The effects of permafrost degradation on the hydrological regime of subarctic peatlands

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ABSTRACT
Permafrost thaw is a direct consequence of human disturbance in Arctic and Subarctic regions. Thin and warm permafrost is most sensitive to surface disturbance and may disappear within a few decades following an initial disturbance. Seismic lines are one of the most common types of linear disturbance, yet their impact is poorly understood. A distinctive feature of seismic lines is their geometry. These straight cut lines cross fens, bogs, peat plateaus, rivers and lakes thereby connecting hydrological units, which were otherwise disconnected. The relatively warm water from lakes and fens may enter these lines contributing to further degradation of permafrost.
The purpose of this study is to characterize ground water dynamics between major hydrological units in the region of discontinuous permafrost in the Scotty Creek basin (at 61.310677N and 121.309181W), approximately 60 km SE from Fort Simpson, North West Territories. A number of geophysical surveys were conducted to delineate permafrost, peat and mineral soil borders. Temperature and water level observations were carried out throughout the year to understand the impact of thawing permafrost on hydrology of the research area. We found that as soon as the permafrost table descends below the water table, the seismic line creates a link between fens and bogs, slowly conveying water along the line. The water flow may take place all year round if it is not interrupted by accidental freeze of the talik layer between the active layer and permafrost.

Les effets de la dégradation du pergélisol sur le régime hydrologique des tourbières subarctiques

RÉSUMÉ
Le dégel du pergélisol est une conséquence directe de la perturbation humaine dans les régions Artique et Subartique. Un pergélisol mince à température élevée est plus sensible aux perturbations de surface et peut disparaître à l'intérieur de quelques décennies suite à une perturbation initiale. Les lignes sismiques sont l'un des plus communs types de perturbation linéaire, bien que leur impact soit encore peu compris. Une caractéristique distincte des lignes sismiques est leur géométrie. Ces lignes coupées droites traversent les marais, les tourbières et plateau tourbeux, les rivières et les lacs, connectant ainsi les unités hydrologiques, qui autrement étaient déconnectées. L'eau relativement chaude des lacs et marais peut entrer dans les lignes et contribuer à la dégradation future du pergélisol.
L'objectif de cette étude est de caractériser les dynamiques des eaux souterraines entre les unités hydrologiques majeures dans la région de pergélisol discontinu dans le bassin Scotty Creek (à 61.310677N et 121.309181O), à approximativement 60 km SE de Fort Simpson, North West Territories. Un nombre d'enquêtes ont été conduites pour tracer les limites du pergélisol, du plateau et des sols minéraux. L'observation de la température et du niveau de l'eau a été effectuée tout au long des années pour comprendre l'impact de la décongélation du pergélisol sur l'hydrologie. Il a été trouvé que, dès que le niveau du pergélisol descend sous la nappe phréatique, la ligne sismique crée un lien entre les marais et les tourbières, ce qui lui transmet de l'eau. Ce débit d'eau pourrait perdurer à longueur d'année s'il n'est pas interrompu par un gel accidentel du talik, situé entre la couche active et le pergélisol.

1 INTRODUCTION

Permafrost covers 40 to 50% of Canada's landmass (Robinson *et al*., 2003). During the second half of the 20th century, when the oil and gas industry expanded beyond the Arctic Circle (AECOM 2009), seismic lines were cut through boreal forest with heavy machinery, leaving long and wide trails that are still visible. Today seismic lines remain the most widespread type of disturbance related to oil and gas exploration (Kemper and Macdonald, 2009). The purpose of seismic lines is to create access to the exploration site for all terrain vehicles and snowmobiles (AANDC, 2001). Seismic cut lines with a width of 10-15 m were common in the 1950's to 1970's, with 5-8 m wide cuts being used in more recent years (Wiiliams *et al*., 2013). The seismic surveys consist of drilling shallow boreholes for dynamite charges, exploding those charges in a specific sequence and recording the seismic signal for further processing and interpretation. The ecological impact of seismic exploration is hard to overestimate. Soil and vegetation disturbance, wildlife habitat and aquatic system disturbance, and the introduction of invasive species are just some of the impacts (NLUG 2003). One of the areas most sensitive to disturbance is the region of discontinuous permafrost, especially the peatlands of western subarctic Canada (Wiiliams *et al*., 2013). The temperature of permafrost in these regions is slightly below zero degrees Celsius and the thickness of the frozen layer rarely exceeds 10-15 m. Any minor surface disturbance can cause an increase in soil temperature, which can be significant enough for the complete degradation of the permafrost. The cut of a seismic line goes far beyond a minor disturbance, and the grid of straight cuts through boreal forest and tundra is easily visible on the ground. The distinctive feature of seismic lines is their geometry. Being cut straight, they can cross fens, bogs, peat plateaus, rivers and even lakes, connecting hydrological units, which are naturally disconnected. The initial soil compaction is followed by surface subsidence, which creates artificial channels that may convey mass and heat for vast distances. This research focuses on the snowmelt runoff event in the narrow channel of seismic line which connects bog and fen in the basin of Scotty Creek, NT.

