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Influence of degrading permafrost on landsliding processes: Little Salmon Lake, Yukon Territory, Canada

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Abstract

A landslide inventory was carried out for the Little Salmon Lake area, Yukon Territory, Canada, in response to observations of several new landslides in the area, suspected to be the result of degrading permafrost. The largest of these landslides, the Magundy River bi-modal flow-slide, has progressed over the last decade until it now involves over $1x10^6$ m^3 of material. The inventory is based on terrain mapping and field work, and includes multiple landslide types. The field work provided the opportunity to examine the slides, ground truth the map, and to examine the progression of the landslide, as well as the massive ground ice exposed in the scarps of the currently active slides.

Permafrost degradation can be driven by anthropogenic or natural agents of change. The study investigated natural agents of change, as anthropogenic sources are not active, due to the remote and undeveloped nature of the area. Temperature data from the area indicates a warming trend of 3ºC over the last 40 years, supporting the theory that climate amelioration is one of the major factors generating the new activation of landslides in the area.

Susceptibility maps were developed to examine the potential for landslide initiation due to permafrost degradation. The most important data required for this work is the distribution of ground ice. In the absence of any borehole or geophysical data in the area, or generally of detailed mapping of permafrost distribution in the Canadian north, an expert system was used to predict the location of ground ice. Therefore, the landslide susceptibility maps are very dependent on the accuracy of this map.

Should development in the valley proceed, more accurate landslide susceptibility mapping would be required. Due to the importance of the ground ice distribution and condition, it would be recommended that data be collected to accurately map the ice and therefore to improve the accuracy of the prediction of possible landslides.

Introduction

With increasing development in areas of discontinuous permafrost in northern Canada, greater emphasis is being placed on slope hazard assessment. The research project reported here was initiated in response to the occurrence of a large bi-modal flow-type slide, the Magundy River landslide, which has progressed over the last 9 years to the point where it now involves over $1x10^6$ m^3 of material. The objective of the project was to identify and characterize slope hazards in the Little Salmon Lake area of the central Yukon (Figure 1): the Magundy River slide is located at the eastern end of this area. The area is largely unpopulated at this time, and covers over 600 km^2. A highway runs along the north side of the lake. There is no development on the south side of the lake at this time.

The objective of this paper is to evaluate the potential for development of landslides triggered by degrading permafrost. A terrain mapping exercise and field work resulted in the development of a landslide inventory map. This work formed the basis for further analysis of several, individual landslides examined in the area, and the development of landslide susceptibility maps. This work is predicated on the assumption that permafrost is found within some of the slopes under investigation, with the expectation that landslides will be triggered by processes resulting in permafrost degradation.

