

# ENGINEERING CHALLENGES FOR TAILINGS MANAGEMENT FACILITIES AND ASSOCIATED INFRASTRUCTURE WITH REGARD TO CLIMATE CHANGE IN NUNAVUT

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Nunavut Kavamat  
Government of Nunavut  
Gouvernement du Nunavut

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**JOURNEAUX ASSOC.**

DIVISION LAB JOURNEAUX INC.

801 BANCROFT, POINTE-CLAIRE, QC H9R 4L6

T (514) 630-4997 F (514) 630-8937

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# 1 INTRODUCTION

*“In September 2011 JOURNEAUX ASSOC., a division of LAB JOURNEAUX INC., was awarded a contract by the Government of Nunavut, with the assistance of National Resources Canada (NRcan), to outline the engineering challenges for large scale infrastructure/tailings management facilities over the vast territory of Nunavut in light of the expected climate changes. Recommendations were to be made for tailings disposal techniques to be used in future mining projects in Nunavut up to the year 2100. Although the types of mines involved were not defined, it was considered that hazardous waste producing mines would be the most challenging, as well as high volume production mines, since the quantities of waste produced can be overwhelming.”*

This report presents a study of the engineering challenges for tailings management facilities in Nunavut, and the associated large scale infrastructure required to build and operate these facilities. Waste (tailings) containment facilities must be designed to provide the best environmental solutions for today and for the future. Over the past 50 years, unprecedented rates of change for both temperature and precipitation have been recorded and future predictions agree with the current trends (Furgal et al., 2008). Climate change is occurring and it is vital to include these effects in the design of future waste containment facilities.

In addition to the general concerns relating to climate change, Nunavut’s cold climate poses its own obstacles for the mining industry. A principle consideration in the construction and operation of tailings facilities in the Arctic is the extremely low temperatures during winter and the very short, mild summer. The combination of future climate changes, current harsh climatic

conditions, as well as the remoteness of mine locations creates a big challenge for the mining industry in Nunavut. Safe storage of mine waste must take these factors into consideration.

In Nunavut, the design of tailings storage facilities relies heavily on the integrity of the permafrost. Permafrost can be used to the advantage of designers to safely store waste material due to the natural containment provisions the frozen ground provides (e.g. limits seepage). In addition, the frozen ground provides a solid foundation for dams, dikes and other infrastructure. However, the integrity of the permafrost over the long-term is of great concern as the region warms and thawing occurs. Alterations in precipitation and evaporation that are expected to accompany climate change will also influence waste facility design. Mine water management design, planning and operation, and the maintenance of adequate water cover over waste zones in the long-term is influenced by precipitation and evaporation estimates. Hydraulic structures (dams, ditches, berms, etc.) may not be adequately designed to account for anticipated heavy rainfall events. Fortunately, future designs of tailings facilities can use the latest climate predictions and apply conservative safety factors to make the necessary design adjustments. Therefore, choosing the most stable disposal technique is the first and most important step.

Several waste disposal methods are used in cold regions and a simplified overview of these methods is provided. The optimum method for disposal from a particular mine will ultimately require a detailed study of all possible alternatives (see, for example, Rykaart, 2005a, 2006; Golder Associates, 2007). Past and present lessons learned from other mining projects can give valuable insight and help to guide future choices. Environmental concerns must be addressed and

future disasters must be avoided, especially in the Arctic, where remoteness constrains clean-up operations and the cold climate results in slow decomposition of pollutants (Pearce et al., 2011).

A review of past and present mining projects, in Nunavut and other cold regions, is presented, with the recommendation that, because of the significant natural freezing conditions in Nunavut, the 'dry stacking' method of waste disposal should be used for future mining projects, using disposal in underground cavities (backfilling) or open pits as much as possible. In recent years, dry stacking has grown rapidly in popularity (Davies et al., 2010). The main arguments for choosing this method over other tailings disposal methods are the environmental benefits and the increased water conservation, which is particularly beneficial in Nunavut's cold and dry climate. Other advantages are discussed and design considerations are detailed. Again, the recommendations are general and under specific circumstances (e.g. where ice entrainment or wind blown dust are big concerns) other disposal techniques could be more desirable.

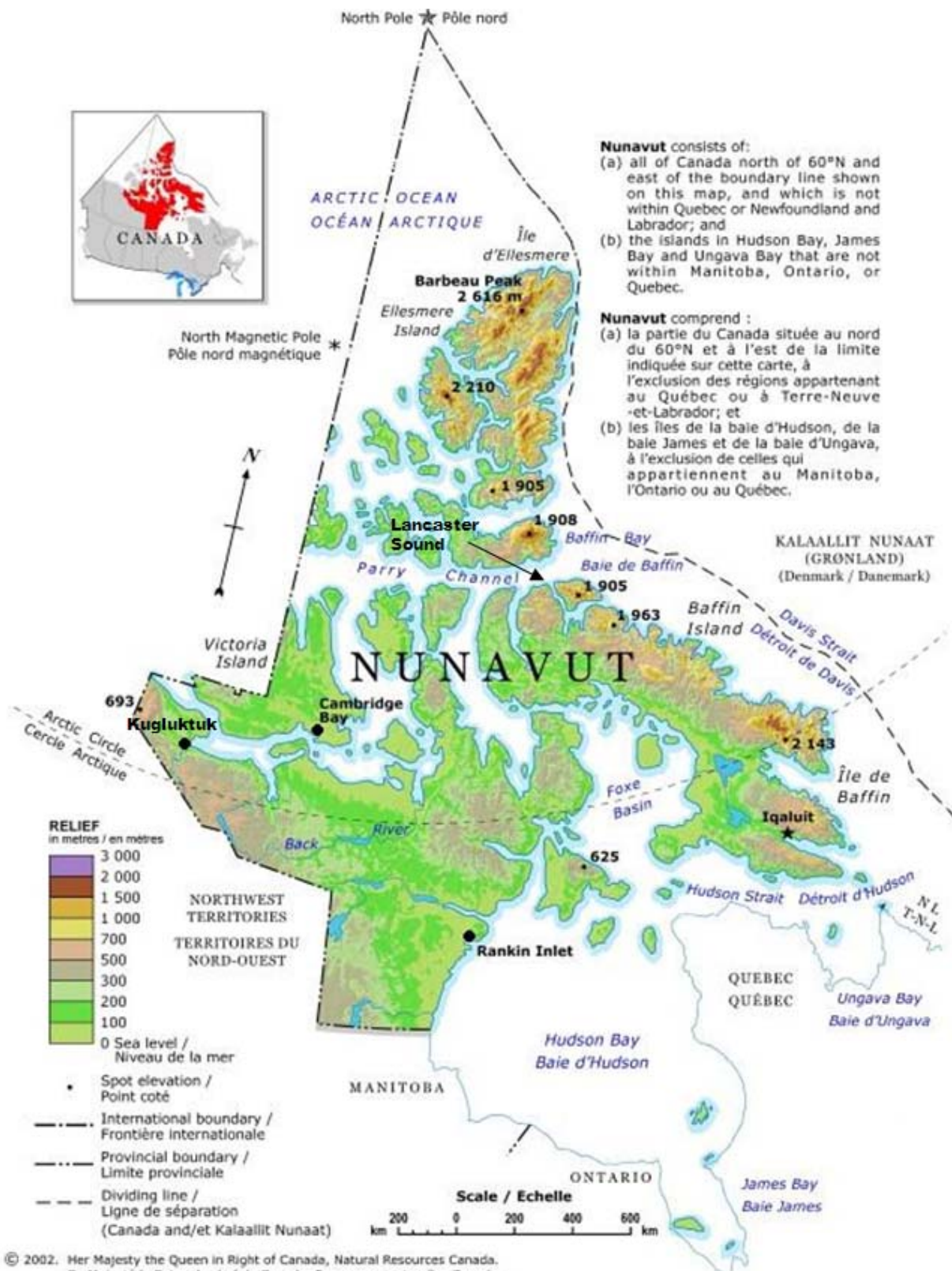
For completeness, a review of Nunavut's territory, landscape, and topography is presented. In addition, current climatic conditions and the expected climate changes in Nunavut are discussed. Special attention is given to permafrost conditions and topics related to tailings facility infrastructures over permafrost, such as ground ice and settlement.



## 2 GEOGRAPHY OF THE AREA

### 2.1 Territory

The Nunavut territory (see Figure 2-1) extends westward from Hudson Bay to the boundary shared with the eastern Northwest Territories. It extends northwards from the southern border, shared with Manitoba (60° N latitude), to the North Pole. More than half of the territory is composed of islands; all the eastern Arctic Ocean islands in James Bay, Hudson Bay and Ungava Bay including Baffin Island, Victoria Island and Ellesmere Island, are within Nunavut. In all, Nunavut covers two million square kilometres, which corresponds to 1/5<sup>th</sup> of Canada's landmass.



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 Sa Majesté la Reine du chef du Canada, Ressources naturelles Canada.

**Figure 2-1: Nunavut territory and relief details (NRCAN, 2002).**

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## 2.2 Physiography, Topography and Glaciation

Three physiographic regions cover Nunavut's vast territory; the Canadian Shield, Arctic Lowland and Innuitian Region. The Canadian Shield covers the mainland and islands around Hudson Bay. The area is underlain by ancient rock formations with generally thin overburden cover. The landscape is often poorly drained and consequently contains numerous rivers, lakes and peat bogs throughout its rolling landscape. A more detailed background and description of the Canadian Shield is given in the next paragraph. The Arctic Lowland lies north of the Canadian Shield and is composed of lowland plains and glacial moraines towards the west and uplands with plateaus and rocky hills towards the east. Baffin Island has a mountainous terrain (elev. of 2000 m), which is largely covered by glaciers and ice fields. The terrain changes to lowlands in the south west where numerous fresh water lakes and rivers exist (thawing only for brief periods during the summer). The Innuitian Region is found in the most northern and remote part of the territory. (Furgal et al., 2008)

The land south of Lancaster Sound (see Figure 2-1) was severely glaciated by the continental ice sheet which expanded outward, approximately 30,000 years ago, from the high land of eastern Baffin Island. Eighteen thousand years ago, the Laurentian continental ice sheet had reached as far south as the northern United States. Climate warming caused the ice sheet to retreat to its present state with some short term fluctuations as climate variations occurred. During this process, the topography of the land was shaped, leaving the resistant Precambrian bedrock formation with thousands of lakes and peat bogs crisscrossed by deep fracture and fault zones, through which the river drainage systems were developed. Figure 2-2 shows a recent satellite image of Nunavut. Usually, a thin cover of glacial till is found on the bedrock with granular

materials deposited in ice scoured fault and fracture zones and in long linear esker ridges usually located in the bottom of broad synclinal geologic structures. In the lower, deeper, scoured basins, the topography is much flatter and basal till deposits are more common, although the thickness varies according to the underlying bedrock geology. In the areas below the highest marine beaches, ice-rich marine clays and silts have been deposited over the underlying glacial tills. In broad valleys and in lakes, deep marine clay deposits can be found at elevations of 300 meters (above present sea level). This is due to isostatic rebound of the earth's crust over the last 10,000 years during which time the western part of Nunavut was mostly free of ice cover. Nunavut is located in the continuous permafrost zone, see Figure 2-3; this figure also shows the ground monitoring stations in the area. The depth of permafrost in Nunavut generally extends several hundred meters below ground.

Nunavut has been the focus of recent geological survey research and mapping. Full details relating to geoscience mapping are available through the Nunavut Geoscience webpage (<http://nunavutgeoscience.ca>), which is a joint initiative of the Canada-Nunavut Geoscience Office (CNGO), Indian and Northern Affairs Canada (INAC), Government of Nunavut (GN), Natural Resources Canada (NRCan) and Nunavut Tunngavik Incorporated (NTI). The webpage provides extensive mapping information including bedrock geology, surficial materials, geologic faults, elevation data and rock types. (Nunavut Geoscience, 2012)



Figure 2-2: Satellite image of Nunavut region, excluding far north (Google, 2012).

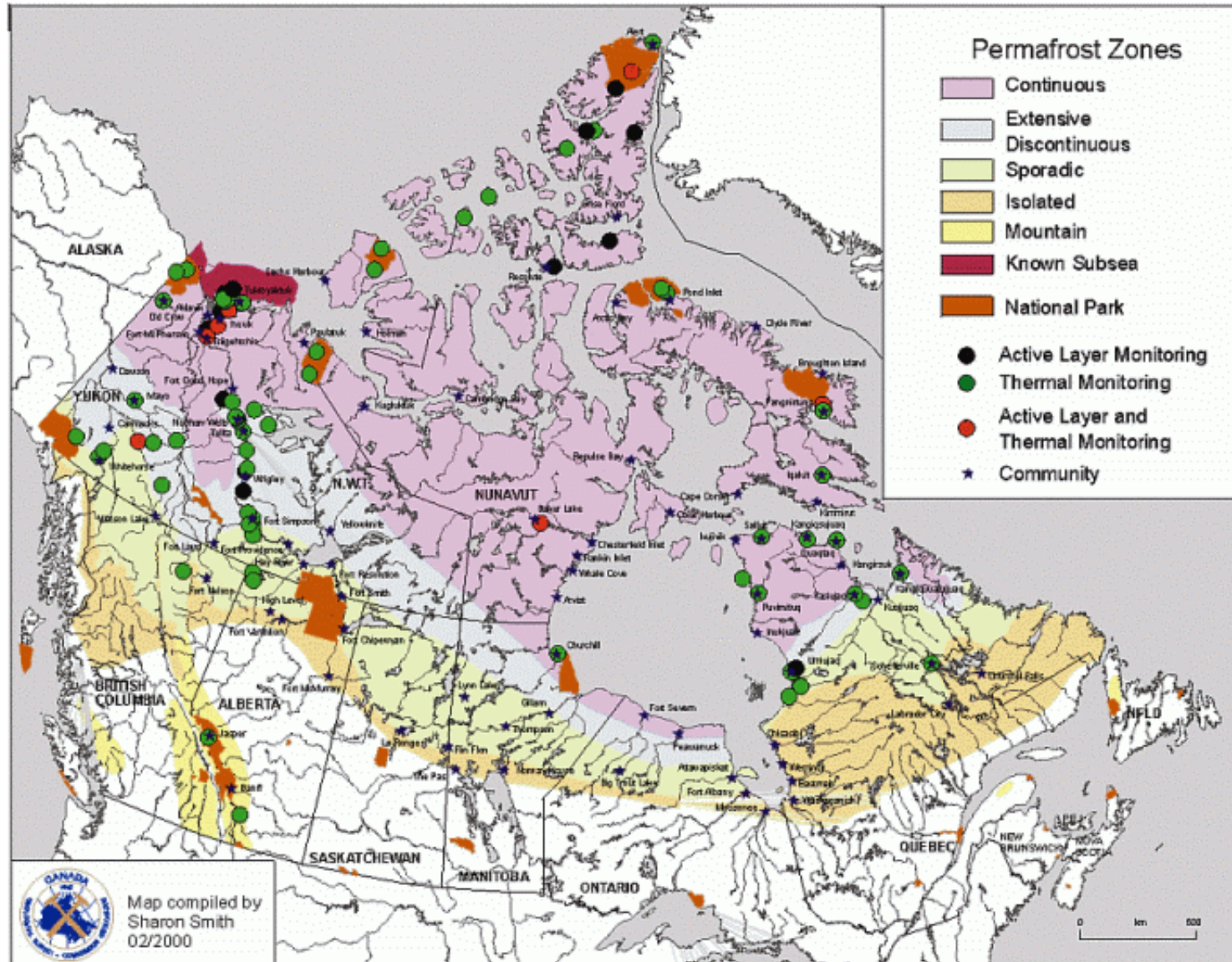


Figure 2-3: Permafrost zones and thermal monitoring stations within Canada (Courtesy S. Smith – GSC, 2000).

## **3 CLIMATE CHANGE CONSIDERATIONS REGARDING TAILINGS MANAGEMENT FACILITIES IN NUNAVUT**

### **3.1 Climate Change Impacts on Tailings Management Facilities/ Infrastructure**

The Arctic Council and the International Arctic Science Committee (IASC) have prepared comprehensive reports relating to climate change in the Arctic and the numerous implications (see ACIA, 2004, 2005). Chapter 16 of ACIA (2005) is dedicated to climate change impacts on infrastructure. Stratos Inc. (2009) performed a literature review related to climate change impacts on mining operations and infrastructure in Canada. The latter provides many references relevant to northern mine infrastructure, tailings management and mine closure with respect to climate change. The U.S. Arctic Research Commission also summarizes climate change effects on civil infrastructure in the permafrost regions (USARC, 2003). Some of the main conclusions relating to tailings facilities and climate change are summarized here:

- Current and future infrastructure in the Arctic will be affected by climate change.
- All future infrastructure projects will require research relating to climate change.
- Climate data, available over the past century, and expected trends can be used to estimate future climatic conditions and their impact on natural processes.
- Cold regions engineers are able to provide solutions using evolving technologies, but future projects must expect additional costs.

Tables 3-1 and 3-2 summarize climate change items and the associated risks for tailings facilities in permafrost regions. The tables also provide timeframes during which the impact is likely to be most significant (e.g. operation or post-closure) and potential mitigation strategies. In general,

the main challenges related to climate change will be associated the post-closure period when compared to the operational time, which is relatively short for most mines.

The impacts on dams are given in greater detail in the following section (Section 3.1.1). Precipitation and water balance impacts are discussed in Section 3.3, more information on waste covers is provided in Section 4.3.2, and disposal sites are discussed in greater detail in the general disposal alternatives section (Section 4.5).



**Table 3-1 : Potential impact of climate change on hydraulic structures and mine water management in permafrost regions and potential mitigation strategies (modified after Stratos Inc., 2011).**

Mine Component / Activity	Description of Potential Direct Impact	Most relevant Climate Change Condition(s)						Most relevant		Potential Mitigation
		Temperature	Mean Annual Precipitation	Extreme Precipitation	Permafrost Degradation	Increased Wind Action	Changes in Water	Operation	Post-closure	
Dam	Settlement				√				√	Provide additional freeboard.
	Seepage through dam due to formation of cracks (flow paths).				√				√	Use frozen core dams and thermosyphons. Be conservative by using flatter slopes and thicker covers. Constant monitoring of ground temperatures. Reduce ground disturbance and avoid thaw-sensitive soil locations.
	Increased seepage below dam.		√	√	√			√	√	
	Slope failure due to rising phreatic surface.		√	√					√	Flatter slopes or buttress required. Implement adequate drainage system in dam.
	Weakening of structure due to erosion of face or gully at base.			√				√	√	Increase erosion resistance of structures (lower slopes, larger diameter rip rap).
	Overtopping			√				√	√	Provide additional freeboard, design with option to increase spillway capacity.
Other hydraulic structures (ditches, berms, holding and tailings ponds, etc.)	Overflow due to insufficient capacity, resulting in more contaminated runoff or infiltration, possible need for temporary measures to be taken (e.g. floodings pits) and possible shutdowns.			√	√			√		Increase capacity of diversion works and storage structures. Design with future climate change predictions and be conservative.
Mine water management	Changes in water balance (see Section 3.3) leading to unforeseen problems in mine water management schemes.						√			Plan water management with future climate change predictions.

**Table 3-2 : Potential impact of climate change on waster covers and disposal sites in permafrost regions and potential mitigation strategies (modified after Stratos Inc., 2011).**

Mine Component	Sub-component / type	Description of Potential Direct Impact	Most relevant Climate Change Condition(s)						Most relevant		Potential Mitigation
			Temperature	Mean Annual Precipitation	Extreme Precipitation	Permafrost Degradation	Increased Wind Action	Changes in Water Balance	Operation	Post-closure	
Waste covers	Insulation cover	Permafrost degradation of entire insulation cover leading to infiltration into the waste layer and increased oxidization and leaching.				√				√	Design 'insulation covers' conservatively and monitor performance.
	Water cover	Drought conditions may lead to a shortage of water in long-term for 'water covers', resulting in increased oxidization. Increased precipitation may lead to need for emergency discharge.			√			√		√	Use alternative cover designs (e.g. insulction cover) or monitor water cover.
	Barrier cover	Soil barrier: cover is eroded leading to increased infiltration. Synthetic barrier: protection layer is eroded and risk of damage to synthetics.	√	√	√	√		√		√	Increase erosion resistance of layer.
	Store and release cover	Vegetaion unable to adapt to changes leading to increased percolation, erosion or metal uptake.	√	√	√	√		√		√	Use adaptable vegetation for expected climate change scenarios, increase erosion resistance (flatter slopes, armoured runoff channels) or increase thickness/capacity of storage layer.
Diposal sites	Tailings ponds	Increased storm magnitude and frequency leading to increased wind and wave action in tailings ponds causing re-suspension of tailings and the formation of ice dams.			√			√			Avoid associated disposal methods; use alternative disposal techniques, such as 'dry' stacking and underground backfilling.
	'Dry' stacked tailings piles	Drought conditions, during the summer, can impact dust suppression efforts via water spraying over dry stack tailings piles. Increased wind action could result in more difficulty mitigating dust spreading.						√	√		Conserve water and plan water management with potential for dry periods. Use other dust suppression methods (see Section 4.4.1.2.).
	Open pits	Permafrost degradation in walls of open pit mines leading to weakening of structural integrity of wall. More precipitation leads to increased water into pit.	√	√	√	√					Install bolts and anchors if feasible to stabilize rock slopes. Avoid runoff into pit by building diversion works.

### 3.1.1 Dams

The thawing of permafrost under dams/dikes is a big concern for tailings management facilities in the North. Dams are commonly required for several disposal alternatives (see Section 4.5). Contaminated mine waste is a perpetual issue (e.g. acid rock drainage – see Section 4.3.1) and dams/dikes, like any structure, will eventually deteriorate. Climate change will increase the rate of deterioration, especially since the structures rely on the underlying frozen ground for stability and seepage containment. Thawing of permafrost below dams/dikes can lead to differential settlements resulting in the opening of cracks (flow paths) within the dam and seepage through the dam itself. In addition, settlement will reduce the available freeboard to prevent overtopping. The underlying ground will be subject to the following, which all result in an increased potential for seepage through the underlying soil:

- Increased pore pressure.
- Increased possibility of piping below foundation.
- Increased flow paths for subsurface flow/increase in overall soil permeability.

The potential for liquefaction of loose saturated material during earthquakes is another concern for degrading permafrost below dams.

An increase in mean annual precipitation (MAP) and extreme precipitation events will increase the potential for seepage (due to increases in the hydraulic head) and slope failure (due to the rising phreatic surface within the dam). The latter depends on the drainage system within the dam and, therefore, the type of dam used (see Section 4.4). Increased magnitudes and frequencies of precipitation events could increase erosion of the upstream face or gullying at the base of a dam, which will result in weakening of the structure. Finally, extreme precipitation

events could result in overtopping. All of these climate change impacts will reduce the capabilities of dams/dikes to contain tailings ponds, holding ponds, etc. Mitigation strategies for dams/dikes in Nunavut are summarized in the following points:

- Use frozen core dams with thick covers and thermosyphons to maintain the core in a frozen state (see Section 4.4.1).
- Use flatter slopes and erosion resistant cover material.
- Monitor ground temperatures constantly.
- Reduce ground disturbance and avoid thaw-sensitive soil locations.
- Provide additional freeboard or increase spillway capacity.

