Chapter 6. Permafrost and climate change in Nunavik and Nunatsiavut: Importance for municipal and transportation infrastructures

Lead authors
Michel Allard, Mickaël Lemay, Carl Barrette, Emmanuel L’Hérault, Denis Sarrazin
Centre d’études nordiques (CEN), ArcticNet, Université Laval, Québec, QC

Contributing authors
T. Bell, and G. Doré

Abstract
Permafrost degradation is seriously affecting the natural environment. The landscape is changing through thermokarst that takes place mostly in the discontinuous permafrost zone and through thicker active layer depth and more frequent slope processes in the continuous zone. Northern residents are affected as vegetation, water bodies and soil drainage are greatly modified, which has an impact on resources traditionally available for humans. The modern built environment is also affected. Transportation infrastructure is being studied and adaptive solutions are sought, applied and tested. To protect and optimize the major investments required for extensive housing and construction, the urban planning of communities calls upon better permafrost maps and prediction of permafrost behavior. Final permafrost degradation around 0°C appears to be primarily under the influence of unfrozen water content and heat brought to the thawing interface by groundwater. This process is also effective in accelerating localized thawing under man-made infrastructures. Collection and organization of permafrost information in geographic information systems (GIS) allows for the integration of essential knowledge and provides a very useful tool for establishing situation diagnostics, sharing information with stakeholders and communities, and supporting multidisciplinary decision making for land use planning. The principal adaptive measures lie in adapting foundation types to mapped permafrost conditions to ensure a prolonged service life of buildings.
6.1 Introduction

Permafrost, soil or rock that has remained at temperatures below 0°C for long periods of time, is the key factor that makes Arctic lands particularly sensitive to climate changes (ACIA 2005). This is in large part because the ice-bearing frozen ground is the physical support for terrestrial ecosystems. Under the influence of larger heat transfer in the ground from the warming atmosphere, permafrost thaws and may become unstable: the terrain often settles, soil drainage conditions are altered (either becoming dryer when water percolates deeper in coarse soils or wetter when the fine-grained ice-rich substrate remains impervious), various slope processes are triggered (such as active layer slides), hollows and ponds are created, and so on. Inevitably, the ecosystem structure changes; and its functioning also changes as increased ground and surface temperatures drive environmental biochemical processes at higher energy levels. Similarly, frozen ground used to provide a solid base for supporting man-made infrastructures. But permafrost thawing now threatens the integrity of municipal, transportation and industrial infrastructures. Engineering methods designed to either preserve permafrost or to adapt infrastructures to loss of frozen ground support have to be applied with increased care and meticulous planning. Understanding the impact of climate change on the natural environment and dealing with maintenance and development of infrastructures call for a better appraisal of permafrost conditions over the territory.

In the Canadian Eastern Subarctic region, recent applied research has already provided some important knowledge regarding the direct impacts of permafrost degradation associated with the accelerated warming recorded in the last decades (Allard et al. 2007, 2009, ACIA 2005, Calmels et al. 2008, Smith et al., 2010). Climate model projections indicate that this trend will continue to prevail, or even accelerate over the coming decades (Sushama et al. 2007, IPCC 2007; see chapter 2). Climate change comes at a time when intense industrial development - particularly linked to mining - and fast growing Inuit populations call for new facilities such as roads, airstrips and railways, hundreds of new housing units in communities along with related service buildings and urban expansion. Huge investments are being made by both governments and the private sector for long-lasting infrastructures. Particularly, the pace of community expansion highlights the need for the establishment of sustainable community development plans to ensure healthy communities.

Urban planning in northern communities needs to reflect the importance and influence that the extreme climate and the highly sensitive nature of the landscape have on development (Forbes et al. 2007, Irvine et al. 2009, Ford et al. 2010). From a sustainable development perspective, it is critical that northern communities adopt specific adaptation techniques and strategies to deal with warming permafrost in order to preserve or expand their current residential, commercial, municipal, and transportation infrastructures. This chapter summarizes recently updated knowledge on permafrost properties and thermal conditions over the territories of Nunavik and Nunatsiavut. It provides a short review of research done in collaboration with governments and local communities to map and characterize permafrost conditions and to forecast expected impacts of climate change in support of regional and community land planning. An example of engineering solutions currently being applied in an adaptation strategy is also illustrated.

6.2 Permafrost: scientific background

Permafrost is a phenomenon directly related to climate. It is soil (or rock) that remains at or below the normal freezing point of water (<0°C) for two or more consecutive years (Harris 1988, Davis 2001, French 2007). Its presence depends mainly on the mean annual temperature at the soil surface, which has to be equal or less than 0°C (with rare exceptions). Permafrost covers 23% to 25% of the northern hemisphere (Zhang et al. 2008) and much of it is thousands of years old (Davis 2001).
As in other cold regions, the geographic distribution of permafrost over the Québec-Labrador peninsula is associated with basic factors that define regional and local surface climate conditions (Figure 1): air temperature, precipitation, topography, types of vegetation cover, soil organic layers and, particularly, snow cover thickness and duration. The zone of sporadic permafrost in Nunavik and Nunatsiavut extends roughly between latitudes 51°N and 56°N where permafrost is mainly confined in peatlands because of the thermal offset effect related to peat’s thermal properties (i.e. peat cools easily when frozen in winter and is a good insulator that prevents warming in

![Figure 1: Permafrost distribution in Québec-Labrador peninsula.](image-url)
Chapter 6: PERMAFROST AND INFRASTRUCTURES

Chapter 6

174

summer) (Brown 1970; Burn 1988). Hilltops devoid of snow cover due to blowing winds are also sites likely to be underlain by permafrost in the discontinuous zone. The zone of discontinuous permafrost is broadly contained between latitudes 56° and 58°N while the zone of continuous permafrost extends northward of latitude 58°N where annual temperatures prevailing since deglaciation allowed permafrost to reach depths over 150 meters (e.g. Tasiujaq) and even as deep as 590 m at the Raglan mine (Allard and Seguin 1987, Chouinard et al. 2007).

In permafrost regions, the ground is characterised by two main layers: the active layer that thaws every summer and the underlying permafrost that remains below 0°C year round (French 2007, Williams and Smith 1989). Both the active layer and the permafrost are affected by seasonal temperature variations (Figure 2), but only the active layer undergoes seasonal thawing (Washburn 1979, Williams and Smith 1989). It is also recognized that the stratigraphic unconformity between the active layer and the permafrost (termed the permafrost table) shifts upwards or downwards over periods of several years following climate variations. One exceptionally warm summer may lead to a thicker active layer. Consequently, the amount of ice near the permafrost table can vary within only a short period encompassing only a few years (Shur and Jorgenson, 2007). Deeper in the permafrost, the maximum depth affected by the annual temperature variations is called the depth of zero annual amplitude (Figure 2); it varies with air temperature and the type of soil (Pissart 1987, French 2007). In Nunavik it is about 22 m deep in bedrock, somewhat less in sands, and 5-6 m deep in clays (Lévesque et al. 1990).