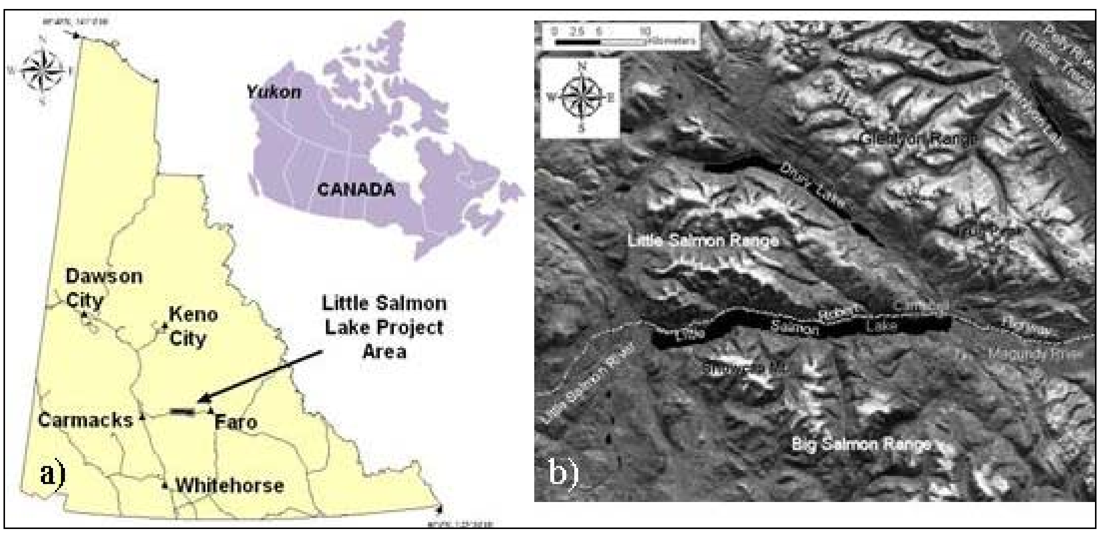


Figure 1: Little Salmon Lake, Yukon Territory, Canada. a) Location, b) Physiography.

Landslide activity in the Yukon

Assessment of the linkage between permafrost and landslide activity (Huscroft et al, 2004a), as well as a regional characterisation of landslide activity has been carried out for the Alaska Highway (Huscroft et al, 2004b) in the southern part of the Yukon. These authors discuss the importance of climate change on forest fire frequency, river migration, glacier mass balance and permafrost degradation, and the increased landslide frequency associated with changes in all of these factors.

Very little is understood about landslides in the central Yukon, with the exception of the Surprise Rapids Landslide on the MacMillan River (Ward et al., 1992), and the retrogressive thaw slumps near Mayo (Burn 2000).

The Surprise Rapids Landslide is located along the South Macmillan River in the Central Yukon, north-east of the Little Salmon Lake area. This landslide, primarily of the bi-modal flow type, has been active for at least 130 years. The complex of debris flows covers an area over 1.7 km^2, making it the largest reported failure in the central Yukon. The initial failure and triggering factors are unknown, though climate amelioration and forest fire activity, coupled with the high ice content of the sediments, are considered likely key factors for the initiation and continuation of the landslide. This slide is of particular interest as it took place mid-slope at a relatively gentle angle (approximately 5° overall) on a forested plateau. Ward et al. (1992) conclude that the exceptional size and rapid growth of the Surprise Rapids Landslide are seen as an example of the potential instability of hillsides with similar slopes and aspects in the central Yukon. It provides a dramatic example of what can happen when “warm” (near 0° C), ice-rich permafrost slopes are disturbed.