## **3.2 Permafrost**

### **3.2.1 General Introduction**

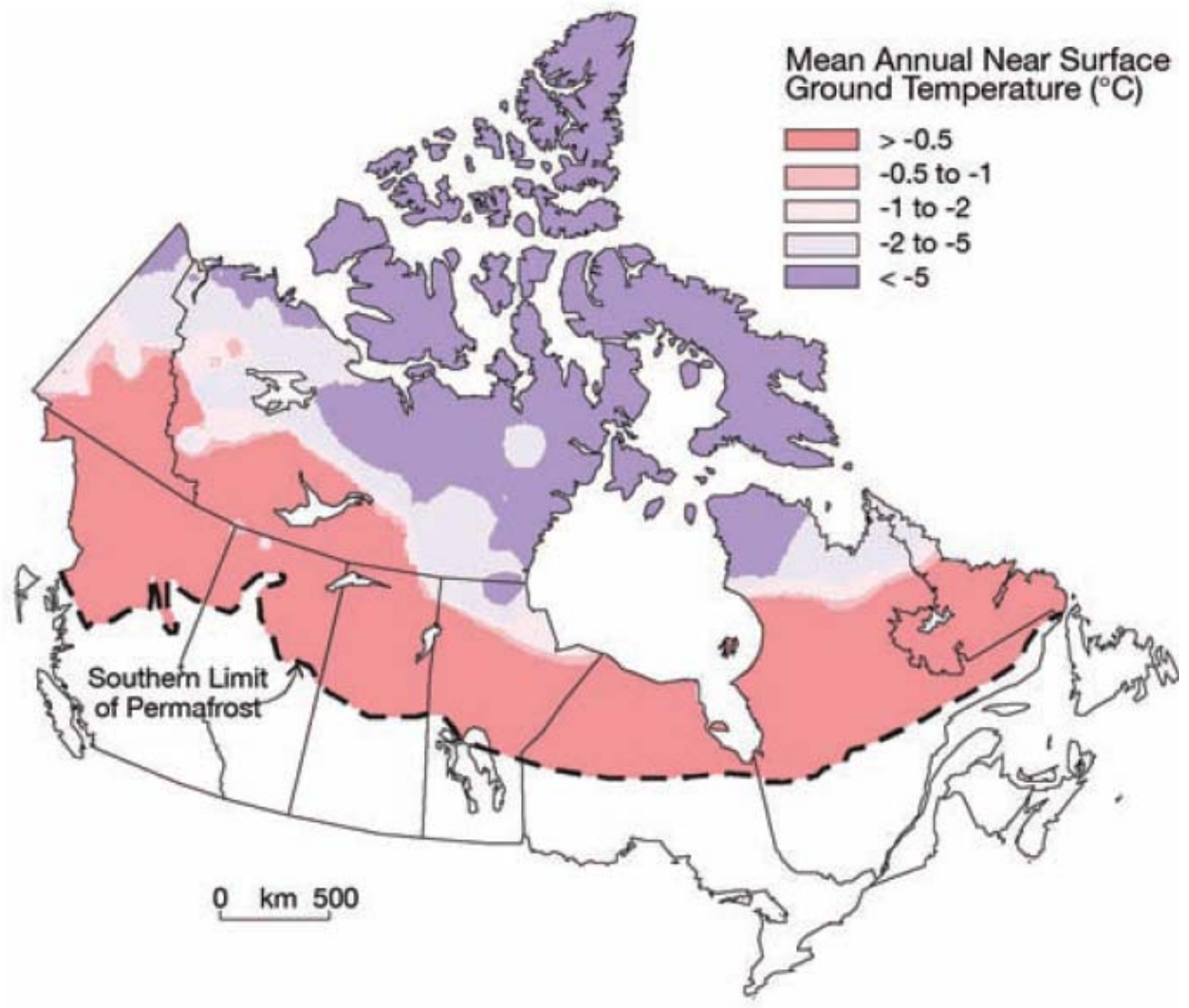
In northern Canada, the ability to understand and predict the physical state of permafrost is a challenge that affects the design, construction, and maintenance of infrastructures. Tailings facilities in Canada's North, built on permafrost, rely on the integrity of permafrost to prevent the movement of toxic mine waste through glacial till and bedrock and into the natural groundwater drainage systems. Design of above ground structures must therefore preserve frozen conditions while limiting thaw. Experience has led to a variety of practices and technologies adapted to cold climates to prevent such hazards. For example, installing a robust and self-controlling freezing apparatus below foundations to freeze and even supercool permafrost will prevent thawing for centuries if thick covers are used. Countless papers relating to permafrost can be found through the International Permafrost Association (IPA) website

(<http://ipa.arcticportal.org/>), where proceedings from the first nine ‘International Conferences on Permafrost’ are available. A report was also submitted to the Government of Yukon concerning permafrost considerations for effective mine development (EBA Ltd., 2004).

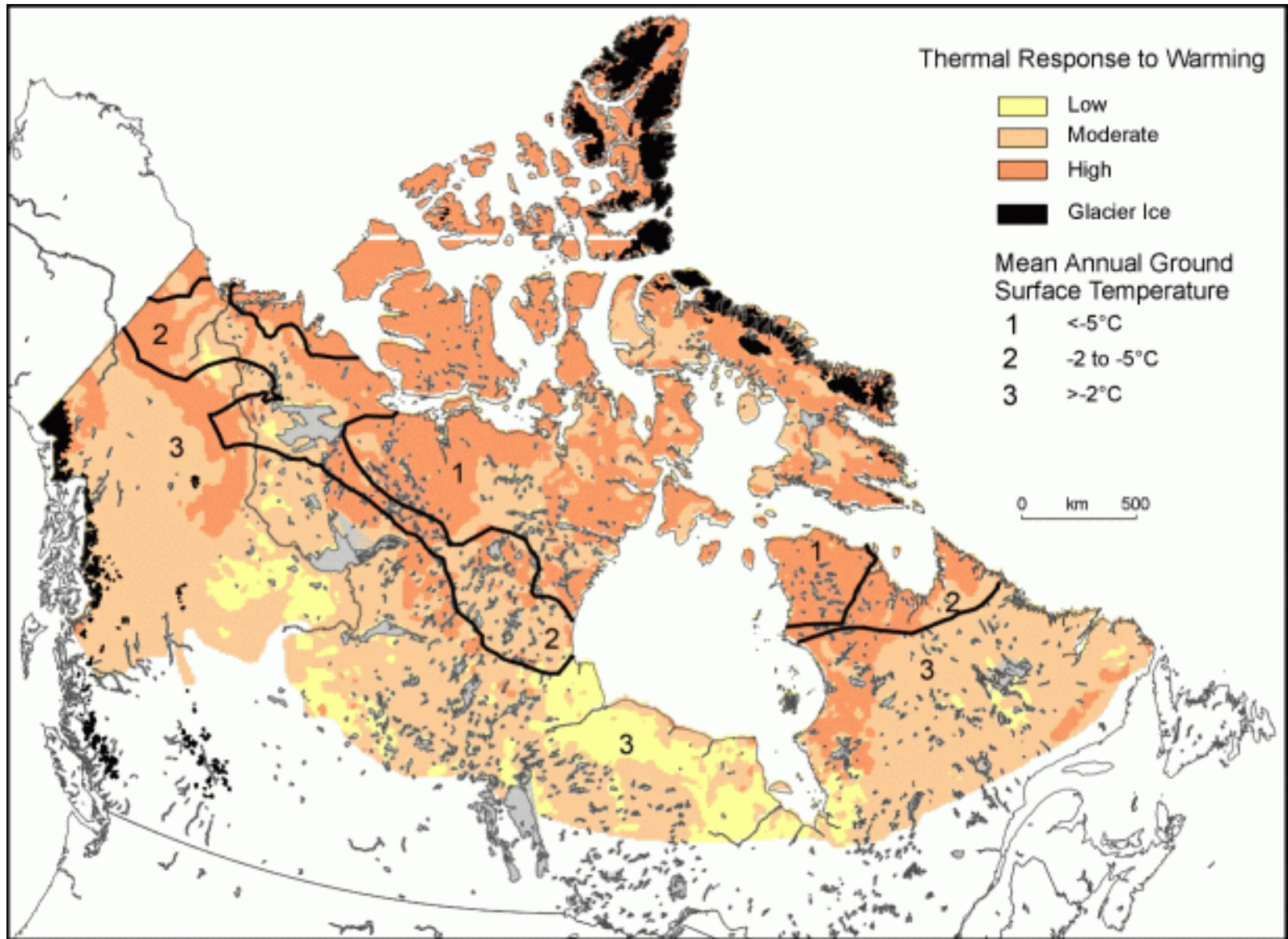
Smith et al. (2001) provides an extensive report of current knowledge relating to permafrost in Canada and Holubec (2004) provides a detailed background on permafrost as well. Permafrost is defined as a soil or rock at or below 0 °C for two or more years. The definition does not consider the depression of the freezing point due to pore water salinity (e.g. from sea water infiltration or mill water within tailings), or the oxidation of reactive tailings. Furthermore, the definition does not include the depth, temperature, location within the stratification or water/ice content, which are useful in determining the physical and chemical properties of the soil when designing infrastructure over permafrost. Another factor that increases the complexity of permafrost is the effect of vegetation. In Nunavut, where permafrost is continuous, (refer back to Figure 2-3) vegetation can accumulate snow cover during the winter and this insulates the ground from cold temperatures. Removing vegetation in continuous permafrost zones could result in permafrost degradation (and possible settlements) during the initial summer construction period, but will eventually re-establish over the cold winter for the new site conditions. The soil and rock types and properties (e.g. moisture content and thermal conductivities), cover types (e.g. grass, asphalt, snow cover, etc.) and respective thicknesses, hydrology and local topography are other parameters that affect permafrost conditions besides the more obvious temperature conditions.

Figures 3-1 to 3-3 (taken from Smith and Burgess, 1998; 2004) show the mean annual near-surface ground temperature (MAGST) and the relative thermal and physical responses to climate

warming in Canada. From Figure 3-1, it can be seen that Nunavut has mean annual near-surface ground temperatures below  $-2\text{ }^{\circ}\text{C}$  where continuous permafrost is found. The MAGST data is useful in the design of infrastructure associated with tailings facilities (e.g. cover design to encapsulate tailings in permafrost – see Section 4.3.2). In Figure 3-2, the thermal ground response has been separated into three zones. The thermal response generally increases with the current mean temperatures and is greatest in zones with lower temperatures. However, the potential for thaw is still greatest in the warmer regions. Nunavut will have a medium to high relative thermal response to warming. Finally, in Figure 3-3, regions where ice-rich sediments are present will have the largest physical response (the relative magnitude of the impact of permafrost thaw and settlement) to climate warming. The ice content of soil is generally larger in fine-grained soils and organic materials (see Section 3.2.2). Nunavut contains a variety of soil types; therefore, individual assessments would be required for particular regions where infrastructure projects are planned.

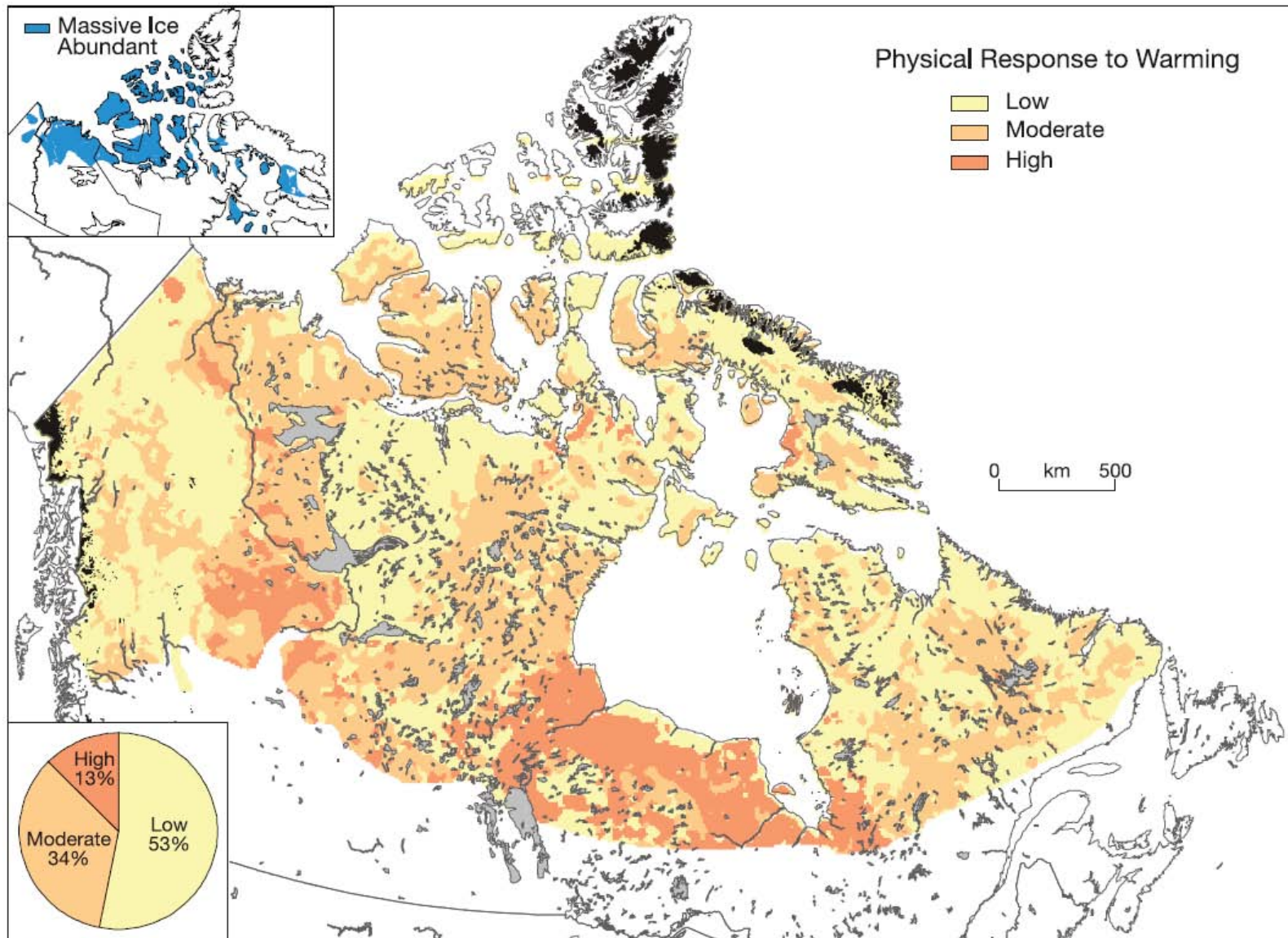


**Figure 3-1: Mean annual near-surface ground temperature (Smith and Burgess; 2004).**



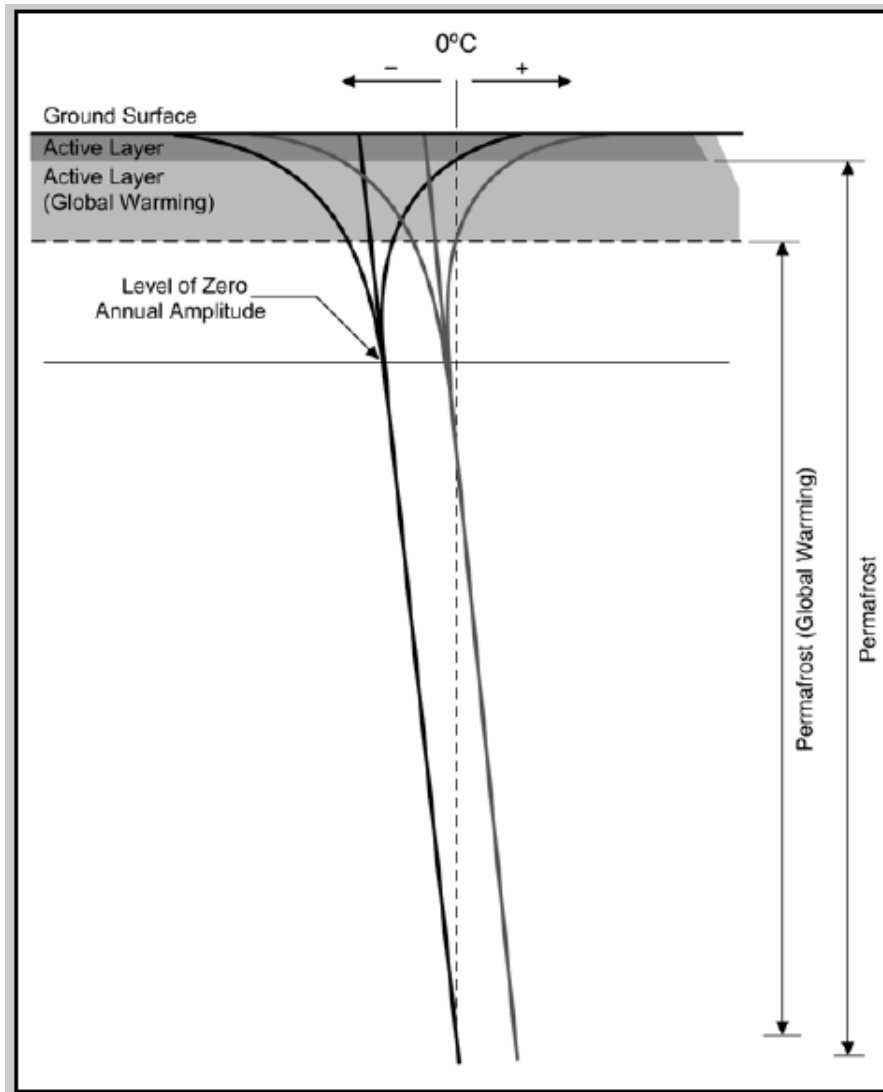
**Figure 3-2: Relative thermal response to climate warming (Smith and Burgess; 1998).**





**Figure 3-3: Relative physical response to climate warming (Smith and Burgess; 2004).**

Figure 3-4 compares typical temperature profiles through permafrost, from the ground surface to the base of the permafrost. The figure shows the simplest approximation of the effects of climate warming; the temperature profile shifts to the right (increased temperature), the active layer increases in thickness and the permafrost level increases in depth. It should be noted, that the summer and winter curves intersect at a certain level (the level of zero amplitude) within the permafrost where temperatures are constant year-round. Above this point the summer and winter curves veer to the right and left, respectively.



**Figure 3-4: Typical ground temperature profiles (after USARC, 2003).**

### 3.2.2 Freezing and Thawing Indices

In order to design structures on permafrost, engineers often rely on the air freezing and thawing indices (given in degree-days) of the proposed site location. [*Note: air freezing index = degree-day freezing (DDF) and air thawing index = degree-day thawing (DDT).*] Freezing/thawing indices are calculated by summing the number of days with temperatures below zero/above zero multiplied by the average temperature during those days. Boyd (1976) presents a paper summarizing how the air freezing and thawing indices are calculated based on normal monthly temperatures. Huschke (1959) used daily average temperatures to calculate the freezing/thawing indices. These mean freezing/thawing indices can be used to assess temperature trends and, in turn, their effects on permafrost degradation.

Design air freezing/thawing indices are calculated in different ways depending on the design codes or other considerations of a given infrastructure project. The design air thawing index is usually calculated by averaging the seasonal thawing indices for the three warmest summers in the past 30 years (if 30 years of data is not available, the warmest summer in the past 10 years is used) and is commonly used to determine the maximum thaw depth. The design air freezing index has received a lot of attention by researchers, since it is used to estimate frost heave, a key factor in cold region foundation design. For most civil engineering projects, the maximum air freezing index that can be expected once in every 25 years is usually sufficient for design purposes (McCormick, 1991). However, for more conservative design, longer return periods may be justifiable. The Canadian Foundation Engineering Manual (CFEM, 2007) reviews other methods for determining the design air freezing index. Once a design index is accepted, it is used to determine the ground surface index.

Surface freezing indices have to account for the variations in ground cover; the relationship between the design and surface indices depends on the ground surface material (e.g. snow, grass, pavement, etc.). An  $n$  factor is used to calculate the surface index (see Equation 1) based on the cover type. Once the surface freezing and thawing indices are determined, the thermal resistance of the cover and thermal conductivity of the soil is required to perform further analysis on individual soil layers (Kersten, 1949). Some empirical relationships may exist depending on the application.

$$I_s = nI_d \quad (1)$$

where  $I_s$  is the surface freezing index,  $I_d$  is the design freezing index.

### **3.2.3 Ice Content in Soils and Settling of Thawing Permafrost**

The ice content in soils will depend on the type of soil, the availability of free water during the freezing period and the salt content in the pore water. In general, in coarse-grained soils that are more elevated and have good drainage, the ice content is related to the original water content of the material and occurs usually as ice coatings on soil fragments and in the original saturated voids of the material. When fine-grained soils are involved, migration of water to the freezing front can cause significant ice lenses and layers. In the marine silts and clays, thick (up to several millimetres) and frequent ice layers are common and this can occur to considerable depths (up to 20 meters). In fine-grained glacial till, vertical ice wedges up to 1 metre wide and extending several meters in depth, are not uncommon. On land, these can be identified by polygonal or linear topographic expressions. These areas should be avoided when constructing dams/dikes or other infrastructure.

The ice content within frozen soils is critical for determining possible settlement as it controls the thaw strain and therefore thaw sensitivity/stability of a soil layer. The Canadian Foundation Engineering Manual offers little design advice for thaw-settlement predictions and stresses the importance of an experienced cold regions engineer to perform the analysis. That being said, Frederick Crory (1973) presented a simple, practical and direct method for predicting settlement associated with the thawing of permafrost. This method uses the water content and dry unit weight of undisturbed samples. An accurate measurement and prediction of the ice content/water content within soil(s) before and after the expected thaw has occurred is essential in performing the settlement analysis. Thaw consolidation settlement has also been extensively studied by several researchers in an attempt to develop empirical relationships based on soil types (see for example Tsytoich et al. 1965; Morgenstern and Nixon, 1971; Hanna et al., 1983). Nevertheless, laboratory consolidation experiments are irreplaceable in assessing in-situ soil responses for a specific site. In addition to thaw-settlement, the issue of creep deformations of frozen soils under applied loads must be addressed. Creep deformation is a function of load, soil type and temperature; creep deformation will increase dramatically if temperatures approach the thawing temperatures of soils. More publications and references to cold regions settlement can be found through the IPA website (<http://ipa.arcticportal.org/>).

