ON THE HAZARDS TO INFRASTRUCTURE IN THE CANADIAN NORTH ASSOCIATED WITH THAWING OF PERMAFROST

R. Couture, S. Smith, S.D. Robinson, M.M. Burgess, Geological Survey of Canada, Ottawa, ON, Canada
S. Solomon, Geological Survey of Canada, Dartmouth, NS, Canada

ABSTRACT
In Canada, about 50% of the ground surface lies within the permafrost region. In the north, the integrity and the performance of infrastructure, including roads, buildings, pipelines, embankments, structures in coastal environments, commonly relies on the stability of the frozen ground. Permafrost degradation in response to development and the warmer climate predicted by climate-change models for northern latitudes may exacerbate the problems related to warming of permafrost, especially in the discontinuous permafrost zones. Climate change impacts on permafrost areas are presented and discussed in terms of infrastructure in the western Arctic, which is a national strategic area for the development of natural resources, transportation corridors, and tourism for some communities. Examples of impacts from two communities (Norman Wells and TuktoyaktuK) in the Northwest Territories are highlighted. Potential adaptation measures to mitigate consequences are also described.

RÉSUMÉ
Environ 50% de la superficie du Canada se trouve en milieu pergélisolé. Au nord, l'intégrité et la performance des infrastructures, incluant les routes, bâtiments, pipelines, talus, et structures en milieu côtier, dépendent de la stabilité du pergélisol. La dégradation du pergélisol en réponse à un climat plus chaud prédit par les modèles de changement climatique pour les latitudes nordiques peuvent exacerber les problèmes reliés au réchauffement du pergélisol, spécialement en zones de pergélisol discontinu. Les impacts du changement climatique sur les zones pergélisolées sont présentés et discutés en regard des risques aux infrastructures dans la région de l'Arctique occidental et de la vallée Mackenzie, laquelle représente une zone nationale stratégique pour le développement de ressources naturelles, de corridors de transport, et du tourisme. Des exemples d'impacts venant de deux communités (Norman Wells et Tuktoyaktuk) des Territoires du Nord-Ouest sont illustrés. Des pistes potentielles de stratégie d'adaptation afin de réduire les impacts sont également décrites.

1. INTRODUCTION

About one quarter of the Earth's land area and about half of Canada's ground surface is within the permafrost region (Figure 1). Within this region, the presence of frozen ground and ground ice influences the properties and the performance of earth materials and plays an important role in land development.

Permafrost is defined as ground (whether soil or rock) that remains at, or below 0°C for at least two consecutive years (International Permafrost Association 1998). The distribution, thickness, and stability of permafrost are controlled by past and current climate, ground temperature, the nature of ground materials and their thermal properties, and geological history. Factors such as vegetation, snow cover, surficial materials, soil moisture content, drainage, and the presence of an organic layer influence the heat transfer between air and ground, and therefore modulate the response of permafrost to changes in climate. In Canada, permafrost thickness varies from a few metres at its southern limit to more than 700 m in the Arctic Islands (Smith et al. 2001b: Fig. 3). Permafrost conditions also exist at high altitudes, mainly in the Canadian Cordillera and in the high plateaus of the Canadian Shield in eastern Canada. Commonly, permafrost conditions are recognizable by the presence of typical landscape features such as pingos, patterned ground, and massive-ice beds (Mackay 1972).

In the north, the integrity and the performance of infrastructure, including roads, buildings, pipelines, embankments, structures in coastal environments, is dependent on the stability of frozen ground. These conditions provide constraints and challenges to development. Although the permafrost regions in Canada are not densely populated, their economic importance has increased significantly in the last few decades. They represent national strategic areas for natural resources (e.g. conventional and unconventional hydrocarbon resource exploitation and, mining),

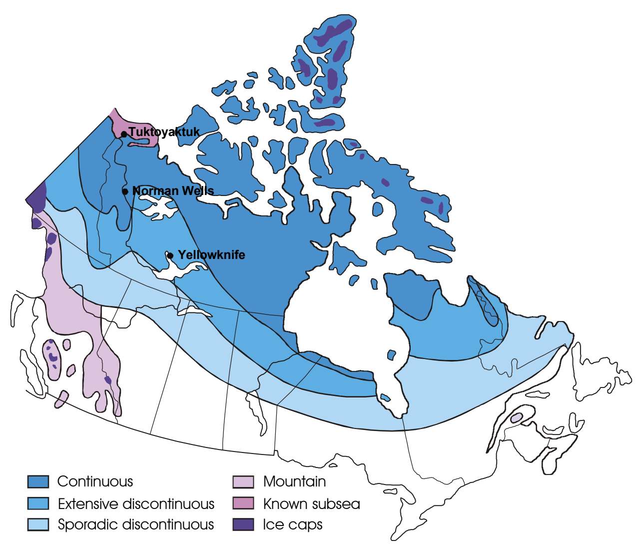

Figure 1. Permafrost map (after Heginbottom et al. 1995).