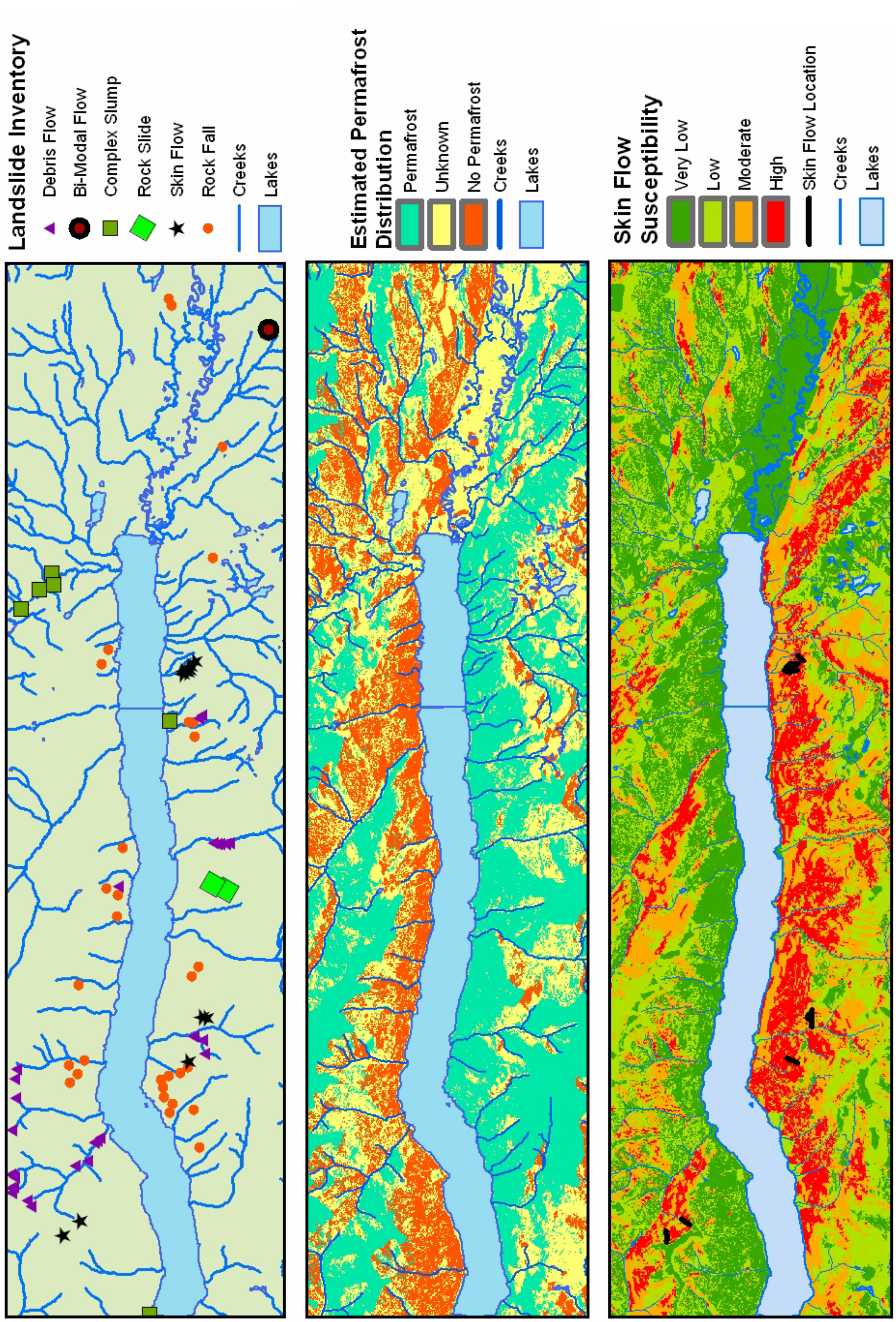
Retrogressive thaw slumps (bi-modal flows) in the Mayo area of the central Yukon have been monitored since 1982 (Burn and Friele, 1989). The slumps occur in glaciolacustrine silty clay in the Stewart River Valley, about 3 km upstream from the village of Mayo. One such slump was active for 44 years prior to stabilization in 1993 due to the exhaustion of ice-rich ground (Burn, 2000).

Slope hazard identification and landslide inventory mapping

Terrain evaluation studies were carried out using airphotos and geological maps, followed by field work, completed in 2004 and 2005. The data collected includes airphotos, Landsat imagery, and maps displaying topography, bedrock geology (Gladwin et al, 2002; Colpron, 2000; Campbell, 1967), surficial geology (Ward and Jackson, 1993; Campbell, 1967), geological processes (Mougeot and Walton, 1996), as well as forestry and forest fire inventories. Over 80 areas of past and present landslide activity were identified in the project area (Lyle, 2006). The failure modes evaluated include skin flows, debris flows, rock slumps, bi-modal flows and complex slides. These slides are described in further detail by Lyle et al (2004). The major active slides in the area started within the last decade.

The field work provided ground truth for the terrain evaluation and provided data to further characterize the most prominent and active landslides, and to confirm the veracity of the landslide distribution and inventory mapping (Figure 2a). From the data collected during the inventory phase of the work, landslide attributes such as slope angle, slope aspect, surficial sediment type, depth of overburden and sometimes geomorphic processes can be developed (Bichler et al., 2004). Further analysis generates maps of distribution of causal factors, such as permafrost distribution (Figure 2b), and landslide susceptibility (Figure 2c).

The bi-modal flow (Magundy River slide: Figure 3) and complex sliding modes (YT slide: Figure 4) are of particular importance, as massive ground ice has been exposed by large failures of these types. As shown in Figure 4b, this provides an opportunity to observe the extent and volume of the degrading permafrost. The Magundy River landslide develops into a continuous mudflow during the summer months, with material supplied by ongoing bank failure and retrogression. The first evidence of the YT slide was the presence of the back scarp crack. Since that time, the slide has progressed through a series of slumps and slides of material.



a) b) c)

Figure 2: Little Salmon Lake mapping: a) landslide inventory map, b) estimated permafrost distribution map, and c) skin flow susceptibility map. North is to the left.

