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Hydrological impacts of seismic lines in the wetland-dominated zone of thawing, discontinuous permafrost, Northwest Territories, Canada

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Abstract:

Intensive seismic exploration in the Northwest Territories began in the late 1960s. Since that time, the legacy of seismic surveys – i.e. straight lines cutting through boreal forest and tundra – has remained visible throughout northern Canada and Alaska. The removal of trees and compaction of the ground surface alter the thermophysical properties of the active (i.e. seasonally thawed) layer to such an extent that the underlying permafrost seriously degrades or even disappears completely. Such a transformation along linear corridors that cut indiscriminately across different terrain types with contrasting hydrological functions has potentially serious implications to the redistribution of water and energy within and among landscape units with feedbacks to permafrost thaw, land cover change and run-off generation. This paper characterizes the flow and storage of water and energy along a seismic cut line in the high boreal zone of discontinuous permafrost in order to improve the understanding of these processes, their interactions and hydrological implications. As such, this paper lays a conceptual foundation for the development of numerical models needed to predict the hydrological and thermal impact of seismic lines in this sensitive region. We used ground-penetrating radar and multi-year ground temperatures and water levels along a seismic line to estimate the degree of permafrost degradation below it. The seismic line studied extends from a permafrost-free wetland (flat bog), over a permafrost body (peat plateau) and into another permafrost-free wetland (channel fen). It was found that once thaw had lowered the permafrost table below the ground surface elevation of the flat bog and channel fen, the seismic line forms a hydrological connection between them. It was also shown that during the permafrost thaw process, seismic lines develop a perennially thawed layer (talik) between the overlying active layer and underlying permafrost and that the talik conveys water as a conduit throughout the year. The implications of such drainage through seismic lines and networks on basin drainage in peatland-dominated regions with discontinuous permafrost are also discussed. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS seismic line; permafrost; water flow; active layer; peat; hydrology

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INTRODUCTION

Permafrost is ground that remains at or below 0 °C for at least two consecutive years (PIWP, 2012). In the Mackenzie River valley of Canada's Northwest Territories (Figure 1), permafrost thickness decreases with decreasing latitude from over 300 m at 68°N to approximately 10 m at 62°N (PIWP, 2012). The zone between approximately 58°N and 62°N is often referred to as the southern fringe of permafrost (Kwong and Gan, 1994), where permafrost is discontinuous, is relatively thin (~10 m) and typically occurs below tree-covered peat plateaus that rise 1–2 m above the surrounding permafrost-free and treeless wetlands (i.e. flat bogs and channel fens) (Beilman and Robinson, 2003). Climate warming-induced permafrost thaw occurs at the highest rate in this southern fringe, where insolation is relatively high and where vertical heat conduction through the active layer is augmented by lateral heat advection from adjacent permafrost-free terrains. The permafrost temperature in this zone is already at or just a fraction of a degree below the melting point (Burgess and Smith, 2000); thus, very little additional energy is required to initiate its thaw. Because permafrost thaw results in ground surface subsidence, the tree-covered plateaus overlying permafrost are flooded as they subside and, consequently, are transformed to open-water wetlands (Osterkamp, 1983). The simultaneous processes of local permafrost disappearance and the resulting land cover transformation characterize the permafrost thaw throughout the southern fringe zone (Rowland *et al.*, 2010).

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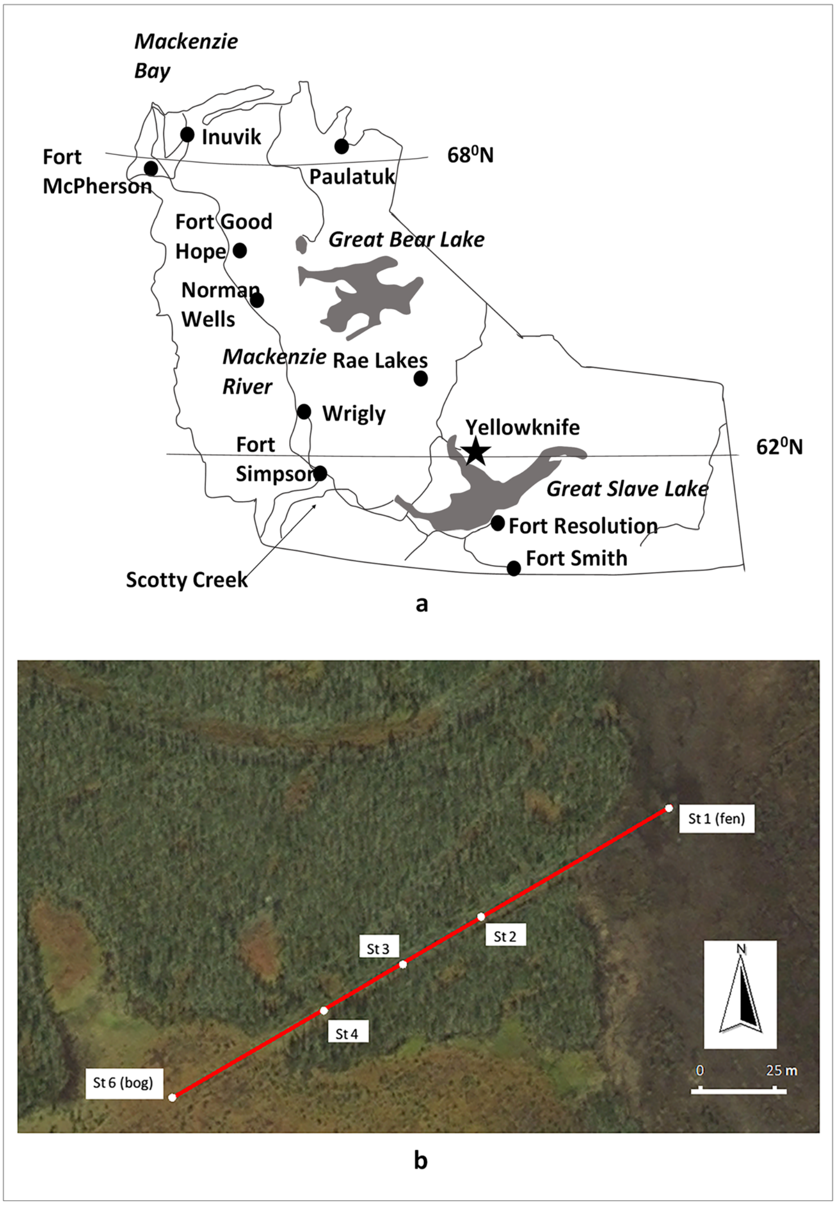