6.3 Impacts of climate warming on permafrost

A warmer climate results over time in a warmer vertical temperature profile in the permafrost and a greater depth of summer thaw, i.e. a thicker active layer. Both an increase in mean annual air temperature and a thicker snow cover result in more heat absorption in the ground. In Alaska, an increase of 0.3°C to 4°C was observed in soil temperatures since 1980 depending on the environmental conditions (Osterkamp 2005). The increase of active layer thickness was observed and monitored in many sites in Subarctic Sweden (Åkerman and Johansson 2008), in Nunavut (Smith et al. 2010, 2005), in Alaska (Osterkamp and Romanovsky 1999, Osterkamp 2003) as well as in the Canadian Eastern Subarctic (Smith et al. 2010). In the Canadian Eastern Subarctic, this warming in fact began in 1993 and a general rise of 2°C in ground temperatures took place until about 2005 (Allard et al. 2007). Temperatures are now warmer than in the past. In eight Nunavik communities spread over the territory, permafrost monitoring data in different surficial materials showed significant changes in active layer thickness and soil temperature, here reported at the 4 m and the 20 m depths since the mid 1990s (Table 1).

When the active layer thickness increases over the years because of climate warming, the thaw of the underlying
permafrost provokes terrain subsidence as the expulsion of ground ice melt water from the thawed soil leads to some soil compaction. This process is called thaw settlement. On sloping terrain, landslides may be triggered due to the release of melt water at the thawing front, which increases pore water pressure at the thawed/frozen interface. Thawing of the permafrost in the natural environment leads to the formation of hollows and ponds, which are end results of a process called thermokarst. As thickness of the active layer increases and thermokarst occurs, the terrain is disturbed and the ecosystems it supports are totally modified. Similarly, in built environments, under buildings and infrastructures such as roads and runways, the thawing of permafrost results in an important loss of bearing capacity because the frozen icy ground that used to be as hard as concrete turns into soft ground or even into mud. As a result of climate warming, an intensification in permafrost degradation is observed at the circumpolar scale and human infrastructures are more at risk than before (Allard 1996, Nelson et al. 2002, Fortier et al. 2007, L’Hérault 2009, Smith et Riseborough 2010).

For instance, destructive slope processes such as active layer detachment failures (a shallow type of landslide; see Lewkowicz and Harris 2005a and b) are more frequently observed. In Salluit (Nunavik), active layer detachments that occurred in 1998 and 2005 have been directly associated with a yearly increase of the active layer thickness more than 9% over the previous summer, which was favoured by an increase in the number of thawing degree-days (i.e. warmer summers) (Figure 3; L’Hérault 2009).

Table 1. *Ground temperature and active layer depth variations at different sites in Nunavik. Derived from Smith et al. 2010.*

<table>
<thead>
<tr>
<th>Site (cable no)</th>
<th>Material</th>
<th>AL 93 (cm)</th>
<th>AL 07 (cm)</th>
<th>Δ AL (cm)</th>
<th>Δ T°C 4M</th>
<th>Δ T°C 20M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salluit (Sal-154)</td>
<td>Gneiss</td>
<td>279</td>
<td>374</td>
<td>95</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Salluit (Sal-155)</td>
<td>Till</td>
<td>168</td>
<td>295</td>
<td>182</td>
<td>2.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Akulivik (Aku-162)</td>
<td>Till</td>
<td>138</td>
<td>222</td>
<td>84</td>
<td>1.7</td>
<td>-</td>
</tr>
<tr>
<td>Akulivik (Aku-232)</td>
<td>Sand / clay</td>
<td>135</td>
<td>143</td>
<td>8</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Quahtaqt (Quaq-156)</td>
<td>Sand / gravel</td>
<td>151</td>
<td>170</td>
<td>19</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Quahtaqt (Quaq-158)</td>
<td>Gneiss</td>
<td>416</td>
<td>519(^1)</td>
<td>103</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Puvurituq (Puv-303)</td>
<td>Gneiss</td>
<td>339</td>
<td>469(^2)</td>
<td>130</td>
<td>3.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Aupaluk (Aupa-299)</td>
<td>Sand / gravel</td>
<td>155</td>
<td>210</td>
<td>55</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Tasiujaq (Tas-304)</td>
<td>Sand</td>
<td>113</td>
<td>207</td>
<td>94</td>
<td>1.7</td>
<td>-</td>
</tr>
<tr>
<td>Tasiujaq (Tas-roc)</td>
<td>Schist</td>
<td>509</td>
<td>552</td>
<td>43</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Kangiqsualujiuaq (Kan-231)</td>
<td>Gneiss</td>
<td>607(^3)</td>
<td>1100</td>
<td>493</td>
<td>3.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Kangiqsualujiuaq (Coastal mound)</td>
<td>Clay</td>
<td>252(^4)</td>
<td>332(^5)</td>
<td>80</td>
<td>1.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Umiujaq (Um-roc)</td>
<td>Basalt</td>
<td>1008(^6)</td>
<td>1556(^7)</td>
<td>548</td>
<td>1.5</td>
<td>1.2(^*)</td>
</tr>
</tbody>
</table>

\(^1\)1995, \(^2\)2005, \(^3\)2004, \(^4\)1994, \(^5\)2007, \(^6\)1997, \(^7\)permafrost now at -0.01°C
Figure 3. This active layer detachment failure in the village of Salluit occurred in 2005.

Figure 4. Palsa field and thermokarst lakes in the region of Umiujaq, Nunavik.
In Subarctic Québec, the number and areal coverage of thermokarst ponds have increased rapidly over the past 50 years (Marchildon 2007, Vallée and Payette 2007, Thibault and Payette 2009). Results of Vallée and Payette (2007) showed an increase of 76% of the thermokarst areas and a decrease of 23% of the permafrost mounds at a studied site along the Boniface River. Marchildon (2007) also observed the degradation of 43% of the permafrost cover and an increase of 65% of the thermokarst areas since 1957 near the Nastapoka and Sheldrake rivers, a region dominated by palsas, lithalsas and permafrost plateaus in discontinuous permafrost (Box 1). This trend was also observed in a monitored palsa field close to Umiujaq (Nunavik) (Figure 4) (Calmels et al. 2008).