### **3.3 Precipitation and Water Balance (Precipitation and Evaporation)**

Precipitation and water balance, in terms of the combination of precipitation and evaporation, are expected to change in the future and these changes will have major consequences on tailing management facilities.

Precipitation data is used in the design of hydraulic structures at mine sites (e.g. dams, dikes, ditches, spillways, tailings ponds, berms). Future mine structures can be designed to withstand anticipated long-term increases in precipitation. However, current mines, which have not accounted for these increases, could be at risk. Insufficient capacity of existing hydraulic structures can lead to runoff of contaminated water and, therefore, detrimental environmental impacts. The MEND 1.61.7 report suggests that more research is required to determine changes to the probable maximum precipitation (PMP) and probable maximum flood (PMF), which are used in the design of dams and collection systems (Stratos Inc, 2011). In general, increased precipitation would be beneficial to mining operations in Nunavut, where water is scarce; however, one negative aspect of increased precipitation would be an increase in the runoff from contaminated areas, which requires costly collection and treatment. Torrential rains have forced the Minto mine, which is located in the Yukon Territory and began operation in 2007, to release untreated water into the Yukon River system twice already, with potentially negative impacts on fish and wildlife. Furthermore, the same torrential rains washed out a four kilometre section of a haul road (Pearce et al., 2011). Water management plans need to incorporate systems that will not be overwhelmed by increasing rain storm magnitudes that can force the release untreated water. Larger collection ponds or diversion works may be suitable solutions.

An evaporation monitoring program, run by the Canadian Water Resources Division (a division of Aboriginal Affairs and Northern Development Canada), has been operational since 1993. There are currently eight evaporation monitoring stations across Nunavut and the Northwest Territories (NWT). The stations are located at the Giant, Salmita, Colomac, Lupin, Silver Bear, Discovery, Nanisivik and Cullaton Lake mine sites. (AANDC, 2010)

Precipitation and evaporation rates are two main components of water balance management plans associated with tailing disposal facilities. Changes in water balance may lead to dryer or wetter conditions in different locations throughout Nunavut. A variety of mine site water management situations can exist for different mines. All mines require a water source for operations (e.g. ore processing), which is typically a nearby lake/river or, in extreme conditions, runoff collection basins. Contaminated water requires treatment before being released back into the environment; mines often recycle tailings water for ongoing ore processing to avoid treatment cost. Sometimes a mine will reach a steady-state situation where they no longer require fresh water from an external source. When too much water (e.g. from precipitation into holding ponds) accumulates, more frequent releases of water to the environment are required. The design of polishing ponds, tailings ponds, pumping stations, ditches and so forth all depend on the local water balance. Changes in the water balance over the lifecycle of a mine should be incorporated into water management plans.

Water balance is also used in the design of water covers to prevent oxidization of reactive tailings and in mine site water management. Long-term changes in the water balance may affect the height of cover; maintaining an adequate water cover is a serious environmental concern for tailings facilities. Tailings disposal sites are regularly abandoned once the mine operation is terminated. Therefore, long-term water balance should be accounted for in their design, along with post-closure monitoring programs, if water cover is the chosen cover method.

## **3.4 Designing for Climate Change Impacts on Tailings Management Facilities**

This section provides an overview of the current state of standard methods used by engineers and other specialists involved in the design of large scale infrastructure relating to tailings facilities. This section will provide an introduction to the main methods available for assessing specific aspects of geotechnical design with climate change.

### **3.4.1 Predicting Climate Change**

Forecasting future climatic trends is an integral part of planning, designing and monitoring future infrastructure. Both ultimate (failure) and serviceability (deformation) limit states must be achieved throughout the life of the project. Future trends in soil properties require predictions of permafrost temperatures, active layer thicknesses, freeze-thaw cycles, frost penetration or combinations of these.

With the many different climate prediction methods available it can be confusing for design engineers to choose a scheme for long-term design. Hayley and Horne (2008) rationalize the design of structures on permafrost (from a Canadian perspective) in their paper by reviewing two case studies; an apartment building with complex foundation conditions and a reclamation project that relies on permafrost stability. They conclude that for structures with a service life of 30 years or less, available climate data can be used to predict climate change effects that should be incorporated into design considerations. For infrastructures with longer lifespans, global climate models (GCM's) are recommended. However, GCM's do not include permafrost dynamics that can potentially provide critical feedbacks on climate changes. Nicolsky et al.



(2007) and Alexeev (2007) compared Community Land Models (CLM3), which is a land based scheme, with observed trends. They give recommendations to increase the total soil depth, incorporate a surface organic layer and modify the numerical scheme to include unfrozen water dynamics and a more realistic phase change representation in models. Geothermal analysis coupled with climate trends and failures modes should be used to predict the long-term stability of structures (see also Section 3.4.2). Past experience should not be overlooked, as lessons learned from historical performance of past projects can provide valuable insight for new designs.

In spite of climate change concerns, the economics of the project will propel the construction to move forward. At this point, experienced engineers must make conservative and realistic decisions in design. For example, the design of a major structure over ice-rich soil, in a sporadic permafrost region, is a complex project with the associated difficulties in estimating settlements. However, appropriate design concepts, such as the use of thermosyphons, adjustable footings, pile or insulation beneath the foundation, as well as safety factors, will allow these types of projects to move forward and ultimately perform adequately. Another example would be the design and construction of a major railway with numerous culverts and bridges that must proceed on sound engineering design based on reasonable projections of permafrost degradation and climatic conditions over the next 100 years. When dealing with the disposal of hazardous tailings, engineers must consider design concepts that promote ease of rehabilitation for future generations, if eventual loss of containment occurs.

### 3.4.2 Computer Modeling

Recently, finite element computational software programs', such as ABAQUS®, COMSOL Multiphysics™ and GEOTHERM®, have been used to analyze a variety of otherwise mathematically rigorous situations relating to infrastructure design in cold climates. Thermal predictions can be coupled with the engineering concepts to assess the settlement and strength of thawing soil over time using finite element programs. Several studies have been carried out to assess the interaction of oil and gas pipelines in permafrost regions (see for example Xu et al., 2009). Shuguang (2011) suggests that conducting numerical simulations on the thaw-settlement of frozen soil can help guide the designs of subgrade and pavement in permafrost zones. With regard to tailings facilities, many recent projects have used finite element modeling (FEM). Tchekhovski (2005) provides a study of present and future thermal regimes for a tailings disposal facility at Kupol Mine, Russia. A detailed geothermal analysis is also presented by EBA Ltd. (2011) to investigate the long-term impact (with global warming) on the thermal regime underlying a future dry stack tailings facility in Yukon (Bellekeno Mine). Six more typical examples of thermal analyses, relating to northern mining projects, are covered by Zhang and Horne (2010). These include:

- 1) The thermal design of a frozen core dam with thermosyphons for a tailings management facility.
- 2) The thermal design of a ventilated duct system building foundation over ice-rich permafrost.
- 3) A feasibility study of artificial ground freezing around an ore body for managing seepage during underground mining.

- 4) The thermal evaluation of water filling a mined-out pit within a permafrost zone close to an active underground operation.
- 5) The thermal evaluation of dewatered stacked tailings placed over ice-rich permafrost.
- 6) The evaluation of long-term thermal performance of a tailings dyke with a closure cover.

Springman and Arenson (2008) summarize recent advances in physical and coupled modeling. Points particularly relevant to tailings management are listed below (for related references see Springman and Arenson's paper):

- Physical modeling:
  - Physical modeling can be a vital tool in assessing mechanisms of deformation and failure in frozen soil and interaction with structures.
  - Stability models of ice filled jointed rocks have been studied using geotechnical centrifuge modeling. These studies, along with direct shear tests, confirmed that the warming of ice sheets inside a joint critical to the stability of a slope could lead to slope failure. Rock slope instability is often encountered in open pit design in mines.
- Coupled modeling:
  - Constitutive and numerical modeling:
    - Coupled thermo-hydro-mechanical (THM) modeling is not at a practical state to fully model all processes together. Often only one or two dimensional models are used, when in reality problems are three dimensional. Mostly, only two of the three elements (thermal, hydrological and mechanical) are modeled at a time.

- Thawing and freezing under variable groundwater regimes can be well modeled.
- Risk assessments in permafrost zones would benefit greatly from transient simulations with varying boundary conditions that continually alter thermal, hydrological and mechanical effects.
- GIS-based modeling;
  - Can be a useful tool in assessing spatial distributions of ground temperature regimes and active layer depth.
  - They are currently limited by the lack of information on the complex interaction between the atmosphere and ground.

### 3.4.3 Site Investigation and Monitoring

Site investigation is the first and therefore, most important step in infrastructure design. Site investigation in northern regions is complicated by the abundance of cold region phenomena that occur throughout the region and can create complex problems for design engineers (see, for example, Washburn, 1973; Rykaart and Hockley, 2009 or Table 4-7, pg. 58). Site investigations, along with monitoring, are essential in providing geotechnical input on the processes occurring underground. In order to characterize the underlying ground, a number of methods are available (for references to the recent advancement listed below, please see Springman and Arenson, 2006):

- *Airphoto interpretation and terrain analysis*: can be used, along with bedrock geology maps, to develop a reasonable interpretation of permafrost distribution and the probability of ice wedges.

- *Geophysical methods:*
  - Ground penetration radar or electromagnetic surveys can help determine relative ice contents.
  - Nunavut Geoscience’s webpage provides several maps both in interactive and publication-style formats.
  - Boreholes and test pits are required to support geophysical methods.
  - Tomographic inversion techniques can be used to determine ground structure and monitor seasonal active layer thaw.
  - Seismic approaches can help estimate small strain stiffness.
- *Ground temperature measurement:* temperature measuring devices can be placed within boreholes before they are re-filled; certain models can be directly driven into the ground depending on the depth of penetration and soil conditions. A connection wire, usually protected by a PVC pipe, is attached to the temperature device and runs upwards to the ground surface. Ground temperature readings can be taken at any time by re-visiting the site and connecting the lead wires to a data acquisition system.
- *Groundwater pressure measurement:* although groundwater measurements are less applicable in Nunavut where the ground continuously frozen, pressure transducers can be used to determine water pressures below ground if any groundwater exists. They are installed in a similar fashion to the temperature measuring devices.
- *Monitoring:* ground temperature and slope stability (e.g. inclinometer) measurements are useful in monitoring the stability of infrastructure over its lifecycle. Monitoring can be used to regulate future maintenance requirements. Inclinometers, installed within tubing,

can be useless if shearing of the tube occurs due to soil movement (e.g. considerable creep).

- *In-situ tests:*

- In-situ permeability tests (e.g. packer tests) can be helpful in assessing seepage, modeling contaminant transport or designing drainage systems.
- Probes can be used to determine thermal properties of the permafrost, although disturbance due to drilling may make the determination of properties difficult (Overduin et al., 2006).
- Pressuremeter, cone penetration or dilatometer testing can be used to determine shear strength and strain stiffness that can be applied to subsequent designs.

- *Soil and rock sampling:*

- Samples must be extracted with refrigerated fluids (e.g. saline solutions at -4 °C) to minimize disturbance, avoiding melting or rearrangement of soil particles. They can be transported accordingly and kept frozen by packing in dry ice (solid CO<sub>2</sub>) for laboratory testing. Sometimes it is impossible to remove intact samples due to the sensitive blocky nature of soils, particularly when they are released from the natural confining pressures experienced underground.
- Drilling with auger, air-rotary, wet-rotary or hammer drills is preferred.
- Soil samples are obtained from auger core barrels, split spoon drive samplers or hammer drill barrels.
- Permafrost that contains large rocks must be drilled using diamond tipped core barrels. In order to preserve samples, the drilling mud must be saline and

temperature controlled (typically  $-4^{\circ}\text{C}$ ). Winter operation can be undertaken by a simple air-to-mud heat exchange system.

Holubec (2010) presents a comprehensive report on geotechnical site investigation guidelines for building foundations over permafrost. The report provides more detail on drilling and sampling, as well as other site investigation information for northern regions.

### **3.4.4 Laboratory Testing**

A knowledge of the geomaterial properties is essential in designing waste containment facilities. For example, the shear strength of a soil is required to assess the stability of slopes and the permeability is used to estimate fluid transport. Laboratory testing can be used to determine a wide range of soil properties (e.g. strength properties, permeability properties, water or ice content, frozen bulk density, grain size distribution, thaw strain and thaw consolidation properties). Interface tests have also been carried out on ice filled rock joints (Günzel, 2008), which can be useful in open pit slope design.

Triaxial tests have been performed on artificially frozen soil samples (see for example Arenson et al., 2004; Arenson and Springman, 2005). Tests can be performed either by applying a constant strain rate or a constant stress to determine the effect of strain rate, temperature, volumetric ice-solid-air contents and confining stress on the mobilised shear strength of the geomaterials. The Young's modulus ( $E$ ) can be determined by taking the slope of the linear portion of the stress-strain curve from a triaxial test. The peak shear strength can also be determined; the shear strength values for artificially frozen rock specimens have shown to increase with lower ice contents and faster strain rates. Many other observations have been

recorded for a variety of geomaterials through triaxial testing. Past research papers on similar or the same type of geomaterial being considered should be consulted for design and for laboratory experiment planning. In triaxial experiments, it is important to incorporate the initial in-situ stress of a sample and the expected changes to the environment. Stress paths and strength properties at specific confining pressures can be used when performing modeling or design calculations. Triaxial tests are costly and can take an extensive time depending on the experimental scheme required. Split Hopkinson Pressure Bar (SHBP) tests can also be used to determine the Young's modulus of frozen soil. This test can be performed relatively quickly and provides stress-strain information. The heterogeneity and size effects of frozen soil specimens can hinder the appropriateness of laboratory experiments used for representing stress paths.

Direct shear, indirect shear (e.g. Brazilian), direct tension and unconfined compression tests can provide designers with ultimate shear, tensile and unconfined compressive strength estimates. If samples are properly strain-gauged or displacements are measured accurately by other means during tests (e.g. tensile, compression or triaxial tests), the Poisson's ratio can also be determined. The Poisson's ratio tends to increase with stress until it reaches its peak value, can change with temperature or may vary with respect to the loading direction depending on the heterogeneity of the geomaterial; therefore, a conservative value should be chosen in design. Many publications relating to frozen geomaterial testing exist; some of these publications can be downloaded free of charge through the IPA website. See, for example, Lee et al. (2002) for more details of common frozen soil laboratory tests. Finally, it should be mentioned that new technological equipment, such as the powerful CT-Scanner at INRS-ETE (Quebec City), could



be extremely useful tools moving towards 3-dimensionally mapping frozen soil specimens and incorporating the results in modeling applications.

### 3.5 Temperature and Precipitation in Nunavut

Environment Canada’s website provides historical meteorological data for stations across Nunavut. A detailed overview of air temperatures in Nunavut is given by Holubec (2004). Table 3-3 presents an overview of the mean annual air temperatures (MAAT) and mean annual precipitation (MAP) recorded at sixteen stations throughout Nunavut (a total of twenty-three stations exist). Figure 3-5 shows the location of these stations and other hamlets in Nunavut.

**Table 3-3 : MAAT and MAP data in Nunavut for the periods 1951 to 1980 and 1971 to 2000 (Holubec, 2004).**

Nunavut				1951 to 1980		1971 to 2000		Change Warming
Station	Lat., N	Long. W	El., m	MAAT	MAP	MAAT	MAP	
Alert	82 31	62 18	30	-18.2	154	-18	154	0.2
Baker Lake A	64 17	98 04	18	-12.2	235	-11.8	270	0.4
Cambridge Bay A	69 08	105 08	27	-15.1	136	-14.4	139	0.7
Cape Dyer A	68 35	81 37	393	-10.3	663	-11	602	-0.7
Cape Hooper	68 28	88 48	390	-11.8	272	-12	282	-0.2
Clinton point	69 35	120 48	101	-11.2	182	-10.6	168	0.6
Clyde A	70 29	88 31	27	-12.2	208	-12.8	233	-0.6
Coral Harbour A	64 11	83 21	64	-11.6	270	-11.6	286	0
Dewar Lakes	68 39	71 10	527	-13.2	244	-13.3	282	-0.1
Eureka	79 59	85 58	10	-19.7	64	-19.7	75	0
Iqaluit A	63 45	68 33	34	-9.3	433	-9.8	412	-0.5
Kugluktuk A	67 49	115 08	23	-11.6	202	-10.6	249	1
Lady Franklin Point A	68 30	113 13	18	-12.9	110	-12.4	121	0.5
Lupin A	65 45	111 15	490	-12	251	-11.1	299	0.9
Pond Inlet A	72 41	77 58	55	-15.2		-15.1	191	0.1
Resolute Cars	74 43	94 59	67	-16.6	131	-16.4	150	0.2
Average				-13.3	237	-13.2	245	0.2

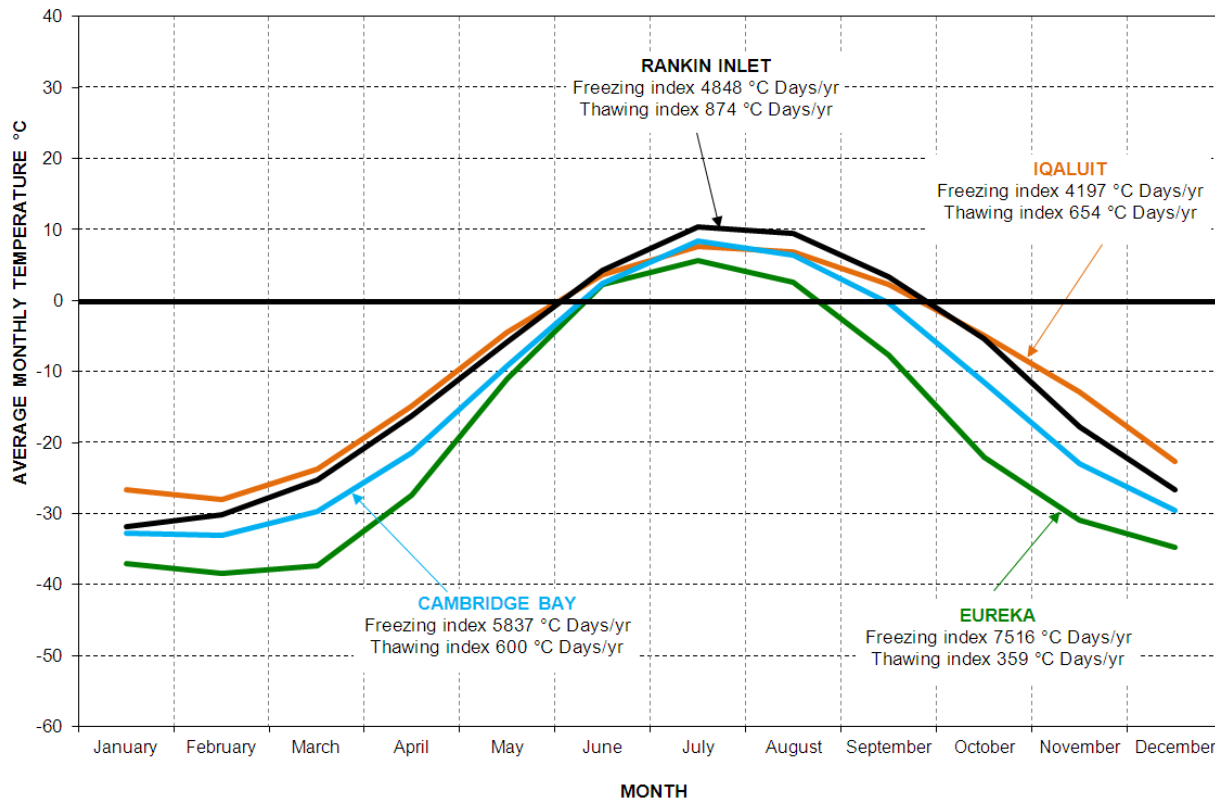
Legend MAAT Mean Annual Air Temperature  
 MAP Mean Annual Precipitation



**Figure 3-5 : Hamlet locations throughout Nunavut (modified after Environment Canada, 2012).**

### 3.5.1 Temperatures in Nunavut

Nunavut has mean annual average temperatures between -9 °C in the southeast (Iqaluit) and -20 °C in the far north (Ellesmere Island). Figure 3-6 summarises the yearly average temperature variation for the 1971 to 2000 period for the villages of Cambridge Bay, Iqaluit, Eureka, and Rankin Inlet. These four villages give a representative distribution of the weather over Nunavut (refer to Figure 3-5 for geographical locations). (Environment Canada, 2012)



**Figure 3-6 : Comparison of average monthly temperatures and air freezing/thawing indices between 1971 and 2000 – Hamlets in Nunavut.**

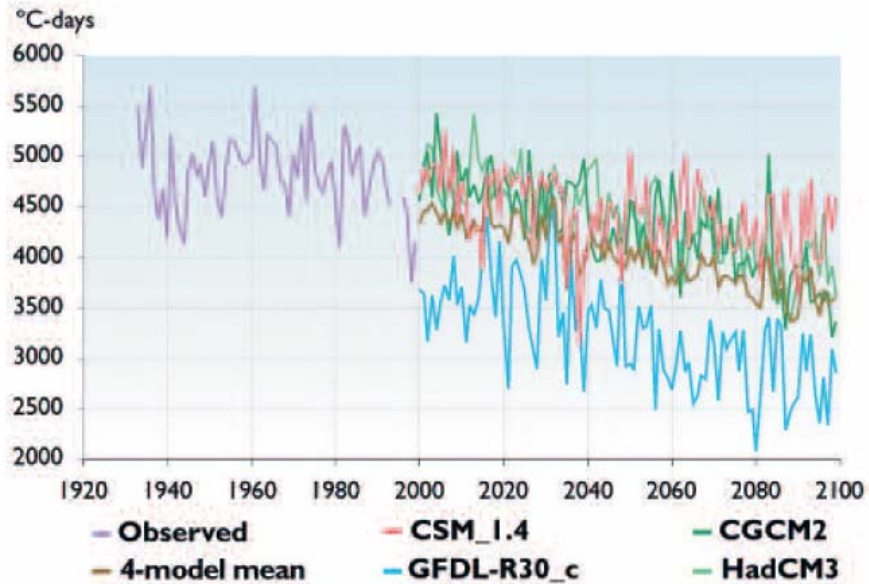
From Figure 3-6, it can be seen that mild temperatures exist between June and September (four months of the year), except in the far north, where the freezing temperatures return earlier. Average temperatures reach a high in mid-July for all villages. Freezing conditions arrive rapidly in autumn to reach very low temperatures (-26 °C to -34 °C) by December and last until the end of February (or into March in the far north). This represents a three month (or four month) period of intense cold. Figure 3-6 also provides the air freezing and thawing indices given in degree-days. The values given emphasize the arctic conditions that exist throughout Nunavut where the ratio of air freezing index (DDF) to air thawing index (DDT) ranges from about 6:1 to 20:1.