Figure 1. (a) The Scotty Creek study site within the Northwest Territories; (b) the examined seismic line (red) and the locations of the measurement stations (white circles). The forested areas (green) are peat plateaus, underlain by permafrost. The remaining area in the image is wetland, including fen (darker surface on right of image) and bog. The examined seismic line (red) and the locations of the measurement stations (white circles). The forested areas (green) are peat plateaus, underlain by permafrost. The remaining area in the image is wetland, including fen (darker surface on right of image) and bog

Disturbance of the ground surface often initiates positive feedbacks (Williams, 2013) that accelerate the thaw and land cover transformations arising from climate warming. The active layer below disturbed ground surfaces is generally thicker and warmer compared with adjacent undisturbed areas (Chapin and Gaius, 1981). When the ground surface of permafrost ecosystems is disturbed, the effects propagate throughout its water, ice, soil and vegetation components (Woo, 2012). For example, the removal of trees increases insolation at the ground surface, increasing the amount of energy available for conduction into the ground. The heavy machinery used in seismic operations increases the bulk density of near-surface soils by compaction (Severson-Baker, 2003). This process also increases the moisture content and therefore the thermal conductivity of these near-surface soils. These changes accelerate the rate of seasonal active layer thaw along seismic lines, leading to the thaw of the underlying permafrost (Williams and Quinton, 2013). Given the high ground ice contents throughout much of the southern fringe of permafrost, permafrost thaw in this region leads to significant thaw and ground surface subsidence (Jorgenson *et al*., 2010), which for seismic lines produces linear depressions (Williams *et al*., 2013).

Degradation of permafrost below seismic lines can alter water flow and storage processes with implications to the water balance at local and regional scales (Williams *et al.*, 2013). Being saturated with ice and a small fraction (<15%) of unfrozen water, permafrost in this zone of high wetland coverage is relatively impermeable to water, as is the frozen portion of the active layer. As such, the zone of liquid water storage and flow is limited to the unfrozen portion of the active layer and, if present, to the talik (i.e. perennially unfrozen) layer situated between the active layer and permafrost. The fragmentation and eventual disappearance of permafrost below a seismic line result in a linear, permafrost-free corridor that cuts through a permafrost body, connecting adjacent permafrost-free terrains and allowing the possibility for heat and mass transfer between them. Because permafrost thaw below the line lowers the ground surface elevation, there is a possibility that subsurface flow through the line can be augmented by surface flow over it. A length of seismic line traversing a peat plateau imports water from upslope wetlands intersected by the line and from the undisturbed forest on both sides of the length. Overland flow along seismic lines is often observed during periods of high moisture supply, such as spring snowmelt and in response to large summer rain events. Knowledge of permafrost distribution below linear disturbances, the rate and pattern of its decay and the possibility of its regeneration contributes to the understanding of the overall hydrological impact of seismic disturbances in the southern fringe of permafrost. The objectives of this paper are to (1) characterize the ground thaw and water flow and storage processes along a seismic line in the wetland-dominated zone of discontinuous permafrost, (2) examine how these processes change over the thaw season, and over the longer term since the initial disturbance, and (3) propose a new conceptual model that describes both these changes and can be used as a basis for numerical simulations.

STUDY SITE

Site characteristics

The 152-km^2 Scotty Creek drainage basin (61°18′N, 121°18′W) is located about 60 km south-east of Fort Simpson, NT, Canada, in the zone of discontinuous permafrost (Figure 1). The 1981–2010 climate normals indicate that Fort Simpson has a dry continental climate with short, dry summers and long, cold winters. On average, the annual average air temperature at Fort Simpson is −2.8 °C, and the annual total precipitation is 353.6 mm, of which 244.3 mm is rainfall (MSC, 2010). The study area is predominantly flat and gently sloping towards the north-west. As in much of the southern fringe of permafrost, the permafrost at Scotty Creek occurs predominantly below peat plateaus, the forested ‘islands’ within a treeless terrain of flat bogs and channel fens. The contrasting biophysical properties of these three peatland types give each a specific role in the water cycle. Plateaus have a limited capacity to store water input owing to their relatively thin active layer. Run-off generated from their sloping surfaces is conveyed into adjacent wetlands (Quinton and Baltzer, 2013). As such, plateaus function primarily as run-off generators, with run-off occurring predominately through the thawed, saturated layer between the water table and the relatively impermeable frost table below it. Because bogs are entirely surrounded by peat plateaus, they are unable to exchange surface or near-surface water with the basin drainage network and as such are predominantly water storage features. The fens are broad, hydraulically rough channels that convey water towards a basin outlet. The water table in the wetlands (i.e. bogs and fens) remains at or within a few centimetres of the ground surface (Williams *et al.*, 2013). By contrast, the plateaus are mantled by an unsaturated layer that may exceed 50 cm during summer. The high thermal resistivity of this layer is critical to preserving the underlying permafrost. The active layer thickness on undisturbed plateaus ranges between 50 and 70 cm.

Measurement stations

Five measurement stations were installed along a 195-m-long segment of a seismic line, which was cut in 1985 and which extends across a 90-m-wide section of peat plateau that separates a channel fen on its east side from a flat bog on its west side (Figure 1). Station 1 (St 1) was located in the fen, approximately 75 m from where the seismic line enters the plateau. St 2 and St 3 were situated about midway between the bog and the fen where the ground surface elevation of the seismic line is greatest, and St 4 was located on the plateau on a floating peat mat at a distance of 10 m from where the seismic line entered into the bog. The next station, named St 6 (i.e. St 5 malfunctioned), was placed in the middle of the bog, 60 m from St 4. Photographs of each site are presented in Figure 2.