transportation/transmission corridors (*e.g.* pipeline in the Mackenzie Valley), and for the development of tourism and ecotourism for some communities. Permafrost degradation occurs in response to disturbance of the ground surface during construction, and this must be considered in the design of northern infrastructure. Additional permafrost degradation may occur in response to climate warming, which may further jeopardize the integrity of northern infrastructure.

In this paper, the focus is directed toward the impacts upon, as well as hazards to human infrastructure and activities due to the degradation of permafrost in response to development and climate warming. Potential solutions to mitigate consequences are also described. Results from a case study in two pilot communities in the Mackenzie Region are highlighted. The present preliminary assessment of the climate change impacts on the infrastructure is restricted to the Western Arctic Region and the Mackenzie Valley.

2. COMMUNITY INFRASTRUCTURE AND FACILITIES IN THE NORTH

With rare exceptions, such as Yellowknife and Whitehorse, human settlements in the permafrost regions in Canada are relatively small, and are scattered along main water bodies. However, these small communities are the locations of important facilities and major engineered works. Their economic and social development was and still is strongly linked with principal economic activities such as traditional native activities, hydrocarbon exploration and exploitation, mining activity and, more recently, tourism. The introduction of a wide variety of infrastructure also accompanied the development of economic activities in these northern communities. As discussed by Smith et al. (2001b), northern development in permafrost areas presents challenges.

For the purpose of this paper, we have classified the northern infrastructure into three categories: (1) Municipal, (2) Transportation, and (3) Resources. Examples of these categories are given in Table 1, and illustrated in Figure 2. Offshore and military infrastructure are not discussed in this paper.

Table 1. Infrastructure types.

Type	Examples
Municipal	Buildings, utilidors, water reservoirs
Transportation	Roads, airfields, railways, highways
Resources	Dykes, dams, pipeline, mining facilities

In the Prairie and Northern Regions in Canada, more than 5,000 km of winter roads are built each year, many of which are used for resupplying communities and industries and for economic development. Obviously, this is not an exhaustive list of structures (Table 1) and many others can be added.

Figure 2. Upper: Utilidor in Norman Wells, NWT (Photo by R. Couture, 1999);
Middle: Oil tanks sitting on duct-ventilated gravel pads, Inuvik, NWT (Photo by R. Couture, 2000);
Lower: Pipeline right-of-way, Mackenzie Valley, NWT. (Photo by M.M. Burgess, 1989).

In addition to these three categories, infrastructure can be divided into linear (*e.g.* pipeline), areal (*e.g.* airfield), and punctual (*e.g.* pylon). More comprehensive studies may be required with respect to the size of their foundation footprints. For instance, linear infrastructure, such as pipelines and highways, encounters many terrain types with varied geological materials, thermal properties, frozen/unfrozen interfaces, and drainage. The complexity of the foundation system on which the infrastructure sits varies with the size and load, the lifespan, the capacity of the structure to withstand deformation, and with the local permafrost conditions. A small dwelling unit requires a less complex foundation system than a permanent large building. Examples of foundation systems are given in Table 2. Geothermal models are commonly used in major infrastructure design; and geotechnical performance and, for critical infrastructure, geothermal conditions are usually monitored.

Table 2. Examples of foundation systems.

Type	Examples
Shallow	Sill, footing, slab, pot and pad, piers
Deep	Piles (timber, H-beam, pipe)
Special	Thermal pile, ventilation duct, sheet pile

3. PERMAFROST AND CLIMATE CHANGE

3.1 Permafrost

Because permafrost is a thermal condition, it responds to variations in climate at time scales of years, decades, centuries, and millennia. Thus, permafrost is a dynamic environment and reacts to extreme climatic events (*e.g.* 1998 El Niño events) and to localized variations in the surface thermal regime caused by changes in drainage, vegetation, and shoreline position, or by the influence of infrastructure. Nelson et al. (2002) defined the role of permafrost in climate change as threefold: (1) it serves as a *recorder* of climatic change through its ability to track temperature trends over longer periods; (2) it can act as a *facilitator* of further climate change through release of greenhouse gases –it can also sequester gases if climate cools; and (3) it can be an effective *translator* of environmental change through its effects on natural and human communities. In this paper, we focus on role (3).

