A practical guide to permafrost vulnerability for Yukon's North Alaska Highway

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Fabrice Calmels, Louis-Philippe Roy, Cyrielle Laurent, Maude Pelletier, Lacia Kinnear, Bronwyn Benkert, Brian Horton, & Joel Pumple
Northern Climate ExChange, Yukon Research Centre, Yukon College, Whitehorse, YT, Canada

ABSTRACT
Northern Climate ExChange (NCE) has partnered with the Highways and Public Works (HPW) to develop a field guide to inform climate change adaptation along the northern 200 km of the Alaska Highway from Burwash Landing to the Yukon/Alaska border. The project examines the potential sensitivity of the permafrost along the highway to present and future climate variability. The project team used a multi-disciplinary approach that included permafrost coring, geocryological analyses, ground temperature and climate monitoring, Electrical Resistivity Tomography (ERT), and remote sensing techniques. Results indicated that the regional glacial history has influenced permafrost distribution and characteristics. Sites underlain by permafrost located within a few square kilometers of each other exhibit a wide range of ages, ground temperatures, thicknesses, and ground ice content and nature. The resulting product of the survey is a field guide that will facilitate the development of appropriate maintenance and remediation strategies, ensuring the highway's continued viability.

RÉSUMÉ
Le Northern Climate ExChange (NCE) s'est associé au départment des travaux publiques du Yukon, pour développer une stratégie d'adaptation concernant 200 km les plus nordiques de la route de l'Alaska. Le projet examine la sensibilité potentielle du pergélisol de cette section à la variabilité climatique présente et future. Une approche multidisciplinaire qui inclue l'échantillonnage, l'analyse géocryologique, le suivi climatique et des températures du sol, la tomographie électrique, et la télédétection, a été utilisée. L'étude a montré comment l'histoire glaciaire régionale a influencé les caractéristiques et la distribution du pergélisol, certains sites pergélisolés, pourtant situés quelques kilomètres appart, montrant une large étendue d'âge, de température et d'épaisseur de pergélisol, et de contenue et nature de glace de sol. Il résulte de l'étude un guide qui facilitera le développement de stratégies d'entretien et d'adaptation, assurant la viabilité de l'autoroute.

1 INTRODUCTION

The Alaska Highway is the central transportation corridor in Yukon. It is crucial to maintaining and expanding economic development, the quality of life of the population and international ties. It is also the only all-season highway that provides access to Alaska's interior.

The 200 km section of the Alaska Highway from Destruction Bay to the Yukon/Alaska border (from 60°45'N to 62°37'N – Figure 1) is underlain by extensive discontinuous, warm (>-2°C), and potentially ice-rich, permafrost. Since its inception, increases in heat flow from the ground surface resulting from construction activities, or changes in surficial conditions (e.g., climate, drainage, ground cover) have induced permafrost thawing, resulting in damage to highway infrastructure. In the future, climate change may accelerate permafrost thaw, further destabilizing the foundation of the highway.

Yukon Government's Department of Highways and Public Works (HPW) has partnered with the Northern Climate ExChange (NCE), Yukon Research Centre, Yukon College, to examine the potential sensitivity of the permafrost along the northern section of the Alaska Highway to present and future climate variability. This project will allow HPW to develop strategies to anticipate and adapt to impacts of climate change.

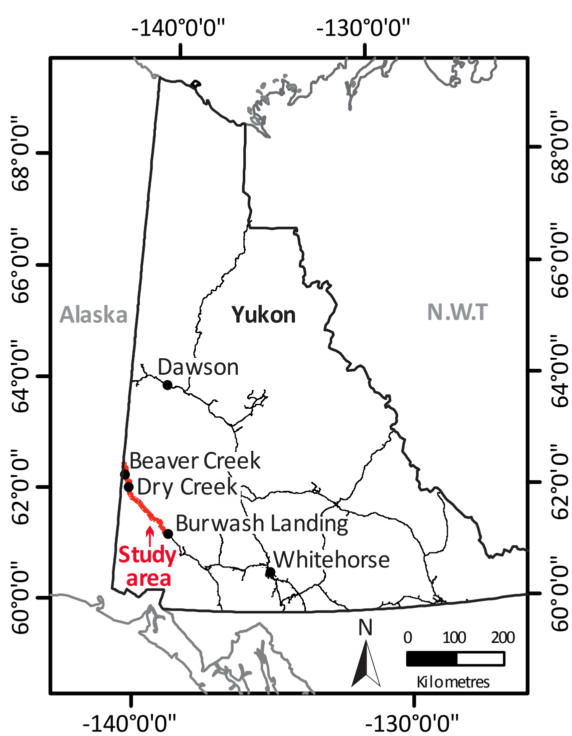

Figure 1. Location of the study area

The objectives of the project were: 1) to identify and characterize sensitive permafrost areas underlying the highway; 2) to identify potential future climate scenarios for the study region; and 3) to estimate the potential impacts of the identified climate scenarios for areas of the highway underlain by thaw sensitive permafrost. A multi-disciplinary approach was used, including permafrost coring, geocryological analyses, ground temperature and climate monitoring, Electrical Resistivity Tomography (ERT), and remote sensing techniques.

