Permafrost characterization of the Dempster Highway, Yukon and Northwest Territories

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C.R. Burn, J.L. Moore, H.B. O'Neill
Department of Geography and Environmental Studies – Carleton University, Ottawa, ON, Canada
D.W. Hayley, J.R. Trimble
Hayley Arctic Geoconsulting, Kelowna, BC, and TetraTech EBA, Whitehorse, YT, Canada
F. Calmels
Northern Climate ExChange — Yukon Research Centre — Yukon College, Whitehorse, YT, Canada
S.N. Orban, M. Idrees
Transportation Engineering Branch — Highways and Public Works, Government of Yukon, Whitehorse, YT, Canada

ABSTRACT
The Dempster Highway was built over permafrost to connect the western Arctic with the national highway system. Mean annual permafrost temperatures along the route are ≥ -4 °C. Most ground ice is found in glacial deposits, and in these materials the embankment is particularly prone to thaw subsidence. Extended periods of rain have led to debris flows blocking the road and wash outs in steep terrain and near rivers. Icings may impede drainage during freshet. These hazards are of varying relative importance along the route. The principal terrain units and permafrost-related hazards are: North Klondike, icing; Blackstone Uplands, thaw subsidence; Engineer Creek/Ogilvie River, debris flows and wash outs; Eagle Plains, relatively unaffected; Richardson Mountains and Peel Plateau, thaw subsidence; Northern Plains, icing.

RÉSUMÉ
L'autoroute Dempster a été construite sur le pergélisol, afin de connecter l'Arctique de l'Ouest avec le réseau autoroutier national. Les températures moyennes annuelles du pergélisol le long de la route sont de ≥ -4 °C. La majorité de la glace de sol est présente dans les dépôts glaciaires, matériaux sur lesquels le remblai routier est particulièrement sujet aux subsidences. Des périodes de pluie importantes ont mené à des coulées de débris bloquant la route et à des glissements de terrain sur les fortes pentes et à proximité des rivières. Des glaçages peuvent obstruer le drainage durant le dégel printanier. Ces risques varient en importance le long de la route. Les principales unités physiographiques et leurs dangers reliés au pergélisol sont: North Klondike, glaçage; Blackstone Uplands, subsidence au dégel; Engineer Creek/Ogilvie River, coulées de débris et glissements de terrain; Eagle Plains, relativement non-affecté; Richardson Mountains and Peel Plateau, subsidence au dégel, Northern Plains, glaçage.

1 INTRODUCTION

The Dempster Highway is the principal transportation artery for Canada's western Arctic. It is an all-season road opened in 1979 between Yukon Highway 2, the Klondike Highway, and Inuvik, NWT (Figure 1). The Dempster Highway was built on continuous permafrost for 90% of its 736 km. As a result, the road structure is an embankment, designed to maintain permafrost and prevent thaw subsidence (Huculak *et al*. 1978). For the first 75 km of its route, north from the junction with Klondike Highway, the road passes over discontinuous permafrost (Heginbottom *et al*. 1995).

Transport Canada (TC) has established a Network of Expertise in Northern Transportation Infrastructure Research to assist governments to adapt roads, airports, and marine facilities to challenges posed by climate change. One of the Network's projects concerns establishment of baseline data collection and assessment of permafrost response to climate warming alongside transportation infrastructure in Yukon and NWT. Given the strategic importance of the Dempster Highway and the record of climate warming in the region (e.g., Burn and Kokelj 2009), the Network has invested considerable effort into this part of our northern transportation infrastructure. In a companion paper, we report a monitoring program to document baseline permafrost conditions and the thermal impact of the embankment on permafrost at key sites along the highway (Idrees *et al*. 2015).