3.2 Recent trends and climate modelling

The northwest region has undergone the most air-temperature warming (1.7°C) over the last century of any region in Canada (Environment Canada 1995). For instance, in the Mackenzie Valley and Delta, mean annual air temperatures have increased by more than 1.5°C in the past 100 years (Maxwell 1997). General Circulation Models (GCM) predict that, for climate warming resulting from a doubling of atmospheric CO_2 by approximately 2050, the Mackenzie region will experience increases in mean annual air temperature reaching 4°C to 5°C. Warming is expected to be greater with increasing latitude, and projected changes are expected to be greatest in winter and spring (Figure 3). Increases in precipitation up to 26% are predicted for Norman Wells by 2080, although there is less confidence placed in GCM results for changes in precipitation. Also, a greater variability in winter temperatures is predicted, which has been observed in air-temperature records from the last few decades.

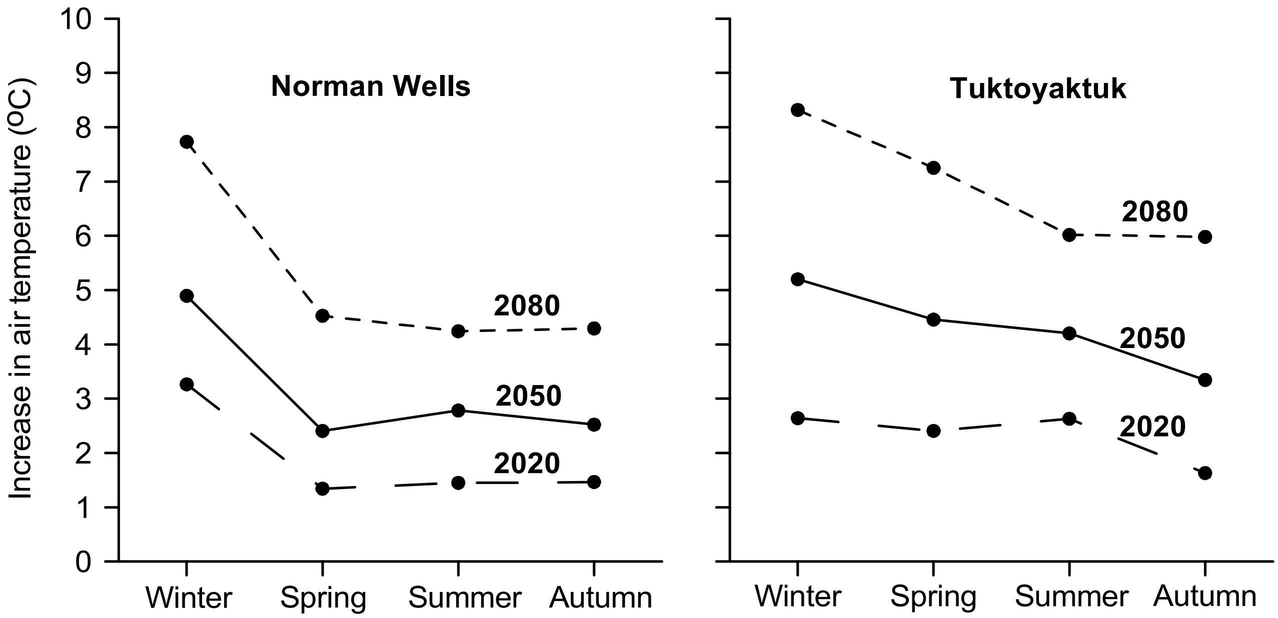

Figure 3. Graphs showing projected changes in seasonal air temperature based on CCCma model for Norman Wells (left) and Tuktoyaktuk (right) for the years 2020, 2050, and 2080, calculated as departures from the 1961-1990 climate normals. Data from the Canadian Centre for Climate Modeling and Analysis model (CGCM1), provided by the Canadian Institute for Climate Studies (http://www.cics.uvic.ca/scenarios/) (after Couture et al. 2001).

3.3 Climate change impacts on permafrost

Sensitivity of permafrost to warming depends on physical and thermal properties of the frozen ground. Ice-rich fine-grained mineral soil and organic terrain with ground temperatures close to 0°C are much more sensitive to climate warming, in terms of thaw settlement, compared with thick sand and gravel with colder temperatures (-7°C). Throughout the Mackenzie Valley, permafrost is considered to be moderately to highly sensitive to climate warming (Figure 4). Results of geothermal modelling for the discontinuous zone, where permafrost is on the order of 5 to 10 metres thick, indicate that complete degradation of permafrost in response to warming may be possible within the next 50 years (Burgess et al. 2000a). Farther north such as sites near Norman Wells where permafrost is thicker (50 m), the permafrost may degrade by several metres over this time and eventually disappear. In the Mackenzie Delta and Tuktoyaktuk Peninsula region where permafrost may be several hundred metres thick, warming would likely result in thickening of the active layer and thinning of the permafrost.