2 SITE LOCATION AND DESCRIPTION

The Scotty Creek basin is located approximately 50 km south-east of Fort Simpson, NT.

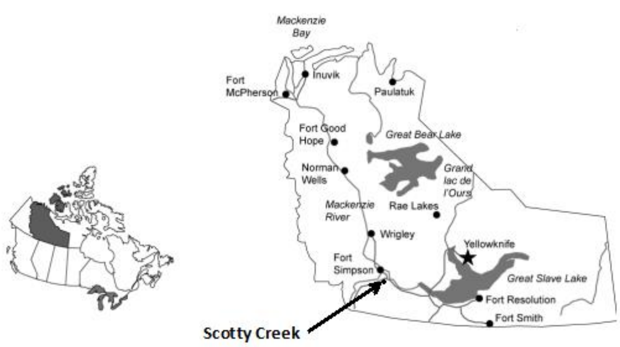

Fig.1 Location of the research site

The average annual temperature in the region is -3.2^0 C. (1964-2013). The average temperatures for July and January are 17.1^0 C and -25.9^0 C respectively. The annual precipitation is 363 mm. This area belongs to the continental climate zone and is situated in the region of discontinuous permafrost. Most of the Scotty Creek basin is a peatlands ecological complex consisting of peat plateau, bogs and channel fens. Peat plateaus elevate about 1.0-1.5 meters above the surrounding bogs and fens (Quinton et al., 2011). Permafrost is a distinctive feature of peat plateaus and the thickness of the perennially frozen layer is about 5-10 m (Burgess and Smith, 2000). The peat deposits are underlain by silty sand which can vary in thickness from several centimeters up to 8 meters. Peat plateaus are covered by black spruce (*P. Mariana*) and shrubs, *Labrador tea*, bog birch and others. Bogs are dominated by *Sphagnum* species and low shrubs. Bogs act mostly as water storage features and fens as water channels connecting small ponds and lakes. The depth of fens is about 20-40 cm, however it can have a tendency to change with vegetation development during the growing season. Vegetation in fens consists of grasses and sedges. Water in the fens is less acidic than in surrounding bogs.

The seismic line, which was chosen for the purpose of this study, was cut in 1985 and has a width of approximately 15 m, with a south west direction. Permafrost is still present under the seismic line at various depths from 1.5 m to 2.5 m, being shallower on the sun-facing side. The thawing of permafrost created a visible channel through the peat plateau, which is about 1 to 2 meters lower than the top of the peat plateaus (Fig. 2)

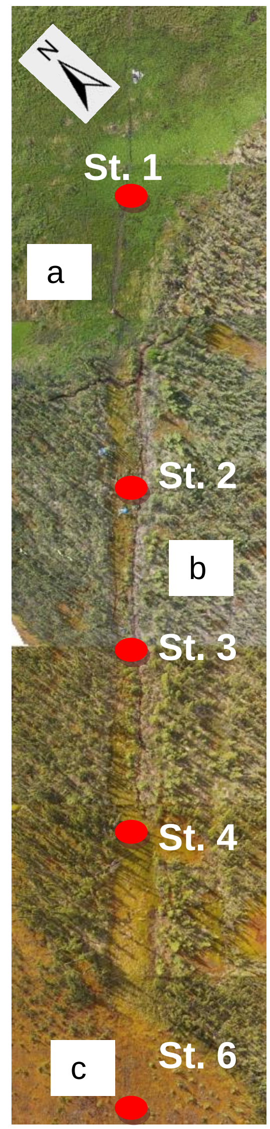

Fig 2. Arial view of the NE stretch of the seismic line. a) channel fen, b) peat plateau, c) flat bog red dots – locations of monitoring stations