Table 3-3 (pg. 35) shows a warming trend between the periods of 1951 to 1980 and 1971 to 2000 for nine stations, a cooling trend for five, and no change for two of the sixteen stations studied in Nunavut. Four of the five stations showing a decrease in temperature trends are located in the eastern part of Nunavut. Holubec (2004) showed warming trends in the eastern Arctic between 1950 and 2000, but noted that the warming trend in this region has reversed since 1990. Regardless, future warming trends are expected in Nunavut and climate warming poses the greatest engineering challenges for the design of tailings disposal facilities (e.g. permafrost degradation).

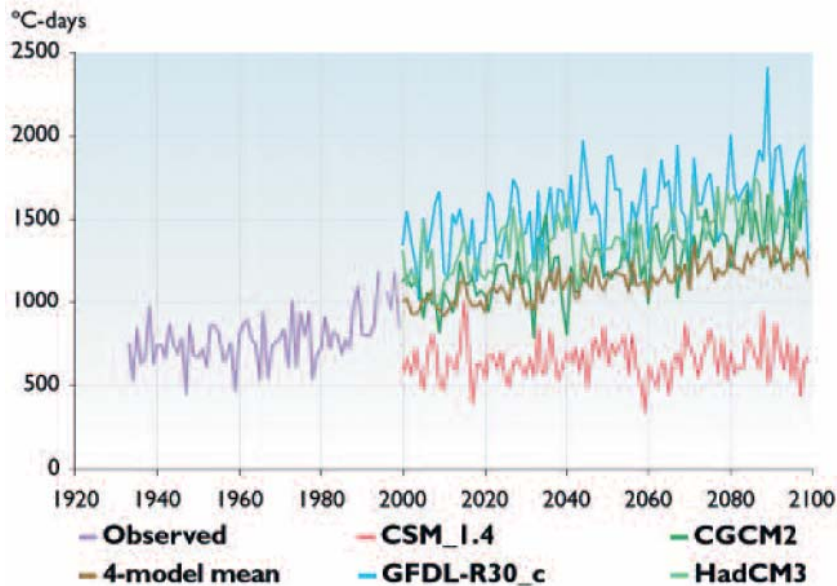
It has been reported that the Arctic Region has experienced three distinct climate changes over the last 100 years. In the period 1900 to 1945, there was a warming trend of 0.03 °C/year. This phase was followed by a cooling period from 1946 to 1965 with an overall cooling of -0.01 °C/year. Another warming trend was reported for the period 1966 to 2003, with an average warming rate of 0.04 °C/year. Recent events and research indicate that the arctic warming will continue in the future and should be taken in account in infrastructure design. (ACIA, 2005)

Currently, many research programs have been conducted to evaluate the expected temperature changes. It has been reported that in the Canadian Arctic there is a possible average increase in air temperatures of 0.04 °C/year for the next 100 years. Therefore, the overall increase in temperature could be about 4 °C by 2100. Model projections also show considerable decreases in the ratios of freezing and thawing index (e.g. decreases in the freezing index and increases in the thawing index). The charts prepared by Instanes and Mjureke (2002) show similar trends for the DDF and DDT in Kugluktuk, Nunavut (see Figures 3-7 and 3-8). These figures give projected

freezing/thawing curves for Kugluktuk, based on five different ACIA-designated models. (ACIA 2005)

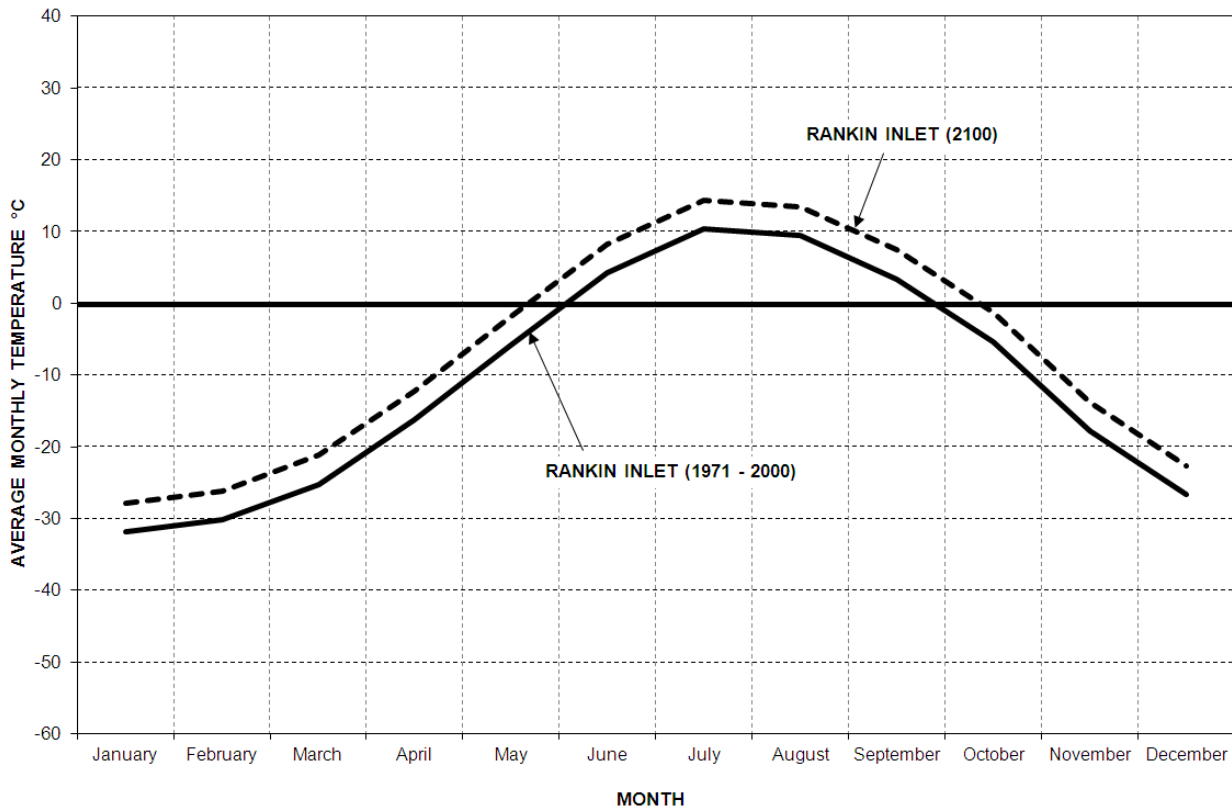


**Figure 3-7: Observed and predicted DDF for Kugluktuk (Coppermine), Nunavut between 1933 and 2100.**



**Figure 3-8: Observed and predicted DDT for Kugluktuk (Coppermine), Nunavut between 1933 and 2100.**

Based on the expected rate of increase in temperatures of 0.04 °C/year, the average temperatures recorded for Rankin Inlet were modified to estimate the temperatures in 2100 (e.g. the average monthly temperatures were simply increased by 4 °C). Figure 3-9 shows the difference in the longer period of above-zero average monthly temperatures (thawing) and the corresponding shorter freezing period.



**Figure 3-9 : Comparison of average monthly temperature conditions between (1971-2000) and (2100) – Rankin Inlet, Nunavut.**

### 3.5.2 Precipitation in Nunavut

The mean annual precipitation for stations in Nunavut is shown in Table 3-3 (pg. 35). The Nunavut area is part of an arctic desert with an average yearly precipitation of only about 240 mm, the majority of which occurs between June and October with little snowfall occurring

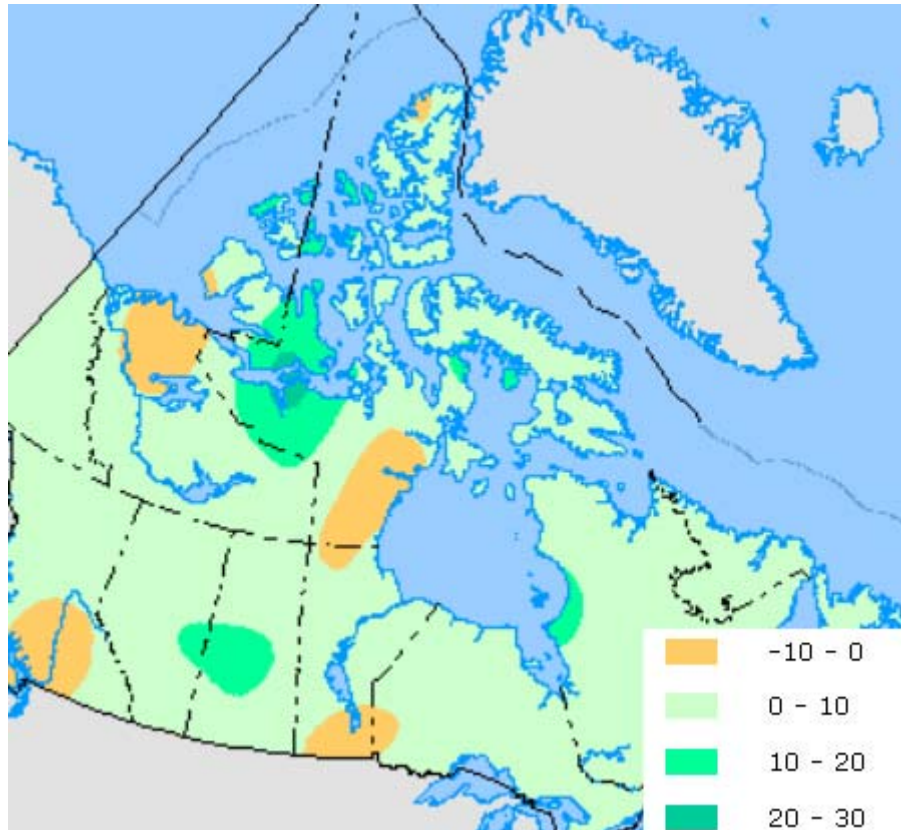
during the winter freezing period. Similar to the temperature distribution, the maximum yearly precipitation (over 600 mm) is found in the southeast and the minimum precipitation (below 100 mm) is seen in the far north on Ellesmere Island. The snow and ice cover over the land and water in the far north prevents evapotranspiration and therefore results in arid conditions.

The low precipitation generally produces low snow cover; the insulating effects of snow cover on the ground are low, and refreezing of the active layer is rapid when a significant lowering of the temperature occurs, particularly under high wind conditions. This therefore explains why Nunavut is in the continuous permafrost zone with the thinnest active layer in Canada. Under these temperature conditions, the active layer in Nunavut should not exceed about 1 metre in ice-rich soils and perhaps 1.5 meters in relatively dry sands or sand and gravel in late summer (August-September).

The low precipitation has the advantage of reducing the volume of water entering basins, providing less flowing water in the tailing storage areas and reducing erosion of drainage channels. The greatest disadvantage is the lack of processing water for large mines where lakes are few or small and shallow (< 2 meters) and freeze to the bottom over winter.

Overall global precipitation is expected to increase as the climate warms up. A simple way to explain this is that more evaporation will occur with warmer weather resulting in increased precipitation. Figure 3-10 shows the expected percentage increase in precipitation for the year 2050 throughout Canada (no forecast is given up to 2100). For the Nunavut region, the figure shows considerable variability in the changes of precipitation from (-10 to +30) %. In addition to

expected average annual changes in precipitation, more frequent heavy precipitation events are projected for Canada (NRTEE, 2010).



**Figure 3-10 : Annual precipitation change (%) from 1961 – 1990 to 2040 – 2050 (Atlas of Canada, 2003).**

## **4 TAILINGS MANAGEMENT IN NUNAVUT**

### **4.1 Overview of the Mining Industry in Nunavut**

Nunavut has substantial mineral potential. Millions of dollars have already been invested in exploration and continued interest is inevitable. The volcanic and metamorphic rock formations across the territory offer numerous possibilities of gold or diamond deposits; the Doris North and Meliadine projects are prime examples of gold mines already in the planning stage, while the



Cullaton Lake/Shear Lake mine produced 77,783 ounces of gold from 1981 to 1985. The Meadowbank Gold Project is expected to produce an average of 360,000 ounces of gold per year over a nine year period (Connell et al., 2008) and is on track to doing so. The Agnico-Eagle Mines (AEM) high grade Meliadine Gold Project is moving quickly to construction in 2014 – 2015. Base metals, such as copper, iron, nickel, zinc and lead, have been detected across the territory. The Baffinland Iron Mine Company is currently working to develop a large open pit iron mine on Baffin Island and Advanced Exploration Inc. is exploring the iron-rich Roche Bay district. The Nanisivik mine (zinc, lead, silver) and Polaris mine (zinc, lead) have been shown to be economically viable. Uranium deposits are also quickly gaining interest; the Areva Kiggaiavik uranium mine project is currently entering a two-year feasibility study and could begin operation as early as 2015. The Kaminac Gold Corp. is exploring the Kivalliq region, located about 300 km southwest of Rankin Inlet, which is believed to hold massive amounts of uranium. (WISE, 2012; NRCan, 1999)

Full details of all active exploration projects in Nunavut are available at <http://nunavutgeoscience.ca>. This webpage provides comprehensive exploration maps and mining overview documents for past years. In 2011, there were 96 mining projects in Nunavut; 38 gold, 14 uranium, 13 base metal, 13 diamond, 7 iron, 5 nickel-copper platinum group element (PGE), 4 rare earth metal and 2 coal related projects. Figure 4-1 shows the locations of closed mines in Nunavut; the Polaris and Nanisivik mines (red) closed in 2002. Figure 4-2 shows mineral exploration sites along with the major rock categories over the territory. Information related to the mining industry in Nunavut can also be found through the ‘Aboriginal Affairs and Northern Development Canada’ website ([www.aadnc-aandc.gc.ca](http://www.aadnc-aandc.gc.ca)).



Figure 4-1: Past mines in Nunavut (after NRCan, 1999).

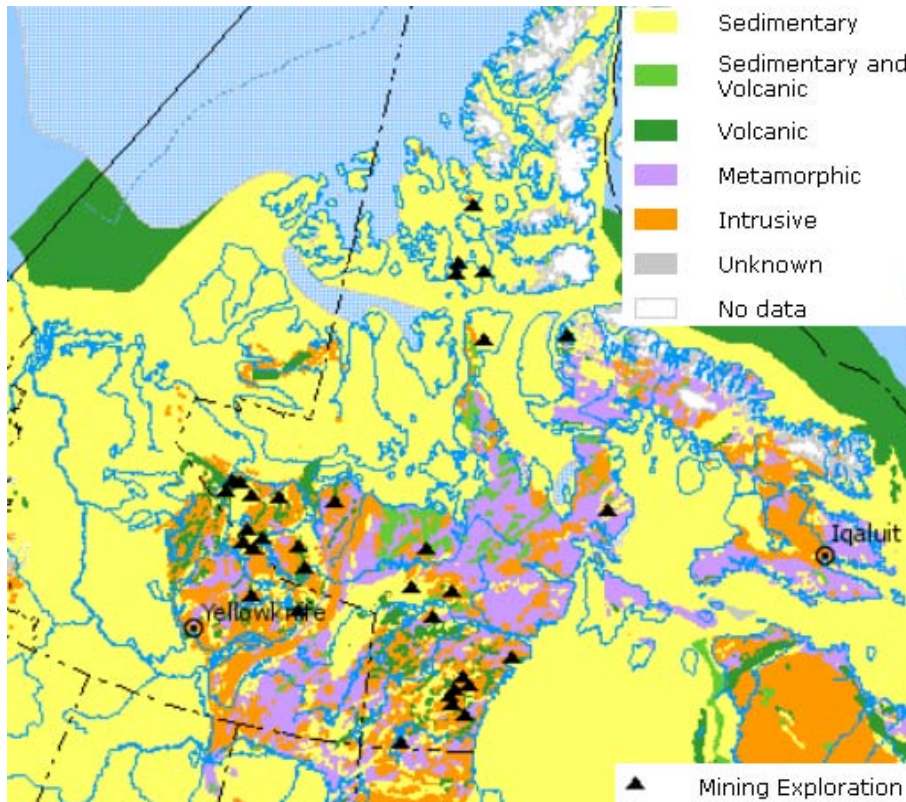


Figure 4-2: Mining exploration and major rock categories in Nunavut (after NRCAN, 1999).

## 4.2 Tailings Disposal Methods Chosen by Mines in Permafrost Regions

Tables 4-1 and 4-2 outline the tailings deposition methods used, or planned to be used, by mines in permafrost regions. The tables identify the chosen methods of disposal for mines in permafrost regions, which can be divided into two main groups; sub-aqueous (underwater) and sub-aerial (land based). Table 4-1 shows the predominance of sub-aqueous disposal as the ‘method of choice’ for recent mines in Nunavut; the Doris North Project and the Meadowbank Gold Project. Both projects give detailed reports in determining the optimum solution for tailings disposal based on numerous environmental, socio-economic, engineering and project economic factors (please refer to Rykaart, 2005a and 2006; Golder Associates, 2007). As mentioned previously, the optimum disposal method for tailings is ultimately a case by case decision. Each disposal method has advantages and disadvantages. The surrounding landscape and climate conditions are primary components in choosing a disposal technique. Within the ‘Notes’ column of the tables, the environmental issues/concerns are highlighted in red. Within the ‘Tailings Disposal Method’ column, cells are highlighted in grey where backfilling disposal methods were or are to be used. In Table 4-2 the mines are given in order, from top to bottom, of tailings water content; mines that dispose slurry tailings are given at the top and mines that dispose dewatered/filtered tailings are shown at the bottom.

**Table 4-1 : Sub-aqueous tailings disposal methods in permafrost regions.**

Mine Name	Current Owner	Location	Tailings Disposal Method	Mining Life	Notes
Ruttan Mine	Hudson Bay Mine and Smelting	Northern Manitoba	Sub-aqueous slurry	1973 - 2002	
Thompson Mine	Vale - Inco	Northern Manitoba	Sub-aqueous slurry	1959 - to date	
Red Dog Mine	Teck Cominco	Alaska	Sub-aqueous slurry	1987 - to date	- Problems with wind-blown ore dust and wastewater discharge have occurred. (GTT, 2011)
Voisey's Bay Mine	Vale - Inco	Northern Labrador	Sub-aqueous slurry	2005 - to date	
Key Lake Mine	Cameco	Northern Saskatchewan	Sub-aqueous slurry	1983 - to date	
Doris North Project	Miramar Hope Bay Ltd.	Nunavut	Sub-aqueous slurry	planned	- Dry stacking was considered too complex. Mine on hold indefinitely.
Rabbit Lake Mine	Cameco	Northern Saskatchewan	Sub-aqueous slurry	1975 - to date	
Polaris Mine	Teck Cominco	Nunavut	Sub-aqueous thickened	1979 - 2002	- Groundwater flow from contaminated lake to Arctic Ocean. (Pollard et al., 1998)
Meladine Mine	Agnico-Eagle Mines	Nunavut	Sub-aqueous thickened (tentative plan)	planned	- Dust and cost are primary concerns for landbased disposal.
Meadowbank Gold Project	Agnico-Eagle Mines	Nunavut	Sub-aqueous and sub-aerial slurry, paste backfill	2010 - to date	- Permafrost encapsulated.
Nanisivik Mine	Breakwater Resources Ltd.	Nunavut	Sub-aqueous and sub-aerial slurry	1976 - 2002	- Initially deposited in lake until filled, permafrost encapsulation.
Jericho Mine	Shear Minerals Ltd.	Nunavut	Sub-aqueous	2006 - to date	- Operation from 2006 to 2008 and planned to re-start shortly.
Ekati Mine	BHP	NWT	Sub-aqueous and sub-aerial thickened (50%)	1998 - to date	- Acid rock drainage problems (Morin, 2003), tailing spill (Mathisen,2008).
Colomac Mine	Comaplex Minerals Corp.	NWT	Sub-aqueous and sub-aerial slurry	1989 - 1997	- Environmental problems with cyanide contamination of tailings water and seepage. (NCSP, 2006)
Kensington Mine	Coueur Alaska Inc.	Alaska	Sub-aqueous, paste backfill	2010 - to date	- Perpetual risk of acid mine drainage. (GTT, 2011)

**Table 4-2 : Sub-aerial tailings disposal methods in permafrost regions.**

Mine Name	Current Owner	Location	Tailings Disposal Method	Mining Life	Notes
Copper Cliff Mine	Vale - Inco	Sudbury, Ontario	Sub-aerial slurry	to date	
FlinFlon Mine	Hudson's Bay Mine and	Northern Manitoba	Sub-aerial slurry	to date	
Fort Knox and True North Mine	Kincross Gold Corp.	Alaska	Sub-aerial slurry	2009 - to date	- In dammed valley: closure will be sub-aqueous using eng. wetlands.
Rankin Inlet Mine	Asamera Mineral Inc.	Nunavut	Sub-aerial slurry	1957 - 1962	- Remediation (1991); permafrost encapsulation. Before, released acidic and metal rich water to Hudson Bay. Oxidized tailings dust spread as well.
Lupin Mine	Echo Bay Mines Ltd.	Nunavut	Sub-aerial slurry, paste backfill	1983 - 2005	- Permafrost encapsulation, cyanide contaminated tailings.
Julietta Mine	Yanskaya Mining and Geo. Comp.	Russia	Sub-aerial: Slurry (present)	2001- to date	- Paste tailings in surface facility (previously)
Kupol Mine	Kincross Gold Corp.	Russia	Sub-aerial slurry	2008 - to date	- Permafrost encapsulation, cyanide contaminated tailings.
Mount Polley	Imp. Metals Corp.	BC	Sub-aerial slurry	1997 - to date	
Kumtor Mine	Cameco, Kyrgyz Govt	Kyrgyzstan	Sub-aerial	-	
Con Mine	Newmount Mining Corp.	NWT	Sub-aerial	1938 - 2003	
Giant Mine	Miramar Mining Corp.	NWT	Sub-aerial	1948 - 2004	- Massive amounts of arsenic trioxide dust (NCSP, 2006). Thermosyphons used to freeze and contain contaminated soils.
Snap Lake Mine	De Beers	NWT	Sub-aerial paste, paste backfill	2008 - to date	- First fully underground diamond mine in Canada.
Diavik Mine	DDMI, Rio Tinto	NWT	Sub-aerial, crushed waste rock or paste backfill	2003 - to date	
Nunavik Nickel Mine	Canadian Royalties	Northern Quebec	Sub-aerial: Thickened tailings and waste rock	Planned	
NICO Project	Fortune Mineral Ltd.	NWT	Sub-aerial: Thickened tailings and waste rock	Planned	
Ryan Lode Mine	Bartholome	Alaska	Sub-aerial: Lined earth dam with reclaimed water system	1987 - 1989	
Kubaka Mine	Omolon Mining Comp.	Russia	Sub-aerial: Two level: Upper dry and lower fluid	-	- Permafrost containment.
Kemess Mine	Northgate	BC	Sub-aerial: Dewatered slurry	1998 - to date	
Huckleberry Mine	Imp. Metals Corp.	BC	Sub-aerial: Dewatered slurry	1997 - to date	
Illinois Creek Mine	Quest Capital Corp.	Alaska	-	1997 - 1998	- Company declared bankruptcy leaving State of Alaska to reclaim mine.
Prairie Creek Mine	Canadian Zinc.	NWT	Paste backfill	Planned	- All tailings will be backfilled.
Greens Creek Mine	Hecla	Alaska	Dry stack, rock fill and cemented paste backfill	1993 - to date	- Environmental concern related to ARD and dust. (GTT, 2011). Nearly 80% of cavities will be re-filled at closure.
Raglan Mine	Xstrata Nickel	Quebec	Dry stack, open pit, paste backfill	1997 - to date	- Permafrost encapsulation.
Minto Mine	Sherwood Copper Corp.	Yukon	Dry Stack, then thickened open pit	2007 - to date	- Upon completion of mining in open pits, thickened tailings will be disposed by pumping in pits.
Bellenkeno	Alexco Resource Corp.	Yukon	Dry stack, paste backfill	2011 - to date	- Tailings disposal plans for 60% surface, 40% underground.
Nixon Fork Mine	St. Andrews Goldfields Ltd.	Alaska	Dry stack (new disposal plan)	1993- to date	- In the past, earth dam was used for tailings disposal.
Pogo Mine	Teck Cominco	Alaska	Dry stack, paste backfill	2006 - to date	

### 4.3 Environmental Considerations

Several reports have been published relating to disposal of contaminated mine waste in the Arctic and in cold climates. The Mine Environment Neutral Drainage (MEND) program has published some of the most comprehensive reports relating to disposal of potential acid generating (PAG) tailings in cold regions (see Table 4-3). These reports provide great detail on cold regions mining and are available through the MEND website.