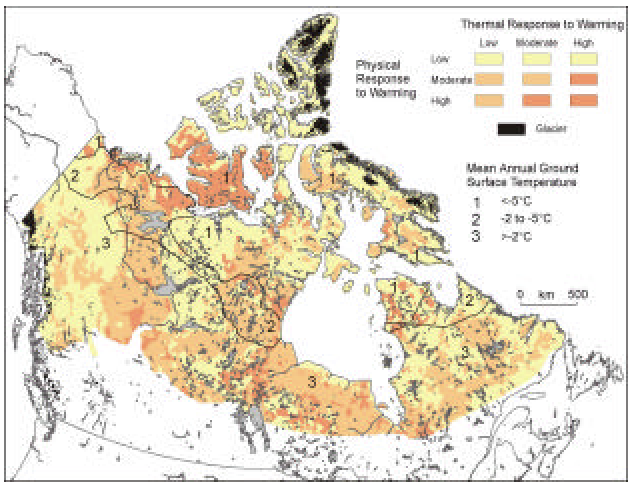

Figure 4. Sensitivity of permafrost to warming. The sensitivity index incorporates both the thermal and physical response (in terms of thaw settlement) to warming (from Smith & Burgess, in press).

Analysis of data from the Geological Survey of Canada permafrost networks in the western Arctic indicates that thaw depths in the Mackenzie Valley and Delta increased in the 1990s (Figure 5), with the largest increase occurring during the warm summer of 1998 (Wolfe et al. 2000; Smith et al. 2001a: Fig. 3). Where ice-rich soils are present, this increase in thaw depth is accompanied by settlement of the ground surface of up to 15 centimetres (Smith et al. 2001a). For ice-rich silty and clayey soils, thaw strains of up to 20% have been observed in the Mackenzie Valley near Norman Wells (Burgess & Smith in press : Fig. 2).

The warming of shallow permafrost is illustrated by a preliminary analysis of temperatures collected at depth s between 10 and 20 m from the mid 1980s to 2002 beneath undisturbed sites along the Mackenzie Valley (Romanovsky et al. 2002). In the central Mackenzie Valley, an increase of 0.03°C/year (Figure 6) was observed in permafrost with mean annual near-surface temperatures around –1°C and a thickness of less than 50 m. However, in the southern Mackenzie valley where permafrost temperature is close to 0°C, there is no significant trend, likely due to the absorption of latent heat required for a phase change. In the northern Mackenzie Region, in colder (-7°C), thicker permafrost, observations of permafrost temperature at a depth of 28 m show an increase of about 0.1°C/year in the 1990s.

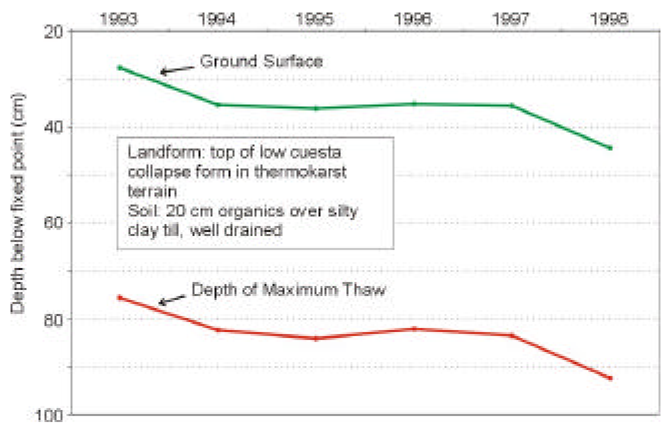

Figure 5. Maximum summer thaw depth (measured from a fixed reference) for a site on the Tuktoyaktuk Peninsula (After Smith et al. 2001).