Finally, permafrost thawing amplifies the rate of occurrence of geomorphological processes that were up to the present only slightly active in the frozen environment (McKenzie et al. 2007). For instance, creeks and stream watersheds that were poorly developed on impervious permafrost terrain are now structuring themselves and expanding to allow surface water to flow through unfrozen

---

**Box 1. Drastic increase in thermokarst lakes is observed in the Eastern Subarctic region**

A thermokarst lake forms when the thawing of ice-rich fine-grained permafrost results in subsidence, creating a depression filled with water. When ponding is first initiated in a depression, more heat is stored in the water; this increases the thawing rate of the permafrost beneath and around the pond, inducing more subsidence. This process feedback accelerates the degradation of the permafrost once it has started (Larouche, 2010). Thousands of such small lakes occur in lowland regions, especially where palsas and lithalsas dominate the landscape. In Nunavik, a major zone of active thermokarst extends east of Hudson Bay, in fine-grained ice-rich soils, between 55° and 58°N. Thermokarst lakes can also be found in other types of soils where the soil contains excess ice.

Periods of past decreases in permafrost areas and increases in active layer depth were also interpreted from stratigraphic reconstructions and radiocarbon dating over the last thousand years in relation to Late Holocene climate changes. However, thermokarst since the end of the Little Ice Age (around 1880 AD), appears to have occurred on an unprecedented scale, with a still faster permafrost degradation rate in recent years (Allard and Seguin 1987, Kasper and Allard 2001).
terrain; ponds are becoming interconnected and soil permeability generally increases (McNamara et al. 1999). In both cases, this new liquid water in the environment induces additional heat in the remaining permafrost underneath lake beds and around the lakes, which contributes to further intensify permafrost thawing and subsidence and modify the landscape (Mackay 1974, Larouche 2010).

### 6.4 Impacts of permafrost degradation on infrastructures

Permafrost thawing threatens the integrity of residential, municipal and transportation infrastructures. Infrastructures are affected in two ways: 1- through thaw settlement and, 2- through terrain destabilization by landslides and thermal erosion. Infrastructures settle and lose their compaction when the permafrost starts thawing underneath. This affects buildings which then settle unevenly with resulting damage such as cracks in walls and warped floors. In large constructions on slabs, such as garages, the floor usually collapses in the central portion of the building and the overall structure deforms inwards. Often, costly corrective measures are necessary. So far, most observed cases of infrastructure settlement can be explained by factors that are not due to climate warming but rather to poor original foundation designs related to a lack of knowledge of local permafrost conditions, particularly the ground ice content. When runways were first built (from 1984 to 1992 in Nunavik), the permafrost table moved upward into the embankment or into the former active layer beneath. Currently, with climate warming the active layer below these embankments still remains in the former ice-poor, but frozen, active layer. Settlement is therefore minimal or negligible; however it will increase and become more damaging in the future as thaw depth reaches deeper into the permafrost in response to the expected continued climate warming.

Two major site factors were observed to generate heat in the ground that leads to permafrost thawing: snow bank accumulation and water ponding along the foot of embankments. The snow banks that accumulate by wind drifting against the flanks of embankments insulate the ground surface and therefore prevent the soil from cooling back to colder temperatures in winter. During the following summers, thaw then progresses deeper and increases the thickness of the active layer, thus provoking ground settlement and leading to collapse of roads and runways. The local snow cover accumulated against an embankment side may even be thick enough to totally prevent the active layer from freezing again. For instance, measurements made with micro-dataloggers in Salluit revealed that a maximum snow thickness (measured at the end of March) of about 1.1 m is enough to keep the ground surface above 0°C, therefore leading to localized permafrost degradation. Similar measurements in Tasiujaq, where the climate is warmer, yielded a threshold snow thickness of 0.8 m to keep the ground surface above 0°C and prevent active layer freeze-back. Drilling and temperature measurements in collapsed ground alongside runway embankments indicated that in 2008, after a period of 10-15 years, the soil was thawed to depths as much as 6-7 m (Allard et al. 2010). For an airstrip, the impact is felt for a distance of several meters inwards of the margins of the runway. For a narrow road, the thermal effect of snow banks on both sides is sufficient to affect the road over its whole width (Fortier et al. 2011).

The influence of seasonal snow accumulation along embankments on permafrost thawing is thereafter further enhanced by the ponding of water in the depressions. In summer this water retains heat from solar radiation which is further transferred into the ground. The increase in water content of the thawed soil under the embankment side thereafter delays freeze-back of the soil due to latent heat effect (the amount of heat that must be extracted to freeze water into ice). The warm bulb extends underneath the embankment and the collapsing spreads inwards in the infrastructure. A good example of this is the degradation observed along the Tasiujaq runway (Figure 5).

Water tracks are shallow depressions in the surface of sloping terrain without a definite creek and where water
Chapter 6
PERMAFROST AND INFRASTRUCTURES

179

flows in thin sheets over the tundra and seeps through the active layer (McNamara et al. 1999). This near surface groundwater flow carries heat by advection, which adds to the heat that warms up the ground in summer through conduction from the surface. When such water tracks flow across a road or a runway embankment, localized transversal depressions are formed by settlement. (de Grandpré et al. 2010).

Ultimately, snow accumulation, water ponding and advected heat from seepage water contribute to warming permafrost and generating thaw settlement, which damages infrastructures. A good example is provided by the multiple, repeated, settlement depressions that affect the road to the airport in Salluit (Figure 6).

At the present time, interventions to restore runways and roads and to extend their lifespan consist firstly, of reshaping side slopes at lower angles to make them more aerodynamic in order to prevent accumulation of snow banks by wind drifting and, secondly, of correcting surface drainage to divert it away from the infrastructures.

Figure 5. Tasiujaq airstrip with two transects showing clear difference in the snow accumulation profiles (A and C) for both sides of the runway. Snow accumulation is directly affected by the dominant winds coming from the Southwest. Letters represent other transects of snow accumulation profiles.
When necessary, culverts and ditches are redesigned. More proactive engineering solutions such as convective embankments, berms and heat drains can be applied in specific cases to prevent further permafrost degradation after restoration. The solutions adopted for the maintenance of the Puviirmituq runway provide an example of a comprehensive intervention designed to stop the impact of both advective heat transfer by water seepage under the runway and snow accumulation on the sides (see Box 2).

In the Eastern Canadian Subarctic Region, active layer failures are a type of landslide commonly observed that have impacts on urban areas (Lewkowicz and Harris 2005a and 2005b). Such landslides may occur in any year; however they have been shown to happen particularly at the end of warmer summers (from mid-August onwards) when the thaw depth is deeper than in the previous years, therefore melting ground ice at the active layer/permafrost transition, which frees water in an otherwise impervious

Figure 6. Access road to Salluit airport showing important deformations with a succession of thaw settlements.