In this paper, we detail the overall approach to the assessment of permafrost sensitivity, and provide highlights of key findings. Full findings are reported in the report entitled "Vulnerability of the North Alaska Highway to Permafrost Thaw: A Field Guide and Data Synthesis" (Calmels et al., 2015). The full field guide describes permafrost sensitivity for thirteen sections of the highway. Each section is approximately 15-20 km in length and may be ranked with multiple permafrost vulnerabilities in smaller sub-sections. In the field guide and the following text, the authors refer to both the highway sections and named kilometre posts. The guide is described in further detail below.

2 METHODS

Data used to determine the vulnerability of the highway to permafrost thaw included both existing and new data collected through the project, as well as assessment of climate projections.

2.1 Assessment of existing data

Yukon Geologic Survey topographic and surfacial deposit maps, as well as aerial and satellite images, and thermal and geophysical data from geotechnical reports that were previously commissioned by HPW, were interpreted. International Roughness Index (IRI) data were obtained from HPW for 2010 and 2011. The IRI data provided insights about highway sections that are already experiencing negative impacts from permafrost thaw.

2.2 Permafrost drilling and sample collection

A light and portable coring Earth-drill system was used to collect permafrost cores at key points along the highway. Cores of 10 cm diameter were collected using a fast-rotating corer with diamonds set in carbide alloy teeth. This made it possible to drill in unconsolidated, fine- to medium grain material (sand to clay). A core catcher was used to extract frozen core from the borehole allowing for the collection of continuous, undisturbed permafrost samples (Calmels et al. 2003). A total of 21 boreholes were drilled at depths ranging from 2 to 6 meters. A water-jet drill was used to deepen some of the boreholes.

Samples were put in polybags and sealed immediately after being extracted. They were kept frozen and taken to the NCE laboratory where they were photographed, described and subsampled for further analyses.

2.3 Permafrost sample analyses

For each core, the cryostructure (i.e., the geometry of the ice in the permafrost) was described using a standard terminology adapted from Murton and French (1994).

On select samples, gravimetric ice content was calculated using weight loss after drying. The volumetric ice content was calculated by immersing the frozen sample, bagged in vacuum sealed polybags, in a container to measure its volume (V_{tot}). The sample was then thawed and oven-dried. The remaining dry material was then re-sealed in a vacuum polybag and immersed again to determine its volume with porosity (V_{sed}). The volume of excess content (V_{ice}) was calculated by subtracting V_{sed} to V_{tot}; calculations taking in account the volume of the polybags.

Grain-size analysis was performed on select samples using sieve and hydrometer analyses following a specifically modified American Standard and Testing Method protocol (ASTM D422-63, 2000).

All core data were logged by assembling laboratory photos of the cores, grain size ratio and volumetric or/and gravimetric ice content (Figure 2).

2.4 Ground temperature and climate monitoring

A total of 13 boreholes were instrumented at depths from ranging between 3.44 and 13.20 m (Table 1). A selection of boreholes was instrumented to monitor ground temperature, beginning in the summer of 2013. In three cases, a borehole made using the portable Earth-drill was deepened using a water jet drill. Four boreholes from the Alaska Pipeline program were also instrumented in collaboration with the Geological Survey of Canada.

Ground and atmospheric temperature were logged using either a Campbell Scientific weather station (two locations) or a HOBO four-channel logger (11 locations).

The Campbell Scientific stations included a CR1000 datalogger for air temperature (109-L) and ground temperature (CU-BOM11012). Ground temperatures were monitored using an 11-thermistor string, with an accuracy of ±0.05°C or better. Wind speed and direction were monitored at one site using an RM YOUNG Wind sensor. The HOBO stations used a four-channel external data logger (U12-008) with temperature sensors (TMC6-HD to TMC50-HD), These had an accuracy of ±0.25°C. In addition, ground surface temperature was monitored using the HOBO Pendant data logger (UA-002-08), a miniature waterproof two-channel data logger with an accuracy of ±0.53°C.

All borehole casings were made of electrical-grade PVC filled with silicone oil.

2.5 Electrical Resistivity Tomography

Electrical Resistivity Tomography surveys were performed to extend borehole observations.

Because the resistivity of a soil or rock profile is governed primarily by the amount and resistivity of pore water present in the profile and the arrangement of the pores, ERT is very well suited to permafrost applications. Permafrost distribution can be inferred based on changes in resistivity between frozen and unfrozen ground because most water content in frozen ground is in the solid phase, and typically has a higher resistivity than unfrozen water content.