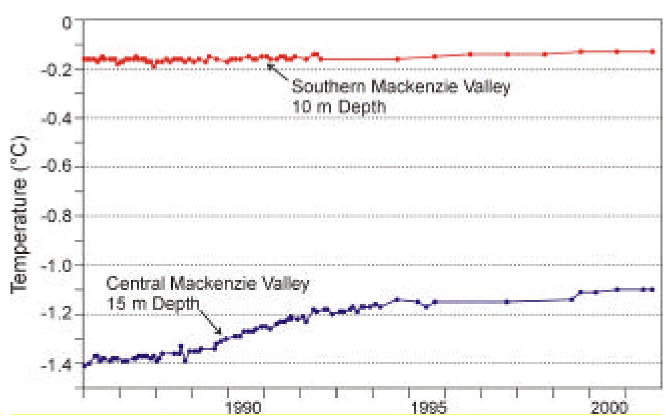

Figure 6. Ground temperatures at 15 m depth in the central Mackenzie valley near Norman Wells and at 10 m depth in the southern valley near Fort Simpson. Note: manual measurements were made more frequently at the beginning of the monitoring period

4. HAZARDS AND ADAPTATION ASSOCIATED WITH THAWING OF SOILS

4.1 Transportation

Warming and thaw of permafrost can result in a reduction of soil strength, ground instability and thaw settlement, all of which can have significant implications for engineering structures, including those in the transportation sector. Transportation infrastructure responds rapidly to climate change, and the subsequent impacts effect the economic activities of the region equally rapidly. Some of these impacts have been observed already during the past several years.

Climate change would lead to an increase in the number of freeze-thaw cycles and an increase of frost heave during the winter, which will result in the requirements for more treatments of the road surface to ensure safety (Table 3). Saturated road embankments may lose structural strength, causing rutting and producing potholes when heavily loaded. In the continuous permafrost zone, occurrence of icings on road surfaces may increase with climate warming, active layers become thicker and subsurface water flows increase.

The rapid degradation of permafrost at the ground surface and the highly variable length and timing of winter road operations are the most important challenges that the transportation sector will face due to climate warming. For example, in 1998, the thawing of the active layer occurred earlier in the Mackenzie Region, as much as 3 weeks earlier at some sites as it was in other years during the 1990s (Smith et al. 2001a). In order to meet that challenge, construction and maintenance costs will have to increase and construction techniques must evolve. For example, stabilization of a section of the airport runway at Yellowknife has required a newly designed foundation system (GNWT, 2002). Adaptation to changing or variable conditions at ice crossings and ferry routes can be, and is already being accomplished by conversion to permanent bridge structures (Bergman, 2002), or conversion of sections of winter roads to all-weather roads. These adaptations require significant, technical and financial commitments.

The transportation network is vital for northern communities and for the social, economical and industrial development in the north. Therefore, climate-change impacts on the transportation sector must be minimized with innovative adaptation strategies. Although most transportation still will be by conventional surface vehicles, suggested adaptation measures or alternatives include, for example, hovercraft technology, preferred resupply route by ship to deep sea harbour and airships (The Transport Institute 2002).

Longer shipping seasons could bring new economic opportunities. However, changes in water levels in rivers may provide constraints to shipping. Because fossil fuel is a large component of the total transported load (e.g. 44% of NWT inbound freight: J. Philips In C-CIARN North 2003), the use of alternative energy sources would also be a potential method for mitigating the impacts of climate change warming on the transportation sector. In general replacement of imported commodities by those which are locally-produced would have the same effect by limiting the transportation volume.

4.2 Municipal

Ground subsidence due to melting of ground ice can cause severe damage to structures, especially if differential settlement occurs. Communities like Tuktoyaktuk, which are established on ice-rich permafrost, may experience severe problems of ground stability due to thermokarst and subsidence caused by climate warming (Figure 5). The thawing of significant concentrated volumes of ice with small surface expressions could lead to the development of major linear depressions. Runoff entering these trenches has the potential to exacerbate the thaw subsidence.

Many communities in the Arctic are situated within a few metres elevation of the sea and, therefore, are vulnerable to rising sea level. However, Arctic communities that are underlain by permafrost (and associated excess ice) potentially are more susceptible to damage as thaw consolidation on the beach and in the nearshore can create accommodation space for eroded sediments and thus increase already high rates of erosion (Solomon et al. 1993; Wolfe et al. 1998; Dallimore et al. 1996). Changes in ice thickness and water temperature affect the annual bottom temperature in the nearshore zone, as well as the active-layer thickness there, in much the same way that changing air temperatures affect the active layer on land. The Hamlet of Tuktoyaktuk, which is underlain by massive ice lenses along the coast, has an ongoing problem of coastal erosion (Figure 7). Potential adaptive measures include a significant investment in engineered coastal defenses against erosion, phased retreat of the community from vulnerable locations, and the development of