Figure 7. This active layer detachment failure in Salluit occurred in 1998 and prompted the abandonment of the development project in this sector as well as the removal of 20 houses already built.
soil, thus creating excess pore pressures just over a perfect slipping plane, i.e. the icy permafrost. A landslide such as this took place on 5 September 1998 in Salluit (Figure 7) near a new urban construction sector, prompting the abandonment of the development project and the removal of 20 new houses (L’Hérault 2009). As for thermal erosion, it occurs when water happens to flow directly along the icy permafrost. Often this occurs at specific places such as at the outlet of culverts and in tracks made by vehicles and machinery in the tundra (Figure 8). Thermal erosion may also take place in the cavities formed by landslides if a creek happens to flow into them or along riverbanks during high flow stages.

Building on permafrost in the context of a changing climate requires looking for innovative solutions designed to prevent gradual deterioration of buildings and infrastructures. Planning for community expansion or for industrial facility construction over permafrost terrain with variable characteristics, ground ice contents and ground thermal regimes, while considering future climate, is a challenging multidisciplinary technical undertaking, which must be pursued for sustainable and economical development. Without planning supported by sufficient local knowledge of permafrost, the risks of expensive management and repair costs are getting higher and higher. Recent climate change and the socio-economic situation in the Eastern Subarctic has compelled governments and researchers to work together to identify major knowledge gaps, produce maps of permafrost conditions for land management, search for applicable engineering solutions and use predictive models of the permafrost thermal regime to set up adaptation strategies.

Figure 8. Thermal erosion process initiated by the passage of a heavy vehicle, Salluit.
6.4.1 Methodological approach for mapping and characterizing permafrost for urban and infrastructure management

Since 2002, an integrated, multi-technique and multidisciplinary, approach has been developed to map permafrost conditions and geotechnical properties for projects pertaining to airports, roads and villages. As the amount of ground ice and structure (e.g. ice lenses, massive ice bodies, network of ice-wedges, etc.) are closely associated with the type of geological surficial material (Table 2), the first methodological step consists of mapping the Quaternary geology using air photographs and high resolution satellite images. This mapped interpretation is then validated with field checks such as terrain observations, test pits and drill holes with recovery. Most shield bedrock types in Nunavik and Nunatsiavut are massive and contain a small amount of ice confined in their structural elements such as joints and bedding planes. The thickening of the active layer therefore has negligible impacts on the stability of rocky terrain (although exceptions exist). Clays contain abundant ice segregation lenses with volumetric ice contents sometimes close to 100%. Till, a mixture of boulders, sand, gravel and silt, is very abundant in Nunavik and Nunatsiavut and often contains large amount of ice making it subject to thaw settlement. In gravel and coarse sand, the ice content is, most of the time, very low. Nevertheless, saturated gravel can experience significant consolidation upon thawing. Geomorphological features on the surface are also indicators of ground ice content and structure. The ones most often observed are frost boils in fine grained, or fine-matrix, ice rich soils, tundra polygons over networks of ice-wedges, and gelifluxion sheets and soil stripes on ice rich sloping soils. Other characteristic indicators of ground ice content and terrain sensitivity are: landslide scars, wetland patterns, stream bank erosion scars and thermokarst features.

For some projects, e.g. eight airport sites, frozen cores of permafrost were extracted by a contractor who used a diamond drill-bit with refrigerated drilling mud. The drilling sites were selected in order to obtain representative samples of all the major surficial deposits and permafrost condition units encountered in the given study area. The ground ice volumetric content is measured by classification of tomdensitometric scans made on the frozen cores (Calmels and Allard 2004). Other laboratory treatments such as grain-size analyses, salt content, and Atterberg’s limits (i.e. plastic and liquid limits) are performed as well. Thaw consolidation tests are also performed on selected samples. Knowledge of the spatial extent of these deposits, their stratigraphy and regional ground ice conditions is further improved with the help of shallow geophysical surveys, particularly Ground Penetrating Radar (GPR) and electrical resistivity (e.g. Ohm-Mapper™). Finally, the information from all these sources is integrated and collated in a Geographic Information System (GIS) application. The information layers encompass the infrastructure, topography, drainage, surface geology, periglacial features and field surveys (i.e. test pits, drill holes, GPR and electrical resistivity).

The high precision maps and DEM are superposed over recently acquired high resolution satellite images (e.g. Quickbird, Ikonos or GeoEye) so that actual towns and infrastructures are visualized in their environmental context. All of this organized information is then used in multidisciplinary meetings (involving geomorphologists, engineers, geophysicists, land planners, administrators) with stakeholders (staff of responsible government agencies, community members and managers, staff of regional governments, consultants, etc.) to analyze situations, evaluate risks and make decisions for adaptations.

Projections of active layer changes and ground thermal regime are thereafter produced by numerical modeling in order to simulate the potential future impacts on permafrost and infrastructures. These simulations make use of Ouranos’s high spatial resolution CRCM outputs (see chapter 2, this volume). Existing thermistor cables from the SILA network, that have been operational in most communities for two decades (Table 1), are used to calibrate numerical thermal analysis and simulations (Barrette 2010). New cables are installed in drill holes either to fill gaps in the network or to obtain specific measure-
### Table 2. Morphologic features of permafrost, geological features and type of ground ice for surficial deposits.