An IRIS electrical resistivity system, consisting of a one-channel imaging unit and two electrode cables, each with 24 take-outs at five-metre intervals, was used for the surveys. Direct current electrical pulses were sent from the resistivity meter along the survey line to the 48 electrodes that were driven into the ground and connected to the electrode cables. Results of the surveys were post-treated and analyzed at NCE using Res2DInv 64 inversion software.

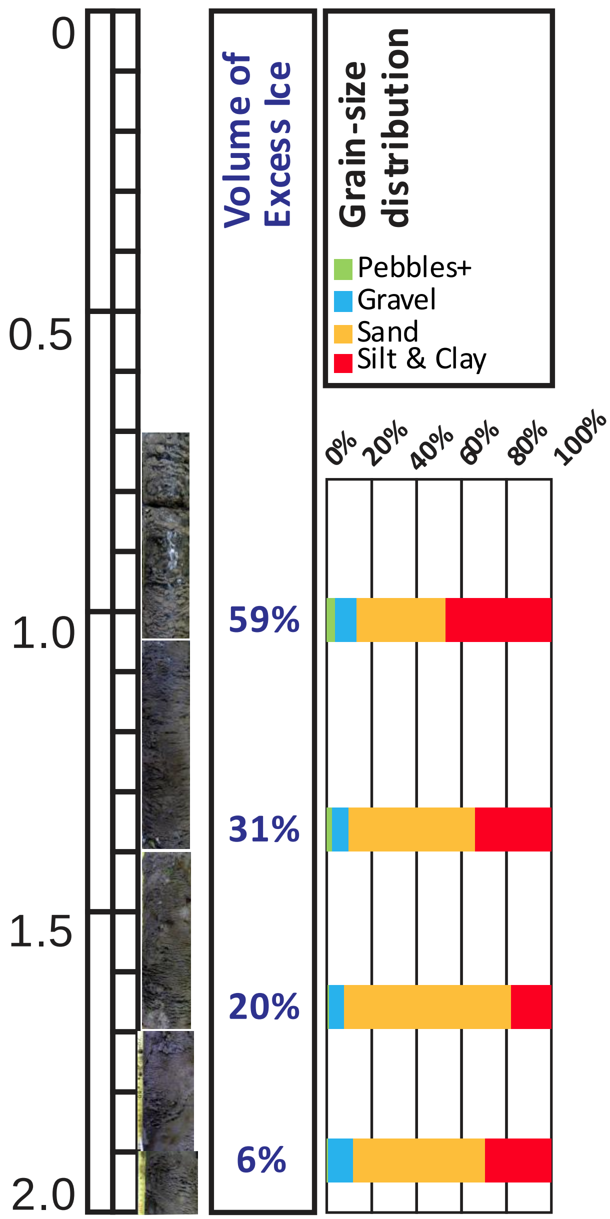

Figure 2. Example of log produced from sample analyses (BH01 at km 1810.2)

2.6 Climate projections

Scenarios Network for Alaska + Arctic Planning (SNAP), located at University of Alaska Fairbanks, provided 2 km^2 resolution downscaled climate projections for the 2030s and 2050s. The SNAP projections used averages of five General Circulation Models (GCMs) that were found to perform best over Alaska and the Arctic (SNAP, 2014).

In order to anticipate a range of potential future conditions, ensembles (the combined average of several models) are presented for the A1B and B1 emission scenarios. The B1 scenario projects low to moderate increases in emissions, with eventual stabilization of emissions over the next century, while the a1b scenario anticipates medium to high emissions with eventual stabilization.

The GCMs are regionally downscaled using data available from the Parameter-elevation on Independent Slopes Model (PRISM). The projected change in climate for each highway section was determined by averaging the grid cells that covered that section.

2.7 Ranking vulnerability to permafrost thaw

The ranking of highway vulnerability was based on the probability of extensive damage occurring as a result of complete permafrost degradation. Vulnerability to permafrost thaw is described in three categories:

Low-vulnerability sections may have no thaw sensitivity due to a lack of permafrost or if highway stability is independent of thermal state. Some low-sensitivity areas may degrade, even intensely, for a relatively short period of time (several years). After that, degradation will be complete and the highway will be thaw-stable.

Moderately vulnerable sections are expected to undergo thaw settlement over time scales of years to decades, but degradation of the highway will be easily manageable.

Highly vulnerable sections may already be degrading and will continue to be affected by thaw for multiple decades, with heavy damage before permafrost degradation is complete. In some areas, it may take decades before any degradation takes place, until the lowering of the permafrost table reaches ice-rich ground, but once that happens, the impact of thaw will be substantial.

Because of the complexity of developing a ranking for the highly diverse permafrost environments encountered along the highway, each unit section was characterized by assessing the relationship of ground excess ice content, ground temperature, and thickness of the permafrost to surficial geology and climate. The classification does not directly consider where permafrost has degraded or is degrading, or where the road is damaged.