Figure 3: Magundy River Landslide: a) overview looking south; b) active thaw slump area (note author for scale); and c) active debris flow.

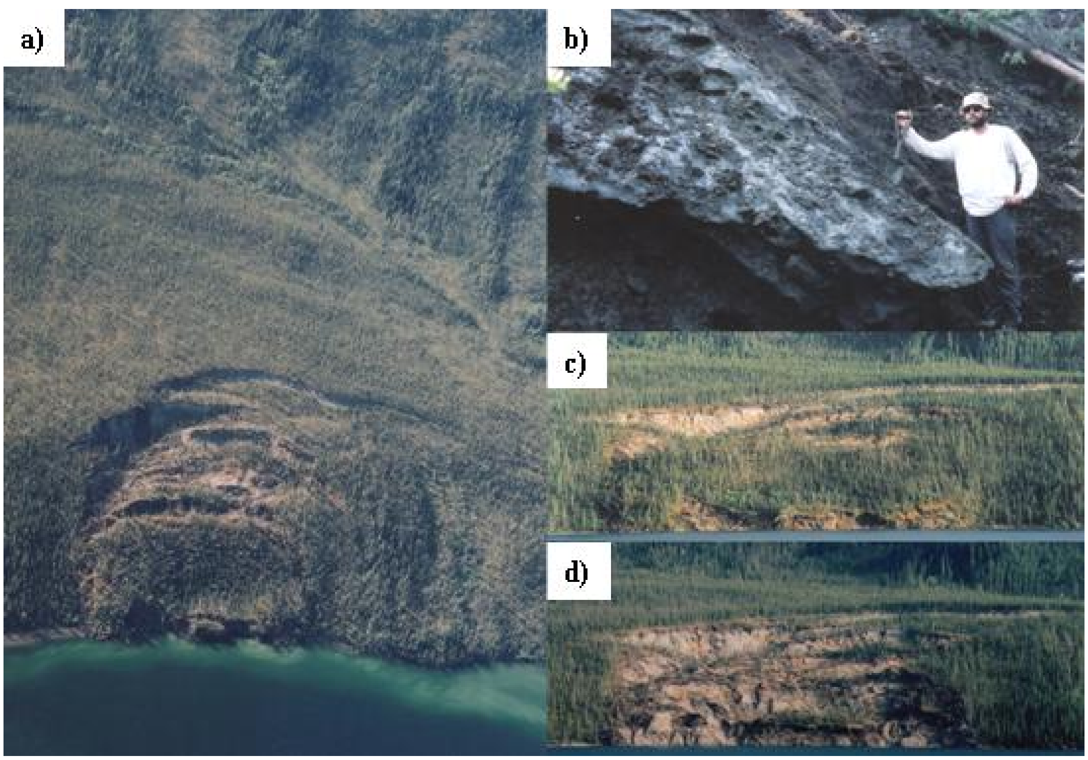


Figure 4: YT Landslide: a) overview, looking approximately south (Aug. 2004); b) massive ice in sediments exposed in landslide scarp; c & d) overview photos, looking south from across Little Salmon Lake. Note the changes between photo (c) taken on Aug. 3, 2004, and photo (d) taken on Aug. 2, 2005.

Permafrost distribution and condition

Permafrost, ground remaining below 0°C for two years or more, is found under approximately one-half of the Canadian landmass (Wolfe, 1998). The Little Salmon Lake area is located at the boundary between the sporadic discontinuous and extensive discontinuous permafrost zones as defined by Heginbottom et al (1995). In general, there is a general lack of knowledge of permafrost conditions in the mountains of northern Canada, since there are no maps available (Lewkowicz, 2004).