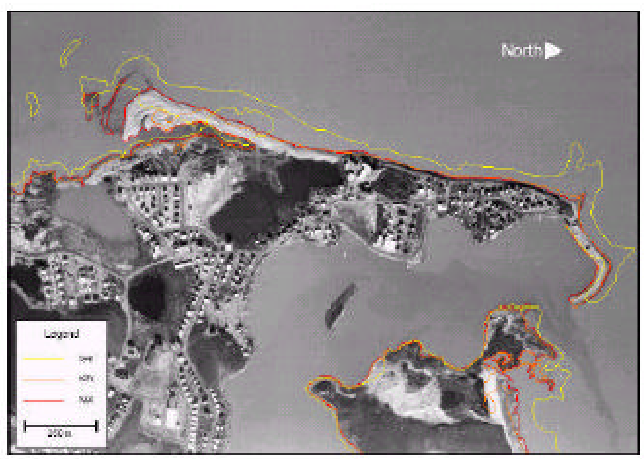

Figure 7. Shoreline positions in 1947 (yellow line), 1974 (amber line), and 1993 (red line) along the west coast of the small peninsula making up part of the Hamlet of Tuktoyaktuk.

innovative techniques for stabilizing ice-rich permafrost in the nearshore. Accelerated thawing of near-surface ground ice at the coast can result in retrogressive thaw failures which are maintained by wave erosion at the toe of the slump. These slumps can threaten coastal infrastructure even when the latter is constructed at some distance from the water's edge.

Buildings, especially those with shallow foundations, can experience severe problems due to loss of bearing strength and thaw settlement associated with thawing of ground ice owing to climate warming. In Tuktoyaktuk, buildings with shallow foundations sitting on ice-rich permafrost represent about 43% of the total number of structures (Couture et al. 2002). In Norman Wells, buildings with shallow foundations account for about 48% of the structures (Robinson et al. 2001). The impact of ground warming and thawing on buildings constructed on deep foundations will likely be significantly less, especially where structures are anchored to bedrock. However, for wooden piles (4.1% of all structures in Norman Wells and 46% in Tuktoyaktuk), once the base of the active layer progresses below the level of the treated portion, piles can rot if drainage is impeded. Also, frost-heaving forces on piles could increase owing to the deeper active layer as the result of permafrost warming.

Linear installations such as utilidors (Figure 2: middle) and water and sewer mains (buried or above-ground) are particularly sensitive to differential settlement because they may cross variable terrain conditions. For example, in Norman Wells, the utilidor and the gas line experienced major problems in the past due to differential settlement (Robinson 2001). Also, changes in water levels and drainage of water bodies in response to permafrost thaw could impact detrimentally upon community water supplies.

One possible method to prevent impacts from permafrost instability or from melting is to replace frost- or thaw-susceptible material in the active layer with permeable, coarser-grained material or insulation. Also, site selection (to avoid thaw sensitive material) based on more detailed characterization of permafrost sensitivity could become more common in land development. This leads to the need for geotechnical databases that include both geological/geotechnical and infrastructure data compiled in a format useful and accessible for end-users and decision-makers. Such databases were compiled for two communities (Norman Wells and Tuktoyaktuk) of the Northwest Territories (Robinson et al. 2001; Couture et al. 2002; Chartrand et al. 2002). The use of special, more expensive foundation systems such as duct-ventilated gravel pads (Figure 2), thermosyphons (passive heat exchangers working in winter to extract heat from the ground, Figure 8) or screw jacks facilitating levelling, is likely to increase.

Figure 8. Thermosyphons used to cool the ground and prevent thaw subsidence of a building foundation, Northwest Territories. (Photo by R. Couture, 2000)

4.3 Resources

Certain types of infrastructure associated with development and exploitation of resources often spans large areas (Figure 2) with varied terrain and permafrost conditions, making them vulnerable to direct, and indirect impacts of permafrost degradation due to climate change. Because of their nature and purpose, some structures often cannot tolerate any differential movements. For example, differential settlement of a dam or dyke could produce unacceptable or uncontrolled seepages that threaten the stability of the structure, possibly causing catastrophic failure. These seepages could threaten the surrounding environment by flooding and erosion, or by the release of hazardous materials (*e.g.* tailings ponds or sewage lagoons). Construction techniques have been developed to maintain the high strength and impermeable nature of frozen ground in earthfill dams, but the use of thermosyphons, such as in the design of dams at the Ekati diamond mine in the Northwest Territories (Figure 8), might be necessary to reduce the impacts of climate warming.

Resource infrastructure, such as pipeline, can be damaged by slope instability which result in flows and slides. These events can be triggered by the warming of ice-rich soils, and the subsequent melting of ground ice. Disturbance to the vegetation cover, such as wildfire (more frequent during abnormally dry summers, like in 1995), or clearing for construction can also trigger instabilities (Figure 9). Also, temporary damming of rivers following slope failures could

Figure 9. Numerous active-layer detachments along the east bank of the Mackenzie River south of Norman Wells, Northwest Territories, following forest fires in June 1995 (Photo by R. Couture, 1998).

have an effect on river transportation and related activities.