**Table 4-3 : MEND reports relating to cold regions mining.**

<b>MEND Project</b>	<b>Title</b>	<b>Year</b>
6.1	Preventing AMD by Disposing of Reactive Tailing in Permafrost	1993
1.61.1	Roles of Ice, in the Water Cover Option, and Permafrost in Controlling Acid Generation from Sulphide Tailings	1996
1.61.2	Acid Mine Drainage in Permafrost Regions: Issues, Control Strategies and Research Requirements	1996
1.61.3	Column Leaching Characteristics of Cullaton Lake B and Shear (S) - Zones Tailings Phase 2: Cold Temperature Leaching	1997
1.62.2	Acid Mine Drainage Behaviour in Low Temperature Regimes - Thermal Properties of Tailings	1998
W.014	Managing Mine Wastes in Permafrost Zones, Summary Notes MEND Workshop	1997
5.4.2d	MEND Manual, Volume 4 - Prevention and Control, Chapter 4.8 Permafrost and Freezing	2001
1.61.4	Cover for Reactive Tailings Location in Permafrost Regions Review	2004
1.61.5a	Mine Waste Covers in Cold Regions	2009
1.61.5b	Cold Regions Cover Research	2010
1.61.6	Update on Cold Temperature Effects on Geochemical Weathering	2006
1.61.7	Climate Change and Acid Rock Drainage - Risks for Canadian Mining Sector	2011

Various reports have been submitted as part of the environmental assessment process for mining projects. These reports provide some information relating to issues that were raised concerning climate change and tailings disposal, and the approaches taken to address them; see, for example, the recent environmental assessment reports for cold regions mining projects in North America: Voisey's Bay Mine (Griffiths et al., 1997), Diavik Mine (CEAA, 1999), Snap Lake Mine (Wray et al., 2003), Pogo Mine (EPA, 2003) and Fort Banks and True North Mines (Golder Associates, 2004). Guidelines of an inclusive framework for an environmental impact assessment are given by Yap (2003), which is available on the Canadian Environmental Assessment Agency webpage ([www.ceaa-acee.gc.ca](http://www.ceaa-acee.gc.ca)). Furthermore, a paper titled "Guidelines for Alternatives Assessments for Mine Waste Disposal" is available through the Environment Canada website ([www.ec.gc.ca](http://www.ec.gc.ca)) (Environment Canada, 2011).

Table 4-4, taken from the report on tailings alternatives for the Meadowbank Gold Project, gives the typical environmental considerations for the construction of a tailings facility. Land or water use and the loss of wildlife are major concerns for any mine. Potential for geotechnical failures are primary concerns when building containment structures. Potential for airborne dust emissions, transported by wind to air, land and water, can be a considerable pollutant (see Section 4.6.1.2). In Table 4-4, acid rock drainage (see next section; Section 4.3.1) and metal leaching from tailings are given as potential threats. Other hazardous chemicals can be generated during mining processes. For example, in order to extract precious metals from the ore, hazardous chemical solutions such as sodium or potassium cyanide (e.g. used for gold processing) and hydrochloric acid are used (MPC, 2000). The main concern is preventing the spread of chemicals to natural water sources. If water is able to enter contaminated tailings piles,

the water can transport the hazardous chemicals to local groundwater sources; therefore, proper cover or drainage and collection of the surface water is crucial.

**Table 4-4 : Typical environmental factors for a tailings facility (Golder Associates, 2007).**

	Sub-Indicators
<b>Environmental Factors</b>	Sub-catchment area
	Footprint area
	Potential for generating dust during operation
	Potential for generating dust after closure
	Potential for Acid Rock Drainage (ARD) generation during operation
	Potential for ARD generation after closure
	Potential for metal leaching (ML) during operation
	Potential for ML after closure
	Potential for seepage to impact groundwater during operation
	Potential for seepage to impact groundwater after closure
	Potential for geotechnical hazards <sup>1</sup>
	Permanent aquatic habitat loss [Lake area impacted] <sup>2</sup>
	Temporary aquatic habitat loss [Number of lakes impacted] <sup>2</sup>
	Visual impact
	Terrestrial wildlife habitat loss (song birds, water fowl and terrestrial mammals) <sup>2</sup>
	Aquatic wildlife habitat loss (water fowl) [Impact on fish and fish habitat] <sup>2</sup>

Note:

- 1 Includes consideration of foundation conditions, impact of seismicity, and height of structure.
- 2 Categories added at request of DFO and EC (i.e., new and additional sub-indicators to original study). Square brackets indicate sub-indicators in original tailings site selection document (Golder, October 2005), and modified for Technical Memorandum (Golder, February 2006).



### 4.3.1 Acid Mine Drainage (AMD)

Acid mine drainage (AMD) is a widely encountered concern and numerous cases of environmental hazards due to abandoned tailings waste have been documented. Many rocks naturally contain sulphide minerals (e.g. pyrite, pyrrhotite, etc.) that, when exposed to air and water, will oxidize and form sulphuric acid. This natural process is referred to as acid rock drainage (ARD). Acid mine drainage (AMD) is essentially the same process, but on a much larger scale. AMD can lead to severe environmental consequences. The more acidic drainage water, which now contains sulphuric acid, will also increase the potential for metal leaching. In order to prevent oxidization, the available oxygen surrounding the tailings should be kept to a minimum. Table 4-5 lists control strategies for AMD (from MEND 1.61.2). In addition, limestone can also be used to neutralize acid drainage when readily available. Co-disposal methods (e.g. inclusion of tailings in mine waste rock) can also be used to reduce oxygen flux and infiltration to control acid mine drainage. Again, refer to the MEND reports (see Table 4-1) for more information related to AMD. (Mehrotra and Singhal, 1992)

**Table 4-5 : Control strategies for acid mine drainage in Arctic (Dawson and Morin, 1996).**

Strategy	Tailings	Waste Rock
Freeze Controlled	<ul style="list-style-type: none"> <li>• Total or perimeter freezing options can be considered</li> <li>• Can freeze up to greater than 15 m annually if freezing in thin layers</li> <li>• Process chemicals could cause high unfrozen water contents</li> </ul>	<ul style="list-style-type: none"> <li>• Requires considerable volumes of non-acid waste rock for insulation protection</li> <li>• Better understanding of air and water transport through waste rock required for reliable design</li> </ul>
Climate Controlled	<ul style="list-style-type: none"> <li>• May not be a reliable strategy for saturated tailings</li> </ul>	<ul style="list-style-type: none"> <li>• Requires control of convective air flow through waste rock, infiltration control with modest measures and temperature controls</li> <li>• Better understanding of waste rock air, water, and heat transport for reliable design</li> </ul>
Engineered Cover	<ul style="list-style-type: none"> <li>• Special consideration for freeze-thaw effects</li> <li>• Availability and cost of cover materials are major impediments</li> </ul>	
Subaqueous Disposal	<ul style="list-style-type: none"> <li>• Special considerations for winter ice conditions and pipeline freeze-up</li> </ul>	<ul style="list-style-type: none"> <li>• Very difficult to dispose of waste rock beneath winter ice</li> </ul>
Collection and Treatment	<ul style="list-style-type: none"> <li>• Costly to maintain at remote locations</li> <li>• Long term maintenance cost</li> </ul>	
Segregation and Blending	<ul style="list-style-type: none"> <li>• Tailings are normally geochemically homogeneous</li> </ul>	<ul style="list-style-type: none"> <li>• May be very effective</li> <li>• Research and development on-going</li> </ul>

### 4.3.2 Cover Design in Permafrost Regions

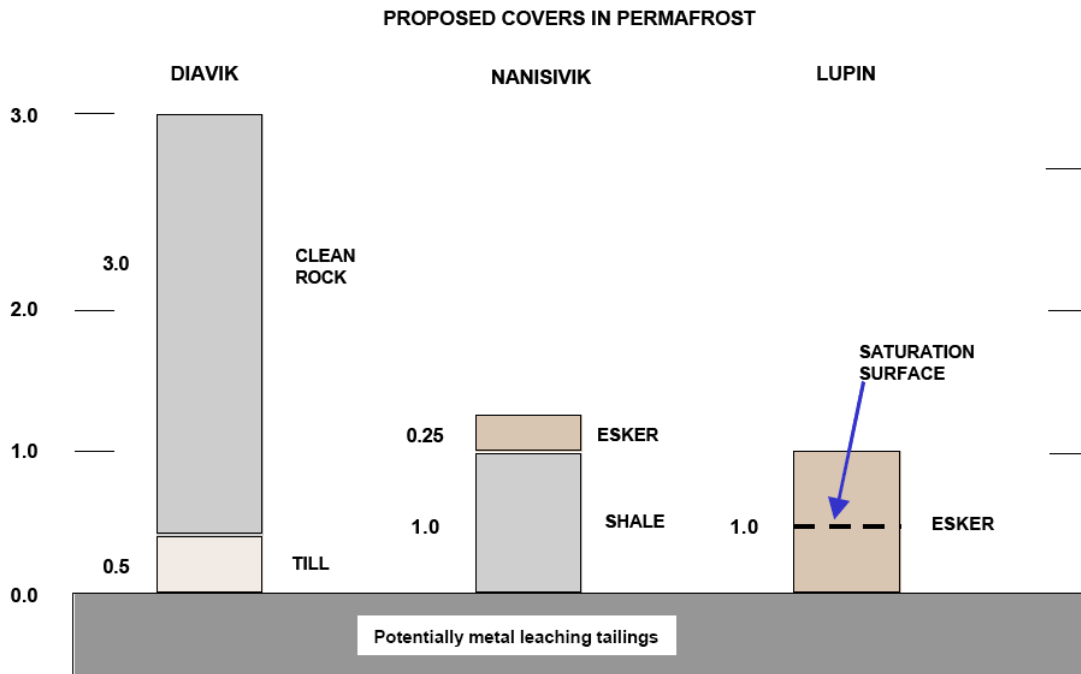
Covers are placed over reactive tailings deposits in order to prevent oxidation of the tailings, which could lead to negative environmental impacts. The design of covers over tailings disposal sites, in continuous permafrost regions, is usually done by encapsulating the tailings in a frozen state. These are referred to as insulation covers. The recommended temperature at the depth/level of zero annual amplitude, see Figure 3-4 (pg.21), [otherwise known as the mean annual ground design temperature (MAGDT)], is -2 °C for cover design by encapsulation. The small difference (~0.3 °C) between MAGDT and mean annual ground surface temperature (MAGST), due to the

generally small thermal gradient, can allow designers to use the available mean annual near-surface ground temperature (MAGST) data for preliminary design or feasibility studies. MAGST data (see Figure 3-1, pg. 18) is also given in more detail by Smith and Burgess in the open file GSC report (File Rpt 3954, 2000). Holubec (2004) presents a relationship between the mean annual air temperature (MAAT) and MAGST, which is linear, but shows that a considerable spread can occur between the two. Ultimately, the report concludes that MAGST data must be measured at a representative location for the final cover design. Encapsulation of permafrost is achieved by covering the frozen tailings, during the winter, with a suitable thickness of material that will contain the active layer within the cover. This is usually achieved in two main ways:

- 1) Using a thicker layer of inert waste rock to contain the active layer or
- 2) Using a thinner inert waste rock cover, underlain by a fine-grained high water content layer, where an ice-rich permafrost zone develops and retards thawing during the summer period.

The designs are obviously limited by cost and material availability. Finer materials will provide more insulation per unit length, since they tend to remain saturated and frozen, thereby providing more insulation. Esker material (e.g. sand and gravel) is commonly used for cover design; however, in the Arctic, these deposits should be conserved as they provide preferred habitats for animals. In addition, they are not always available in close proximity to the site and can only be obtained after the summer thaw. This does not provide for a long construction period unless the material is drilled and blasted at the beginning of the thawing period. The use of inert waste rock or blasted quarry rock provides for a longer construction period.

Another design alternative used in cold regions is to cover the tailings with a saturated zone of esker material (e.g. sand and gravel). A 0.3 m saturated and frozen zone of esker material can prevent oxidization of the tailings below by limiting oxidization. The three main design concepts for covers in permafrost regions are displayed in Figure 4-3. (Holubec, 2004)



\* Note: All dimensions are in meters.

**Figure 4-3: Typical design concepts for cover in permafrost regions (Holubec, 2004).**

Historical field data for cover designs has only recently become available; Holubec (2004) presents detailed investigations of cover designs for the first field projects. Table 4-6 summarizes the main conclusions obtained from these studies (e.g. Nanisivik, Raglan, Lupin and Rankin Inlet mines), which highlight the benefits of constructing tests pads, during operations, to monitor the performance of cover design alternatives. These benefits include optimizing the final cover design and providing valuable research for future cover design endeavours.

**Table 4-6 : Control strategies for acid mine drainage in Arctic (after Holubec, 2004).**

Mine and location	Cover design	Key notes and observations
<p><b>Raglan Mine</b> Northern Quebec</p>	<p>Total thickness of 2.4 m; bottom layer 1.2 m (crushed sand and gravel esker) top layer 1.2 m (mine waste rock).</p>	<p>- Provides an example of difficulties in establishing long-term and extreme climatic conditions in remote Arctic Region.</p> <p>- Provides field data supporting the theory that the active layer thickness decreases as the bottom layer accumulates water, via snow runoff and rain infiltration, which saturates zone directly over the tailings. Crushed esker layer contains a min. of 10 % fines to hold moisture (increases latent heat and retards thawing process). It is assumed a fully saturated/frozen zone will develop at the base of the cover.</p>
<p><b>Nanisivik Mine</b> Nunavut</p>	<p>Total thickness of 1.25 m; 1 m of shale overlain by 0.25 m of sand and gravel.</p>	<p>- For a given moisture content, the thaw depth is governed by the thawing index (from 8 years of monitoring). The thaw depth was a function of moisture content, as moisture content increased, thaw depth decreased.</p> <p>- Lighter cover material will likely reduce the thaw depth based on observations.</p>
<p><b>Lupin Mine</b> Nunavut</p>	<p>Sand and gravel esker material of varying thickness (0.6 m to 1.6 m).</p>	<p>- Active layer was observed to be a function of groundwater table. The lower the groundwater table (e.g. saturation level), the deeper the active layer penetrated into the cover (or in some case into the tailings below).</p> <p>- A 0.3 m thick layer of saturated esker may be even more efficient than 0.3 m of stagnant water cover in preventing oxidation. (Note: 0.3 m of stagnant water was shown to be sufficient in preventing oxidation in southern mines).</p> <p>- Durability of the cover is not based on permafrost, therefore, temperature warming alone is not an issue for this type of cover design.</p> <p>- As has been previously shown with gravel pads, thinner esker covers (e.g. 1 m or less) could support and promote vegetation because they contain more moisture or the groundwater table is near ground surface.</p>
<p><b>Rankin Inlet Mine</b> Nunavut</p>	<p>Sand and gravel esker material of 1 m thickness.</p>	<p>- Shows difficulties encountered when pore water in tailings has a depressed freezing point. The freezing point can be depressed (lowered) as a result of infiltration of sea water, mill water chemistry or sulphide oxidation. Establishing temperatures at which freezing occurs is difficult. A zone of unfrozen water is created as salinity increases.</p>

Another variable affecting the active layer thaw depth, besides those mentioned in Table 4-6 (e.g. vegetation cover, moisture content and colour/albedo), is surface orientation. This should be taken into account in the design; orienting tailing facilities to minimize sun exposure could help reduce the active layer depth at no additional cost. Since the publication of Holubec's report (MEND report 1.61.4), a lot of research has been carried out on cold regions cover design and MEND reports 1.61.5a and 1.61.5b provide the latest advances. The MEND report 1.61.5a provides several recommendations, relating to cover design, for practitioners, regulators and others involved in the mining sector. Designers should be aware of the wide range of considerations associated with cover design. In addition to a knowledge of special cold regions phenomena (cold regions features and processes), in-depth site investigations are required to establish specific site conditions required for design. Cold regions phenomena that could affect cover design are given in Table 4-7.

**Table 4-7 : Cold regions phenomena that may affect cover designs (Rykaart and Hockley, 2010).**

	Cover Types						
	Water Cover	Wet Cover	Barrier Cover	Geomembrane Cover	Store-and-Release Cover	Isolation Cover	Insulation Cover
<b>Frozen Ground Phenomena</b>							
Ground freezing and ground ice formation	N	N	E1	E2	E1	E2	E3
Ground thawing and thaw settlement	N	N	E2	E2	E2	E2	E2
Freeze-thaw cycles	N	N	E1	E2	E1	E2	E3
Cryoturbation	N	N	S2	S2	S2	S2	S2
Mass-wasting (including solifluction/gelifluction)	N	N	S1	S1	S1	S1	S1
Convective cooling	N	N	N	N	N	S2	E1
Ice wedges	N	N	S1	S2	S1	S2	S2
Palsas	S1	S1	N	S2	N	N	N
Pingos	S1	S1	N	S2	N	N	N
Thermokarst	N	S2	E1	E2	E2	E3	E3
Patterned ground	N	N	S1	S1	S1	S2	S1
Boulder fields and pavements	N	N	S1	S2	S2	S2	S2
Mounds and/or hummocks	N	N	S1	S2	S2	S2	S2
Seasonal frost mounds	N	N	S1	S2	S2	S2	S2
Mudboils, circles and diapirs	N	N	O3	O3	S1	S1	S3
Involutions	N	N	E2	E2	E2	E2	S3
Rock glaciers	N	N	N	N	N	S3	S3
Ploughing boulders	N	N	S2	S2	E2	S2	S2
<b>Cold Region Hydrologic Phenomena</b>							
Snow accumulation and ablation	N	N	E2	E2	E1	E2	E1
Snowmelt	N	N	E2	E2	E1	E2	E1
Evapotranspiration	N	N	E2	E2	E1	N	E2
Surface water drainage	E2	E2	E2	E2	E1	E2	E2
Aufeis	N	S2	N	N	S1	S2	S2
Infiltration to frozen soils	N	N	E1	E2	E1	E2	E3

**Note: Explanation of Codes:**

Strength of evidence:  
O – Observed  
S – Suspected  
E – Expected to occur but not yet observed  
N – Not expected to occur

Likelihood of detrimental effects  
1 – Likely  
2 – Unlikely  
3 – Uncertain

The MEND report 1.61.5a expands on several topics of cold regions phenomena that can affect covers. These subjects are outlined and expanded briefly below (Rykaart and Hockley, 2009):

- Industry experience:
  - A list of cover designs implemented or planned in cold regions, in North America and Europe, is provided. Few of the covers designed have been reviewed from a “cold regions” perspective and detailed reports for these sites are not always available, so few case studies can actually be studied in detail. The industry is still at the beginner phase in terms of cover design knowledge and understanding.
- Cover selection and design considerations:
  - *Cover types*: isolation covers, barrier covers, store-and-release covers, water covers and, most notably for cold regions, insulation covers.
  - *Cold regions effects on mine waste*:
    - Permafrost degradation below mine waste facilities: settlement of structures, movement of waste and changes to seepage.
    - Ice entrainment: ice within the mine waste occupies a volume that otherwise would contain tailings and the ice may be intermediate or long-term. This results in possible differential settlement concerns. Ice entrainment in waste rock piles or during construction of covers can affect the cover design (e.g. ice melting/movement can damage geosynthetics).
    - Other frozen ground features within mine waste: no records of large scale features observed, but tailing could be susceptible to growth of ice lenses,



frost heave, formation of pingos and palsas and desiccation cracks leading to possible formation of ice wedges.

- Convective cooling of mine waste: based on grain size distribution of the waste rock, it should be susceptible to convective cooling leading to the aggradation of underlying permafrost.
  - Geochemical weathering: low temperatures tend to slow the oxidation process.
- Frozen ground effects on cover performance:
    - *Freeze-thaw effects*: usually leads to significant increases in permeability.
    - *Frost susceptibility*: required combination of fine-grained soils, sufficient water and sufficient cooling to cause soil to freeze.
    - *Migration of fines through covers*: the term ‘boils’ has been adapted to describe the occurrence of mounds of fines appearing through the covers.
    - *Other potential ground effects*: frost heaving, solifluction (slow down-slope flow of saturated unfrozen earth), boulder fields (frost action pushing cobbles and boulders to the surface in loose till, whereas in dense till cobbles and boulders can move downwards).
  - Hydrological effects on cover performance:
    - *Snow and surface water*: difficulties in predicting hydrology.
    - *Soil water and groundwater*: covers that include interflow drains can be subject to formations of a sheet-like mass of layered ice (aufeis).

- *Cold regions hydrological process models*: several models designed to represent snowmelt and frozen ground infiltration processes are discussed in the report.
- Other effects on cover performance:
  - *Vegetation*: concerns that root penetration can lead to preferential flow paths and metal uptake by vegetation. Shallow rooted species sometimes preferred.
  - *Animals*: caribou migration over or near tailings facilities may result in substantial erosion or local liquefaction and boils of covered tailings. Also, the presence of salts in waste areas can attract animals.
- Effects on cover construction:
  - *Logistics*: very remote locations experience great difficulties in transporting material. As an example, the proposed Doris North Project located near Kugluktuk in Nunavut, has opted to bring in annual supplies by barges staged out of Hay River. Their estimated shipping time is eight weeks; therefore, proper planning of supplies required must be carried out well before the first shipments arrive in August and must provide a full year's requirements (Rykaart, 2005b). The available work force is usually housed in a camp and transportation to and from the site is costly. The use of geosynthetics or other more complex design materials requires that specialists be brought on site, making these already expensive construction alternatives even more costly.
  - *Productivity*: worker productivity is lower in extreme climate conditions and daylight hours can be limited.
  - *Soil placement*: quick freezing of soils, snow fall and compaction issues.