The fen contains areas of open water that appear impounded or are slowly moving. Other areas of the fen support vegetation that conceals the water surface. As such, flow over the fen is highly diffuse and tortuous, with rills meandering through sedge tussocks (e.g. *Eriophorum vaginatum* and *Carex stricta*) and other aquatic vegetation. A *Sphagnum* (mainly *Sphagnum fallax*) mat is the lowest level of living vegetation on the fen surface. At St 2 on the plateau, the ground surface is saturated and covered with *Sphagnum* moss. Black spruce (*Picea mariana*), 0.5–2 m tall, sparsely occupies the north (i.e. south-facing) side of the seismic line, while

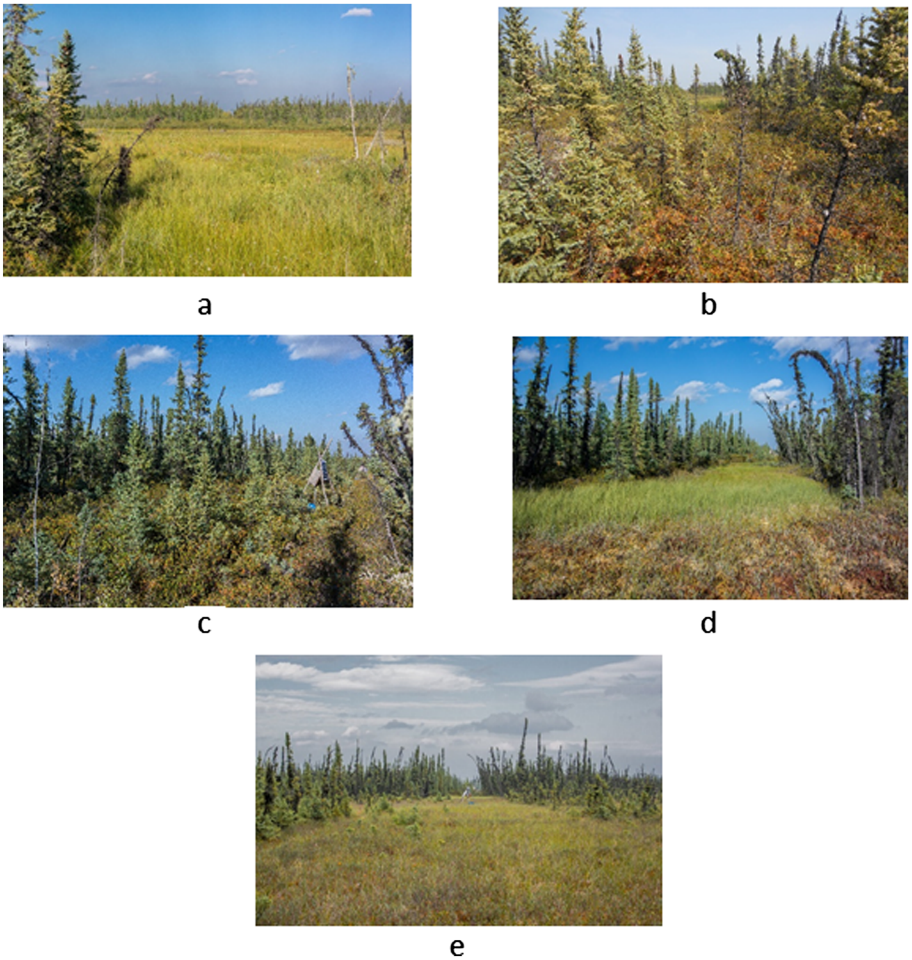

Figure 2. Photo of instrumented sites: (a) station 1, (b) station 2, (c) station 3, (d) station 4 and (e) station 5

no trees are present on the opposite side. Labrador tea (*Rhododendron groenlandicum*) covers the entire width of the line. The ground surface slopes towards the south side where the forest floor of the adjacent peat plateau is about 1 m above the seismic line. However, the slope of the ground surface between the relatively flat forest and seismic line surfaces is much greater. On the south of the line, this slope is approximately 70° over a horizontal distance of 1–2 m, while on the north side, the slope is only about 5° over a distance of 5–10 m. At St 3, the ground surface is much dryer than at St 2. Black spruce occupies about 80% of the ground surface at this site and rises to a maximum height of roughly 2 m on the north side and 0.6 m on the south. As at St 2, Labrador tea covers the entire width of the line at St 3. The south side of the line at this site is also characterized by black spruce trees at the forest edge, leaning into the seismic line in a way often described as 'drunken forest', a clear indicator of permafrost thaw. By contrast, the forest edge on the northern side appears to be regenerating with numerous black spruce saplings present, as well as willow shrubs. At St 4, about 80% of the seismic line width is occupied by a floating peat mat. As a result, the water table remains close to this adjustable peat surface (Fritz *et al.*, 2008) composed of *Sphagnum* moss with sparse sedge tussocks. The surface at the St 6 site is covered by the light brown wet *Sphagnum* moss with sparse sedge tussocks. Black spruce trees 0.5–1.0 m are present elsewhere in the bog, but not along the seismic line.