Thaw-sensitive permafrost is perennially frozen ground which, when it thaws, will experience significant settlement and lose the strength required to support the highway. Consequently, ice-rich permafrost is thaw-sensitive, and the more ice-rich the permafrost is, the more intense the thermokarst processes will be during its degradation. Highway sections that cross ice-rich permafrost rank as highly vulnerable.

Warm permafrost (with a ground temperature between –2 and 0°C) is more likely to degrade than colder permafrost. Permafrost with warm temperatures all along a vertical profile is symptomatic of ice-rich, fine textured permafrost. Therefore, warm permafrost is more likely to undergo heavy thermokarst processes when degrading, and will rank as highly vulnerable.

The thicker the permafrost, the longer its degradation is expected to last. Thick permafrost, even with moderate ice content, will produce major thermokarst processes over a longer period of time as climate changes.

The relationships among these three factors are summarized conceptually in Figure 3.

Using this approach, sites with very dissimilar permafrost setups can be ranked in the same category. For example, moderately ice-rich, but thick permafrost may be ranked equally to ice-rich yet significantly thinner permafrost. This simplification increases the potential applicability of the vulnerability assessment as a general tool to inform decision-making.

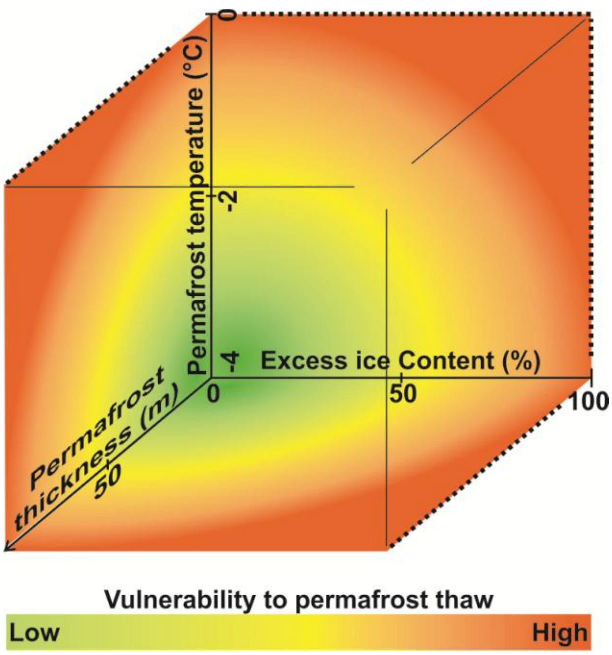

Figure 3. Conceptual diagram of vulnerability to permafrost thaw

3 RESULTS

3.1 Ground ice

Three general types of ground ice were observed through coring or/and ERT surveys: aggradational/segregated ice, buried ice, and wedge ice.

Aggradational and segregated ice is observed in most permafrost environments. Aggradational ice is mostly associated with syngenetic permafrost within fluvial, glaciofluvial, or loess deposits. Segregated ice is more widespread, but especially prevalent in frost-heave mounds such as palsas and lithalsas, and permafrost plateaus, where it can occur down to approximately 20 m.

The presence of buried ice was first suspected at the Dry Creek rest area, near km 1840. Following the excavation of gravel at this site, major thermokarst processes were initiated. ERT surveys indicate a very high resistivity body (10^6-10^7 Ohm.m magnitude, Figure 4) that is several metres thick. The examination of earlier geotechnical reports and the Alaska Highway Borehole database confirmed the occurrence of thick massive ice in the area. Finally, the massive ice was sample at Dry Creek in April 2014 by a research team from Laval University (Benoit Loranger, personal communication). The buried ice was systematically found in glaciofluvial gravel corresponding to outwash deposits; it can extend as deep as 25 m.

Wedge ice only was observed starting at around km 1860. Having grown syngenetically, multi-generational ice wedge networks were confirmed as deep as 20 m from ERT profiles and archived borehole logs.

3.2 Ground temperature

The mean annual ground temperatures recorded at the maximal depth of the each monitored boreholes are presented in Table 1.

Table 1. Ground temperature recorded along the North Alaska Highway.

location (km)	Depth	2013/2014 mean annual temperature
1791.1	3.4 m	-1.6°C
1738.7	4.3 m	-0.3°C
1776.1	6.0 m	-0.2°C
1793.5	4.7 m	-1.1°C
1810.2	6.0 m	-0.1°C
1841.3	9.3 m	-1.0°C
1841.4	9.5 m	-1.3°C
1865.2	9.5 m	-0.6°C
1866	9.2 m	-2.4°C
1886	8.5 m	-1.5°C
1894.4	9.5 m	-3.2°C
1896.3	13.2 m	-2.0°C
1897.8	5.4 m	-1.2°C

The warmer temperatures, around 0°C, were recorded in frost-heave mounds and permafrost plateaus surrounded by wetlands areas. Slightly colder temperatures, around -1°C, were observed in similar landforms but in drier environments.