- *Trafficability*: construction over soft unconsolidated tailings is a considerable challenge.
- *Use of geosynthetics*: generally less economical unless natural material is not readily available. Geosynthetics have a specified lifespan and strict specifications on handling, transporting and storing.
- *Availability of material*: the thawed active layer is only accessible in late summer or autumn and is often limited in quantity unless acquired from drill and blast methods. Construction can be accelerated using inert waste rock or blasted rock and screening.

Phase 2 of the mine waste cover in cold regions report (MEND report 1.61.5b) expands on the current research; the following items are specifically covered in the report:

- The role of vegetation on cold regions covers is reviewed and literature relating to evapotranspiration, erosion and rooting is presented.
- Modeling of cold regions soil covers and related hydrologic processes are reviewed and related literature is provided.
- Convective cooling application in cover design is reviewed and possible applications for both flat and sloping soil cover designs are examined.
- Insulating layers within low permeability barrier covers are reviewed.
- Tables that summarize recent cover trials or cover research programs are provided.

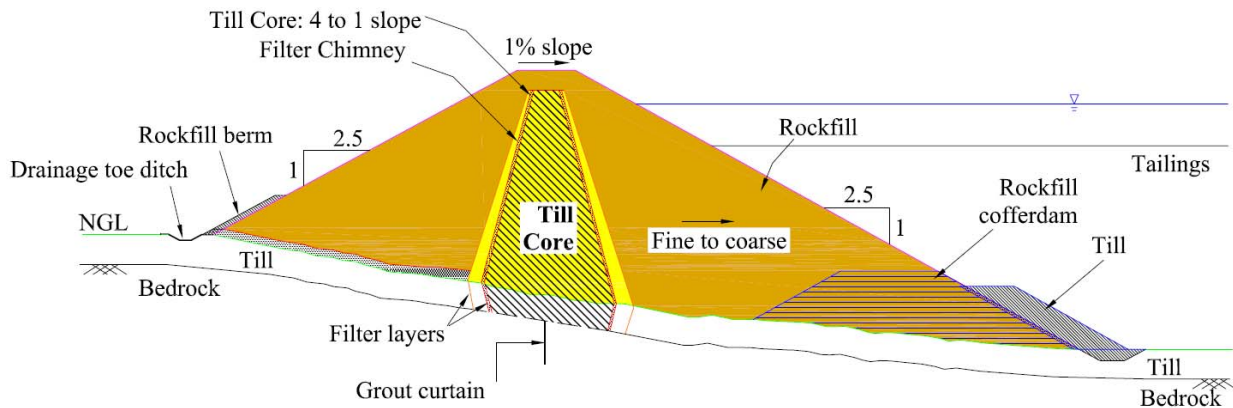
#### 4.4 Dam Construction in Permafrost Regions

In some cases, temporary dams are required for water diversion; however dams are usually required to be permanent structures for tailings disposal facilities. This section focuses on dam construction and design alternatives for permanent dam construction. A detailed alternative evaluation of a water retaining dam construction for the Doris North Project in Nunavut is given in Rykaart (2005a). Martin et al. (2002) provide a brief review and perspective of tailings dam failures, outline dam construction techniques to prevent failure and outlines the use of impermeable lined impoundments for containing highly contaminated tailings. The construction of tailings dams on permafrost is similar to construction in the more temperate zones except that the dams are usually built on bedrock or permanently frozen till which, if degraded, will result in differential settlements of the retaining structures. This could lead to cracking and fracturing of the dam and may result in leakage or dam failure. Smith (1996) provides a review of earth dams construction in cold regions. Russian engineers have been constructing dams over permafrost for many years; one of the first examples dates back to 1792. In continuous permafrost regions, like Nunavut, the ‘cold construction method’ is the most practical construction method. The cold construction method entails maintaining the underlying ground and most of the dam in a frozen state (e.g. frozen core).

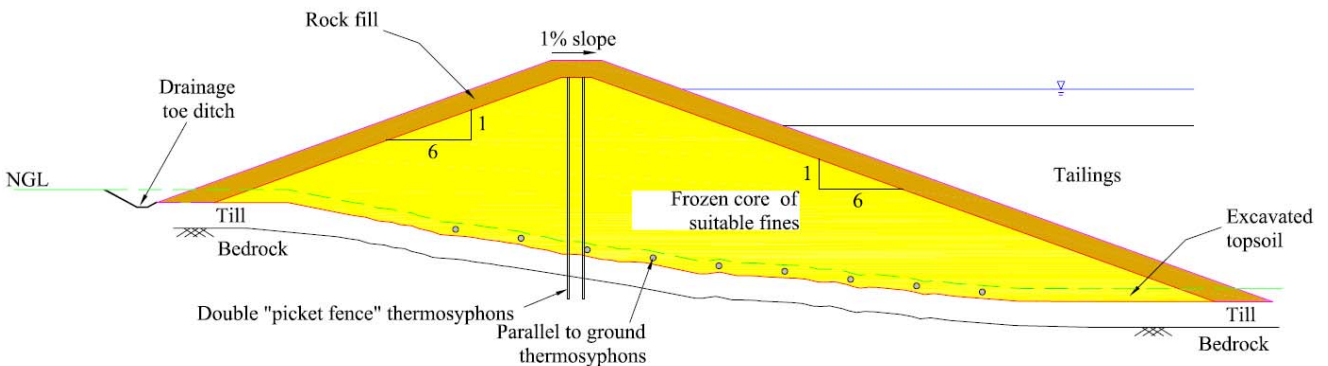
Not all dams built in continuous permafrost regions are built on completely frozen ground. Taliks, which are year-round inclusions of unfrozen ground within the permafrost, exist throughout Nunavut and are often found beneath lakes or rivers. They are also found in areas with heavy vegetation (shrubs) and organic matter, which accumulate snow in the winter, thereby reducing frost penetration to the underlying ground. These unfrozen layers will create

additional problems for seepage and stability. For example, the main tailings dam at the Colomac Gold mine, in the Northwest Territories (NWT), was built over a talik. Seepage increased from 23 L/minute in 1996 to about 1140 L/minute by 1999, probably due to the growth of the unfrozen zone. A seepage pump back system (SPS) was installed as a remediation measure. A new geomembrane-lined rockfill dam was built over an area with no unfrozen zones to control seepage. Thermosyphons were installed to cool the foundation for 20 years and the zone was predicted to remain frozen for an additional 150 to 200 years depending on global warming scenarios. Water retaining dam constructions for the Diavik mine, in the NWT, used rockfill earth embankments with HDPE liners. A talik (10 m deep by 40 m) wide was encountered and design provisions were made by excavating to the permafrost and modifying the dam cross-section in this localized area. (Scott, 2009; Holubec et al., 2003)

Typical tailings storage dams built over bedrock in the Arctic are shown in Figures 4-4 and 4-5. Figure 4-4 shows a typical dam cross-section that contains a till core, uses drainage filters and a grout curtain. The grout curtain prevents seepage losses if thawing of the frozen bedrock occurs and develops pervious pathways. Figure 4-5 shows a typical frozen core dam cross-section, which includes thermosyphons, aligned vertical and parallel to the ground surface, to prevent the core and underlying bedrock from thawing. Thermosyphons can be installed in a vertical “picket fence” alignment from the top of the dam to a considerable depth into the support till and bedrock (e.g. 5 m). Each thermosyphon can create a localized frozen layer (usually a maximum of 3 m in diameter in saturated till and even larger in dry bedrock). If several thermosyphons are installed along the length or width of the dam, they can create a frozen barrier, which will protect the frozen core and underlying bedrock from thawing.



**Figure 4-4: Typical dam cross-section with till core and grout curtain.**



**Figure 4-5: Typical cross-section of a frozen core dam.**

#### 4.4.1 Recommendations for Dam Construction in Nunavut – Frozen Core Dam

Frozen core dams are recommended in Nunavut because no settlement or seepage should occur provided the underlying ground remains frozen. The cold climate in Nunavut is favourable to this type of construction. Frozen core dams have been shown to be successful in Arctic regions. An older example of a frozen core dam was constructed in the 1940's in Klondike, Yukon (Beistline, 1963). The Ekati Diamond Mine, in the NWT, was one of the first mines to use frozen core dams in Canada and the “Leslie Long Lake Frozen Core Dam” has won several design awards (Nuna, 2010). In Cape Dorset, Nunavut, a frozen core dam has performed satisfactorily

to date (Cavanagh and Tchekhovski, 2010). Construction of frozen core dams should be carried out during the winter. Scheduling of the excavation and placement is critical in encouraging freezing of the foundation and core. The lessons learned from past projects must be incorporated in new designs. Another critical part of any water retaining dam is to ensure that no leakage occurs at the ends of the dam; proper sealing of natural ground to the end of the dam, particularly in the active layer, is essential. Detailed design drawings of this section are commonly disregarded. Leakage around the ends of a dam constructed at Raglan Mine forced the requirement of the installation of steel piles, which had to be flown to the site, leading to large repair cost (~ 35 million dollars).

#### **4.5 General Methods for Tailings Disposal in the North/Nunavut**

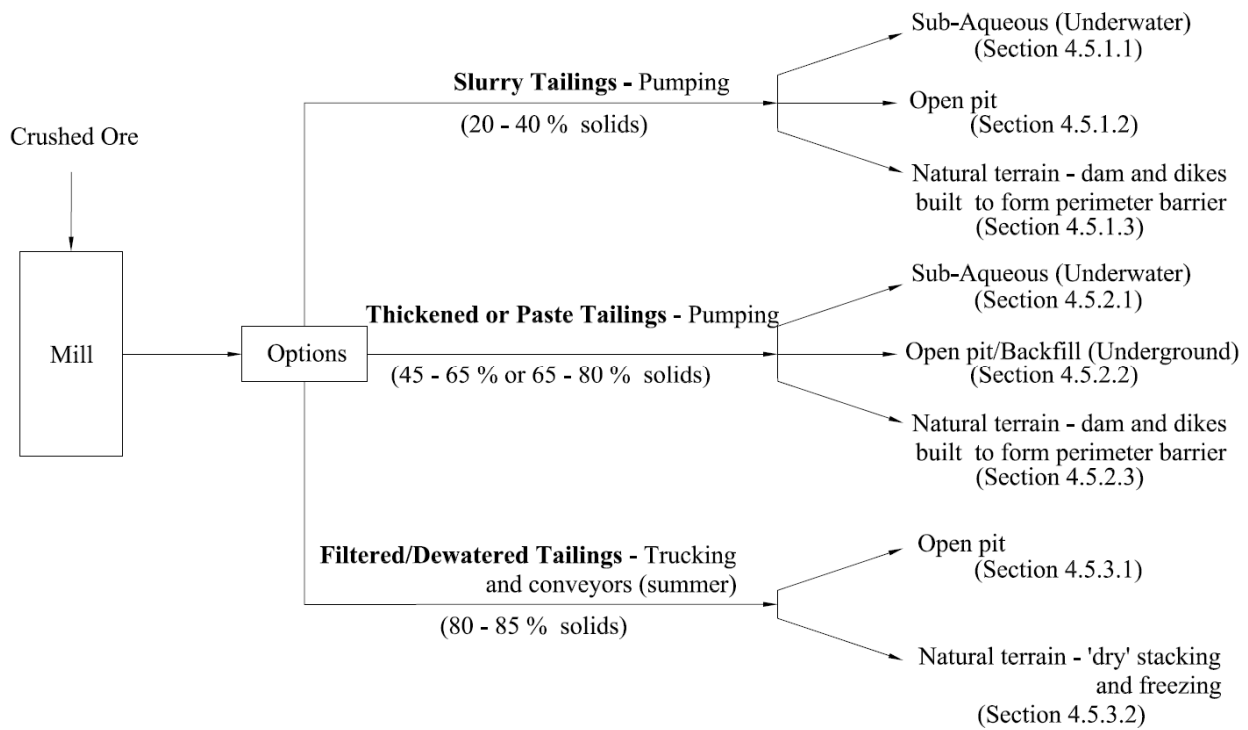
Tailings can be disposed in a variety of ways. Choosing the best disposal method will go hand in hand with the geotechnical and chemical properties of the tailings after final processing. Tailings will normally be in a slurry state after the valuable material is extracted from the ore. Whether or not more processing will be done to reduce the water content will depend on the chosen disposal method. The consistency of tailings (e.g. slurry, paste, thickened or filtered tailings) will normally govern whether tailings will be pumped through pipelines or trucked to the disposal facility. Transportation will be affected by the loss of pipeline and road integrity, with the thawing of permafrost and melting of ice roads. Therefore, considerations should be made in planning tailings disposal sites to address these concerns, as well as the risks of nearby slope failures that could cause landslides and block transportation routes. Climate change is also expected to affect mineral processing operations; most notably, water scarcity can limit

production rates, especially for those processes that are highly water dependent. (Pearce et al., 2009; 2011)

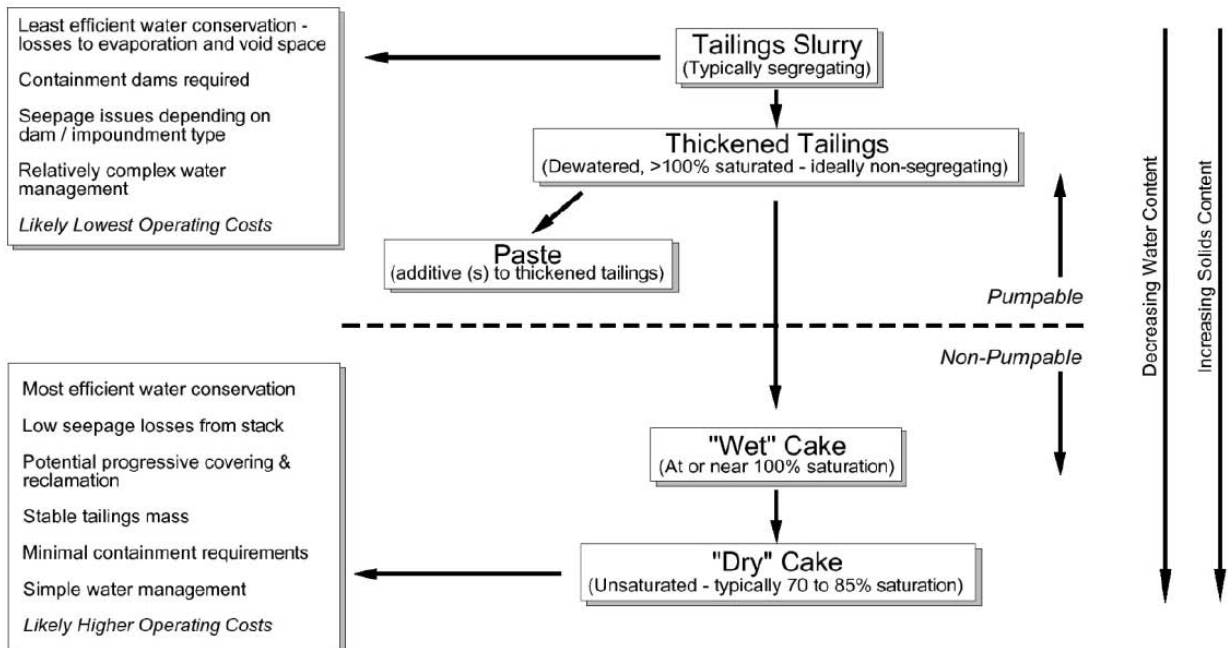
It should be noted that co-disposal methods (e.g. disposal of tailings and mine rock in one integrated disposal facility) are used to improve disposal methods in cold regions (e.g. can reduce acid mine drainage, metal leaching, storage facility footprints, increase compaction and facilitate progressive closure). Some co-disposal methods are covered in Section 4.5 and 4.6 (e.g. for dry stack facilities waste rock placed around perimeter increases stability and crushed rock placed overtop reduces dust generation). Waste rock can be used to construct dams/dikes and berms, while tailings can be deposited in a way that promotes staged raising of dikes. For more information on co-disposal techniques in cold regions see, for example, Habte and Bocking (2012), which provides case studies of co-disposal techniques used at Nunavik Nickel, Green's Creek and Snap Lake mines in order to demonstrate that deposition techniques for the proposed NICO co-disposal facility consisting of thickened tailings and mine waste rock can be successful in a cold climate.

Figure 4-6 illustrates the typical options for tailings disposal in cold regions based on the consistency of the tailings, while advantages and disadvantages are outlined in Figure 4-7. Please note, for the purpose of this section, thickened and paste tailings were grouped together. The following sections (4.5.1 to 4.5.3) outline the disposal methods by order of presentation, from top to bottom, in Figure 4-6. Further advantages and disadvantages of the specific disposal methods used in Nunavut are also provided. Climate change effects for particular methods are described. Final recommendations are given in Section 4.6.





**Figure 4-6: Tailings disposal options for cold regions.**



**Figure 4-7: Tailings disposal options – advantages/disadvantages (Davies, 2011).**

## 4.5.1 Slurry Tailings Disposal Options

### 4.5.1.1 *Sub-aqueous (Underwater/Under Ice) Slurry Tailings Disposal*

Underwater tailings disposal techniques, often referred to as sub-aqueous slurry disposal, involve direct placement of the tailings slurry in an existing body of water. Typically, this disposal technique is used for tailings that can produce acid rock drainage or severe dust problems. Due to the generally large volumes of tailings and/or the necessity of adequate water cover to prevent oxidation of sulphide minerals in tailings, large and deep bodies of water are required. An acceptable water body is usually a deep natural lake if available. Artificial ponds contained behind retaining dikes, dams and spillways, to increase water depth, are another sub-aqueous option for disposing of smaller volumes of tailings. The authors are against deep sea disposal, which has effectively been banned in Canada since 1977, due to the lack of scientific evidence to prove its effects on the marine environment and the lack of remediation strategies in the case of a disaster (Coumans, 2002).

Conventional slurry, typically with 20 to 40 % solids can be pumped to the desired discharge location(s). Discharging presents a special problem due to the formation of deltas or cones at the pipe outlet and backing up of the coarse tailings particularly in cold climate. The presence of snow has shown to have the opposite effect; the tailings travel a longer distance and settling could be poor (Habte and Bocking, 2012). The discharge location, within the water body, is often moved to take full advantage of the disposal area. Single or multiple discharge outlets can be used. Multiple outlets (see for example Figure 4-8) will reduce the discharge velocity and help spread tailings over the area. Figure 4-8 illustrates summer discharging from multiple spigot points supported on a typical sand dike built by pushing or dozing sand from the basin. Single

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point discharge has the advantage of providing a low surface area to volume ratio in cold climates, where freezing near the outlet can be a problem.

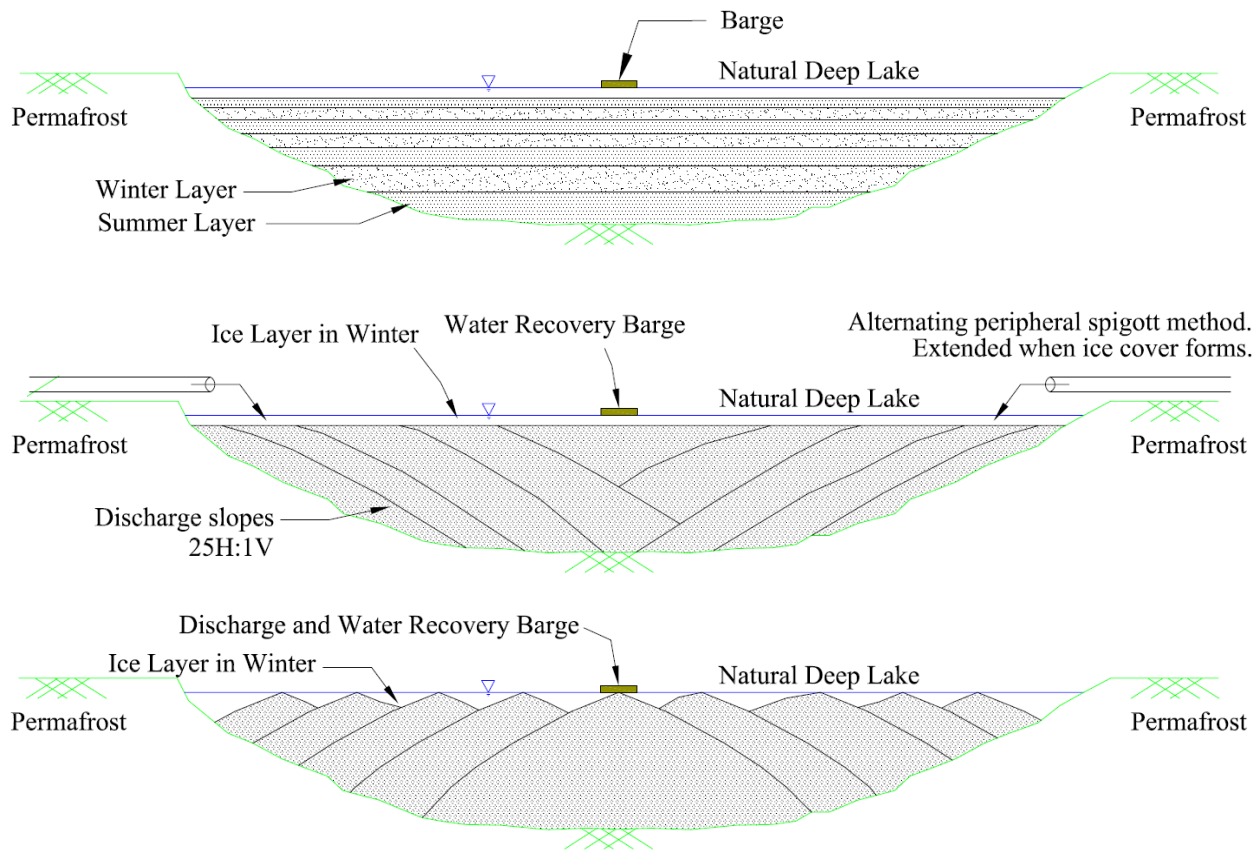


**Figure 4-8: Example of multiple thickened tailings discharge outlets in the summer on level ground in Fort McMurray, Alberta. (Photograph by Rick MacWilliam, Edmonton Journal)**

Over time, solids within the tailings will settle out and water/ice will collect on the surface far from the discharge point(s) depending on the weather conditions. The water can then be recirculated for plant operations. The process water is usually recovered by pumping from floating barges or through holes in the ice cover. In some cases, decant towers are used to recirculate the process water around the main dams and back to the plant site.