<table>
<thead>
<tr>
<th>MORPHOLOGY AND CRYOSOLS</th>
<th>SURFICIAL GEOLOGY TYPES</th>
<th>TEXTURE</th>
<th>PERMAFROST ZONATION</th>
<th>GROUND ICE TYPES</th>
<th>POSSIBLE PRESENCE OF EXCESS ICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frost mounds</td>
<td>Silts and marine clays</td>
<td>Silty clays Fine to medium sands</td>
<td>Discontinuous and widespread Discontinuous and dispersed</td>
<td>Segregation</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Sands (low mounds)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palsas</td>
<td>Peat</td>
<td>Fabric or hemic peat over fine grained deposits</td>
<td>Discontinuous and widespread Discontinuous and dispersed</td>
<td>Segregation</td>
<td>Yes, in mineral sediments under peat</td>
</tr>
<tr>
<td></td>
<td>Peat/silts and clays</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peat/sand or till (rare)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermokarst lakes</td>
<td>All possible deposits; mostly fine grain and peaty sediments</td>
<td>Peat Silty-clay Sands</td>
<td>Discontinuous and widespread</td>
<td>Segregation</td>
<td>NA</td>
</tr>
<tr>
<td>(associated with palsa and frost mounds)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice-wedge polygons</td>
<td>Tills</td>
<td>Peat Fine to coarse sands</td>
<td>Continuous Ice wedge polygons with pore ice</td>
<td>Yes, in polygon networks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluvial terrace sands</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carex sands</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil wedge polygons</td>
<td>Tills (on drumlin ridges) Glacifluvial deposits (outwash and deltas), beach sands</td>
<td>Heterometric coarse sands and gravel deposits</td>
<td>Continuous Discontinuous and widespread</td>
<td>Pore ice</td>
<td>No</td>
</tr>
<tr>
<td>Low center mudboils</td>
<td>Tills, diamictons (uplifted tidal flat), often associated with soil wedge polygons and solifluction lobes.</td>
<td>Heterometric coarse sands and gravel deposits with very fine sands or silts</td>
<td>Continuous Discontinuous and widespread</td>
<td>Pore ice Small amounts of segregation ice</td>
<td>No</td>
</tr>
<tr>
<td>High center mudboils</td>
<td>Marine and lacustrine deposits. Abundant on top of cryogenic mounds</td>
<td>Fine sands and silty clays</td>
<td>Continuous, discontinuous and widespread Discontinuous and dispersed</td>
<td>Segregation</td>
<td>Yes</td>
</tr>
<tr>
<td>Striped soils</td>
<td>Tills Slope deposits</td>
<td>Blocky diamictons in fine matrix</td>
<td>Continuous Pore ice</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Solifluction lobes</td>
<td>Tills Marine sands Slope deposits</td>
<td>Heterometric deposits in fine sandy or silty matrix</td>
<td>All zones Pore ice, Small amounts of segregation ice</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Hummocks</td>
<td>Tills and diamictons over poorly drained low land</td>
<td>Heterometric deposits in fine sandy or silty matrix</td>
<td>Continuous Discontinuous and widespread Pore ice</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Seasonal frost mounds with ice-cores and icing</td>
<td>All deposit types</td>
<td>All grain size deposits and organic soils, near streams and spring run-offs</td>
<td>Continuous Discontinuous and widespread Intrusive (significant and fast up-lift in winter and subsidence in summer)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Ejection mounds or blocs</td>
<td>Rocks (fractionated)</td>
<td>Continuous Discontinuous and widespread Discontinuous and dispersed</td>
<td>Intrusive ice? Segregation ice?</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>
ments of particular situations (for instance the thermal regime under an embankment or under a restored site to monitor the recovery of the thermal regime).

6.4.2 Urban expansion and management

Historically, most of the communities of Nunavik and Nunatsiavut were located in environments that were originally selected by Inuit for access to surrounding food resources, drinking water, camping grounds, protected shorelines, etc. Organizations such as churches and the Hudson’s Bay Company joined them on these sites. Many town sites are in marine embayments or at river mouths where they provide a wind shelter and good access to the sea; their locations favour the traditional way of life organized around camping, hunting, fishing and gathering. The fast population growth and modernization of the late 20th Century was not entirely expected. Around the end of the 1960s, the development of a sedentary lifestyle emerged following the provision of health, social, education, administrative and economic services by governments. Community growth and socio-economic development led to the construction of new houses, schools, arenas, health centres, and municipal and service infrastructures. Communities have expanded their infrastructures over the years sometimes in less favourable geomorphological zones (e.g. on fluvial and marine ice rich sediments) or are now bounded by a restricting topography or by expanses of poorly drained terrain. Each community is located in a specific geomorphological and climatological setting, some being more favourable to adaptation to modern expansion than others.

Nowadays, the population growth of Inuit communities is amongst the highest in the world. In Nunavik, population growth rate ranges from 2.3% in Kuujjuarapik to 23.4% in Inukjuak, with a mean growth rate for the 14 communities of 10.46% between 2001 and 2006 (Table 3A). However, an opposite trend is observed in most communities in Nunatsiavut where the overall growth rate is negative (-6.0%), ranging from -15.1% in Rigolet to -5.2% in Hopedale between the years 2001 and 2006 (Table 3B).

Despite the recent negative demographic trend in Nunatsiavut, the need for houses remains significant due to the rapid deterioration of the existing housing stock and because of inadequate housing construction programs in past years. A project initiated in 2010 by the Environment

Table 3. Demographic context in Nunavik (A) and in Nunatsiavut (B) for 2001 and 2006.

<table>
<thead>
<tr>
<th>Table A</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipalities *</td>
<td>2001</td>
</tr>
<tr>
<td>Akulivik</td>
<td>507</td>
</tr>
<tr>
<td>Aupaluk</td>
<td>174</td>
</tr>
<tr>
<td>Inukjuak</td>
<td>1 597</td>
</tr>
<tr>
<td>Ivujivik</td>
<td>349</td>
</tr>
<tr>
<td>Kangiqsualujjuaq</td>
<td>735</td>
</tr>
<tr>
<td>Kangiqsujuaq</td>
<td>605</td>
</tr>
<tr>
<td>Kangirsuk</td>
<td>466</td>
</tr>
<tr>
<td>Kuujjuak</td>
<td>2 132</td>
</tr>
<tr>
<td>Kuujjuarapik</td>
<td>568</td>
</tr>
<tr>
<td>Puvirnituq</td>
<td>1 457</td>
</tr>
<tr>
<td>Quaqtaq</td>
<td>315</td>
</tr>
<tr>
<td>Salluit</td>
<td>1 241</td>
</tr>
<tr>
<td>Tasiujaq</td>
<td>248</td>
</tr>
<tr>
<td>Umiujaq</td>
<td>390</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10 784</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table B</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipalities +</td>
<td>2006</td>
</tr>
<tr>
<td>Nain</td>
<td>1 034</td>
</tr>
<tr>
<td>Cartwright</td>
<td>552</td>
</tr>
<tr>
<td>Happy Valley-Goose Bay</td>
<td>7 572</td>
</tr>
<tr>
<td>Makkovik</td>
<td>362</td>
</tr>
<tr>
<td>Rigolet</td>
<td>269</td>
</tr>
<tr>
<td>Postville</td>
<td>219</td>
</tr>
<tr>
<td>Hopedale (division 11)</td>
<td>530</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10 538</strong></td>
</tr>
</tbody>
</table>

*Statistics Canada 2006; *Institut de la statistique du Québec 2006
Division of the Nunatsiavut Government and the Nain Inuit Community Government - in partnership with Memorial University - has among its main goals to map the nature and distribution of permafrost, to assess the impacts of changes in permafrost conditions and active layer thickness on present and planned community infrastructures, and to investigate how modifications to building design and practice may improve overall integrity and sustainability of infrastructures under a changing climate and environment. The current practice of laying some buildings directly on the surface of the gravel and sand pads has created a series of structural issues, including cracking and shifting of walls and disruption of water and sewer services, which has led to condemned houses and commercial buildings, disruption of community services and increased costs for maintenance and heating (Figure 9). An important outcome of the current project is the development of a composite landscape hazard risk map for Nain, which will be integrated into community planning to help ensure human safety and security associated with existing and future development. A longer term goal is to inform decision making for more sustainable communities in Nunatsiavut, including construction practices, development strategies, and infrastructure design and energy efficiency.