The coldest ground temperatures, >-2°C, were recorded along the northern part of the highway, in the area that was not glaciated during the McConnell Glaciation, the last glacial episode in the region.

3.3 Permafrost thickness

Permafrost thickness varies depending on the geomorphological context. In areas that are known to have been glaciated during the last McConnell glacial age, permafrost thickness is unlikely to exceed 20 m. A maximum thickness of about 17 m was found at two locations (km 1791 and 1793.5), but at nearby wetlands, the permafrost base did not appear to extend below 10 m.

At the Dry Creek rest area (the location where the buried ice was identified), the lower limit of the ice body (location of the permafrost base) was located at a maximum depth of 25 m.

In the terrain that remained unglaciated during the McConnell Glaciation, ERT assessments returned resistivity values up to 40 m depth, but they did not indicate a permafrost base at that depth. The ground temperature envelope curves from the deepest boreholes located in this area (at km 1894.4 and km 1896.3 – Table 1) did not indicate an inflection point, so it was not possible to extrapolate the depth of the permafrost base. In similar unglaciated areas elsewhere, ground temperature records and literature suggest that permafrost could be as thick as 60 m (Brown 1967, 1970, French 2007).

3.4 Climate Projection

The climate change projections in Table 2 show little variation in projected temperature between the different sections of the highway for both A1B and B1 scenarios in the 2030s. The only noticeable difference is a slightly greater increase in temperature between Sections 2 and 6.

According to both scenarios, the temperature is projected to increase by 2.5°C to 4°C by the 2050s. Although there is no variation in the projected change in precipitation, the projected magnitude in both scenarios would contribute to permafrost degradation by affecting the speed of thaw.

3.5 Vulnerability

A summary of the vulnerability of permafrost to thaw for the 13 sections is presented in Figure 5. Overall, for the 200-km section between Burwash Landing and the Yukon/Alaska border, 42.7% is highly vulnerable to permafrost thaw, 38.5% is moderately vulnerable, and 18.8% has low vulnerability.

Section 10 (1855-1868) and Section 13 (km 1890-1902) are ranked as the most sensitive to permafrost thaw, while section 7 (km 1813-1825) and section 11 (km 1868-1878) appear to be the most resilient (Figure 5).

3.6 Field Guide

The field guide developed through this project is designed to convey information to a variety of end users. It is intended to be a tool for engineers, technicians, and maintenance workers working along the highway, as well as for members of the communities along the highway. It is intended to provide key information about permafrost along the highway in a format that is easily portable in the field. Users can also retrieve additional details from a geographic information system (GIS) database that was developed in conjunction with the guide.

The guide is made up of five chapters and three annexes. Chapter 1 provides an introduction to the report; Chapter 2 details the field and lab methodologies; Chapter 3 provides specific guidance on using the report; Chapter 4 provides an overview of findings; and Chapter 5 comprises the section-by-section interpretation of thaw vulnerability along the highway, with 13 section maps.

Annex 1 provides the supporting data (e.g., borehole logs and any other analyses performed on cores, results of ERT surveys, and plots of ground temperature) used to determine vulnerability for each section. Annex 2 provides a glossary of terms used in the report. Annex 3 provides a list of references cited in the report.

The section-by-section interpretation of thaw vulnerability along the highway (Chapter 5) is the key feature of the guide.

Six key pieces of information are shown in each map: satellite photos, symbols for key features, surficial geology, soil texture, ground ice nature, and a colour-coded assessment of permafrost vulnerability to thaw. The vulnerability to permafrost thaw section is shown in one of three colours: green (low), yellow (moderate) and red (high). An example of map is shown a Figure 6.

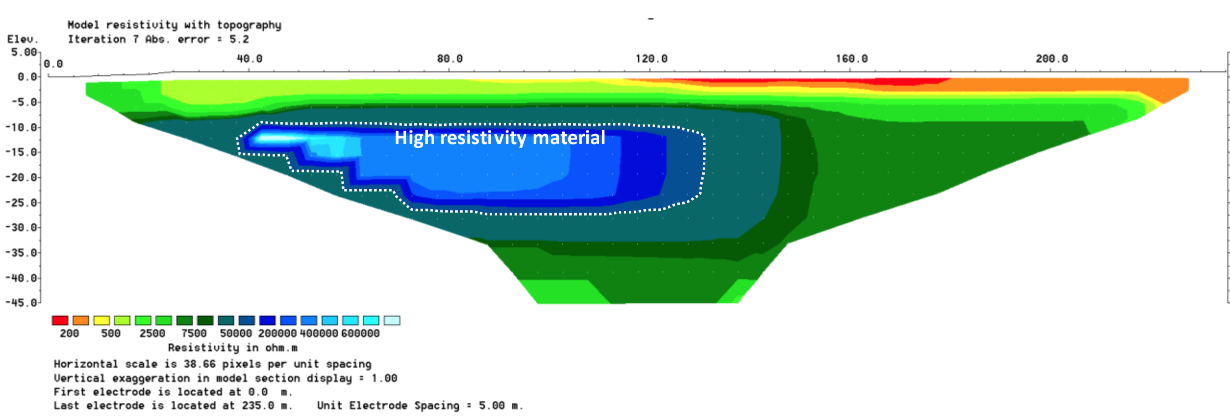

Figure 4. ERT profile at Dry Creek rest area; the high resistivity material in buried massive ice.