In this paper, we present a summary of ground temperatures that have been collected along the highway from several sources: the TC monitoring program; Northwestel's microwave repeater stations; investigations sponsored by the NWT Cumulative Impacts Monitoring Program (CIMP) (e.g., O'Neill *et al*. 2015a); and the published literature. These data span most of the highway route (Figure 1). In addition, since 2005, significant research on ground ice conditions along the route has been published (e.g., Lacelle *et al*. 2007; Kokelj *et al*. 2013; Lacelle *et al*. 2015). This has accompanied recognition of terrain hazards due to ground ice thawing, and a

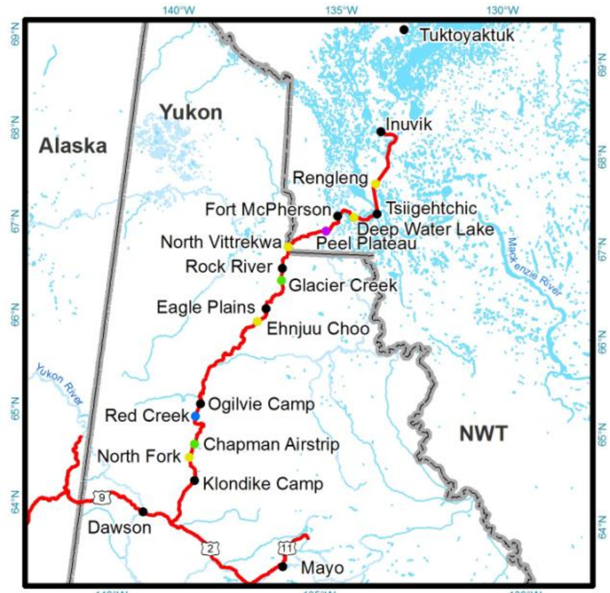

Figure 1. The Dempster Highway, Yukon and NWT, with locations mentioned in the text. Colours code data sources in Tables 2 and 3: yellow – Northwestel; green – Baseline study; purple – NWT CIMP; blue – Lacelle *et al*. (2009); black – communities and weather stations.

rehabilitation program for the highway in the NWT, from the territorial border to Tsiigehtchic (Figure 1), with particular effort west of the Peel River Crossing at NWT km 74. However, in several sections of the highway in Yukon, the primary terrain hazards are associated with hydrologic processes. We present a terrain vulnerability characterization for the route, combining knowledge of ground temperatures and ground ice conditions with the dominant geomorphic processes along the road.

2 PHYSIOGRAPHIC CHARACTERIZATION

For much of its length, the Dempster is a mountain highway that traverses Ogilvie and Richardson mountains of the northwestern Cordillera (Figure 2). In Ogilvie Mountains, the road follows valley floors (Figure 3), while in Richardson Mountains it crosses the ranges. The highest elevations occur in the southern sections (Figure 2). The road follows the rolling terrain of the upland Eagle Plain for about 180 km, and similarly crosses the uplands of Peel Plateau to the east of Richardson Mountains (Figure 4). From Peel River to Inuvik, the terrain is remarkably flat and at low elevation. As a result of changing elevation and latitude, the route passes through forest and tundra. Terrain units along the route are summarized in Table 1 and indicated in Figure 5.

2.1 Geological factors

The bedrock outcrops in the ranges of the Cordillera are of uplifted ocean floor deposits. The rocks are sandstones, shales and limestones, covered by veneers of glacial or colluvial deposits. The limestones have weathered mechanically to boulder size, while the sandstones and shales have been broken into finer-grained soils (Richardson and Sauer 1975).

2.2 Glacial legacy

Glaciation has left a variable imprint on the terrain. A central portion of the highway, km 116-495, passes through unglaciated terrain. As a result, some sections of the route are dominated by colluvial sediments, or weathered bedrock. In contrast, southern parts of the route, between about km 75 and km 116 km, experienced valley glaciation during the Wisconsinan period, while north and east of km 495 Peel Plateau and the plains of NWT were covered by the Laurentide ice sheet.