3 METHODS

3.1 Geophysical survey - GPR

The mapping of the subsurface stratigraphy with Ground Penetrating Radar (GPR) is based on a contrast in the dielectric properties of different soil layers (Arcone *et al*., 1998). The resolution of investigation is directly proportional to signal frequency, however with an increase in resolution the depth of signal penetration decreases. (Scott *et al*., 1990) Four layers with contrasting dialectical properties due to temperature difference and two contrast layers due to different morphology were expected to be distinguished:

- snow frozen ground – top of active layer
- active layer-talik (perinially unfrozen ground between permafrost and active layer)
- talik-permafrost
- peat-mineral soil

Taking into account the fact that the water table in the research area is very close to the ground and peat has very high porosity at about 0.8, the dielectric properties of the soil are governed mostly by the amount of frozen and unfrozen water. The mineral soil in the area is mostly silty sands with a dielectric constant somewhere in between ice and fresh water, which makes it easy to detect with the Ground Penetrating Radar. The MALÅ RTA (Rough Terrain Antenna) System with a 100 MHz antenna was used for this research and RflexW from the Sandmeier Scientific Software was used for data processing. Interpretation of GPR profiles. Nine GPR transects were conducted in the area (Fig. 3), covering all possible types of hydrological units in the area.

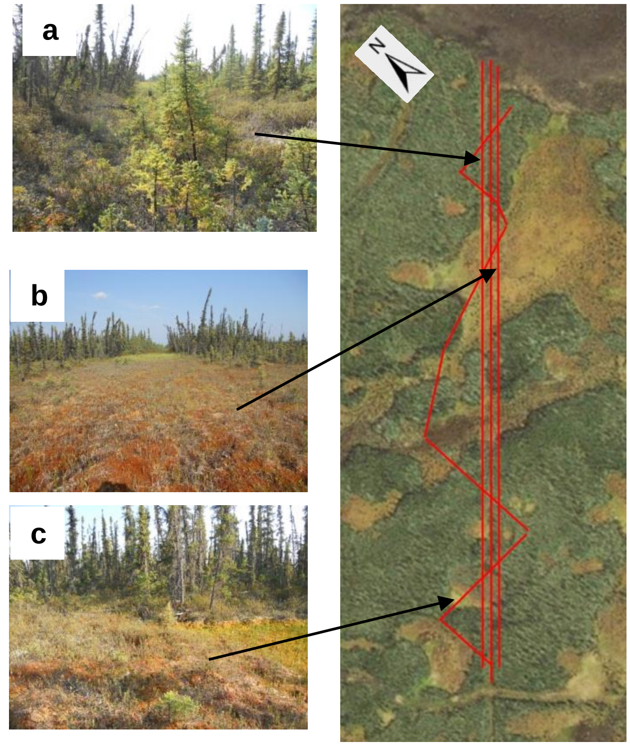

Fig. 3 GPR profiles: left straight line ~3m of NE edge, central straight line: along center line of seismic line, right straight line ~10 of the SW edge of seismic line, broken line covered undisturbed area including peat plateau(a) isolated flat bogs (c), fen-like bog and open bog (b)

3.2 Ground Temperature and Water level Monitoring

Ground temperature and water level monitoring equipment was installed during the 2012-2013 field season (Fig. 2). Relative elevations of the ground and water levels were surveyed in June 2013 with auto-level and rod and adjusted to the Digital Elevation Model (DEM) of the area. Soil temperatures were collected with a Campbell Scientific data-acquisition systems at depths of 15 cm to 250 cm below ground level and HOBO water level loggers were installed in 2 inch slotted PVC pipes about 1.5 m below ground level at each monitoring station. Temperature readings were taken every minute, averaged and recorded every hour. The water levels were recorded every 6 hours. The depth of permafrost at the peat plateau monitoring stations was evaluated using a hand auger in August 2012.

3.3 LIDAR.

The LIDAR data acquired in 2010 was used in this study for elevation analysis. It was collected by Applied Geomatics Research Group, NS, Canada with a scan angle of ±20°, and processed based on two returns from m2 and 2m resolution digital elevation model (DEM) was created. (Chasmer *et al.* 2011).

3.4 Dupuit assumption

Based on Darcy's law, Dupuit developed the theory of ground water flow assuming the following necessary conditions:

1. The ground water flow is steady two dimensional and without acceleration in the vertical direction.
2. The slope of the surface is very small
3. The Hydraulic gradient is equal to the slope and does not change in the vertical direction of aquifer.