In Nunavik, the rapid population growth has led to a severe housing crisis. Indeed, the Kativik Municipal Housing Bureau (KMHB) assesses that with the current population in Nunavik of over 12,000 residents (Statistics Canada, 2012) living in 2100 houses, there is a need for an additional 915 units. In a report published in 2007 by the Commission des droits de la personne et de la jeunesse, overcrowding of the houses was identified as one of the main factors responsible for the mistreatment of children and the loss in quality of life. Under its Plan Nord, the Québec Government has just launched a new major housing program to begin to address these concerns. Planning for expansion on permafrost terrain now becomes even more urgent to support the expansion of communities driven by this construction program and to protect major public investments. Due to the variability of permafrost conditions within each community and

Figure 9. Ground subsidence related to permafrost thaw causing structural damages and infrastructure maintenance issues in Nain, Nunatsiavut.
between communities as well as to the large variations in climate throughout the Eastern Subarctic region, the problems for management and expansion on permafrost are often specific from case to case. Some of them need only minor adaptation solutions while others are facing challenges requiring a significant involvement and capacity strengthening of the local managers and stakeholders. Each community is also a group of people sharing a common regional history and is largely autonomous in developing a vision for its future; therefore it has a major say in development planning. The choice of the appropriate construction techniques and foundation types directly depend on the local characteristics of the permafrost and the type of buildings the communities decide to request (e.g. single vs multiple dwellings, community buildings, schools, etc.).

Some construction techniques specially adapted to permafrost are currently applied in the North. For instance, adjustable posts on pads is a foundation design broadly used in northern villages. Ground temperatures measured underneath these types of foundations showed that they are efficient construction techniques in the face of permafrost warming (Allard et al. 2004). Correctly designed piles is another technique that has proven to be efficient for bigger buildings such as schools and hospitals, as well as thermosyphons which are mostly used for garages built on slab-on-grade foundations. Another known technique rarely applied in Nunavik and Nunatsiavut is duct-ventilated compacted fill foundations (i.e. pads ventilated by metal pipe-ducts) (Andersland and Ladanyi 2004). The costs largely vary from one building type to another and the best construction method used. Consequently, to minimize the potential impacts of thawing permafrost under existing and future infrastructures and to adopt affordable solutions and management strategies, a good knowledge of the permafrost conditions in the northern communities is required.

A research project conducted in 11 Nunavik communities (i.e. where permafrost is present) by CEN’s team (Centre d’études Nordiques, Allard et al. 2007) provided preliminary maps of spatial variability of permafrost conditions in the communities and their surroundings and allowed the general identification of favourable zones for expansion as well as of problematic zones where thaw settlement and other difficulties are to be expected. This project developed a general mapping approach based on the correlation between geomorphological features and surficial geology perceptible on aerial photographs and high resolution satellite images and the type of ground ice found (summarized in Table 2). These maps (Figure 10) now constitute a management tool available to help communities to orient their management strategies. However, since this mapping method was mainly based on observation and interpretation of geomorphologic features, and because ice contents can vary greatly locally within the same geomorphological unit (as showed by L’Hérault 2009), these maps only represent a starting point and a more advanced characterization program is now underway under the Regional Adaptation Collaboratives (RAC) program of Natural Resources Canada administered in Québec by Ouranos, in partnership with the Kativik Regional Government and four communities. This program also involves knowledge transfer and training of Northerners on practical permafrost issues by the Kativik Regional Government.

**Case Study: Salluit**

Among all Nunavik and Nunatsiavut communities, Salluit is the most documented case in terms of permafrost. It exemplifies the complexity of the expansion and management of communities on sensitive permafrost. Salluit currently accommodates approximately 1300 inhabitants and its population is expected to grow to 1700-2000 individuals by 2025 (Institut de la statistique du Québec). In 2008, the housing numbers were already showing a shortage of 131 units (Allard et al. 2009). However, Salluit must expand in a difficult and restrictive geomorphological context (Pluritec 1974). Most of the community is confined to a deep valley limited by steep cliffs (L’Hérault 2009). Flat expanses of land are limited and are usually underlain by sensitive ice-rich sediments such as saline
marine clays or tills. Rocky terrain with gentle slopes is also limited in extent. On ice-rich permafrost, even gentle slopes are unstable. Facing this complex situation, provincial authorities decided in 2007 to bring together permafrost and climate specialists, economists, engineers, architects and managers from various government levels in order to explore possibilities and develop the best management and expansion strategies with a concern for integrating the expected effects of climate warming on the stability of permafrost and the frequency of geomorphological hazards associated with ground instability.

This project generated substantial as well as useful knowledge on climate and permafrost within and around Saluit. Climate and ground thermal profiles monitored since 2002 allowed for an understanding of climate conditions triggering permafrost processes such as thaw settlement, active layer failures and thermal erosion. This information helped in orienting the development and validating modeled projections of permafrost behaviour according to different climate scenarios. This project also generated technical and engineering solutions to maintain and/or restore permafrost conditions suitable for construction. For instance, an experimental pad was designed and installed in a former degraded terrain in attempt to restore the permafrost. Monitoring shows that the permafrost is returning to its near-natural state and that it shall aggrade further beneath this experimental pad, therefore providing stability for many years to come.

Expansion needs required the creation of a detailed map of permafrost conditions. In total, over 100 boreholes were drilled between 2002 and 2008. Maps of the surficial geology and depth of the bedrock, and maps of permafrost conditions were produced (i.e. ground ice contents and cryostructure for a deposit of given grain size soils and expected behaviour upon thawing). Ice content varies greatly at the local scale, and consequently, it is necessary to produce maps as precise as possible that will be essential management tools when the time comes to invest in new developments. A major outcome of this project has been the development of risk management maps resulting from the integration of all the geographic information produced (Figure 11). These maps are based on a risk index integrating three layers of information: slopes, permafrost conditions and identified zones of severe constraints for construction (e.g. such as wetlands, ice wedge polygon networks, concentrations of frost boils and areas of active layer detachment scars). Afterwards, the risk index allowed for production of maps of construction potential where, for any given terrain category, the suitable foundation types according to the existing engineering solution guidelines are proposed (see map legend of Figure 11).