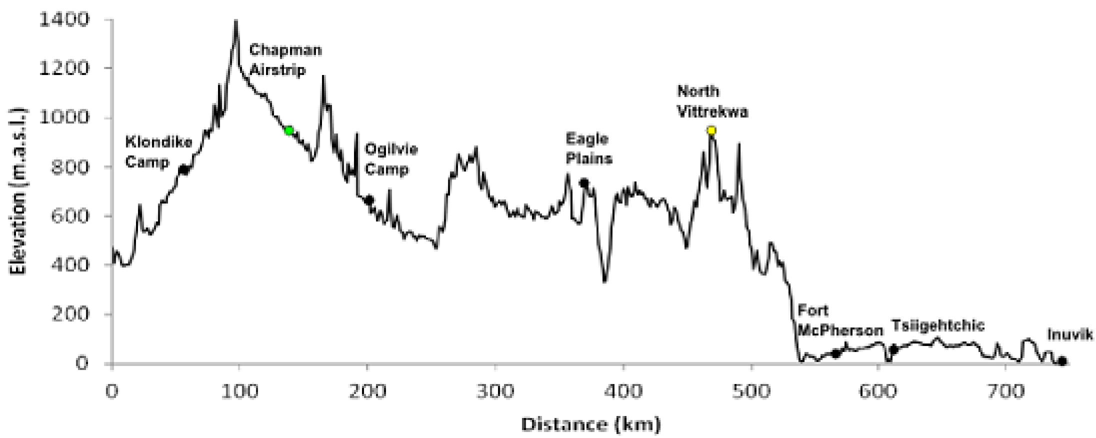

Figure 2. Schematic topographic profile for the Dempster Highway. Source: Google Earth.

Figure 3. Dempster Highway in the valley of Ogilvie River, at km 210, August 2011. Photo by S.N. Orban.

Figure 4. Peel Plateau, near NWT km 60, August 2012. Photo by H.B. O'Neill.

2.3 Climate

The region has a subarctic climate (Table 2), modified by the mountainous terrain of the region. Topographic shading and cold-air drainage lead to extremely low temperatures in valley bottoms during winter, as at Ogilvie Maintenance Camp. Air temperatures rise with elevation within atmospheric inversions, so that lapse rates in winter are less than in summer (Lewkowicz and Bonnaventure 2011; O'Neill *et al*. 2015b). Precipitation is reduced by the continental-scale rain shadow of St Elias Mountains, but rainfall has been increasing recently in the region (Kokelj *et al*. 2015). Blowing snow in tundra areas leads to significant accumulations alongside the embankment and where vegetation acts as a snow trap (O'Neill *et al*. 2015a).

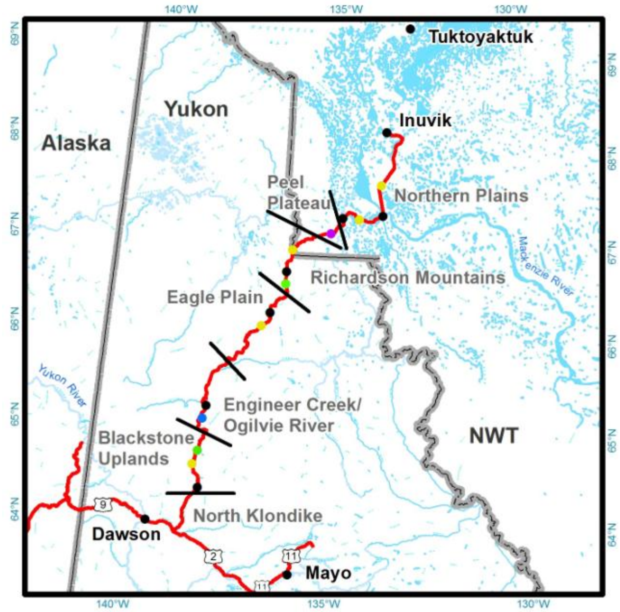

Figure 5. Physiographic units along the Dempster Highway.