Impermeable water retaining dams/dikes are commonly required for sub-aqueous disposal to prevent the spread of the hazardous tailings into connecting water bodies. In addition, diversion

structures (berms, ditches, etc.) are normally required to prevent clean, uncontaminated, natural water from flowing into the storage facility, which would lead to a reduction in available storage volume and additional water treatment. Figure 4-9 shows typical cross-sections in which slurry tailings are disposed into a deep lake using three different deposition methods. The idealized version (top) shows tailings spread evenly around a natural lake. As mentioned above, this is unrealistic; deltas (or mounds) would be formed at discharge locations with coarser-grained material gathering nearby and the fines carried further away into deeper water. Alternating peripheral spigot discharge is a popular disposal technique (middle of Figure 4-9) in arctic regions and entails discharging the tailings around the perimeter of the water body. A barge can also be used, during the summer, to transport pumping equipment to discharge tailings in desired locations within the lake or to pump out water from the lake. (Golder Associates, 2007; Rykaart, 2005a)



**Figure 4-9: Schematic cross-section of slurry tailings disposal in a deep lake - From top to bottom: idealized, alternating peripheral spigot and barge deposition.**

The major advantage for this disposal option is the low operational cost of storing large tailings volumes. With regard to climate change, this disposal method has serious long-term risks associated with dam stability and containment capabilities (refer back to Table 3-1, pg. 11). Changes in water balance, leading to dryer conditions, can also compromise water covers. The more complex water management system required makes it even more challenging to create water management plans to incorporate the uncertainties associated with climate change. The risks of clean water entering the contaminated storage site, due to the overflow of diversion works from natural runoff water, are a concern. The long-term risks are particularly high, with

projected continual increases in storm magnitudes and intensities and the lack of maintenance after plant shutdown. The following points summarize the general disadvantages:

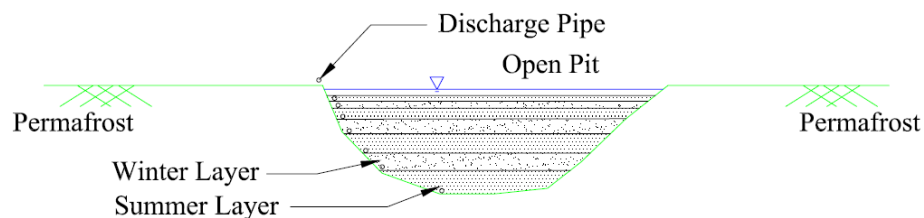
- Water retaining (impermeable) dams/dikes are commonly required to contain hazardous tailings from mixing with connected water bodies.
- Diversion structures are required to divert clean water from flowing into the storage facility.
- Large quantities of material are required for dams; glacial till is only readily available after thaw and material may not be available in the vicinity of the site.
- Special consideration must be taken to prevent water and/or pipe freezing.
- Losses to aquatic life. Re-compensation plans for no net losses are mandatory, but temporary loss could have severe impacts on local people and wildlife and re-compensation can take extended periods of time.
- Possible seepage of contaminated fluid through the lake bottom and into groundwater.
- Complex water management systems.
- Least efficient water conservation (e.g. losses to evaporation and void space within tailings).
- May require winter and summer discharge points to minimise ice formation in the storage area.

#### *4.5.1.2 Open Pit Slurry Tailings Disposal*

Figure 4-10 shows a typical schematic cross-sectional view of an open pit filled with slurry tailings (the uniform deposition is an idealized scenario). Slurry tailings can be discharged into

an abandoned and possibly water/ice-filled open pit where the reservoir is contained within the permafrost. Refilling open pits is desirable to reduce the environmental footprint left by tailings. However, seepage from contaminated tailings can enter groundwater sources and become an environmental concern. Few examples of open pit disposal in cold regions were encountered during research for this report (two examples, however, are given in Section 4.5.2.1). This is due to the fact that it can be a difficult and dangerous process to place tailings within an abandoned pit and, more to the point; very few abandoned open pits are available during production. Only after local deposits have been completely mined out will pits become available for storage.

Slurry tailings can be deposited in similar ways as described in Section 4.5.1.1; as in the deep lake disposal option, surface water can be removed and recycled for processing. Infiltration zones from the walls of the pit must be sealed by using a combination of grouting and freezing using thermosyphons. Climate warming will increase slope stability concerns of the walls for open pits with thawing permafrost and melting ice within the bedrock interfaces.



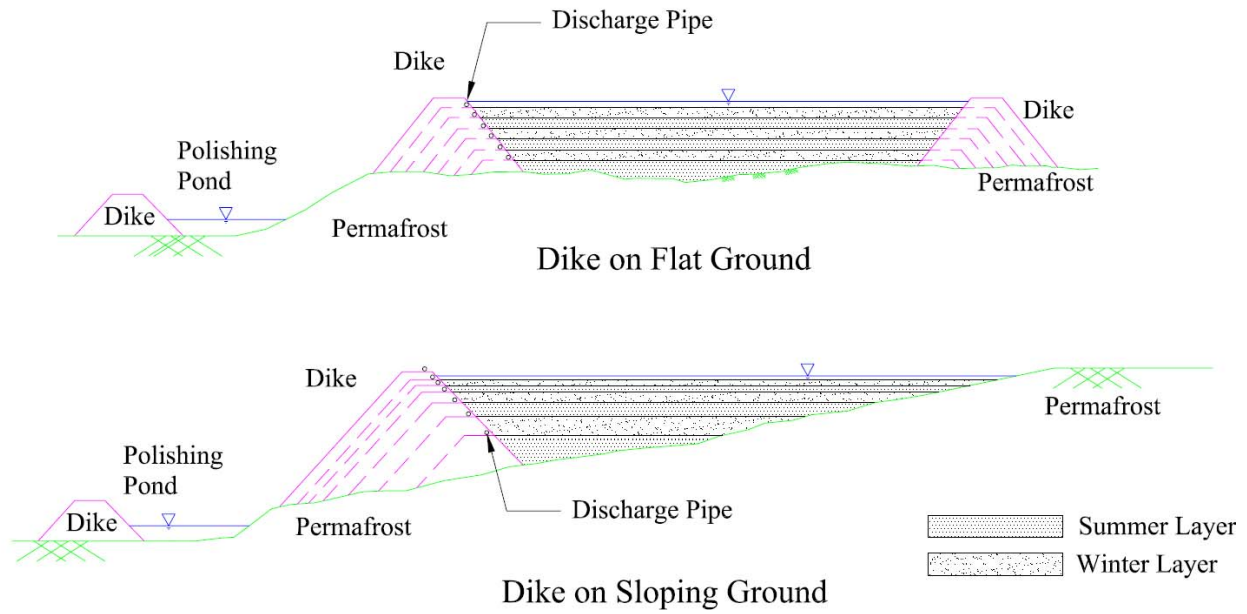
**Figure 4-10: Schematic cross-section of idealized slurry tailings disposal in an abandoned open pit.**

### *4.5.1.3 Natural Terrain Slurry Tailings Disposal*

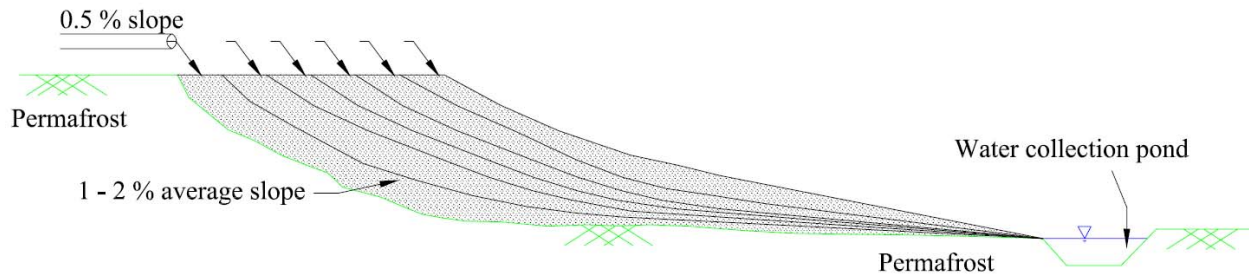
Please refer to Section 4.5.2.2. Slurry tailings disposal on land is similar to thickened tailing disposal on land. The main differences are the greater volumes of tailings and the slower freezing of tailings due to the higher water content. Figure 4-11 shows examples of slurry tailings disposal on natural terrain using dike construction. The dams/dikes are usually built in a progressive manner as the waste pile increases in height. Entrained ice is not displayed in the figure, but would be present. Normally the tailings water will freeze downstream from the discharge pipe as it cools and turns to ice, sometimes 1 to 2 km from the discharge point, depending on the fluidity, temperatures and slope. Referring back to Figure 4-7 (pg. 68), the likely lower operational cost is the main advantage of this method; however, material availability in Nunavut may result in very high capital costs for dam/dike construction. Seepage issues, water management complexity, perpetual risks of dam failure and large footprint areas are the main disadvantages, particularly when climate change scenarios are taken into consideration.

Inert slurry tailings can be disposed of on steep landscapes (e.g. high slopping valley) without the need for dam/dike containment (see Figure 4-12). Examples of where inert tailings disposal sites could be located in Nunavut are the proposed Baffinland Iron Project and the Advanced Explorations Roche Bay Project. The basic concept of this disposal method is that the tailings will flow down the slopping terrain, freeze in place and water can be collected in a pond at the far end. These facilities could be up to several kilometres long. Since these tailings are inert, very little infrastructure, apart from the collection pond facility, is required and the method does not pose environmental risks even with climate change.





**Figure 4-11: Schematic cross-sections of idealized slurry tailings disposal on natural terrain.**



**Figure 4-12: Inert slurry disposal on sloping land in the summer.**

## 4.5.2 Thickened or Paste Tailings Disposal Options

### 4.5.2.1 *Sub-aqueous (Underwater/Under Ice) Thickened or Paste Tailings Disposal*

Sub-aqueous disposal of slurry tailings is covered in Section 4.5.1.1. Disposal of thickened or paste tailings in the same manner (e.g. deep lake) requires higher capital investments for tailings processing and increased operational cost. These costs may be offset by lower water management cost, minimal particle segregation which increases deposited density and reduces storage volume, increased water conservation, less ponded water reduces footprint and can facilitate closure.

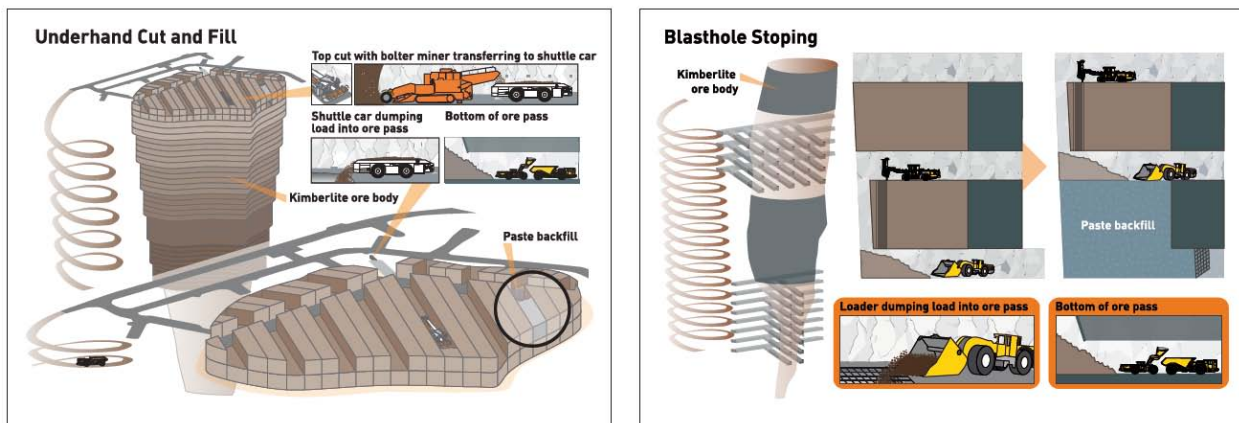
### 4.5.2.2 *Open Pit/Backfill Thickened or Paste Tailings Disposal*

Open pit tailings disposal involves refilling an excavated pit with tailings (refer back to Section 4.5.1.2). According to a report for Minto Mine in Yukon (Scott et al., 2010), the mine was expected to have switched disposal methods, in mid 2011, from dry stacking to open pit (in-pit) sub-aqueous thickened tailings disposal. The disposal method change is expected to bring a significant cost savings and reduction in disturbed land over the current dry stacking method. The tailings with elevated copper will be segregated and disposed in a way that limits copper leaching (e.g. co-disposal) and by installing vertical dewatering wells. In order to maintain stability of the Main pit, in which tailings will be stored up to the year 2015, a waste rock buttress was to be constructed. Slurry deposition will be used in select locations to facilitate uniform distribution of tailings and the winter deposition plan may need to be modified in cases of extreme cold weather. A floating barge will be used to recycle and remove excess water from the pit from freshet inflow (flood resulting from heavy rain or spring thaw).

The Doris North Project evaluated the use of an open pit as a disposal alternative (Rykaart, 2006). A rock dike would be constructed to section off a portion of the open pit from the access portal and a separate water management pond would be constructed on the surface. The use of open pit disposal with an active portal was described as unprecedented. The tailings would be in a thickened state and pumped into the pit. Excess water in the pit would be pumped out to the water management pond. After final placement, the tailings would be covered with a geosynthetic clay liner (GCL) and waste rock to ensure long-term integrity and prevent infiltration. The water management pond would be excavated of sludge and underlying soil for treatment and secure storage. Ultimately, this alternative was disregarded since it was deemed to be an uneconomical option and the design was not deemed technically unfeasible or flexible in case of reasonable disturbance conditions. The long-term risks of metal leaching, loss of land and terrestrial habitat (e.g. from water management pond construction), ice build-up, hydrologic uncertainties, potential for tailings dust, and very high risks and cost to ensure human safety (e.g. pit wall stability) were the main concerns. This alternative assessment provides insight into the common concerns for open pit disposal, but is exaggerated by the fact that the open pit would be still operational.

Backfilling has become a popular method (e.g. Meadowbank, Kensington, Lupin, Snap Lake, Diavik, Greens Creek, Raglan, Bellenkeno, Prairie Creek and Pogo mines). Backfilling is a word used by the mining industry to describe the refilling of underground cavities (e.g. mined out cells). Backfill material may be hydraulic backfill (alluvial sand, mill tailings and cement), cemented paste backfill (mine tailings, water and binders) or rock fill (waste rock, tailings, water and cement). The backfill material must satisfy certain properties, mainly compressive strength

and stiffness, to ensure safe underground working environments. Snap Lake mine expects to backfill 50% of its waste over the life of the mine, leaving half for above ground storage, thereby reducing the aboveground footprint. Another benefit of backfilling is that sometimes additional extraction of the ore can be achieved (e.g. a 5-10% extraction rate increase is expected at Snap Lake). Figure 4-13 shows two underground mining methods used at the Diavik mine that incorporate backfilling techniques (DeBeers Canada, 2011, Rio Tinto, 2009). The main disadvantage of backfilling is usually cost-related, since cement and other admixtures are expensive, particularly in remote Arctic locations. Climate change should have little to no direct affect on this disposal technique, since the facilities are located well below ground.

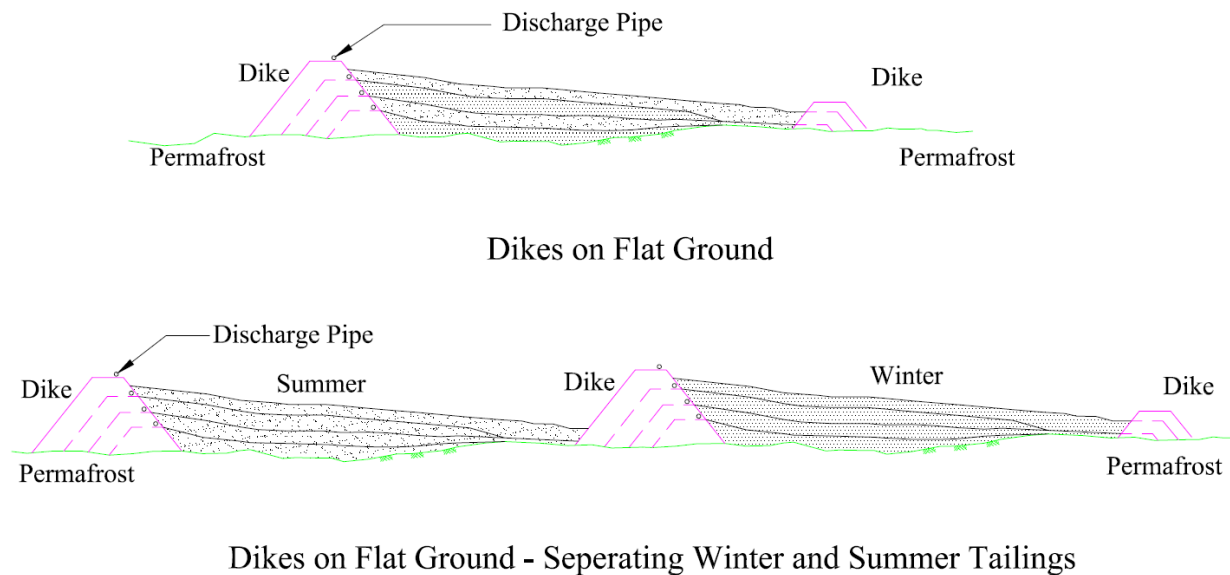


**Figure 4-13: Underground mining methods for Diavik mine where backfilling will be used (Rio Tinto, 2009).**

#### 4.5.2.3 Natural Terrain Thickened or Paste Tailings Disposal

Generally, a large valley would be chosen for this disposal technique. Minimizing dam or dike construction is an important criterion for selecting a land disposal site. Sometimes, a single earthworks structure will create a storage area, but when peripheral ring dikes are necessary to

complete the basin large capital investment is required. Water within the tailings may eventually exit by means of drainage, seepage or evaporation. Excess process water is collected and recycled to the plant. Exterior diversion works may be required to by-pass the storage facility and to prevent natural runoff water from entering. Furthermore, closure of the site requires an adequate cover over the reactive tailings and the long-term risks of dam or dike failure is always present. In Nunavut, the cold weather could increase freezing problems, which would make water management and tailings placement very difficult. Figure 4-14 shows schematic cross-sections of facilities on natural terrain (ice-lenses and/or layers are not shown in Figure 4-14, but would be present). Entrained ice should be accounted for when sizing storage facilities.



**Figure 4-14: Schematic cross-sections of thickened or paste tailings disposal on natural terrain.**

Thickened or paste tailings will freeze more quickly than slurry tailings and, therefore, mounds, deltas or sloping ground occurring at the discharge points will be more pronounced. Therefore,

the disposal operation would require even more continual shifting of the discharge locations than with slurry tailings disposal. Other advantages of thickening tailings for this type of disposal method are (Habte and Bocking, 2012):

- Smaller tailings pond is required (lower environmental impact).
- Reduced storage volume (smaller footprint).
- Less complicated water management and increased water conservation.
- Typically less risks of dust generation and ingress of oxygen due to reduced particle segregation.
- Typically less risks of seepage due to lower hydraulic head.
- Can be suitable for co-disposal with mine rock (increased stability).
- Typically has reduced concern of long-term maintenance and dam stability.

Again, climate alterations will increase the concerns for long-term dam stability and diversion work dependability and create even more difficulties for water management plans, with permafrost degradation, increases in storm magnitudes/intensities and uncertainties in future water balance conditions.

### **4.5.3 Dewatered Tailings Disposal Options**

#### *4.5.3.1 Open Pit Dewatered Tailings Disposal*

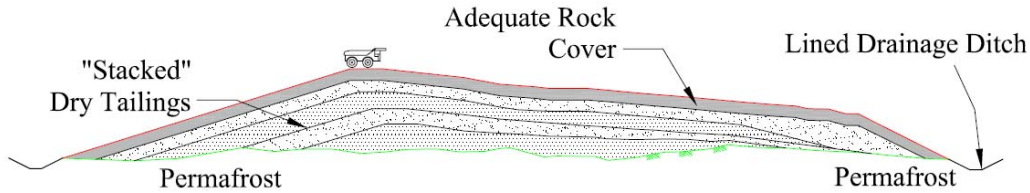
As stated earlier (see Section 4.5.1.1), open pit disposal is essentially refilling a previously excavated pit with tailings. For open pit disposal, the advantage of disposing of dewatered tailings (~15 % water content), rather than tailings with higher water contents, is that a greater volume of solids is disposed in the same volume of tailings (due to the higher density of the

tailings), with a reduction in the seepage water conservation is achieved. Dry material could be trucked, dumped, spread and compacted in dry open pits. Any problems with slope stability of open pit walls, precipitation and ice are likely to be magnified by climate change. The main disadvantages are the additional cost required for dewatering the tailings and transporting the tailings.

#### *4.5.3.2 Natural Terrain 'Dry Stacking' and Freezing Tailings Disposal*

Filtered dry stacked tailings are becoming more and more popular in mines even though the costs are still relatively higher than, for example, underwater deposition. The basic concept involves dewatering the fine ground tailings to the desired water content through a series of filtering units (mechanical or vacuum). Recent developments in dewatering techniques and filtering technologies now allow for greater amounts of tailings to be processed in this manner at reduced costs. Filtration units of up to 10,000 tons per day are available. For large tonnage mines additional units can be added. The use of this type of equipment is also ideal for producing dry material that can be placed and frozen as an upstream blanket on a rock fill dike. The tailings can be trucked (or conveyed in the summer) to the disposal site (see Figure 4-15). Placement is performed by spreading evenly and compacting the tailings to the maximum over a given area. Dry stacks can be built to any height. The frozen stack is ultimately unsaturated, dense with flat slopes and, in the Nunavut, very stable. The hydraulic and mechanical properties of the dewatered tailings are critical to design. Recently, several mines in cold regions have opted to use the dewatering/drying and dry stacking technique: Raglan Mine (Quebec), Pogo Gold Mine (Alaska), Green Creek Mine (Alaska), Nixon Fork Mine (Alaska), Bellekeno Mine (Yukon) and

Minto Mine (Yukon). The following section covers dry stacking in more detail and outlines the advantages and disadvantages of the method.



**Figure 4-15: Schematic cross-section of dry stack disposal on relatively flat terrain.**

#### **4.6 Discussion and Recommendations for Tailings Disposal (Dry Stacking, Backfilling or Open Pit Disposal)**

In Nunavut, the optimum disposal method for tailings is ultimately decided on a case by case basis depending on the surrounding terrain, nature of the tailings and local climate conditions. However, the general recommendation for tailings disposal in Nunavut is dry stacking, while refilling open pits and underground cavities (e.g. backfilling) should be done as much as possible. Ideally, safely depositing all tailings within previously mined out regions would be preferred, but this is not entirely feasible for a mine, due to operational difficulties and project economics. Dry stacking has several advantages over other options and the main benefits are discussed in the following paragraphs. The advantages are also summarized in point form at the end of this section.