Maps of construction potential represent a powerful and useful tool intended for policy-makers and managers for generating regulated urban management plans that will ensure quality and sustainability of northern infrastructures.

### 6.4.3 Airports and roads: managing the costs of building on unstable ground

Northern communities are dispersed over a vast territory and transportation of both people and goods is carried out by sea and air. The heaviest goods are brought North by ship but air transportation provides flexibility, speed and year-round services that are crucial to northern communities. Air transportation is the main means of travel between northern communities and provides the principal link with southern regions. Most airports and access roads were built during the 1980s and early 1990s at a time when climate was considered stable and, indeed, was even cooling in the Eastern Subarctic (Wang and Allard 1995, Allard et al. 1995). As air temperatures increased during the 1990s and 2000s, permafrost degradation problems like ground instability and thaw settlement started to affect runways and access roads. In severe cases, depressions in runways due to thaw settlement have raised safety issues. Maintenance rates had to be intensified, which increased significantly the operating costs. Research involving scientists and governments
Figure 10. Map of permafrost conditions (ice content) in Salluit according to the spatial variability of surficial geology and geomorphologic features. Modified from Allard and L’Hérault 2010.
Permafrost conditions

Bedrock and superficial deposits with no or little ice content

+ Isolated rock outcrops

1a Massive bedrock of Precambrian age with a very sparse thin and discontinuous cover of sand, gravel and boulders (till). Active layer depth varies across the terrain from 2.5 to 3.5 m.

Layered sand and gravel deposits. Contain pore ice and occasional ice lenses in fine sand and silty layers.

Ice-rich permafrost in superficial deposits

2a Thin cover of sand, gravel and boulders over bedrock. The thickness of the deposits is generally less than 2 m. Topography is controlled by bedrock. Scattered rock outcrops. Active layer depth varies across terrain from 1.5 to 2.5 m. Thaw settlement of permafrost restricted to the superficial cover. Volumetric ice contents in the surface sediments vary from 15 to 70%.

2b Thick cover of sand, gravel and boulders (till) over bedrock. The thickness of the deposits is generally more than 2 m with occasional bedrock outcrops. Estimated maximum depth to bedrock is about 8 m. Frost boils are present and gelification lobes occur on slopes. Subject to thaw settlement. Active layer depth varies from 1.5 to 2.5 m across the terrain. Volumetric ice contents vary from 15 to 70%.

2c Thick cover of Quaternary sediments, poorly drained with a peat cover. Thickness is more than 2 m and can be as much as 6 m. The deposits are ice rich and a polygonal network of ice wedges is present. Active layer depth varies from 50 cm to 2.5 m.

2d Fine-grained sediments of marine origin. Occasionally covered by a thin layer of sand or gravel. Subject to differential thaw settlement and to active layer failures on slopes. Often surface is pitted with frost boils. Active layer thickness varies in the terrain from 50 cm to 1.2 m. Volumetric ice content in the permafrost is constantly above 30% and may be as high as close to 100%.

Infrastructures

Roads
Buildings
Airport runway
Body of water

Projection: MTM NAD 83 zone 9
Updates: Alland M. and L’Hérault E. (avril/april 2010)
Figure 11. Risk management map for potential construction development in Salluit. Derived from Allard and L’Hérau 2010.
Chapter 6
PERMAFROST AND INFRASTRUCTURES

Construction potential and foundation design adapted to permafrost conditions and slopes

Bedrock and superficial deposits with no or little ice content

1a - Massive bedrock of Precambrian age with a very sparse thin and discontinuous cover of sand, gravel and boulders (till). Active layer depth varies across the terrain from 2.5 to 3.5 m.
- All types of northern foundations. Adaptations to rugged topography are often necessary.
- Terrain manageable for construction (slope < 7.5°).
- Terrain manageable for construction but may require significant earthwork (slope between 7.5 and 15°).
- Terrain unsuitable for construction (slope > 15°).

1b - Layered sand and gravel deposits. Contains pore ice and occasional ice lenses in fine sand and silty layers.
- Northern foundations on adjustable post and pad or on piles. Buildings with slab-on-grade foundations might need elaborated techniques to retain permafrost in its frozen state (ex.: thermosyphons).
- Terrain manageable for construction (slope < 5°).
- Terrain manageable for construction but may require significant earthwork (slope between 5 and 10°).
- Terrain unsuitable for construction (slope > 10°).

Ice-rich permafrost in superficial deposits

2a - Thin cover of sand, gravel and boulders over bedrock. The thickness of the deposits is generally less than 2 m. Topography is controlled by bedrock. Scattered rock outcrops. Active layer depth varies across terrain from 1.5 to 2.5 m. Thaw settlement of permafrost restricted to the superficial cover. Volumetric ice contents in the surface sediments vary from 15 to 70%.
- Terrain manageable for construction (slope < 4°).
- Terrain manageable for construction but may require significant earthwork (slope between 4 and 8°).
- Terrain unsuitable for construction (slope > 8°).

2b - Thick cover of sand, gravel and boulders (till) over bedrock. The thickness of the deposits is generally more than 2 m with occasional bedrock outcrops. Estimated maximum depth to bedrock is about 8 m. Frost boils are present and gelifluction lobes occur on slopes. Subject to thaw settlement. Active layer depth varies from 1.5 to 2.5 m across the terrain. Volumetric ice contents vary from 15 to 70%.
- Pile foundations feasible but require deeper drill-holes for pile driving. Adjustable post and pad foundations also feasible. Buildings with slab-on-grade foundations need elaborated techniques to retain permafrost in its frozen state (ex.: thermosyphons). Steeper slope sections may be affected by gelifluction and may require specific foundation design.
- Terrain manageable for construction (slope < 4°).
- Terrain manageable for construction but may require significant earthwork (slope between 4 and 8°).
- Terrain unsuitable for construction (slope > 8°).

2c - Thick cover of Quaternary sediments, poorly drained with a peat cover. Thickness is more than 2 m and can be as much as 6 m. The deposits are ice rich and a polygonal network of ice wedges is present. Active layer depth varies from 0.5 to 2.5 m.
- Problematic terrain to be avoided.
- Terrain unsuitable for construction.