2.4 Permafrost

The area is almost entirely underlain by permafrost (Heginbottom *et al*. 1995). Ground water flow in the mountainous terrain modifies the condition of perennially frozen ground and may create considerable surface icing in winter (Idrees *et al*. 2015). Boreholes drilled at Chapman Airstrip (km 124) in glacial outwash penetrated through permafrost at only 7 m depth (Idrees *et al*. 2015). Ground water was observed in these boreholes, suggesting that convection in the ground water may restrict the thickness of permafrost. In the mountains, development of frost blisters at the base of hillslopes and accumulation of river icing demonstrate that ground water may emerge or freeze as intrusive ice within the active layer or at the ground surface throughout the winter (Pollard and French 1984; Hu and Pollard 1997).

Ground temperatures reported from the region indicate the annual mean temperature of permafrost within the boreal forest and taiga is ≥ -3.0 °C (Table 3) (Lacelle *et al*. 2009). In the taiga near Inuvik, annual mean ground temperatures ≥ -2.0 °C have been measured in peatlands, where the soils may have a long zero curtain due to high porosity, wet ground, and deep snow accumulation (Burn *et al*. 2009). Similar temperatures have been measured in shrubby tundra on Peel Plateau, due to the influence of atmospheric inversions and accumulation of blowing snow (O'Neill *et al*. 2015b). Below, we report recently compiled measurements of ground temperatures from a range of sites along the route.

Table 1. Physiographic units of the Dempster Highway. See Figure 5.

	Location (km) (NWT)	Terrain type	Surficial materials
North Klondike	0 - 74	Mountain hillsides	Colluvium and till
Blackstone Uplands	74 - 160	Valley floor	Till and outwash
Engineer/Ogilvie River	160 - 246	Narrow valleys	Colluvium and alluvium
Eagle Plain	246 - 405	Rolling uplands	Weathered bedrock
Richardson Mountains	405 – 492 (27)	Mountain slopes	Colluvium and alluvium
Peel Plateau	492 (27) – 539 (74)	Rolling plateau	Glacial till
Northern Plains	539 (74) – 732 (267)	Open plain	Glacial till

Table 2. Climate data for the Dempster Highway, 2004. Annual mean air temperature (AMAT), winter (D,J,F) mean air temperature (WMAT), summer (J,J,A) mean air temperature (SMAT), and precipitation are available for this year.

	km	Elevation (m)	AMAT (°C)	WMAT (°C)	SMAT (°C)	Rainfall (mm)	Snowfall (cm)
Dawson	0	346	-4.2	-18.9	15.6	78.6	237.4
Klondike Camp	65	966	-4.9	-19.2	12.3	243.3	304.3
Ogilvie Camp	195	588	-9.2	-29.7	13.2	104.4	176.5
Eagle Plains	369	729	-6.0	-24.3	14.8	81.1	94.0
Rock River	457	735	-6.8	-22.0	12.6	-	-
Fort McPherson	550	22	-8.7	-28.2	15.0	67.8	117.6
Inuvik	732	15	-9.4	-27.5	13.1	83.4	246.0
Tuktoyaktuk	-	0	-11.6	-28.5	10.4	56.0	151.3

3 PERMAFROST TEMPERATURES

Two complementary investigations have recently begun to yield new ground temperature information for terrain adjacent to the Dempster Highway. The first is from a series of boreholes drilled to approximately 10-m depth at microwave stations operated by Northwestel. The drilling and thermistor cable installation was by EBA Engineering, and data retrieval has been since 2009. Data are compiled by Northwestel and hosted online by Yukon College. Data acquisition has not been complete in all years. The second investigation has been sponsored by TC to obtain baseline information on permafrost temperature within the highway right-of-way, and, over time, to assess the impact of climate change on permafrost and the active layer within the embankment, at the toe, and in undisturbed ground. These sites were installed in late 2013, and data have been collected for one year. Temperature sensors were installed to 8 m below the surface in undisturbed ground. In addition, comparable data from undisturbed sites has been collected under CIMP. We have compiled data from these sources and the published literature in Table 3, where we report temperatures collected at depths ≥ 5 m.