METHODS

Ground surface and active layer properties

High-resolution (1-m horizontal, 0.2-m vertical) airborne lidar data were collected in July 2010 by the Applied Geomatics Research Group, NS, Canada. The processing and interpretation were completed and described by Chasmer *et al.* (2008). These data were used to generate a digital elevation model (DEM) of the seismic line and surrounding terrain (Figure 3). Every 10 m along the 90-m plateau portion of the seismic line, a transect perpendicular to the line was used to measure the depth of

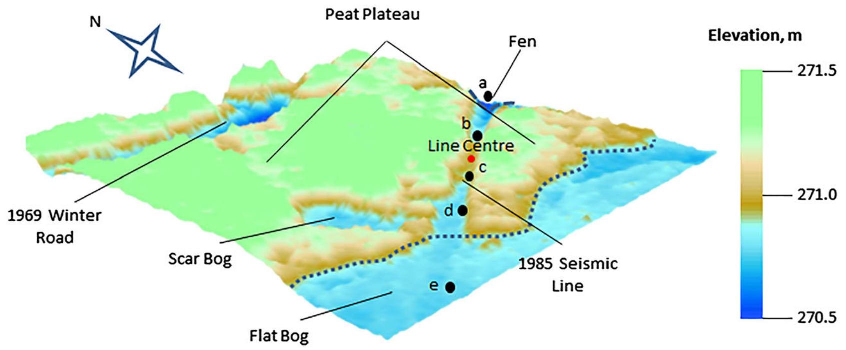

Figure 3. Lidar-derived digital elevation model of the seismic line and adjacent bog and channel fen. Black dots represent location of the measurement stations. (a) Station 1, (b) station 2, (c) station 3, (d) station 4 and (e) station 5

thaw at 1-m intervals for a total of seven measurements on each transect. Measurements were made using a 2-m-long graduated steel frost probe biweekly between 28 May 28 and 25 July 2013. Five boreholes ranging in depth between 2.2 and 6 m were excavated at the stations described earlier. Permafrost was detected in boreholes at St 2 (2.2 m), St 3 (1.7 m) and St 4 (2.6 m). St 1 (fen) was equipped with three thermistors (0.2, 0.5 and 1.0 m), St 2 with three (0.6, 1.1 and 2.3 m), St 3 with five (0.2, 0.7, 1.2, 1.7 and 1.8 m), St 4 with five (0.3, 1.3, 1.8, 2.3 and 2.4 m) and St 6 with five (0.15, 0.7, 1.15, 1.7 and 2.15 m). All thermistors are manufactured by Campbell Scientific and have an accuracy of ±0.2° C. Temperature was measured every 1 min and averaged and recorded every 1 h. Each station was also equipped with a pressure transducer manufactured by Solinst (0.1-cm accuracy) at 1.5-m depth for continuous measurement. Water pressure was measured every 30 min and averaged and recorded every 6 h. The sensors were left in the talik (perennially unfrozen) layer through the winter (31 August 2012–28 August 2014), so that during summer, they measured the pressure due to the height of water above them, while during winter, they measured the pressure in the talik below the freezing or frozen active layer. Measurements were corrected for atmospheric pressure recorded by a separate barometric sensor housed at a meteorological station approximately 500 m to the north. Ground temperature monitoring began on 26 March 2013 with measurements taken every minute and averaged and recorded every hour. The thermistors cables were attached to 0.05 × 3-m PVC pipe and driven into predrilled boreholes. The bottom of each pipe was sealed, and the pipe was perforated throughout its length. Transducers were placed into the same pipe below the expected maximum depth of frost penetration. Weekly average air and ground temperatures were computed from the higher-frequency measurements to minimize the effects of diurnal temperature variations and meteorological events. The frost table depth (i.e. thaw depth) along the seismic line was measured during the 2013 field season (28 May–25 July).

GPR survey

The presence of a talik below the seismic line was investigated during the preliminary site investigations in August 2012 and found to be present and ranging in thickness between 0.5 and 1.4 m according to temperature data. The presence of the talik aids in delineating the upper boundary of permafrost boundary from ground-penetrating radar (GPR) surveys given the high contrast in dielectric properties between frozen and unfrozen water. GPR surveys were conducted on 27 January 2013 and 23 March 2013. At these times, the active layer was frozen and as such provided very little attenuation of the electromagnetic pulse. Four layers with contrasting dielectric properties were distinguishable from the change in dielectric properties at the following boundaries: snow–active layer, active layer–talik, talik–permafrost and peat–mineral sediment. The bottom of the permafrost however could not be detected because of the limitations of the sensors. The MALA GPR system with a 100-MHz unshielded antenna was used for this purpose. The approximate sensing depth range for this antenna is about 2–15 m, and the lower limit of the object target size is 0.1–1.0 m. The transmitter and receiver of the antenna were mounted in an in-line configuration and have a fixed distance of 1 m. The temperature during the surveys ranged between −10 and −25 °C. A GPS unit was used to track the location of the survey transect in January so that it could be repeated for the March survey. Both the transmitter and receiver were towed over the snow surface along the 195-m distance between St 1 and St 6 at an average speed of 2 km h^{-1}.

The raw data produced during the GPR surveys were analysed using the REFLEXW software with the Dewow filter to eliminate low-frequency signals. The band pass frequency filter was used to suppress noise when it differed from the signal in its frequency content. The static correction filter was used to compensate for a possible time delay in the snow layer, shifting up all traces towards smaller times. The background removal filter was also used so that background noise arising from ringing in the antenna could be removed. The signal from the depth range 5–15 m was amplified by 10–30 times.

Active layer thaw

Energy enters the active layer by thermal conduction, warms the ground ice to the temperature of the freezing point depression and then melts the ice. For any depth position in the active layer containing appreciable ice, continued warming (above the freezing point depression) is delayed until after the ice content is melted. While thawing, the thawing active layer therefore contains an upper, thawed zone with positive temperatures, a lower zone with negative temperatures and an intervening downward-moving frost table at the temperature of the freezing point depression. For peatlands, where, except for a thin (approximately 0.05-m) surficial layer, the active layer can remain saturated, 86–88% of the total ground heat flux is used to melt ice in the active layer (Hayashi *et al.*, 2007).