2d - Fine-grained sediments of marine origin. Occasionally covered by a thin layer of sand or gravel. Subject to differential thaw settlement and to active layer failures on slopes. Often surface is pitted with frost boils. Active layer thickness varies in the terrain from 0.5 to 1.2 m. Volumetric ice content in the permafrost is constantly above 30% and may be as high as 100%.
- Adjustable post and pad foundations. Buildings with slab-on-grade foundations need elaborated techniques to retain permafrost in its frozen state (ex.: thermosyphons).
- Terrain manageable for construction (slope < 1°).
- Terrain manageable for construction (slope between 1 and 2°).
- Terrain unsuitable for construction (slope > 2°).

Infrastructures

Roads - Buildings - Airport - Water bodies

Projection: MTM NAD 1983 zone 9
Box 2. Puvirnituq runway case study: an engineered adaptation design

Puvirnituq is located on the Hudson Bay coast of Nunavik. The airstrip construction ended in 1992. It was decided in 2008 to extend the runway in order to accommodate larger aircrafts, for instance Air Inuit’s Boeing 737 and the Government of Québec’s Challenger ambulance aircraft. Along most of its length, the runway embankment lies on bedrock with the exception of a 200 m long section that crosses a small valley floored by ice rich marine clay. By 2005 a depression of about 20 cm had appeared in the runway, near its south side, at this valley crossing (Beaulac and Doré 2005). The embankment in this section of the runway is 8 m thick. Wind drifting used to accumulate a deep snowbank against the embankment side, with the result that permafrost had locally thawed to a depth of 8-10 m beneath the toe of the embankment, which was generating the observed settlement. An additional heat source was water flowing through the runway from a little stream percolating into the embankment on the north side and seeping out at the toe of the embankment on the south side, thus locally enhancing permafrost thaw. The clay was sampled by drilling and coring to a depth of 15 m. Temperature measurements and a seismic refraction survey (MASW: Modal Analyses of Surface Waves) resolved the thawed zone at the foot of the embankment. As the elongation of the runway offered an opportunity to mobilize a contractor and as future runway safety was calling for corrective measures, a custom engineered berm and a specifically designed ground cooling system were put in place to stabilize the runway sides. The heavy berm is a counterweight that strengthens the thawed clay underneath and prevents it from liquefying and sliding. The berm is made of screened, decimeter-size, rock fragments that allow air to flow through in order to cool the underlying ground in winter and will, hopefully, favour the recovery of permafrost towards the surface. This set up is called a convection berm. Air ducts at the foot and at the top of the convection berm facilitate the convective effect of cold air flow through the stones to improve the cooling efficiency. The flow of water entering on the north side of the runway was diverted by digging a new ditch, and a new, albeit smaller, convective berm, was built on this side in order to help refreeze the ground and seal the embankment. The final installation has been equipped with slope movement and temperature sensors and its performance is currently being monitored (Boucher and Grondin 2010).
was conducted to provide geotechnical information and detailed information of processes affecting runways and roads as well as to organize maintenance practices.

The increasing air traffic and the larger aircrafts the airlifters now want to use require longer runways and larger parking aprons. Airport expansion calls for improved permafrost knowledge and inclusion of prediction of impacts of climate warming in the design of expansion projects. A recently terminated research program lead by Ministère des Transports du Québec applied a methodological approach similar to the one for villages; it aimed to provide adaptation strategies for eight airports deemed more sensitive because of specific permafrost conditions (Inukjuak, Puvirnituq (see inset box 2), Akulivik, Salluit, Quaqtaq, Kangirsuk and Tasiujaq, L’Hérault et al. 2012). A similar research project is supported by Transport Canada for the paved Kuujjuaq runway, which is the region’s hub.

Despite the technical, engineering and managerial advances, further research is still needed to better assess the expected thaw settlement rate and amplitude, as well as potential effects of increased ground wetness and seepage as the active layer deepens. This will help with planning longer term strategies for the airports built on sensitive permafrost areas.

### 6.5 Conclusion

Permafrost degradation is seriously affecting the natural environment. The landscape is changing through thermokarst formation that takes place primarily in the discontinuous permafrost zone and through thicker active layers and more frequent slope processes in the continuous zone. Northern residents are affected as vegetation, water bodies and soil drainage are changing, which has an impact on resources traditionally available such as berries that are shaded in the understory of shrubs that expand in thermokarst hollows (see chapter 4). These wide scale ecosystem changes affect animal populations as well, such as caribou feeding habits and migration patterns (see chapter 9). Sediment and carbon release from thawing permafrost have the potential to affect water quality thereby affecting fish populations and water intakes for human consumption. The modern built environment is particularly affected. Transportation infrastructure is being studied and adaptive solutions are developed, applied and tested. Now necessary for the protection and optimization of the major investments in housing and infrastructures, the urban planning of communities calls upon better permafrost condition maps and improved prediction of permafrost behavior.

Collection and organization of permafrost/geoscience information in geographic information systems (GIS) allows for the integration of essential knowledge and provides a very useful tool for establishing situation diagnostics, for sharing information with stakeholders and communities, and for supporting multidisciplinary decision making for land use planning. New technologies such as high precision LIDAR imaging that provide more detailed and precise DEMs are now being used. Another forthcoming technology, is interferometric analysis of satellite-borne radar data that makes it possible to monitor subtle topographic changes over the years and therefore detect permafrost related changes both in the natural and constructed environments (Liu et al. 2010).

Further applied research should include developing a better understanding of the permafrost-processes/climate system and producing risk assessments based on climate predictions. Specific advances will be more and more necessary in the management of surface drainage and groundwater flow around thaw lakes and beneath man-made infrastructures as the role of convective heat transfer appears to play a major role in permafrost thawing. This still poorly quantified process recurs everywhere in the landscape. Indeed, final permafrost degradation around 0°C appears to be in great part under the influence of unfrozen water content and heat brought by groundwater flow. The principal adaptive measure lies in adapting foundation types to mapped permafrost conditions in
order to ensure a prolonged service life of buildings. In this respect, Salluit now appears as the first major case where difficult permafrost and topographic conditions have led to the creation of a model approach from which lessons are being learned and extended to other northern communities.

6.6 References


Beaulac, I., and Doré, G. 2005. Bilan de la condition des pistes et des chemins d’accès menant aux aéroports du Nunavik, Université Laval, Département de génie civil, Québec City, Québec.


Burn, C. M. 1988. Observation of the thermal offset in near-surface mean annual ground temperatures at several sites near Mayo, Yukon Territory, Canada. Arctic, 41:99-104.


Kasper, J. N., and Allard, M. 2001. Late-Holocene climatic changes as detected by the growth and decay of ice wedges on the southern shore of Hudson Strait, northern Québec, Canada. The Holocene, 11:563-577.


Vallée, S., and Payette, S. 2007, Collapse of permafrost mounds along a subarctic river over the last 100 years (northern Québec), Geomorphology 90:162-170