Permafrost degradation, leading to ground subsidence and landsliding, can result from a number of influences, whether anthropogenic or natural (Figure 5). Thawing of ground ice is the greatest hazard associated with permafrost (Dyke, 2004) for when ice occurs in excess, significant landscape changes will take place upon thaw. Climate warming or forest fire effects can and will lead to thawing of ground ice, leading to surface subsidence, increases in slope failures, and sediment deposition in water bodies (Heginbottom, 2000). Although forest fires cause the most widespread disturbance to surface conditions in permafrost areas (Haeberli and Burn, 2002), inventory data indicates that no major fire activity has occurred in the Little Salmon Lake area for at least 60 years.

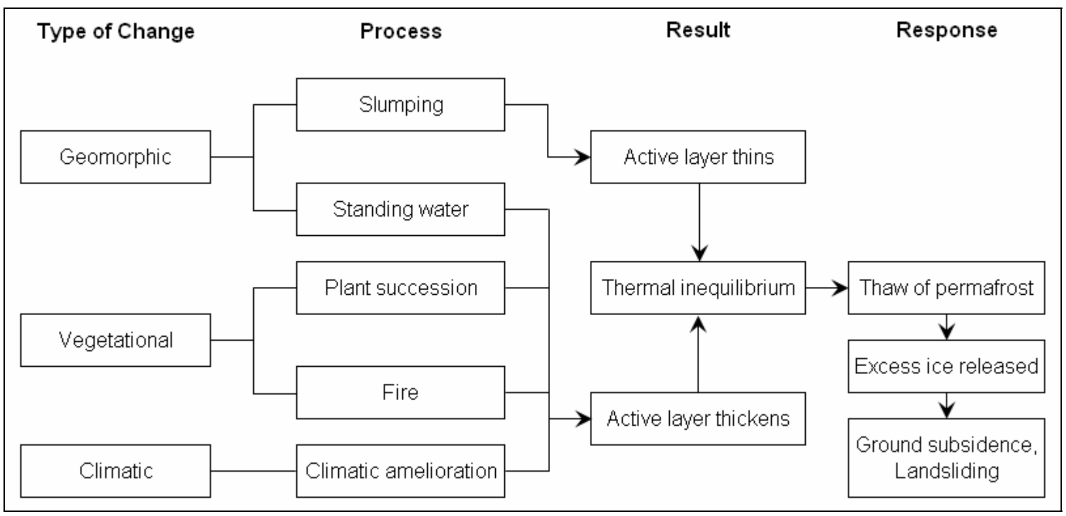


Figure 5: Natural agents of change leading to permafrost degradation (modified from French, 1996). Anthropogenic sources are also discussed by French (1996).

Most climatological models suggest an accelerating global warming trend, and northern regions are expected to experience the greatest increases in temperature (Serreze et al., 2000). It is believed that the warming trend, observed in climate records from Environment Canada (Fig. 6) will lead to more extreme climatic events, which, in turn will increase landslide frequency (Huscroft et al., 2004b, Haeberli and Burn, 2002, Harris et al., 2001, Nelson et al., 2002, Evans and Clague, 1994).

Primary controls on permafrost distribution in the region include slope aspect, elevation, surficial material type and age, vegetation cover and drainage conditions. Local climatic effects such as snow depth variation and temperature inversions may also control permafrost distribution. In general, permafrost is thicker and more widespread on north-facing slopes where hill-slope shading, thick vegetative mats and poor drainage conditions exist.