The ground heat flux, Q_G (W m^{-2}) can be described by Fourier's law:

$$Q_G = -\frac{\rho c_p K(T_1 - T_2)}{z_1 - z_2} \tag{1}$$

where ρ is the bulk density (kg m^{-3}), c_p is specific heat capacity (J kg^{-1} K^{-1}) and K is the thermal conductivity (W m^{-1} K^{-1}). Because the top of the frozen, saturated layer remains at the freezing point while the active layer above it thaws, ground thaw can be computed from the peat porosity, latent heat of fusion for ice and the assumption that 85% of the heat flux into the ground is used to melt ice. However, estimating the mean annual ground surface temperature is more problematic. To overcome this difficulty, we assumed that on undisturbed peat plateaus, soil physical properties are uniform with depth and heat enters the active layer from both below and above, but in the vertical direction only. The geothermal heat flux Q_{GEO} (W m^{-1} K^{-1}) is computed from

$$Q_{GEO} = KG_g \tag{2}$$

where G_g [TL^{-1}] is the geothermal gradient independent of the presence of permafrost. The temperature at any depth can therefore be determined from

$$T_z = T_s + G_g z_p \tag{3}$$

where T_s (T) is the temperature of the ground surface and z_p (L) is the depth at which the soil temperature exceeds the ground surface temperature owing to the geothermal gradient:

$$z_p = (T_{fp} - T_s)/G_g \tag{4}$$

By combining Equations (2) and (4), the surface temperature can be computed from

$$T_s = z_p + \frac{Q_G}{K} + T_{fp} \tag{5}$$

Using the parameters presented in Table I, we derived a mean annual ground surface temperature of −0.5 °C, which is just 0.2 °C below the freezing point depression as reported by Quinton and Baltzer (2013). Therefore, warming of the ground surface by more than 0.25 °C can lead to the formation of a talik at the interface of the active layer and permafrost. The formation of this perennially unfrozen layer has the potential to thermally decouple the underlying permafrost from the cold atmosphere during winter.

The specific discharge [LT^{-1}] through the thawed, saturated layer of the line can be described by Darcy's law:

$$q = K_H\left(\frac{dh}{dx}\right) \tag{6}$$

where K_H is the saturated hydraulic conductivity of the peat in the horizontal direction [LT^{-1}] and d*h*/d*x* is the dimensionless hydraulic gradient along the line. Quinton *et al.* (2008) used field and laboratory measurements to investigate the depth variation of hydraulic conductivity at Scotty Creek. They demonstrated that K_H is uniformly high (200–300 m day^{-1}) in the upper ~20 cm of the active layer and uniformly low (~1 m day^{-1}) in depths greater than ~40 cm (Quinton *et al.*, 2008). Based on these findings, the authors proposed the following function, which represents changes of peat hydraulic conductivity K with depth z [L]:

$$\log K_{sat}(z) = 0.15 + 2.41 \Big/ \left[1 + \left(\frac{z}{0.15}\right)^{4.3}\right] \tag{7}$$

Table I. The parameters used to compute the mean annual surface temperature for a peat plateau

Parameters		Value	Unit
Thermal conductivity	K	1.4	W (m K)$^{-1}$
Geothermal heat flow	Q_G	0.035	W m^{-2}
Geothermal gradient	G_g	0.025	K m^{-1}
Permafrost thickness	z_p	10	m
Freezing point depression	T_{fp}	−0.3	°C

This equation was developed for the peat below a variety of disturbed and undisturbed peat plateau surfaces at Scotty Creek and as such was assumed to adequately represent peat from seismic lines.

RESULTS AND DISCUSSION

Permafrost characteristics below the seismic line

The DEM shows a distinct narrowing of the line with distance into the plateau from both the bog and fen edges to the point on the line midway between the two wetlands, suggesting thermal erosion from both the fen and bog sides. The DEM also reveals a steeper slope on its south side of the line throughout its 90-m length over the peat plateau, as described earlier for St 2.

The permafrost body under the peat plateau was readily identified by the intensity of reflections (Figure 4). As indicated by the DEM (Figure 3), the geophysical data also show that permafrost degradation was most pronounced near the plateau's boundaries with the fen and bog, where the permafrost table was about 1 m deeper and the permafrost thickness (2–4 m) was less than half the permafrost thickness midway between the two wetlands (about 9 m). These findings are consistent with those of McClymont *et al*. (2013) who used electrical resistivity imagery at Scotty Creek to demonstrate that permafrost thickness is greatest below the centre of plateaus and least at their margins. Likewise, Baltzer *et al*. (2014) showed that active layer thickness within 10 m of plateau–wetland margins was significantly greater than the active layer thickness below the interior of plateaus (i.e. at greater distances from the margin). As for the present study, both the McClymont *et al.* and Baltzer *et al.* studies were conducted on plateaus known to be shrinking because of permafrost thaw and whose shrinkage was documented over a period of decades by Quinton *et al*. (2004) and by Connon *et al*. (2014).

The top of the mineral sediment is between 7 and 8 m below the ground surface (Figure 4, line C) in the permafrost-free parts of the seismic line. Where the mineral–organic interface occurs within the permafrost, it cannot be discerned because of the insufficient difference in reflectance of mineral and organic material when both are saturated and frozen. During plateau formation, the degree to which the ground surface is displaced upward increases with the amount of ground ice formation below that surface (Zoltai and Tarnocai, 1975). Consequently, the topography of the ground surface roughly approximates that of the permafrost table. As a result, it is possible to deduce local areas along the seismic line where the underlying permafrost is most degraded as indicated by depressions in the ground surface.