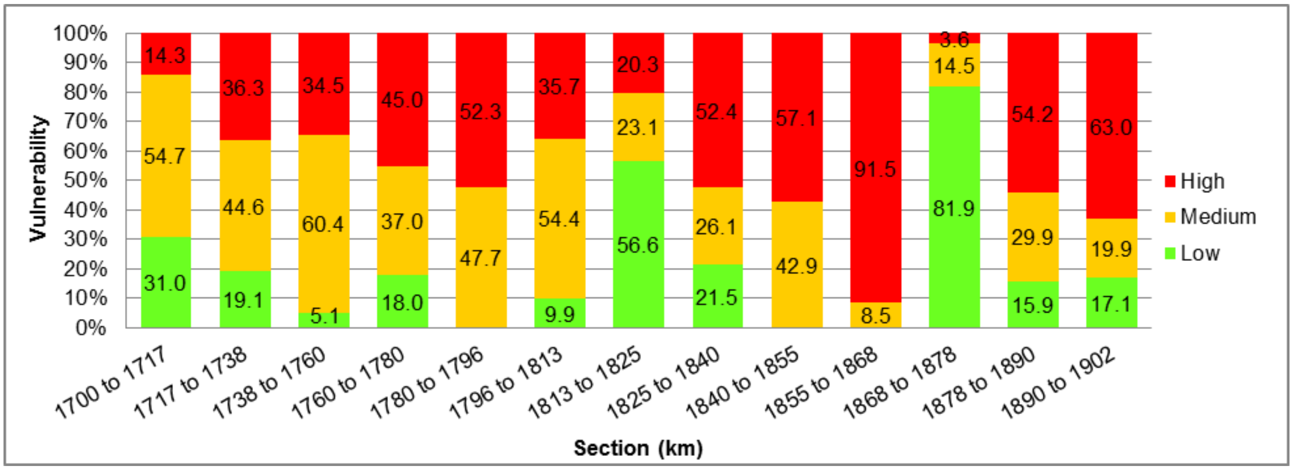

Figure 5. Vulnerability of the North Alaska Highway to permafrost thaw (%) by section

Table 2. SNAP climate projections for the North Alaska Highway

Highway section (named km markers)	Temperature increase (°C)				Precipitation increase (mm)			
	2030		2050		2030		2050	
	A1B	B1	A1B	B1	A1B	B1	A1B	B1
1700-1813	1.5-2.0	2-2.5	3.5-4.0	2.5-3.0	40-50	20-30	70-80	30-40
1717-1760	1.5-2.5	2-2.5	3.5-4.0	2.5-3.0	40-50	20-30	70-80	30-40
1760-1780	1.5-2.0	2-2.5	3.5-4.0	2.5-3.0	40-50	20-30	70-80	30-40
1780-1813	1.5-2.5	2-2.5	3.5-4.0	2.5-3.0	40-50	20-30	70-80	30-40
1813-1840	1.5-2.0	2-2.5	3.5-4.0	2.5-3.0	40-50	20-30	70-80	30-40
1840-1902	1.5-2.0	2-2.5	3.5-4.0	2.5-3.0	40-50	20-30	70-80	40-50

Information presented in the maps is supported by a written description that includes five components: (i) the vulnerability assessment that briefly explains the key points that determined the vulnerability for the section; (ii) the geology paragraphs that summarize the surficial geology and ground texture; (iii) the permafrost paragraphs that describe the physical and thermal properties of corresponding permafrost; (iv) the climate paragraphs that summarize climate projections and possible impacts on permafrost thaw, according to the corresponding cell-grid scale of the SNAP climate projection; and (v) A list of the supporting data that are presented in Annex 1.

4 DISCUSSION

The distribution and thickness of permafrost along the North Alaska Highway have been significantly influenced by the glacial history of the area. The glacial limit of the McConnell Glaciation, approximately 22 k yr ago, was located at about km 1958 (Duk-Rodkin, 1999), with unglaciated land to the north. The coldest and deepest permafrost has been observed north to this limit, at km 1866 and 1894.4 (Table 1), in terrains that were left unglaciated during the last 200 k yr. Consequently older and deeper permafrost have formed under colder Pleistocene climate. The importance of glacial limits and their relationship to permafrost distribution and thickness have been demonstrated by Brown (1967, 1970) who report that in areas with similar history and climate, permafrost thickness can exceed 60 m. Our temperature and ERT data support this hypothesis for the North Alaska Highway. Another noticeable fact is that wedge ice was only observed north of this glacial limit.