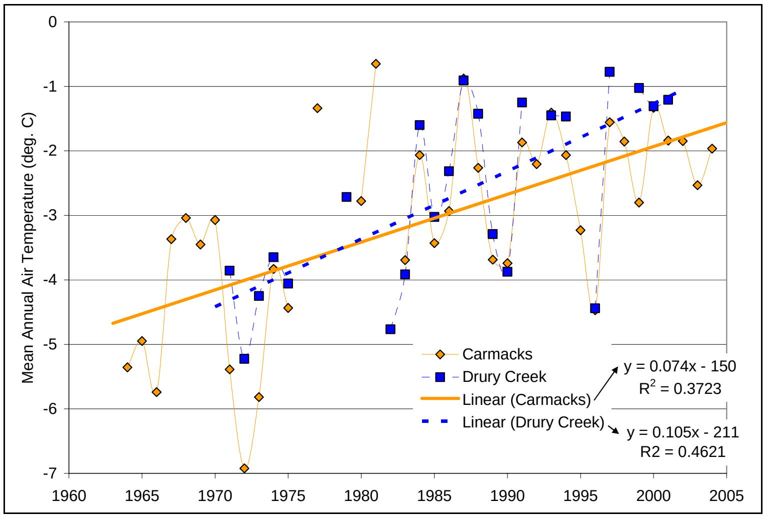


Figure 6: Climate data for Drury Creek (eastern end of lake), and Carmacks (100 km west).

Of critical importance to assessing the ongoing and future stability of this area is the evaluation of the extent and amount of ground ice. Unfortunately, ground ice content cannot be easily predicted without subsurface data. Subsurface data is very sparse in northern Canada, with exceptions being the geotechnical drilling databases available for the Mackenzie Valley and the Alaska Highway (Huscroft et al, 2004a).

Due to the lack of data, an expert system rule set was developed to estimate the permafrost distribution. This was based on work by Côté (2002), who examined the influence of elevation and slope aspect on permafrost distribution at Keno Hill, located 200 km north of Little Salmon Lake. The expert system for Little Salmon Lake is based on slope aspect, land cover and elevation data (Figure 7), and was used to create the permafrost distribution map (Figure 2b). Discussion of the logic used in the rule set development is presented by Lyle (2006).This process provides a starting point for the analysis, in spite of the limitations and assumptions of this methodology.

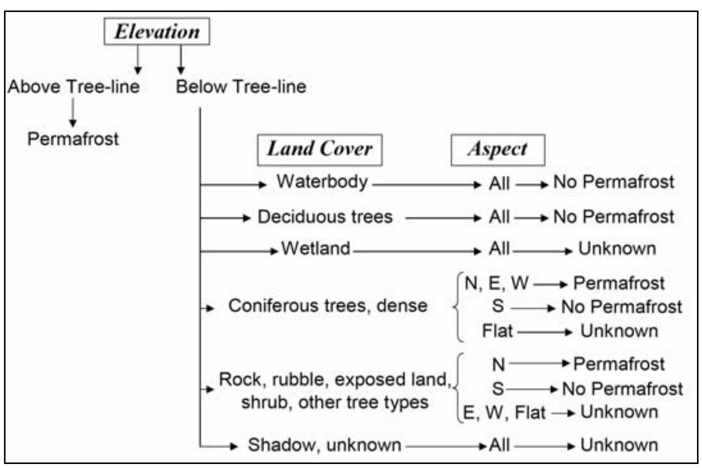


Figure 7: Rule set for the determination of the presence of permafrost in the Little Salmon Lake area using tree-line, land cover and slope aspect data. Based on Côté (2002).

These data were then combined with other important landslide causal information to develop landslide susceptibility maps, using both a geomorphological analysis and a qualitative map combination approach (defined by Soeters and van

Westen (1996)), at a regional scale (Lyle, 2006). The approach includes a detailed inventory of slope instability processes (Fig. 2a), study of these processes in relation to their environmental setting, analysis of preparatory and triggering factors, and a representation of the spatial distribution of these factors (Fig 2b).

The assessment of the susceptibility of stable and marginally stable slopes to landsliding is based on the assumption that hazardous phenomena that have led to failure in the past provide suitable information to predict future failures. Therefore, the mapping of these phenomena is very important in susceptibility mapping. The absolute and relative timing of the occurrence of causal factors is very difficult to predict and the majority of hazard maps thus aim to predict where failures are most likely to occur without indicating when that failure might occur (Carrara et al., 1995).

Qualitative map combination was used to create the skinflow susceptibility map shown in Figure 2c. This was done by combining permafrost, slope aspect, land cover, slope angle and surficial geology parameter maps, with qualitative weight values given to each class of the parameter maps and each map's contribution weighted according to its importance. Weighting values were determined based on the field knowledge of the mapper about causal factors of skinflows, and are described in more detail by Lyle (2006). Though the results shown in Figure 2c) fit well with the existing skin flows in the area, this does not represent a validation of the model, particularly given the uncertainty with respect to ground ice distribution and condition in this area where no intrusive work has been carried out.

