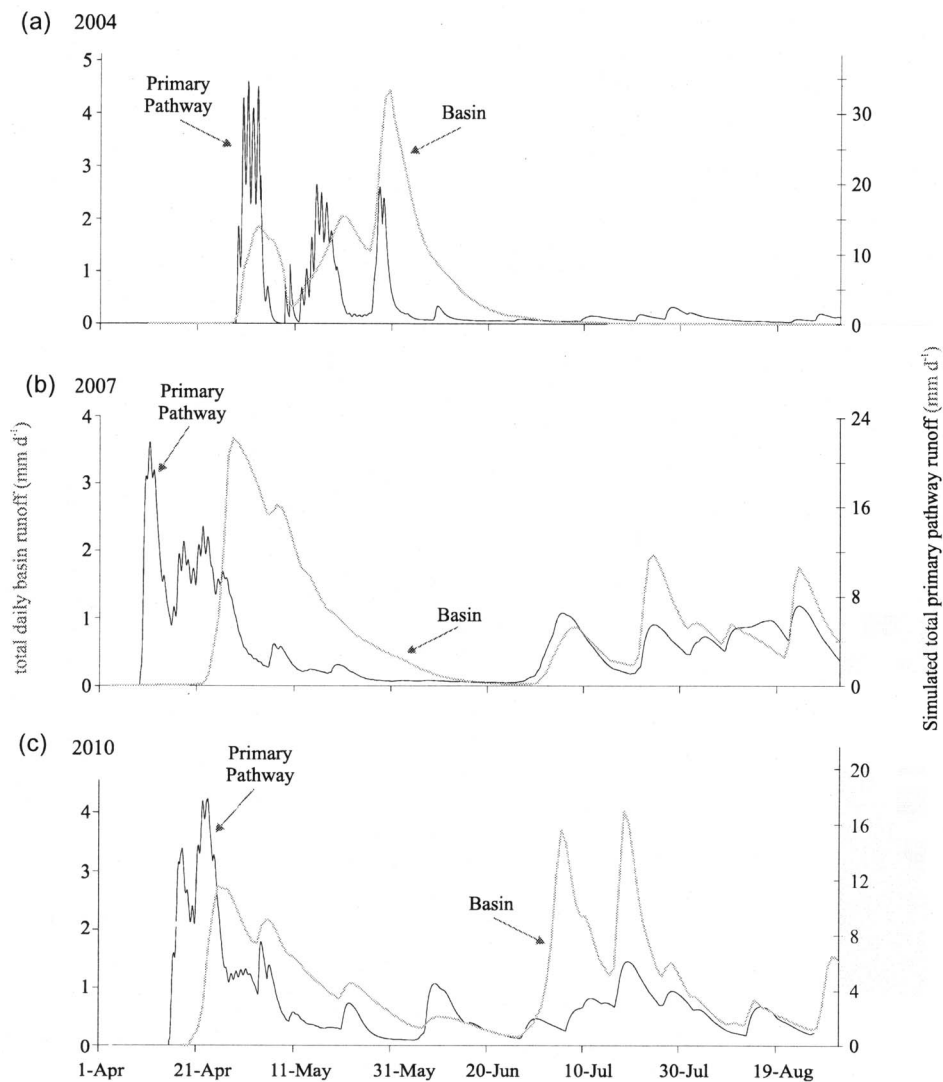


Fig. 3 Primary runoff hydrographs simulated using CRHM for 2004 (a), 2007 (b) and 2010 (c).

and 14.0 mm (16 July) rain events that elevated the plateau water table into the transitional and uniformly high K zones, enabling rapid water transfer from plateaus into channel fens and onward to the basin outlet. These high water table elevations on the plateaus in May 2004 and July 2010 also represent periods of high water table elevation throughout the basin. Such a condition facilitates the development of hydrological connections between bogs and channel fens, which effectively expands the basin runoff contributing area. This may explain the relatively large basin hydrograph peaks of May 2004 (Fig. 3(a)) and July 2010 (Fig. 3(c)). In contrast, rain events in July 2004 produced water table responses entirely within the zone of uniformly low K . These low water table elevations indicate low rates of subsurface water transfer from the plateaus and that hydrological connections between bogs and fens were not well established. As a result the rain events of July 2004 generated only minimal hydrograph responses from the plateau and no response from the basin outlet (Fig. 3(a)).

Potential impacts of permafrost thaw on basin runoff

Increasing streamflows over recent decades in northwestern Canada have been attributed to “reactivation” of groundwater systems (St. Louis & Sauchyn, 2009). However, given the characteristic hydrological functions of bogs, fens and plateaus, and given their rapidly changing proportions on the landscape (i.e. expansion of bogs; shrinkage and disappearance of plateaus) due to permafrost thaw, we suggest that changing flow and storage processes of surface water systems may also have contributed to the observed streamflow increases. As permafrost thaw proceeds, plateaus become increasingly fragmented and as a result the total length of edge separating plateaus from fens increases. As such, the length of plateau edge yielding primary runoff to the basin drainage network increases proportionately. Figure 4 illustrates the thaw of permafrost between 1977 and 2008 at Scotty Creek in the vicinity of a channel fen. Examples can be seen of bogs that were isolated from the drainage network in 1977 but had become connected to it by 2008. This process of “bog capture” can further increase basin runoff since it adds to the channel fen the primary runoff entering the bog that was ‘captured’ and therefore incorporated into the basin runoff producing area. As permafrost thaw proceeds and bogs (and their watersheds) connect to the fens, a greater proportion of the surface water system becomes available for basin runoff.