3.1 Northwestel installations

The Northwestel stations are surrounded by a fence. The three cables at each site are located inside the fence, at the fence, and outside fence. We have compiled annual mean temperatures for each thermistor string for the most recent complete year of available data. We report the basal temperatures from outside the fence at each site in Table 3, since, of the data available, these are the best indicators of long-term undisturbed conditions. There is considerable surface disturbance at the Rengleng and Deep Water Lake stations. The annual mean temperature decreases with depth at these sites, indicating that permafrost is degrading. The values from North Fork and North Vittrekwa indicate relatively low ground temperatures at higher elevations along the route. The lowest annual mean temperature was recorded within the fence at North Vittrekwa (-5.8 °C), where infrastructure influences snow drifting and scouring.

3.2 Baseline characterization

Data collected during the characterization of baseline ground temperatures near and beneath the embankment are presented in Idrees *et al*. (2015). In Table 3 we present data from the undisturbed ground at two sites. The data collected from nearby Northwestel stations are consistent with measurements at these sites, even though the data in Idrees *et al*. (2015) are for 2014/15, and measurements at North Fork and North Vittrekwa were collected in 2013/14 and 2012/13, respectively.

The data presented in Table 3 do not display a consistent trend with latitude, as with annual mean air temperature (Table 2). There is a small difference between the annual mean ground temperatures collected in the forest/taiga and at tundra sites, with the difference between the two means, -2.0 and -3.0 °C, respectively, being significant at the 5% level under a one-tailed Student's t-test. The difference, 1 °C, represents the level of variation in ground temperature between tundra and taiga along the route.

Table 3. Annual mean ground temperatures and active-layer thicknesses in undisturbed terrain at sites along the Dempster Highway, Yukon and NWT. Data are from various sources described in the text. The Peel Plateau sites are in shrub tundra. Sites in the boreal forest or taiga are marked by *. Locations of sites are on Figure 1.

Site	Region	km post (NWT)	Depth (m)	MAGT (°C)	Active layer (cm)	Source
North Fork	Blackstone Uplands	98	10	-3.7	75	Northwestel (this paper)
Chapman Airstrip	Blackstone Uplands	124	1.0	-2.7	80	Idrees *et al*. (2015)
*Red Creek	Engineer/Ogilvie River	167	7.0	-2.5	110 (est.)	Lacelle *et al*. (2009)
*Ehnjuu Choo	Eagle Plain	347	10	-1.2	150	Northwestel (this paper)
Glacier Creek	Richardson Mountains	421	8.0	-3.6	40	Idrees *et al*. (2015)
North Vittrekwa	Richardson Mountains	465	10	-3.8	40	Northwestel (this paper)
Peel Plateau A	Peel Plateau	516 (51)	5.0	-1.8	70	O'Neill *et al.* (2015a)
Peel Plateau B	Peel Plateau	525 (60)	5.0	-2.6	75	O'Neill *et al.* (2015b)
Fort McPherson	Peel Plain	556 (91)	5.0	-2.5	40	O'Neill *et al.* (2015b)
Deep Water Lake	Peel Plain	572 (107)	10	-3.4	130	Northwestel (this paper)
Rengleng	Anderson Plain	645 (180)	10	-1.4	100	Northwestel (this paper)
Inuvik	Anderson Plain	722 (257)	5.0	-1.2	55	Burn *et al.* (2009)

4 GROUND ICE CONDITIONS

Ground ice conditions along the route are available from several reports that have been published recently, and for the boreholes that were drilled in the baseline characterization program (Idrees *et al*. 2015).

4.1 Buried ice

Buried glacier ice is increasingly recognized as an important component of the terrain close to the glacial limits of northwest Canada (Kokelj *et al*. 2013; Lacelle *et al*. 2013). Large retrogressive thaw slumps on Peel Plateau occur within the limit of Laurentide glaciation (Lacelle *et al*. 2015). At present, such slumps, although visible from the highway, have not yet posed a hazard to the road in NWT. Nevertheless, we may assume that thick masses of buried glacier ice may underlie some stretches of the road in Peel Plateau. Similarly, buried glacier ice has been exposed and described in the Chapman Lake moraine at km 116 (Lacelle *et al*. 2007).