Conclusions

It is anticipated that continuing warming trends in the climate will continue to melt the ground ice, triggering further landslides in the Yukon. The recent development of several new landslides in the Little Salmon Lake area, without any other known causal factor influence, is taken as an indication of the effects of continued warming. Landslide mapping approaches have been applied to this problem, including creation of a landslide inventory map and development of permafrost distribution maps.

The scale of mapping was constrained by the challenges met within this project, including limited access to many parts of the area mapped, sporadic historical aerial photographic coverage, limited detail provided by regional scale surficial and bedrock geology mapping and a coarse scale digital elevation model. Furthermore, the most critical parameter, the presence of permafrost and ground ice, was inferred from an approach applied to other areas in the Yukon, based on substantial assumptions, but not verified by intrusive, subsurface investigation.

Acknowledgements

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References

Bichler, A., VanDine, D., and Bobrowsky, P. (2004). Landslide Hazard and Risk Mapping – A Review and Classification. *Proc. of the 57th Canadian Geotechnical Conference*, Session 5C, 1-12.

Brown, R.J.E. (1970). *Permafrost in Canada: It's Influence on Northern Development.* Toronto: University of Toronto Press, 234 p.

Brown, R.J.E., Johnston, G.H., Mackay, J.R., Morgenstern, N.R. and Shilts, W.W. (1981). Permafrost Distribution and Terrain Characteristics. *In G.H. Johnston (ed.): Permafrost: Engineering Design and Construction*. Toronto: John Wiley and Sons, 31-72.

Burn, C.R. (2000). The thermal regime of a retrogressive thaw slump near Mayo, Yukon Territory. *Canadian Journal of Earth Sciences*, **37**, 967-981.

Burn, C.R. and Friele, P.A. (1989). Geomorphology, Vegetation Succession, Soil Characteristics and Permafrost in Retrogressive Thaw Slumps near Mayo, Yukon Territory. *Arctic*, **42**, 31-40.

Campbell, R.B. (1967). Reconnaissance Geology of Glenlyon Map-Area, Yukon Territory (105L). *Geological Survey of Canada Memoir 352*. 92p. (2 maps)

Carrara, A., Cardinali, M., Guzzetti, F., and Reichenbach, P. (1995). GIS technology in mapping landslide hazard. In *Geographical Information Systems in Assessing Natural Hazards,* Carrara and Guzzetti (eds.), Kluwer Academic Publishers, 135-175.

Colpron, M. (2000). *Geological map of Little Salmon Lake (parts of NTS 105L/1, 2 & 7), central Yukon (1:50,000)*. Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File 2000-10.

Colpron, M., Bond, J.D., Lipovsky, P.S., Gladwin, K., Gordey, S.P., Murphy, D.C., Nelson, J.L., Plouffe, A., Roots, C.F., and Abbott, J.G. (2003). *Digital compilation of bedrock geology and till geochemistry, Glenlyon (105 L) and eastern Carmacks (115 I) map areas, Yukon Territory.* Geological Survey of Canada, Open File 1561, Digital Media.

Côté, M.M. (2002). *The influence of elevation and aspect on permafrost distribution in central Yukon Territory*. Unpublished M.A. Thesis, Carleton University, 148 p.

Dyke, L.D. (2004). Stability of frozen and thawing slopes in the Mackenzie Valley, Northwest Territories. *Proceedings of the 57th Canadian Geotechnical Conference*, Quebec City, Quebec, Session 1G, 31-38.

Evans, S.G. and Clague, J.J. (1994). Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology,* **10**, 107-128.

French, H.M. (1996). *The Periglacial Environment*. Essex: Addison Wesley Longman Co., 341 p.

Gladwin, K., Colpron, M., and Black, R. (2002). *Geological map of Truitt Creek (NTS 105L/1), central Yukon (1:50,000)*. Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, Open File 2002-5.