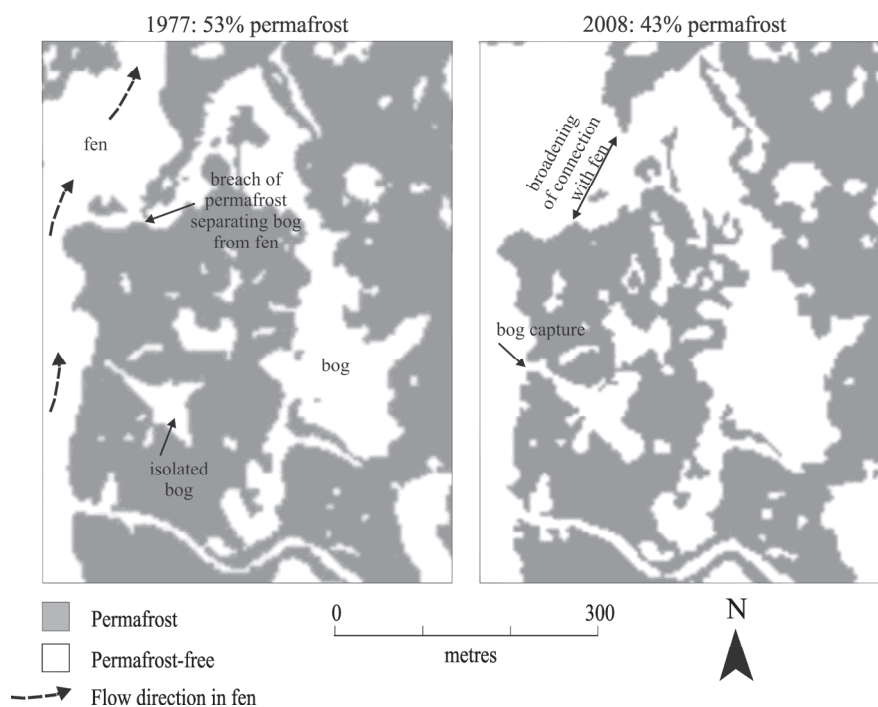


Fig. 4 Change in permafrost cover between 1977 and 2008, and resulting increase in the plateau edge contributing primary runoff to the basin drainage network.

CONCLUSIONS

This paper explored the how climate warming and permafrost thaw induced changes to surface water systems may have contributed to observed increases in streamflow over recent decades in northwestern Canada. It was shown that the hydrological functions of bogs might be changing as the surrounding permafrost thaws and disappears. Bogs that were recently connected to a channel fen by the thaw of the permafrost that separated them display the hydrological (e.g. flowing water) and the initiation of the ecological transition to fen-like vegetation. The premise that the hydrological functions of plateaus, bogs and fens are fixed cannot account for increasing basin runoff due to thaw-induced changes to the hydrological function of bogs. This model should be superseded by a new model that accounts for permafrost-thaw induced changes to the hydrology of the bogs, fens and plateaus. Such changes also have the potential for homogenisation of wetland ecological communities by increasing the flow of water between bogs and fens, and as such the new conceptual model should incorporate both hydrology and ecology, and the feedbacks between them.

An additional, though yet unexplored possibility, is that forest loss is contributing to elevated wetness in this system. In addition to thaw of permafrost and resulting addition of previously frozen water to the system, loss of permafrost equates to net loss of the overlying forests as described above. Trees act as efficient conduits for the transport of water to the atmosphere via transpiration. Ewers *et al* (2005) quantified species-level contributions to stand-level canopy transpiration at a site in Thompson, Manitoba. The contribution by *P. mariana* ranged from 3 to 332 mm with older, pure stands of *P. mariana* ranging from 183 to 332 mm. Based on preliminary dendrochronological analysis, forests in Scotty Creek may be 170 years or older (Sniderhan & Baltzer, unpublished data). While it is likely that trees would be functioning at a lower physiological level than the maximum rates in the previously mentioned study due to the harsher climatic conditions, there is the distinct potential that net forest loss associated with permafrost thaw in this system is contributing to greater retention of water in the system, which would feed back positively on the enhanced conditions of wetness at the site. Certainly, a common response of tree removal is increased soil moisture (e.g. Gray *et al.*, 2002). Such eco-hydrological feedbacks require more attention to further refine our evolving conceptual models of the functioning and response of boreal peatlands in the face of rapid climate warming.

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