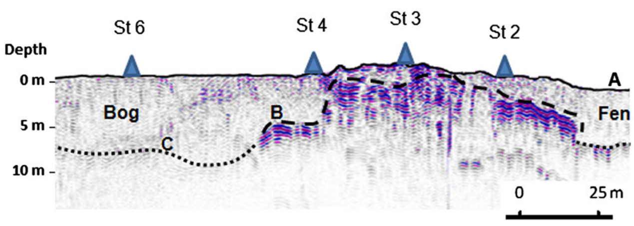

Figure 4. Ground-penetrating radar transect between bog and channel fen. The solid line (A) represents the ground surface measured from the 2010 lidar survey with vertical exaggeration: 1.5. The dashed line (B) represents the upper boundary of permafrost, and the dotted line (C) represents the interface between the peat and the underlying mineral sediment. The solid vertical lines indicate the edge of the bog and the fen. The locations of the measurement stations are identified (solid triangles)

Water flow through the seismic line

Given the relatively high topographic position of the bog, the general flow direction was from the bog through the seismic line and into the channel fen. This mean flow direction was verified by the relative pressures recorded at the five stations, which on average for the 2012–2014 period indicated flow towards the fen, where pressure was lowest (Figure 5f). This flux direction persisted through the winter months, although, during this time, flow occurred only through the talik that separates the frozen active layer above and the permafrost below (Figure 5d and e). However, there were deviations from this mean flow direction depicted in Figure 5 for short (i.e. seasonal) periods. For example, during the summers of 2013 (Figure 5b) and 2014 (Figure 5c), subsurface flow diverged from the middle of the seismic line towards both the bog and the fen. The only time when water entered the seismic line from the fen was during the 2013 spring freshet when the high water pressure in the channel fen temporarily reversed the hydraulic gradient such that flow, including overland flow, was driven into the seismic line (not shown in Figure 5). The minimum, mean and

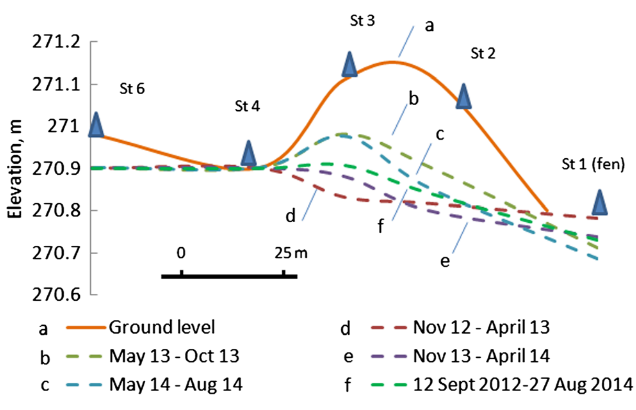

Figure 5. The arithmetic mean hydraulic head (m) recorded by the transducer at each station (dashed lines) with respect to ground surface elevation (solid line) for the next periods: (a) 12 Sept 2012–27 Aug 2014, (b) 6 Nov 2012–30 Apr 2013, (c) 5 Nov 2013–29 Apr 2014, (d) 7 May 2013–29 Oct 2013 and (e) 6 May 2014–27 Aug 2014

maximum annual soil temperatures for selected sites indicate a relatively thin (<60-cm) seasonally frozen layer in the bog (Figure 6a) and fen (Figure 6d), which are free of permafrost. At St 3 (Figure 6c), the maximum active layer thickness is approximately 60 cm. By contrast, the maximum active layer thickness at the St 4 bog (Figure 6b) (the plateau station closest to the bog) was estimated at about 0.9 m; however, with negative temperatures being very close to zero, the bottom of the active layer could not be defined with certainty.

As noted earlier, the talik enabled the seismic line to continue conducting subsurface flow throughout the winter. During the summer months, the cross-sectional area for subsurface flow through the line is the product of the line's width (i.e. the distance between the permafrost 'walls' on either side of the line) and the depth of the flow zone (i.e. the depth from the water table to the impermeable frost table, or in the case of full active layer development, the depth to the permafrost). Both the frost table and permafrost table vary with distance along the seismic line as depicted in Figure 4.

The average depth of the water table in May–Oct 2013 and May–Aug 2014 was 0.06 m between the bog and St 3 and 0.11 m between St 3 and the fen. Based on Equation (7), the hydraulic conductivity for the saturated zone of the active layer was computed as 1.8 m day^{-1} between St 3 and St 6 (bog) and as 1.6 m day^{-1} between St 3 and St 1 (fen). Using these values of K, the specific discharge through the seismic line between St 3 and St 1 (fen) and between St 3 and St 6 (bog) was calculated (Figure 7). During winter, the bog drains into the fen via the talik below the seismic line, while in summer, the flow direction on the bog side of St 3 alternates in and out of the seismic line (e.g. Figure 5d), thereby interrupting bog drainage towards the fen, while isolating the bog from the basin drainage network.

Active layer thaw in the seismic line

An analysis of the rate and pattern of active layer thaw in the seismic line for the period May 28–July 25 2013 shows a distinct bidirectional heat flux towards St 3 near the mid-point of the seismic line (Figure 8). Being free of permafrost, the fen and bog are heat sources during winter. After the spring freshet, the ground temperature started rising first in the fen (St 1) and then in the bog (St 6). This was followed by the warming of the stations on the seismic line closest to these wetlands. The station at greatest distance from the wetlands (St 3) warmed and thawed last (Figure 8). The initial temperature rise was most pronounced in the fen (St 1) and on the fen half of the seismic line. Although the bog temperatures rose later than fen temperatures, they reached higher temperatures by midsummer, and as a result, the seasonally frozen layer thawed earlier in the summer in the bog than in the fen. Comparative analyses of micrometeorological data from bogs and fens at Scotty Creek (Wright *et al.*, 2008) indicated that the relatively low albedo and absence of ventilation by flowing water resulted in higher ground surface temperatures in bogs than in fens.