The Dupuit equation describes the flow per unit width (Fig. 4) as:

$$q' = \frac{1}{2}K(\frac{(h_1-h_2)}{L} \qquad (1)$$

Where:

- *q'* is the flow per unit width
- *K* is hydraulic conductivity
- h_1 is the head at the origin
- h_2 is the head at *L*
- *L* is the flow length

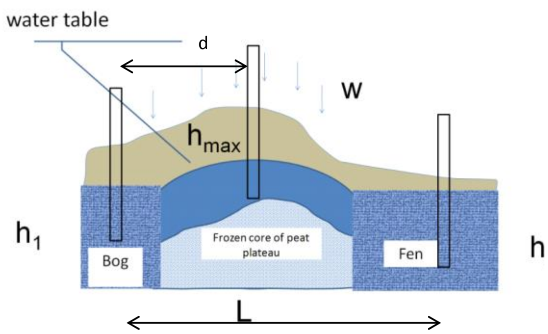

Fig. 4 Unconfined flow with recharge (after Fetter C.V. 2011)

If infiltration occurs, the crest of water table appears at the divide and can be calculated as:

$$h_{max} = \sqrt{h_1^2 - \frac{(h_1^2 - h_2^2)d}{L} + \frac{w}{K}(L-d)d} \qquad (4)$$

Where:

- h_{max} is the water elevation at the divide.
- *w* is the recharge rate
- *d* is the distance from the origin to the divide

4 RESULTS

4.1 GPR mapping

GPR measurements were performed along center line as well as on both sides of seismic line.

Analysis of GPR imagery provides three major thermal regimes along the seismic line (Fig. 5). They can be identified as:

1. Completely frozen core of peat plateau (I)
2. Unfrozen peat in fen and bogs (II)
3. Partly frozen peat with high unfrozen water content (III), (IV)

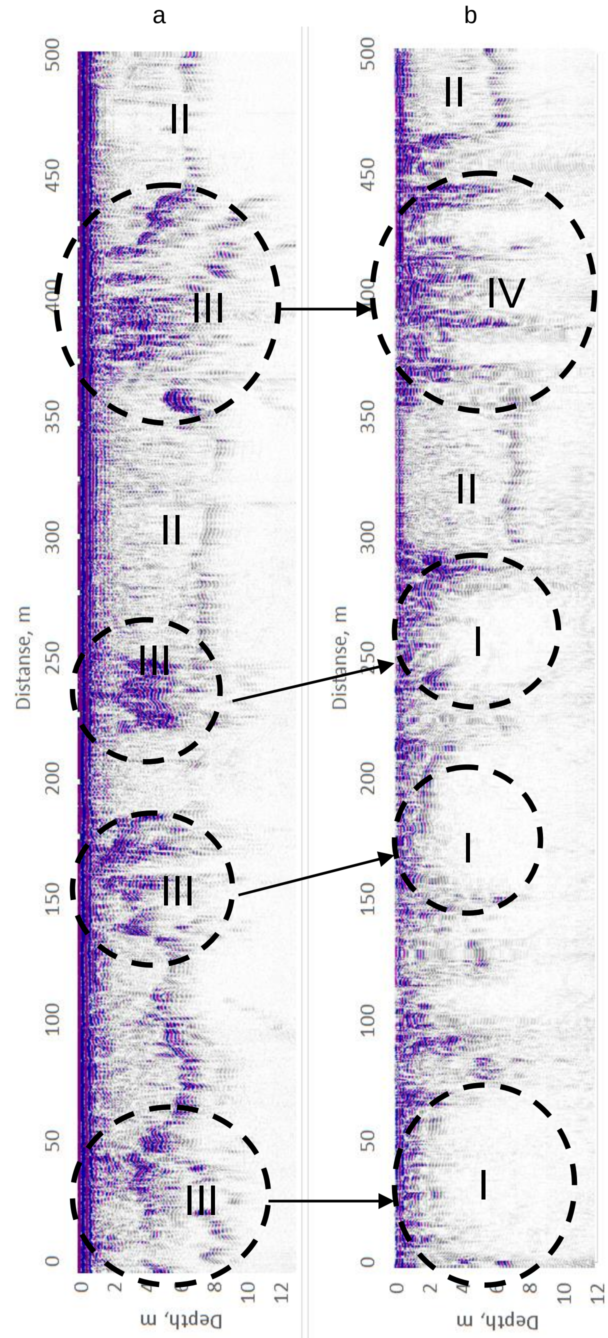

Fig. 5 GPR profile a) center line, b) 10 m SW of the edge of the seismic line (undisturbed area). Circular lines represent peat plateau. Note the difference in signal reflection over disturbed and undisturbed areas.