Haeberli, W. and Burn, C.R. (2002). Natural Hazards in Forests: Glacier and Permafrost Effects as Related to Climate Change. In *Environmental changes and geomorphic hazards in forests*, R.C. Sidle (ed.), IUFRO Research Series, **9**, 167-202.

Harris, C., Davies, M.C.R. and Etzelmuller, B. (2001). The Assessment of Potential Geotechnical Hazards Associated with Mountain Permafrost in a Warming Global Climate. *Permafrost and Periglacial Processes*, **12**, 145-156.

Heginbottom, J.A. (2000). Permafrost distribution and ground ice in surficial materials. In *The Physical Environment of the Mackenzie Valley, NWT: A Base Line for the Assessment of Environmental Change*, L.D. Dyke and G.R. Brooks (eds.). Geological Survey of Canada Bulletin **547**, 31-39.

Heginbottom, J.A., Dubreuil, M.A. and Harker, P.A. (1995). Canada – Permafrost. *In National Atlas of Canada*, 5th ed. National Atlas Information Service, Natural Resources Canada, Ottawa. Plate 2.1: MCR 4177.

Huscroft, C.A., Lipovsky, P.S. and Bond, J.D. 2004a. Permafrost and landslide activity: Case studies from southwestern Yukon Territory. In *Yukon Exploration and Geology 2003*, D.S. Emond and L.L. Lewis (eds.), Yukon Geological Survey, 107-119.

Huscroft, C.A., Lipovsky, P.S., and Bond, J.D. 2004b. A regional characterization of landslides in the Alaska Highway corridor, Yukon. *Yukon Geological Survey Open File 2004-18*, 65 p.

Lewkowicz, A.G. (2004). Permafrost and Landslide Initiation in Northern Canada: Changing Climates, Changing Roles. In *Vulnerability of Landslide Risk to Climate Change*. Kulkarni and Blais-Stevens (eds.). Proceedings from C-CIARN Landscape Hazards Workshop 2003, Vancouver, BC. C-CIARN Landscape Hazards Report 04-01. 8 p.

Lyle, R.R. (2006). *Landslide susceptibility mapping in discontinuous permafrost: Little Salmon Lake, Central Yukon*. M.Sc.(Eng) thesis, Queen's University, Kingston.

Lyle, R.R., Hutchinson, D. J., and Preston, Y. (2004). Landslide processes in discontinuous permafrost, Little Salmon Lake (NTS 105L/1 and 2), South-central Yukon. *In: Yukon Exploration and Geology 2004*, (eds.) D.S. Emond, L.L. Lewis and G.D. Bradshaw, Yukon Geological Survey, Whitehorse, 193-204.

Mougeot, C.M. and Walton, L.A. (1996). *Yukon Geoprocess File (2002), Geological Processes and Terrain Hazards of Glenlyon, 105L*. Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada. (1:250 000 scale map and notes)

Nelson, F.E., Anismov, O.A. and Shiklomanov, N.I. 2002. Climate Change and Hazard Zonation in the Circum-Arctic Permafrost Regions. *Natural Hazards*, **26**, 203-225.

Serreze, M.C., Walsh, J.E., Chapin III, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., Barry, R.G. (2000). Observational evidence of recent change in northern high-latitude environment. *Climatic Change*, **46**, 159-207.

Soeters, R. and van Westen, C.J. (1996). Slope Instability recognition, analysis and zonation. In *Landslides: Investigation and Mitigation*, Turner and Schuster (eds.). Transportation Research Board Special Report 247, 129-177.

Ward, B.C. and Jackson Jr., L.E. (1993). *Surficial Geology, Telegraph Mountain, Yukon Territory*. Geological Survey of Canada, Map 1789A, scale 1:100 000.

Ward, B.C., Jackson Jr., L.E., and Savigny, K.W. (1992). *Evolution of Surprise Rapids Landslide, Yukon Territory*. Geological Survey of Canada Paper 90-18. 24 p.

Wolfe, S.A. (editor). (1998). *Living with Frozen Ground: A Field Guide to Permafrost in Yellowknife, NWT*. Geological Survey of Canada Miscellaneous Report 64, Ottawa, Ontario.