The glacial history also impacts the burial of the massive ice that was found under glaciofluvial gravel between km 1822 and 1856 where the road follows the outwash deposit. This situation is especially treacherous because such thick coarse material is typically assumed to have little thaw-sensitivity. The section of highway that crosses the glaciofluvial unit in the outwash area may have few signs of major degradation at this time, but these deposits can contain bodies of massive ice that are hard to detect because they are deeper than 10 m. While they have been stable since the construction of the highway, an increase in temperature or changes in precipitation, and resulting groundwater, may trigger degradation. If this occurs, the impact on the road will be substantial and long-lasting.

In areas that were covered during the McConnell Glaciation, vulnerability to thaw is often elevated. There was no permafrost below the glaciated area, so it is recent and less thick than unglaciated areas. However, in this area, permafrost is also more likely to be ice-rich and as thick as 20 m with the higher ground ice content are in the first 10 m. With ground temperature records indicating that permafrost is warm (about –1°C or less), small changes in temperature and precipitation would contribute to rapid degradation of the road. Once permafrost has degraded below the most ice-rich layer, the ground surface should stabilize.

Finally, highway sections located near Beaver Creek are highly vulnerable to thaw settlement because of the presence of ice wedges that may be as deep as 20–25 m. Because permafrost is colder and probably as thick as 60 m in this area, it is expected that permafrost degradation will be both long-lasting and high magnitude under a warming climate, and that it may be several decades before this degradation is completed.

Warming atmospheric temperatures will lead to ground warming through heat transfer. Increasing precipitation leads to ground warming through increased insulation in winter and increased soil moisture and shallower groundwater in summer. Both warming and increased precipitation may cause permafrost to degrade.

The magnitude of projected warming and precipitation increase is substantial in an area where many parts of the highway cross warm permafrost with a ground temperature close to 0°C. In fact, for Sections 2 and 3, the recorded mean permafrost temperature was between –1.5°C and –0.3°C and in Section 6 was between –1.2°C and –1. With a ground temperature that is already this warm, both scenarios could induce complete permafrost thawing along some parts of the highway between 2030 and 2050

The projected changes in climate are expected to have a greater impact in the northern and southern sections of the highway than in the middle sections since the permafrost is somewhat colder in the middle sections.

Although the Alaska Highway crosses what is now a zone of discontinuous permafrost, the projected change in climate would be large enough to make permafrost increasingly sporadic and isolated by 2050.

5 CONCLUSION

Since its construction, the 200-km of the Alaska Highway between Burwash Landing and the Yukon/Alaska border has been affected by permafrost thaw. While located in extensive discontinuous permafrost zone, this section is almost completely built on permafrost. Less than 20% of the road is located on ground that has a low vulnerability to permafrost thaw.

Assessing the vulnerability of such an infrastructure at a large scale is a challenge because the natural variability of permafrost complicates the understanding of the potential impacts of climate change on the foundation of the North Alaska Highway. This difficulty can only be overcome through knowledge of the Quaternary history of the study area.

Another challenge is to concretely address the issues resulting of the impact of climate changes on Northern societies. In partnership with the Northern Climate ExChange, Yukon Government's Department of Highways and Public Works has taken the first steps by developing a practical tool that can be used to support decisions regarding road maintenance and future measures to mitigate permafrost thaw.

ACKNOWLEDGEMENTS

The writers would like to acknowledge Paul Murchison, Muhammad Idrees, and Bill Stanley, from Highways and Public Works, Government of Yukon, as well as Sharon Smith, of the Geological Survey of Canada, Natural Resources Canada, Government of Canada, for their support. Funding for this project was provided by Aboriginal Affairs and Northern Development Canada, Government of Canada, and in-kind contributions were made by project partners including Duane Froese (University of Alberta), and Joel Cubley (Yukon College), who provided some of the research equipment.

REFERENCES

Brown, R.J.E.1967. Comparison of Permafrost Conditions in Canada and the USSR, *Polar Record* 13:741-751.

Brown, R.J.E.1970. Permafrost in Canada: Its Influence on Northern Development, University of Toronto Press, Toronto, ON, Canada.

Duk-Rodkin,A. 1999. Glacial limits map of Yukon Territory; Geological Survey of Canada,Open File 3694, Indian and Northern Affairs Canada Geoscience Map 1999-2, scale 1:1 000 000.

French, H.M. 2007. The Periglacial Environment, 3rd Ed., John Wiley and Sons, Hoboken, NJ, USA.

Howes, D. E. and Kenk, E. 1997. Terrain classification system for British Columbia. Version 2. Ministry of Environment, Lands and Parks, Victoria, B.C. www.for.gov.bc.ca/hts/risc/pubs/teecolo/terclass/appiii.htm.