The presence of relatively warm channel fen water in close proximity to permafrost in area IV causes lateral heat flux towards the seismic line. Thus area III under the seismic line as well as area IV under the undisturbed plateau has highly scattered signal reflections, suggesting the presence of a high amount of unfrozen water (Fig. 5) The low intensity of the reflected signal in areas II indicates the presence of unfrozen saturated peat, which is underlain with a layer of mineral soil at a depth of approximately 8 m. The frozen core with relatively low liquid water content (area I) was detected only under undisturbed peat plateau. No similar results were observed under the seismic line. The permafrost under the linear disturbance is thinner compared to undisturbed peat plateau. Ground surface elevations are typically associated with the presence of permafrost in both disturbed and undisturbed areas.

4.2 Ground temperature and water level observations

Ground temperature monitoring began in March 2013. (Table 1) Ground temperature monitoring results indicate a relatively thin (less than 60 cm) seasonally frozen layer in the bog and fen as well as in close proximity to the fen (St. 2). At the same time, the active layer on the peat plateau under the seismic line reached a depth of more than 1 m, being thickest (more than 2 m at St. 4) farthest away from the fen. The annual range of mean temperatures is greater on the peat plateau stations and not very profound in the fen and bog. St. 4 has an active layer of more than 2.39 m and the peat at station 3 was frozen to a depth of about 1.5 m. Average temperature in the fen was 5.5^0 C, and 4.1^0 C in the bog.

	Depth(bgl), cm	Average annual	January mean	July mean	Min annual	Max annual
fen	20.0	5.06	-0.25	13.59	-1.03	15.19
	50.0	5.40	1.05	11.47	0.40	12.70
	100.0	6.13	3.55	8.63	2.28	10.12
2	61.0	n/a	n/a	6.40	n/a	n/a
	116.0	n/a	n/a	2.62	n/a	n/a
	229.0	n/a	n/a	0.14	n/a	n/a
3	16.5	2.84	-2.24	13.57	-6.55	21.56
	65.5	2.37	0.03	5.69	-0.07	9.22
	115.0	1.19	-0.04	1.89	-0.11	4.97
	164.5	0.44	0.07	0.49	0.03	1.41
	177.5	0.28	0.07	0.28	0.04	0.87
4	29.0	4.23	-0.10	12.88	-0.56	17.49
	129.0	1.66	0.49	2.87	-0.04	4.83
	179.0	0.86	0.47	1.03	-0.03	2.24
	229.0	0.17	0.04	0.09	-0.13	0.89
	239.0	0.04	-0.02	-0.02	-0.12	0.31
6 - bog	14.0	5.19	-0.87	14.85	-2.98	18.72
	64.0	4.89	1.33	9.52	0.57	12.66
	114.0	4.67	2.87	6.27	0.78	11.64
	164.0	4.56	4.02	4.41	2.15	8.86
	214.0	4.36	4.56	3.57	2.81	5.98

Table 1 Soil temperatures for the period March 2013- March 2014

5 DISCUSSIONS

5.1 Water levels analysis.

Based on the data collected, the following conceptual model of permafrost disturbance is proposed. Being undisturbed, the peat plateau is underlain by permafrost, the active layer is about 50-70 cm thick and the permafrost table is above the water level of adjusted fens or bogs. The cut of a seismic line triggers the change of thermal regime of the active layer, causing permafrost thaw. At one point, permafrost descends below the water level of adjusted fens and bogs. When the depth of the permafrost table under the seismic line becomes lower than the ground water table, the seismic line becomes a link between fens and bogs, slowly conveying water between previously disconnected hydrological units.
The water levels recordered in the period of October 2012 to August 2013 are shown in Fig. 6.

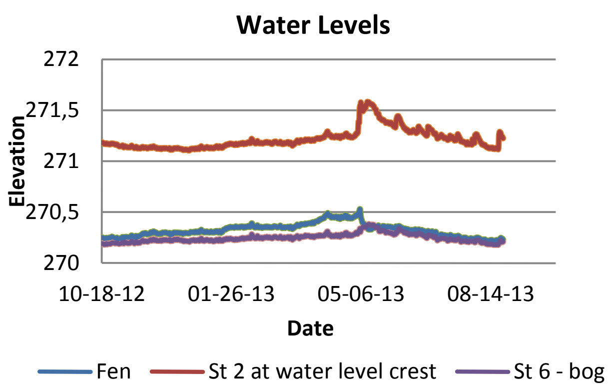

Fig. 6 Water table elevation along the seismic line

The bog has the lowest water level, except for the period between May 8 to May 18. Water levels at the crest are almost a 1 m higher than in the fen. Taking into account the fact that the hydraulic conductivity of the underlying permafrost layer is significantly lower than that of the top peat layer, the water flow can be described as a steady flow in an unconfined aquifer and it is subject to the Dupuit equation. The peat hydraulic conductivity was evaluated from laboratory tests and for this study it was determined to be 0.14 m/d. Thus, the only unknown in eq. 4 is the recharge value that can be found through the following equation/be defined as:

$$w = [h_{max}^2 - h_1^2 + \frac{(h_1^2 - h_2^2)d}{L}]\, K/(L-d)d \qquad (5)$$

The computed recharge is shown in Fig 7. The average recharge value is about 7 mm per day, which corresponds to the peat plateau runoff value, which is in the range of 0-20 mm/day, as describede by Wright et al. , 2008.

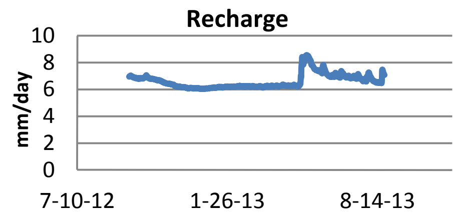

Fig.7 Recharge rate at the seismic line between bog and fen

The steady surplus of water recharge, even in winter time, from surrounding peat plateaus may indicate permafrost thaw and that widening of the seismic line is still taking place.
The constant flow from the fen into the bog was interrupted for a short period of time between May 8 and May 18, 2013. Analyses of soil temperatures along the seismic line revealed that on May 8 the gap between the permafrost and the descending seasonal frost table was completely blocked by a “frozen dam”. Only on May 19 the top of the peat became unfrozen, re-establishing the connection between fen and bog.

5.2 Elevation variations along seismic line

The analysis of LIDAR transects across the seismic line as well as GPR data and results from borehole drilling allowed us to build 3-D conceptual model of the degrading permafrost along the seismic line (Fig 8).

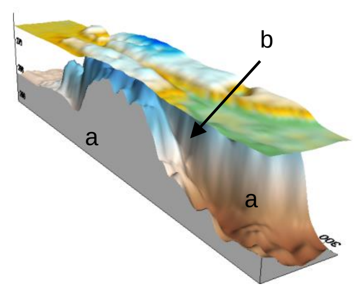

Fig. 8 3D conceptual model of the seismic line a) frozen peat plateau, b) loss of permafrost under the seismic line

It revealed a distinctive “v” shape profile of the line with a relatively steep slope on the south side and a gentler slope on the northern side of the line. Field studies show that 2.5 m of permafrost thaw results in a surface subsidence of 0.5 m. Taking in account that average peat porosity is of 0.8 and an estimated liquid water content is of 30% this corresponds to ~ 900 m^3 of ice loss for each 100 m length of the seismic line over the peat plateau over a period of 28 years. For the same period of time, volume loss due to surface subsidence and peat consolidation is about 300 m^3 for 100 m of seismic line.

6 CONCLUSIONS

This study examined the effect of seismic lines on the connectivity and storage capacity of peat lands in the zone of discontinuous permafrost. Based on the observations made we can conclude that:

1. The frozen core of peat plateaus plays a major role in the surface and ground water distribution in the peatlands in the region of discontinuous permafrost. Acting as a frozen dam, it separates water bodies, such as lakes, flat bogs and channel fens. Permafrost degradation caused by the surface disturbance such as seismic line can lead to irreversible redirection of the water flow with unpredictable hydrological effects. The most profound thaw effect takes place in the vicinity of large water bodies such as open bog or channel fen.

2. When the depth of the permafrost table becomes lower than the ground water table, the seismic line creates a link between fens and bogs, slowly conveying water along the line. When the active layer is frozen to its maximum depth and there is no talik, the flow can be interrupted until a partial thaw of the active layer. Constant water recharge is required to maintain flow between the fen and bog and the slow degradation of permafrost can be one of the sources of water recharge.

3. The storage capacity of wetlands in the region of discontinuous permafrost is affected by surface disturbances, such as seismic lines. The volume of unfrozen soil line. Once the permafrost has melted the unfrozen peat stays submerged, leaving no available avenu for additional water absorption. Due to the consolidation process the potential storage capacity is reduced with a reduction in porosity.

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