Figure 6. Ice-wedge polygons near the highway in Blackstone Uplands. Image from Google Earth.

4.2 Ice-wedge polygons

Ice-wedge polygons may be recognized along the route in many sections, as, for example, in Figure 6. These polygons characteristically have slight depressions above the wedges, and lack the raised rims formed by actively growing ice wedges. They are most commonly seen at tundra sites. The ice wedges are of massive ice (e.g., Idrees *et al*. 2015, Fig. 6).

4.3 Syngenetic segregated ice

The uppermost layers of permafrost terrain in unconsolidated, fine-grained sediments are commonly ice rich. The ground ice is in the form of segregated ice lenses that develop near the top of permafrost and remain there if the permafrost table rises (e.g., French and Shur 2010). The ice-rich zone has been called the transient layer of permafrost, to recognize that active-layer thickness may change as climate varies. Such a layer is common in frost-susceptible soils, as in the silty till cover of the Peel Plateau (site 4 of Idrees *et al*. 2015, Fig. 6). However, a similarly ice-rich zone may develop as a result of sedimentation and aggradation of the surface. Unglaciated parts of the highway route contain both sites of long-term erosion, and sites of long-term deposition. At the latter, a thick layer of ice-rich ground may have developed in aggrading deposits, as at Glacier Creek (site 2 of Idrees *et al*. 2015, Fig. 6).

4.4 Intrusive ice

Intrusive ice is most commonly recognized as a seasonal form, developed within the active layer (e.g., Pollard and French 1984). In mountainous terrain, such as along the Dempster Highway, it is associated with hydraulic gradients due to elevation. Frost blisters are best known from the Blackstone Uplands, but Richardson Mountains provide similar terrain conditions for the development of massive intrusive ice. Intrusive ice may occur as sheets of pure ice as well as the commonly identified frost blisters.

4.5 Icing

Development of surface icing over winter is apparent in spring after snow melt, because extensive masses of ice may linger in river beds. Icings develop in the rivers of Ogilvie Mountains because of groundwater systems that have developed in limestone bedrock. Intrusive ice is commonly associated with discharge through the active layer, but icings that continue to form throughout winter may originate from deeper, sub-permafrost circulation. Icings occur when water flows over surface ice, allowing greater thicknesses to form than by downward freezing alone (Hu and Pollard 1997).

5 VULNERABILITY CLASSIFICATION

The principal terrain hazards along the route stem from the nature of the mountainous terrain and the presence of ground ice in permafrost. A key hazard in all permafrost environments is the potential for thaw subsidence from melting of ground ice. This varies along the Dempster Highway because ground-ice occurrence is associated with the different glacial histories along the route. In narrow valleys, the embankment is subject to blockage by mass movements and erosion by rivers in flood where the road abuts watercourses. The likelihoods that both of these hazards may occur during periods of rainfall are magnified by the impermeability of permafrost terrain. Groundwater discharge in winter leads to extensive river icing, blocked culverts, and, if water overtops the embankment, a dangerous driving surface.

The highway route may be divided into several physiographic regions, in each of which permafrost-related terrain hazards differ in their importance. Throughout the length of the road, annual mean permafrost temperatures are ≥ -4 °C, indicating that all soils with massive ice have a high sensitivity to disturbance either due to changes in surface conditions or climate (Hayley and Horne 2008).

Figure 7. Culvert at km 32.5 (North Klondike River valley), filled with icing, May 2014. Photo by C.R. Burn.

5.1 North Klondike – Surface icing

The principal terrain hazard in the first 80 km of the route is development of icings that block culverts and impede drainage (Figure 7). If discharge continues through the winter, the embankment may be insufficiently high to retain the accumulating water (ice), and it may flow onto the driving surface. This is a principal hazard in winter, but in freshet, blocked culverts may lead to alternate routing of surface water and washout of the embankment.