Murton, J.B. and French, H.M. 1994. Cryostructures in permafrost, Tuktoyaktuk coastlands, western Arctic, *Canada. Canadian J. of Earth Sciences*, 31: 737-747.

Calmels, F., Roy, L.-P, Laurent,C., Pelletier, M., Kinnear, L., Benkert, B., Horton, B., and Pumple, J. 2015. Vulnerability of the North Alaska Highway to Permafrost Thaw: A Field Guide and Data Synthesis, Northern Climate ExChange, Yukon Research Centre, Yukon College.

SNAP (Scenarios Network for Alaska). 2014. *Projected database.* www.snap.uaf.edu/tools/data-downloads.

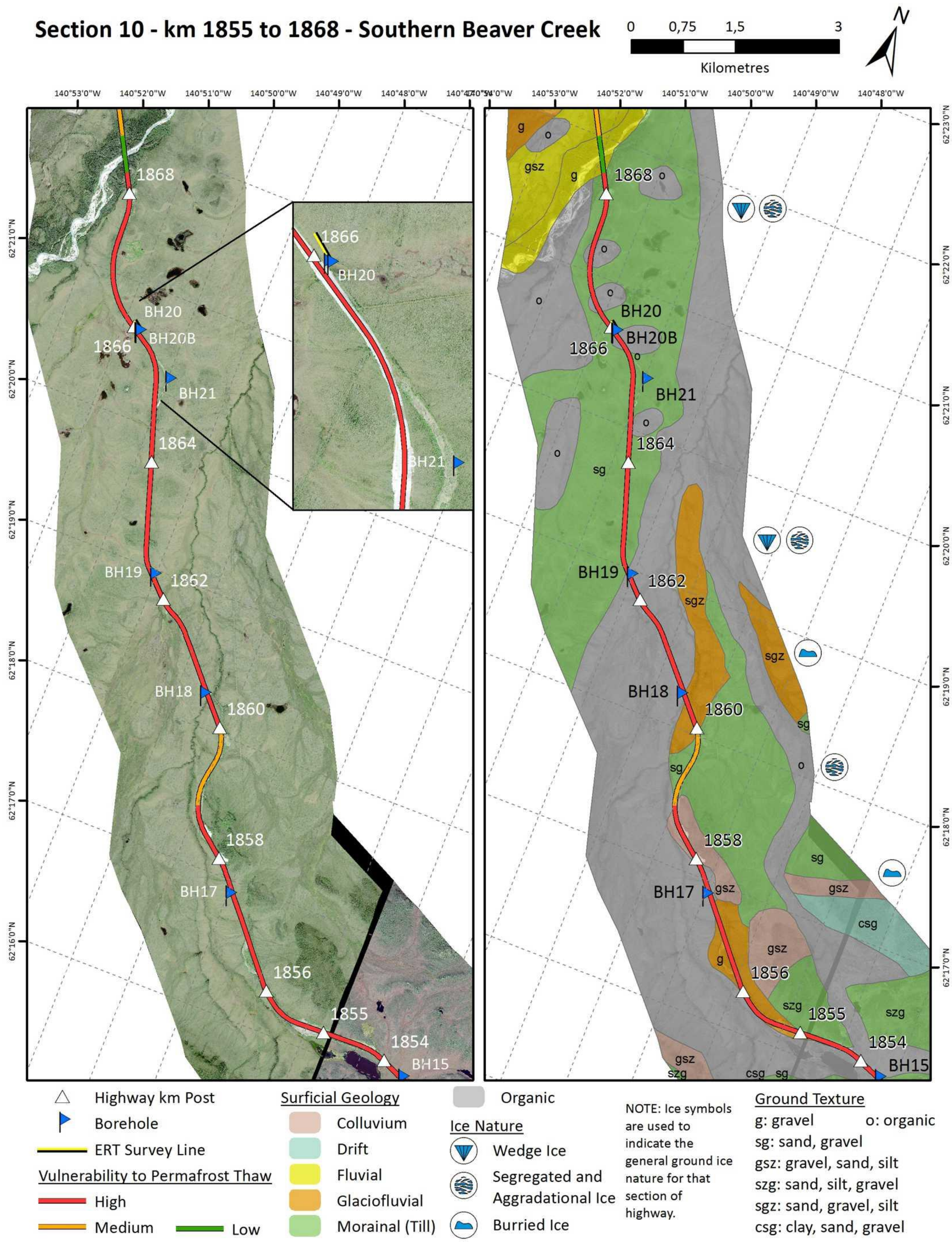

Figure 6. Example of field guide vulnerability maps for section 10 km 1855 to 1868, south to Beaver Creek, YT. The ground texture is described using the Yukon Terrain Classification System, which is an adaptation of the British Columbia Terrain Classification system (Howes and Kenk 1997).