The increase in differential settlement may imply problematic consequences for linear infrastructure such as pipelines. Studies along the Norman Wells pipeline indicate that increases in thaw depth following right-of-way clearing was on the order of 3.5 m in ice-rich lacustrine soils (near Norman Wells) over a period of 17 years, and this is associated with up to 0.7 m of settlement (Burgess & Smith in press).

Climate-warming impacts on ground surface, watercourses, or ditches could lead to changes in drainage patterns and levels of water bodies, thereby impacting on water supplies (communities or industrial plants). The presence of more running water also means potential problems to under-designed culverts, thus impacting on infrastructure safety.

5. CONCLUSION

Climate warming will affect many aspects of the existing infrastructure, with the severity of the impact dependent upon soil type, permafrost conditions (temperature and ground ice content), type of foundation, design life of the infrastructure, changes in ambient temperature and capacity to adapt, and the availability of mitigative measures and their associated cost.

A thorough evaluation of available thermal and geotechnical information on permafrost, such as those done at Norman Wells and Tuktoyaktuk, is needed to determine where problems related to permafrost degradation may occur and affect existing infrastructure. This will assist the specialist to identify the appropriate measures required to preserve the integrity of the infrastructure. Determination of sensitive areas to climate change requires these evaluations in order to minimize impacts of climate change and to be integrated in the designs of new structures. New construction and design techniques will have to be adapted to reflect the increased instability of the permafrost regime on which northern infrastructure depends.

Table 3. Impacts of permafrost thaw upon infrastructure (after Couture et al. 2001).

Infrastructure	Impacts or Issues of Concerns
Building foundations	• Loss of bearing strength, significant settlement, induced creep • Increase in the thickness of the active layer, reduce the total adfreeze strength of piles • Frost-heaving force on the pile
Housing and small infrastructure	• Loss of bearing strength and significant settlement, especially with shallow foundation
Roads and highways	• Higher maintenance due to increased frost heave and thaw settlement (similar to airfields) • Time operational window of winter and ice roads reduced; increased road icings
Airfields	• Enhanced seasonal frost effects, thaw settlement for paved and plowed airfield surfaces
Linear infrastructure	• Increase of vertical displacement generating higher maintenance (differential settlement) • Increase in frequency of active layer detachment and increase in slope unstability
Slopes	• Increase of frequency of active-layer detachment slides; and rotational failure due to the increase of active-layer thickness and the decrease in permafrost thickness; • Increase in thaw settlement; loss of strength, creep of frozen ground, especially in discontinuous permafrost
Special infrastructure	• Increase of surface temperature of slopes associated with embankments, dykes and dams • Open pit wall instability, dam failure, release of contaminants, seepage under/through dams
Others	• Coastal erosion due to increased storm frequency and water-level, combined with increase of active layer • Change in drainage patterns could enhance thaw settlement or frost heave

6. REFERENCES

Bergman K. (2002). Roads at risk: assessing potential impact on winter roads. *Weathering Change*, Northern Climate Exchange, Fall 2002: page 7.

Burgess M.M. and Smith S.L. (in press). 17 Years of thaw penetration and surface settlement observations in permafrost terrain along the Norman Wells pipeline, Northwest Territories, Canada. Proceedings of the 8th International Permafrost Conference, July 2003, Zurich (Switzerland).

Burgess M.M., Desrochers, D.T., and Saunders R. 2000a. Potential changes in thaw depth and thaw settlement for three locations in the Mackenzie Valley. In *The Physical*

Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (eds.) L.D. Dyke and G.R. Brooks, Geological Survey of Canada Bulletin 547: 187-195.

C-CIARN North (2003). *First Online Workshop – Climate Change and Infrastructure*, January 8-9, 2003, Canadian Polar Information Network.

Chartrand J., Lysyshyn K., Couture R., Robinson S.D., and Burgess M.M. 2002. *Digital Geotechnical Borehole Databases and Viewers for Norman Wells and Tuktoyaktuk, Northwest Territories*. Geological Survey of Canada, Open File Report 3912. CD-ROM.

Couture R., Robinson S.D., and Burgess M.M. 2001. Climate change, permafrost degradation and impacts on infrastructure: two cases studies in the Mackenzie Valley. *Proceedings of the 54th Canadian Geotechnical Conference*, Calgary (AB), Vol. 2: 908-915.