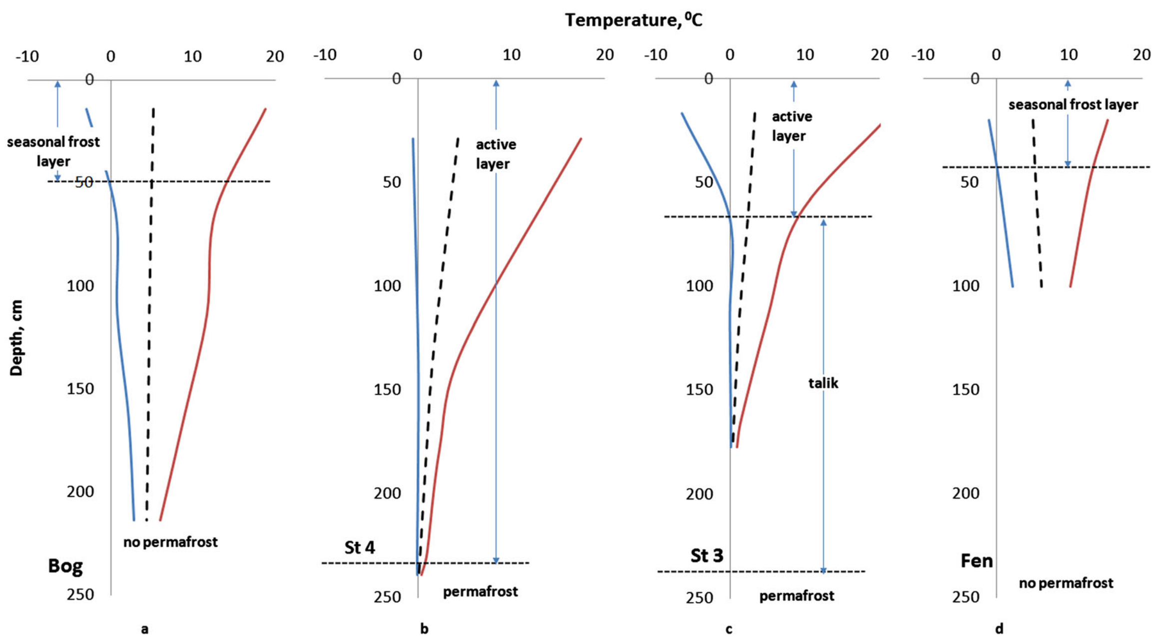

Figure 6. Minimum, maximum and mean annual soil temperature variations for the period 17 July 2013–17 July 2014 at the (a) bog (station 6), (b) station 4, (c) station 3 and (d) fen (station 1) stations. (Station 2 is not presented because of failure of logger)

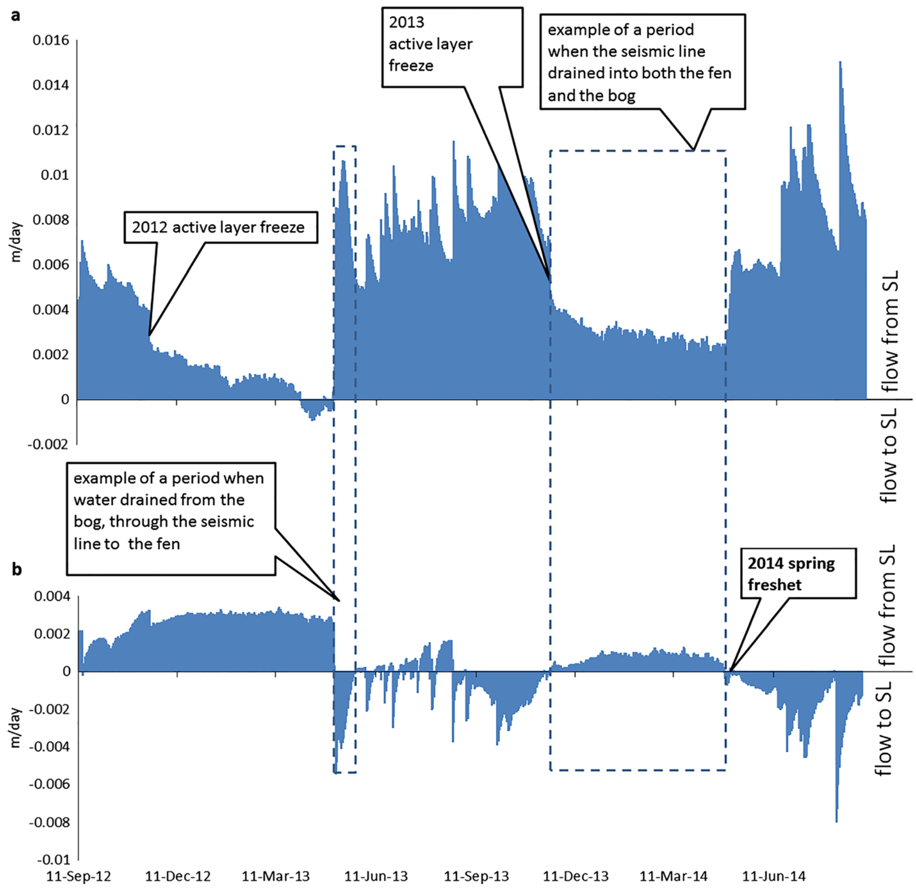

Figure 7. Subsurface flow along the seismic line for the sections between (a) station 3 and the fen (station 1) and (b) station 3 and the bog (station 6). Positive values indicate the water flow from the seismic line (SL), while negative values indicate flow towards seismic line

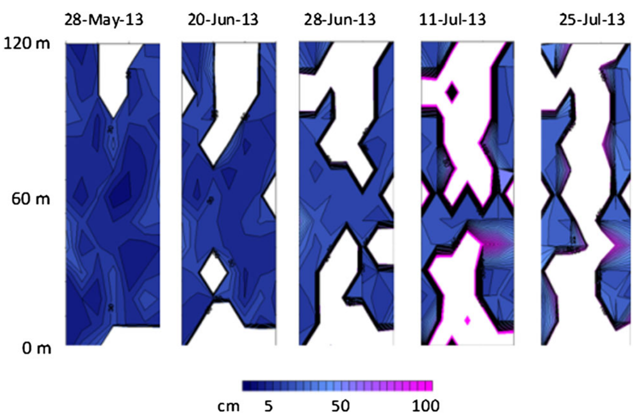

Figure 8. Variation in the depth of thaw along seismic line over the peat plateau between the plateau–fen edge (0 m) and the plateau–bog edge (120 m). White areas indicate absence of seasonal frost

Conceptual model

The insights gained from this study have given rise to a new conceptual model describing coupled thermo-hydrological processes within seismic lines in the high boreal zone of discontinuous permafrost. Linear seismic disturbances in this region appear to initiate a thermal and hydrological response with three distinct and consecutive stages.