5.2 Blackstone Uplands – Thaw subsidence

Buried glacier ice has been identified in the moraine at Chapman Lake (km 116) (Lacelle *et al*. 2007). In 2006, Yukon Highways realigned the road in this area because erosion of the riverbank threatened the integrity of the embankment. The new alignment was built as a cut in order to reduce vertical curvature. The cut was in ice-rich till containing buried glacier ice. Deterioration of the embankment was observed shortly after construction. Remedial work on the section has been necessary almost continuously since then.

Two Moose Lake (km 102) is within the glacial limits in Blackstone Valley, and is surrounded by moraine. Thermokarst development of the lake has brought the shoreline to the road embankment, so that temperatures beneath the road are now affected by the lake (Figure 8). Continual maintenance has been required at this point.

Figure 8. Thermokarst expansion of Two Moose Lake has brought it to the highway embankment. Image from Google Earth.

5.3 Engineer Creek/Ogilvie River – Mass movement

The road follows the narrow valleys of Engineer Creek and Ogilvie River. Where the bedrock is carbonate, rock falls are a recognized hazard, as the slopes are bare of soil. In clastic bedrock, a surface veneer of soil rests on permafrost. During heavy rain, landslides and debris flows may block the road (Figure 9), with the occurrence facilitated by the relatively impermeable permafrost.

High discharge and coarse bedload in the streams during freshet and following rain storms may erode the riverbank supporting the highway and bridge abutments, requiring reconstruction of the road bed (Figure 10). Drainage structures may appear to be over designed in summer for the magnitude of flow, but even these may still be damaged in the spring flood.

Figure 9. Debris flow at km 244, August 2010. Photo by C.R. Burn.

Figure 10. Wash out of the road by Ogilvie River at km 245, June 2013. Photo by S.N. Orban

5.4 Eagle Plain – relatively unaffected

The highway route follows the upper surface of Eagle Plain. The route avoids many hazards associated with permafrost due to the shallow soils and absence of water courses. The Eagle River crossing is a short exceptional section, due to the abundance of water and frost-susceptible, floodplain deposits.

5.5 Richardson Mountains – Thaw settlement

Subsidence of the embankment due to thaw of ground ice is a principal hazard in this section (Figure 11). The ground ice is localized, because the mountains were not glaciated. It may occur as ice wedges or bodies of intrusive ice. However, given the extensive time available for hill slope movement, any surface expression of the ice formation may have been covered by subsequent deposits. Figure 11 shows thaw subsidence of the road embankment at km 27. Degradation of the driving surface is generally managed through routine maintenance along the route. Shoulder rotation due to thaw settlement of the toe may be observed in several places.

Figure 11. Thaw subsidence of the embankment at NT km 27, August 2011. Photo by C.R. Burn.

5.6 Peel Plateau – Thaw settlement

Thaw settlement is the principal hazard on Peel Plateau because of the ice-rich till that covers the terrain unit and the buried glacier ice that underlies some sections of the landscape.

5.7 Northern Plains – Surface icing

The northern plains are covered by a veneer of till, and in places thaw subsidence is a hazard. However, massive ice is not as prevalent as in Peel Plateau, and so the hazard is reduced. Drainage is locally awkward where creeks flow out of lakes for a long portion of the freezing season, and icing accumulates beside the road.

6 CONCLUSIONS

(1) For most of the Dempster Highway, with the exception of Eagle Plain and North Klondike River valley, the ground is highly sensitive to disturbance, either by surface modification or from climate warming, because the temperature of permafrost is ≥ -4 °C and the area has ice-rich soil. Thaw subsidence is the primary terrain hazard for much of the route.

(2) In the Engineer Creek/Ogilvie River valleys, the principal hazards are related to the impermeability of permafrost terrain heightening runoff, and hence flooding, and also increasing the potential for mass movement on hill slopes.

(3) Throughout the mountainous terrain of the route, ground water discharge in winter leads to surface icing and blockage of culverts, threatening the integrity of the embankment during freshet.

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