Couture R., Robinson S.D., Burgess M., Solomon S. 2002. *Climate Change, Permafrost and Community Infrastructure: A Compilation of Background Material from a Pilot Study of Tuktoyaktuk, Northwest Territories*. Geological Survey of Canada, Open File #3867: 83 pages.

Dallimore S.R., Wolfe S.A., and Solomon S.M. 1996. Influence of ground ice and permafrost on coastal evolution, Richards Island, Beaufort Sea coast, NWT. *Canadian Journal of Earth Sciences*, 33: 664-675.

Environment Canada 1995. *The State of Canada's Climate: Monitoring Variability and Change*. Environment Canada's State of the Environment Report, No. 95-1.

Government of Northwest Territories 2002. The Effects of Warmer Winters in the NWT: An Indication of Future Trends? *Weathering Change*, Northern Climate Exchange, Fall 2002: pages 1-3.

Heginbottom J.A., Dubreuil M.A., and Harker P.A. (comp.) 1995. *Canada-Permafrost*. National Atlas of Canada (5th Ed.), Plate 2.1, Geomatics Canada, National Atlas Information Service, and Geological Survey of Canada, MRC 4177, scale 1:7 500 000.

International Permafrost Association 1998. *Multi-language Glossary of Permafrost and Related Ground Ice Terms*, version 2.0; (ed.) R.O. vanEverdingen, University of Calgary, Alberta: 278 p.

Johnson K. 2001. Northern experience in wastewater recycling casts Canada in leading role. *Newsletter of the Association of Professional Engineers, Geologists and Geophysicists of Alberta*, Vol. 29, No. 9, Octobre 2001.

Mackay J.R. 1972. The world of underground ice. *Ann. of the Assoc. of Amer. Geog.*, 62: 1-22.

Maxwell B. 1997. *Responding to Global Climate Change in Canada's Arctic: Volume II of the Canada Country Study: Climate Impacts and Adaptation*. Environmental Adaptation Research Group, Atmospheric Environment Service, Environment Canada, Vol. 5: 119-126.

Nelson F.E., Anisimov O.A., and Shiklomanov N.I. 2002. Climate change and hazard zonation in the Circum-Artic permafrost regions. *Natural Hazards*, 26: 203-225.

Robinson S.D., Couture R., and Burgess M.M. 2001. *Climate Change, Permafrost, and Community Infrastructure: a Compilation of Background Material from a Pilot Study of Norman Wells, Northwest Territories.* Open File Report D3913: 1 CD-ROM.

Romanovsky V., Burgess M., Smith S., Yoshikawa K., and Brown J. 2002. *Permafrost Temperature Records: Indicators of Climate Change*. EOS, Transactions of American Geophysical Union, 83 (50): 589.

Smith S.L. and Burgess M.M. (in press). *Sensitivity of Permafrost in Canada to Warming*. Geological Survey of Canada Bulletin, in press.

Smith S.L., Burgess M.M. and Nixon F.M. 2001a. Response of Active-Layer and Permafrost Temperatures to Warming During 1998 in the Mackenzie Delta, Northwest Territories and at Canadian Forces Station Alert and Baker Lake, Nunavut. Geological Survey of Canada, *Current Research 2001-E5*: 8 pages (Online; http://www.nrcan.gc.ca/ gsc/bookstore).

Smith S.L., Burgess M.M., and Heginbottom J.A. 2001b. *Permafrost in Canada, A Challenge to Northern Development*. In A Synthesis of Geological Hazards in Canada, G.R. Brooks (ed.), Geological Survey of Canada Bulletin 548: 241-264.

Solomon S.M., Forbes D.L., and Kierstead B. 1993. *Coastal Impacts of Climate Change: Beaufort Sea Erosion Study*. Geological Survey of Canada, Open File Report 2890.

The Transport Institute 2002. *Airships to the Arctic*. Symposium organized by University of Manitoba, Winnipeg, October 22-24, 2002, (Online; http://www.umanitoba.ca./transport_institute/airship/airship.html).

Wolfe S.A., Dallimore S.R., and Solomon S.M. 1998. Coastal permafrost investigations along a rapidly eroding shoreline, Tuktoyaktuk, N.W.T. In: *Proceedings of the Seventh International Conference on Permafrost, Yellowknife*, Canada, Collection Nordicana, Lewkowicz & Allard (Eds.), Université Laval: 1043-1048

Wolfe S.A., Kotler E., and Nixon M. 2000. Recent Warming Impacts in the Mackenzie Delta, Northwest Territories, and northern Yukon Territory Coastal Areas. Geological Survey of Canada, *Current Research 2000-B1*: 9 pages.