Stage 1: thaw driven by internal processes. The first stage is initiated by the over-winter removal of the tree canopy over the line. In the following spring, ground surface depressions resulting from the heavy machinery used to cut the line serve as focal points for permafrost degradation in subsequent years. During periods of excess moisture (e.g. end-of-winter snowmelt), water accumulates in these depressions so that they become areas of preferentially high soil moisture, which may include ponding. Because wet soils are better thermal conductors than dry soils (Hayashi *et al.*, 2007), preferential wetting of the depressions results in active layer thickening and therefore permafrost thaw below the depressions. This results in the subsidence of the ground surface and therefore a further deepening of the depression, which increases the local hydraulic gradient, enabling the depression to draw water from further afield. As such, a moisture–thaw feedback is initiated that increases not just the depth of depression but also its width, a process causing individual depressions to coalesce along the line. Over time, preferential thaw and coalescence transform the seismic line into a linear depression that often takes on the appearance of a broad (~10-m-wide) ditch through the forest. The processes described earlier modify the seismic line so that it can conduct water along its length by overland flow and subsurface flow through the active layer.

Stage 2: development of continuous flow connection. Thaw along the line in the first stage was driven largely by internal processes within the portion of the seismic line traversing the peat plateau. The second stage is initiated once permafrost thaw has lowered the permafrost table below the elevation of the water table of the adjacent fen and/or bog. Once this occurs, the water in the bog and fen is no longer impounded by the intervening raised permafrost, and as a result, water and energy can flow from these adjacent wetlands onto the seismic line. Early in the second stage, water incursions over the ground surface and through the active layer from the bog and fen are separated as depicted in Figure 3, as in the middle of the fen (i.e. St 3), the ground surface and the underlying permafrost are elevated above the fen and bog water tables. However, with further permafrost thaw and ground surface subsidence, the bog and fen eventually become hydrologically connected, intermittently by overland flow, seasonally by flow through the active layer of the seismic line and eventually throughout the year by flow through the underlying talik. In the extreme case, stage 2 would lead to the complete removal of permafrost throughout the line.

Stage 3: differential permafrost thaw and recovery. At the time of this study, we considered the seismic line to be at stage 2. However, in the following, we describe stage 3 as the most likely scenario. Stage 3 is initiated once the seismic line shows indications of permafrost recovery. Whether this stage is reached depends upon the regional climate and other local factors affecting the heat flux into the ground (e.g. snow accumulation regime, density and height of tree canopy adjacent to the line, orientation of the seismic line, recovery of vegetation within the transect and proximity of the line to wetland water sources). The seismic line in the present study is oriented west–east, and as such, its north side (i.e. south facing) has relatively high insolation. Williams *et al*. (2013) found that this results in a dryer ground surface on the north side of the line, enabling greater regeneration of vegetation, including black spruce. As a result, the ground below the north side is better insulated than on the south side, where water accumulates preferentially and surfaces are wet and therefore more thermally conductive. Thermal erosion is therefore greater on the south side, where the edge of the seismic line forms a steep embankment, which continues to thaw as evidenced by the leaning of trees over the south side of the line. Permafrost regeneration on the north side and permafrost loss on the south side give the appearance on aerial imagery that the line is slowly migrating southward. In addition to permafrost regeneration on one side of the line as described here, Zoltai and Tarnocai (1974) found that isolated patches of permafrost can develop throughout seismic lines where permitted by local topographic and drainage conditions. The flow through the talik on the northern side of the line became much less significant than on the southern side because of permafrost regeneration. Preferential permafrost thaw on the south side of the seismic line may also, in part, be driven by the preferential flow through the active layer and talik along that side of the line.

SUMMARY AND CONCLUSIONS

This study characterized thaw and flow processes along a typical seismic line in the southern fringe of permafrost, in north-western Canada. Ground surface characteristic, including widening of the line near the plateau–wetland boundaries, and variations in topography and vegetation across the ~10-m width of the line were explained by preferential permafrost thaw and the resulting ground surface subsidence. Variations in subsurface properties, such as ground temperatures, ground thaw rates, depth to permafrost and presence and thickness of a talik, were also explained in these terms, and in relation to the flow of water through the seismic line. It was found that the seismic line is a highly dynamic pathway for subsurface flow in terms of both rate and direction. At some times of the year, it conveyed water from the bog into the channel fen on the other side of the intervening plateau, while at other times, it drained into both the bog and the fen. For the 2-year study period, water was conveyed from fen to bog only once and for a relatively brief period during the 2013 freshet. Overland flow and flow through the active layer are reasonably well-understood processes in this environment, and these processes are transferable to seismic lines. This study identified the perennially unfrozen (i.e. talik) layer and demonstrated its importance as a subsurface flow path. This is an important finding, as it was also shown that while flow through the active layer stops during the winter months, flow through the talik continues throughout the year, and at an appreciable rate – for the annual period starting September 2012, approximately 50% of the total flow through the seismic line was conveyed through the talik. This study has important implications to how we view the potential hydrological impacts of seismic lines in this region. For example, it was shown that seismic lines disrupt the characteristic storage function of bogs by allowing them to drain into fens and onward to basin outlets. Not only do seismic lines have the potential to increase the run-off-contributing area and therefore the amount of run-off produced by basins, but by cutting indiscriminately across bogs, fens and plateaus, they also have the potential to short-circuit the natural drainage network, thereby reducing run-off transit times. Over longer periods, these effects have the potential to alter the water of basins, especially where the density of seismic lines (i.e. the cumulative length dived by the basin area) is high. At Scotty Creek, the density of seismic lines is approximately seven times larger than the natural drainage density. Further research is needed to investigate these potential hydrological impacts of seismic lines. The new conceptual model describing coupled thermo-hydrological processes within seismic lines provides a foundation for such research.

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