From an environmental standpoint, especially over the long-term, dry stacking offers the best solution for mine tailings disposal. For potential acid generating tailings and other hazardous tailings, dry stacking is a stable and safe choice. After closure, maintaining the active layer within thick covers will provide long-term containment of the waste. Geosynthetic covers are the



least affected by climate change (Stratos Inc., 2011). Holubec (2004) noted that encapsulating tailings is generally feasible for all of Nunavut for the next 100 to 200 years. Other land-based methods require impermeable till core dams/dikes that could be problematic due to stability and seepage issues that might occur in the long-term with climate change. Underwater disposal is considered to be a safe choice for preventing acid mine drainage at the lowest costs. Rykaart (2005a) describes sub-aqueous disposal as a pro-active, rather than reactive solution, since mine waste must oxidize in order to become detrimental and it will be unable to do so if directly placed underwater. However, groundwater contamination can present a sizeable risk for other types of hazardous waste (e.g. cyanide contaminated waste). In addition, dams are commonly required to separate the storage facility from connecting water bodies, which increases the costs.

Land used for disposing tailings via dry stacking, can be covered and re-vegetated. Loss of wetlands is a central concern for dry stacking; however, when compared to other land-based disposal methods, dry stacking facilities consume a smaller total area (footprint) than standard tailings ponds where dams and dikes are required (see for example Condon and Lear, 2006). The main reason for this is the increased water removal from the tailings. In, addition, to minimize the footprint, dry stacks can be built high in suitable natural terrain by using features such as deep crevasses, hill sides and broad valley floors. Sub-aqueous storage on the other hand, if permitted, can completely fill pristine natural lakes, where aquatic habitat will be permanently lost. Mandatory compensation plans are in place to mitigate this undesirable loss. However, the remediation plans may only take affect after extended periods of time, during which negative impacts on wildlife or local inhabitants can occur. The Kensington mine had planned to actually increase aquatic life after mine closure for a shallow lake (Lower Slate Lake), by increasing the

water depth using earthworks and introducing fish and other aquatic life (Coeur Alaska, 2006). Unfortunately, recent developments in the regulations caused deviations from the original plan and the lake has subsequently been contaminated with waste tailings (Earthjustice, 2011).

Water conservation is another major advantage of dry stacking; water removed from the tailings and storm runoff collected by drainage channels surrounding the dry stacks can be re-used for mine processing. Water conservation is particularly beneficial in Nunavut's dry climate. Water management in dry stacking is also much simpler in comparison to other tailings disposal techniques; therefore, planning for future uncertainties related to climate change is more feasible.

The major advantage of dry stacking over other storage techniques, in Nunavut, are summarised below:

- Involves smaller storage volumes because of low water content (~ 15%).
- Conserves water.
- Easily constructed with standard earth moving equipment (dozers, compactors, haul trucks).
- Freezes pore-water in place; avoids seepage concerns and leads to stable slopes.
- Avoids construction of costly retaining dikes and dams requiring large borrow pits to provide the materials necessary for dam construction, which are not readily available.
  - Avoids developing long roads with culverts and bridges to reach borrow pits for zoned dike construction for tailings ponds.
- Can be built around or over topographic obstacles, including rock outcrops, and in small localised zones to maximise terrain use, while avoiding streams and lakes.
- Can be designed to use thick inert waste rock covers to conform to changes in active zone depth or unstable permafrost due to climate warming.

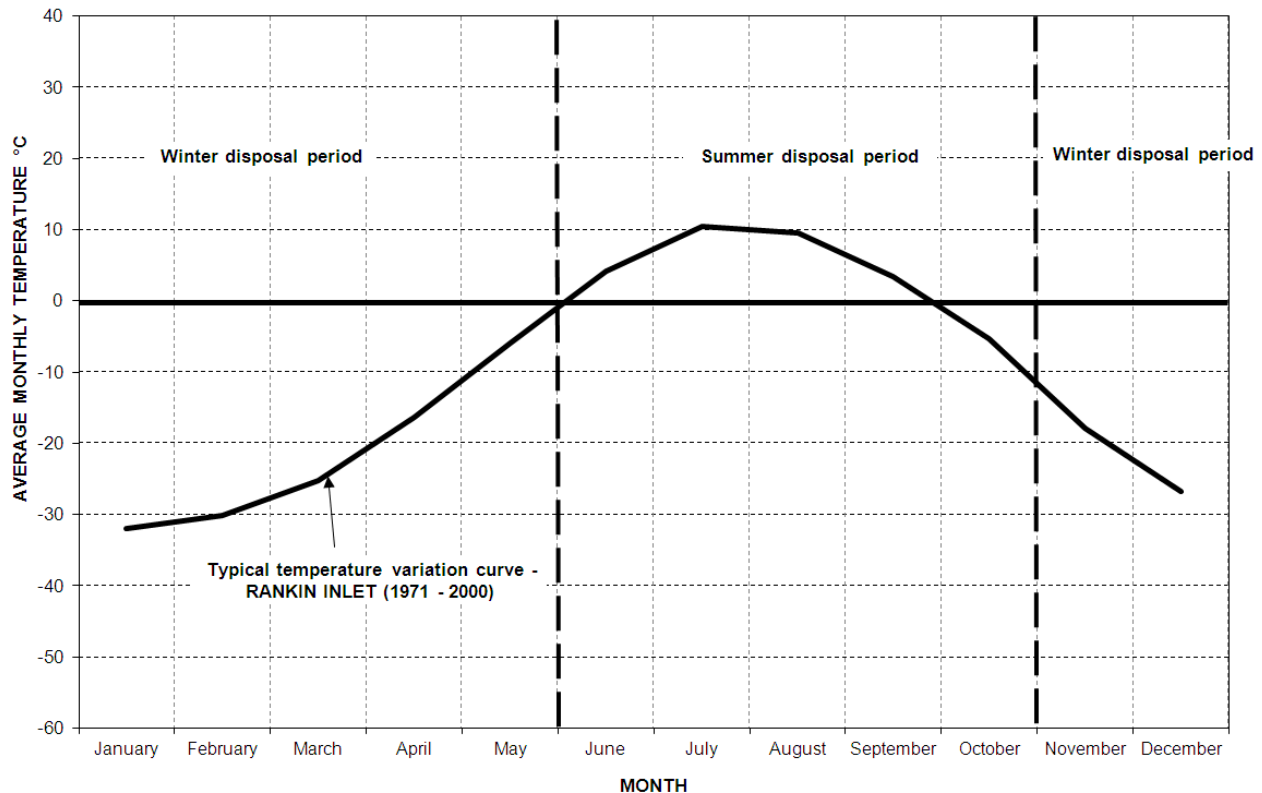
- Can be buttressed with inert mine waste rock for added stability on steep slopes.
- Avoids risks involved with complicated storage using dams and spillways, and polishing ponds, which are subject to possible seepage and perpetual monitoring after closure.
- Avoids pipelines and associated mechanical equipment subject to freezing in winter.
- Involves a simple closure plan using adequate cover for projected active layer thickness, while providing permanent dust free storage.
- Easily accessible in the event of a need for additional mitigation measures.
- Relatively low capital cost for preparation of storage sites at the start of the mining operation.
- In the end, may prove more cost effective over the life of the mine and permanent closure periods.

#### **4.6.1 Design Guidelines – Dry Stacking**

##### *4.6.1.1 Transportation, Compaction and Placement of Tailings for Dry Stacking*

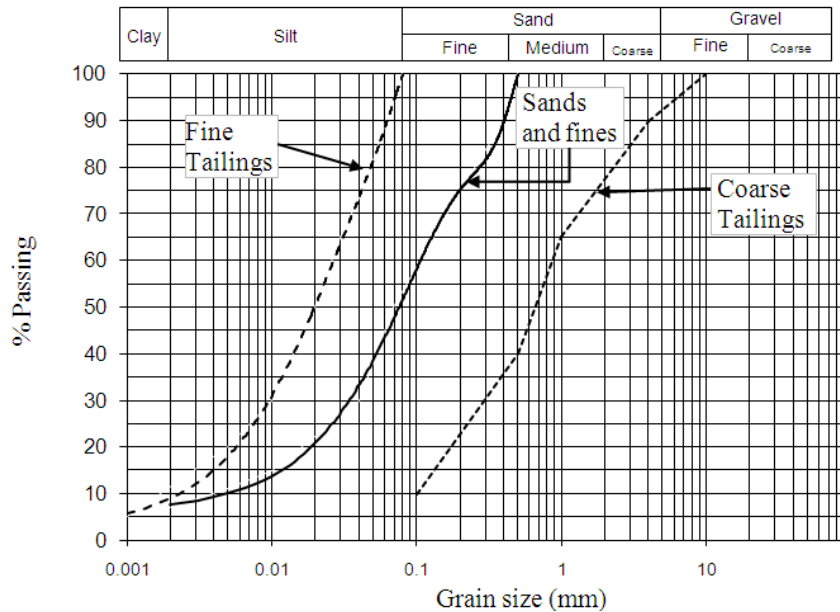
The general scheme involves using a fleet of trucks to transport the material to the site where it is dumped, spread and immediately compacted. In the winter period, the material can be spread and compacted in thin, 300 mm thick, lifts over a large area and this low water content material will freeze rapidly under the cold temperatures experienced in Nunavut. The tailings can be deposited in a secondary ‘summer’ storage facility in the summer period. During this period, an active layer will develop in the ‘winter’ storage facility. Drainage should be controlled and infiltration should be prevented by graded surface to shed water to the perimeter, constructing runoff water diversion berms, finger drains or flow-through drains. Infiltration is usually low due to the normally low permeability of the tailings; however underdrain systems may be required to collect seepage. In addition, entrained ice within the active layer of the tailings will melt and can

be drained from the pile. During the summer months, tailings can be placed in the ‘summer’ storage area and compacted to a total depth of about 2.5 meters (or the estimated freezing penetration into a specific tailings site during the following winter with some safety margin). The severe cold and high winds, inherent to Nunavut, will quickly freeze the summer layer to the bottom. While freezing occurs, the disposal operation will be transferred to the original winter section. This process can be repeated year by year. In this manner, these stacks can be built to considerable heights and can conform to almost any topography. A hypothetical time distribution for summer and winter disposal is given in Figure 4-16. The figure illustrates the how winter disposal period can be started after a month of freezing temperatures to allow the active layer to refreeze. In reality, the division of summer and winter disposal requires a more in-depth study based on local climatic conditions, tailings thermal properties, and so forth.



**Figure 4-16: Hypothetical example of winter and summer disposal over a year.**

The water content of the material should be near the optimum value for compaction purposes (around 15% depending on the grain size of the tailings). The coarser the tailings, the easier the material can be placed in the winter. However, in the summer, coarser tailings will absorb more precipitation. Caution should be taken to avoid saturation of the working platform. The tailing stack layout should be construction is such a way that drainage from precipitation or storm runoff would be diverted away from the dry stack. Figure 4-17 shows grain size distribution for typical fine to coarse tailings.



**Figure 4-17: Grain size examples for fine tailings to coarse tailings.**

Transportation and storage of tailings in the permafrost regions of Canada must contend with severe winter cold; transportation in the winter will require insulated and heated truck boxes (similar to concrete trucks) especially if the storage site is located some distance from the mill. This will prevent freezing of the material to the truck boxes. Many trucks have exhaust pipes that

lead to the truck box, which helps to prevent freezing. Condon and Lear (2006) provide trucking and placement details for Green Creeks Mine, Alaska.

Once dumped on site in the winter, the material will freeze very rapidly under low temperatures and high winds and small particles will become coated with ice, which will lead to poorer compaction. Each truckload must therefore be spread and compacted immediately. The number of dozers, graders and compactors equipped with heating equipment must be suited to this rapid compaction. Naturally, in summer this is not such a problem, but the high summer temperatures may cause accessibility issues for heavy trucks due to the thawing of the active layer. Drier material may be required to support the equipment. Rapid freezing of the compacted tailings, in cold periods, will increase stability for vehicles and allow for additional layering to be performed in shorter timeframes. Operation and planning is therefore critical in terms of placement of tailings. Large working platforms are required to allow the layer to freeze before the equipment returns to place the next lift. The placing of these waste materials for freezing is similar to roadway construction and therefore can be built progressively over any type of flat or sloped terrain. Because of processing challenges, not all tailings will be exactly to specifications; therefore, when less optimum tailings are encountered, they should be placed in the central region, where support and strength is less important. Likewise, compaction purely for strength purposes (e.g. increasing the friction angle) is not necessary in non-structural (central) areas of the dry stack facility.

#### 4.6.1.2 *Wind Blown Dust*

Wind blown dust should be kept to a minimum. Some regions in Nunavut experience high winds and blizzards. Baker Lake (see Figure 4-18) experiences a high number of blizzards each year, thereby, making dry stacking a less attractive disposal option in this area (see for example Leader et al., 2009). Prevention measures can be taken to reduce dust emissions. Lower topographic regions are less susceptible to high winds. Additives (e.g. cement) can be used to bond waste together, while also providing additional strength to the dry stack. Spraying the waste piles with water, during the summer periods, or other dust suppressant liquid/solid agents may also be effective in preventing dust generation. In the design stage, having a holding pond in close vicinity to the dry stack facility would simplify dust suppression with water during the summer. Placing a thin layer of waste rock, immediately after the tailings have been spread and compacted, during windy periods is another option. When possible, trees can be used to form tree screens (a line of thick evergreen trees) around the site, which can help contain dust. This may be an option to help contain dust in the Baker Lake region, where it is windy and still within the tree line.

Lime and cement were used to stabilize tailing at a zinc refinery in Valleyfield, Quebec. The tailings were previously deposited in ponds in a slurry form. The tailings were thickened and lime and cement were added to create an inert substance. This process, or a similar one, could be beneficial in creating a substance less prone to wind issues and could also completely change hazardous tailings into inert substances (Benoît and Getahun, 2000).



Figure 4-18: Average number of blizzards across select villages in Canadian Arctic (Environment Canada, 1999).

#### 4.6.1.3 Closure and Reclamation of Tailings Site

Apart from the minimal effects of climate change on frozen tailings in Nunavut, one of the main advantages of dry stacking is the ease of mine closure and land reclamation. A cover must be placed over the tailings with an appropriate design in order to prevent negative impacts on the surrounding environment at closure (see Section 4.2.2 and Section 4.4.1.4). Over the long-term, the area can be covered with topsoil and re-vegetated to its original vegetative state in a relatively fast and economic manner when compared to other tailings disposal options. Trial vegetation plots during operation are recommended to optimize the re-vegetation process. Dry stack facilities have low slopes, which helps to promote the growth of vegetation. Finally, continual monitoring is recommended; specifically, temperature monitoring within the dry stack itself and in the surrounding ground is beneficial for assessing the design performance.

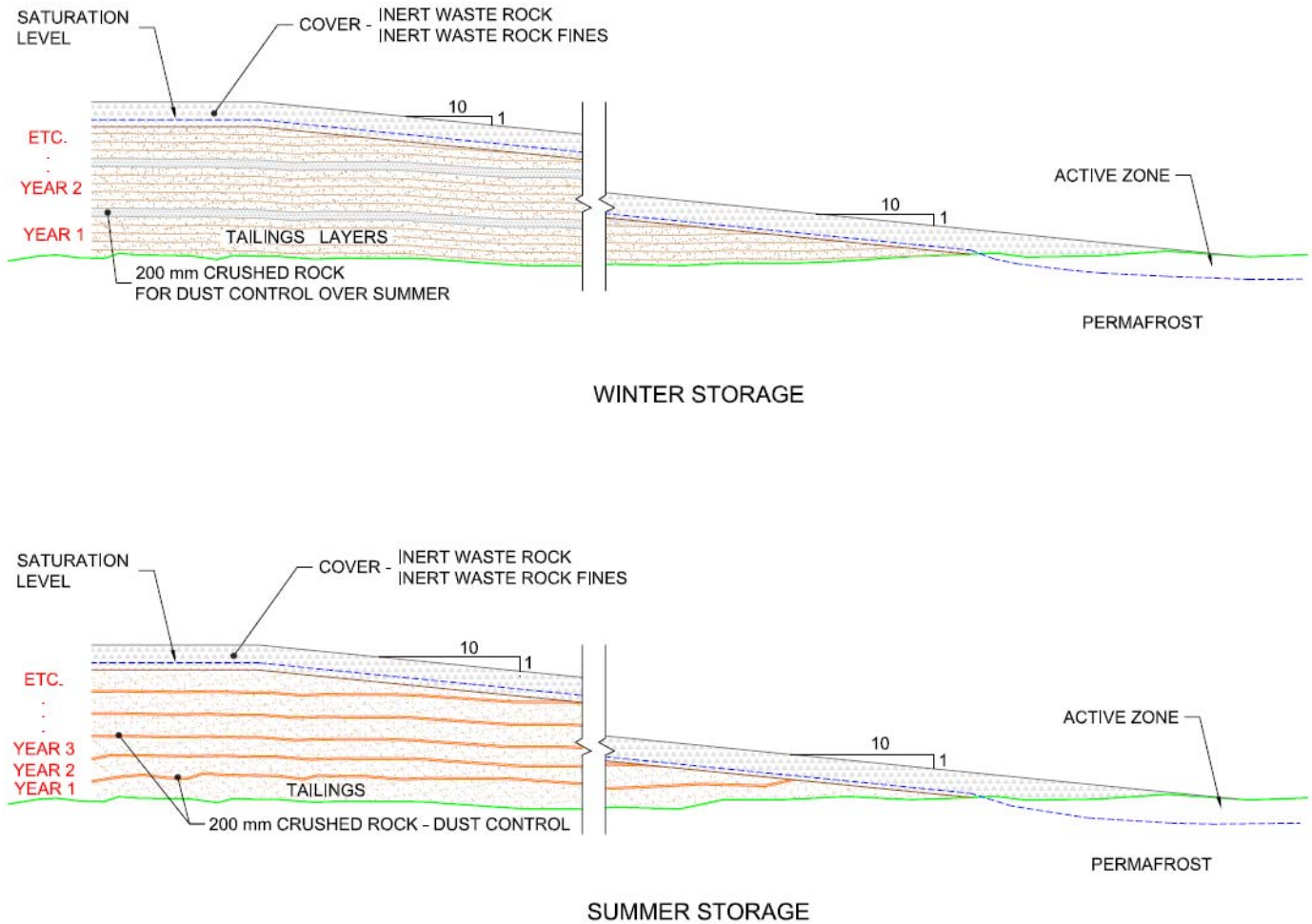


#### *4.6.1.4 Design Concept for Dry Stacking*

This section presents a design concept for tailings disposal using dry stacking in Nunavut. A schematic cross-section of the design concept is shown in Figure 4-19. To eliminate the effects of climate change on the degrading permafrost in Nunavut, the perimeter tailings slope should preferably be no steeper than 10H:1V. The flatter slope will result in a larger footprint, which may not be possible or desirable in many situations. However, the flatter slopes have many advantages, including increased stability, ease of placement and freezing, more conducive to vegetation growth after closure and decreased erosion. Flatter slopes will displace the active thaw zone further from the stack, thus increasing stability. At the end of each season, 200 mm thick layers of crushed rock can be placed over tailings to control dust.

At closure, a similar cover design concept to those used at the Raglan and Diavik mines, where a fine layer is placed over the tailings and develops into a fully saturated frozen barrier, is recommended. Establishing the active layer within the cover is obviously essential. An adequate cover design consisting of inert waste rock fill underlain by fine crushed rock can suffice. After closure, precipitation will seep through the cover and collect in the fine layer. Over the following cold period, the water will freeze in place and saturate this layer. This frozen, high ice content layer will mitigate the future possibility of thawing due to climate warming by prolonging the zero-curtain effect (Carey and Woo, 1998). Past experience in Schefferville (Qc.) supports this method. A frozen snow and ice layer, below the active layer of about 3 m and within the fine-grained soil (e.g. no convective cooling), has been maintained over the past fifty years, where the freezing and thawing indices are 3163 °C days/yr and 1270 °C days/yr, respectively. In

Nunavut’s warmest regions, climate warming predictions for the next 100 years will lead to approximately the same freezing and thawing conditions as were seen in Schefferville over the last 50 years.



**Figure 4-19: Schematic cross-section design for hypothetical dry stacking facility in Nunavut.**

## 5 CONCLUSION AND RECOMMENDATIONS

This report covers a variety of issues related to tailings management facilities and associated infrastructure with the growing concerns of climate change in Nunavut. Dry stacking combined

with backfilling and/or open pit disposal are recommended as the tailings disposal techniques for

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future mining endeavours. These disposal methods are deemed to be the best practices for tailings disposal in Nunavut. Dry stacking is recommended for its environmental benefits of containing hazardous waste through freezing in Nunavut's cold temperatures, in both the short and long-term and the reduced footprints that are left behind. In addition, dry stacking avoids the perpetual risk surrounding other methods that require dams, which have limited lifespans, particularly with the degradation of the underlying permafrost that would occur as the climate warms. The main concern of dry stacking is dust generation during operation; therefore, more research is recommended on ways to reduce dust generation, particularly for mine operations in windy environments. Backfilling, with paste backfill, is currently being used to dispose of tailings at several mines in cold regions and has been successful in reducing land consumption. In addition, backfilling has the advantage of being relatively insensitive to climate change-related issues, due to the considerable depths at which the disposal facilities are located.

Environmental disasters from contaminated tailings facilities are certainly preventable, barring unpredictable scenarios. Technologies are available to ensure safe containment of hazardous material. Cost is the main restraint for designers, but relatively small investments today can prevent future liabilities and environmental losses. Applying higher factors of safety in the design of waste covers and hydraulic structures is highly recommended, particularly in view of the uncertainties of climate change. Research and development of cover designs should be continued. For dry stacking, more field research should be done and made available to determine the thickness of a waste layer that can be frozen over a cold period and the corresponding thaw depth during the warm period, in order to produce empirical relationships for designers to consult. Further research in tailings processing is crucial in moving forward to sustainable

tailing disposal sites. Creating inert tailings should ultimately be the goal of any tailings disposal site. If long-term environmentally safe methods are not applicable (e.g. not economically or technically feasible) for mining projects, the non-renewable resources should simply not be mined.

# Government of Nunavut

## ENGINEERING CHALLENGES FOR LARGE SCALE INFRASTRUCTURE IN THE NORTH NUNAVUT

Prepared by :

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**JOURNEAUX ASSOC.**

DIVISION LAB JOURNEAUX INC.

801 BANCROFT, POINTE-CLAIRE, QC H9R 4L6

T (514) 630-4997 F (514) 630-8937

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**JOURNEAUX ASSOC.**

DIVISION LAB JOURNEAUX INC.

801 BANCROFT, POINTE-CLAIRE, QC H9R 4L6

**T (514) 630-4997 F (514) 630-8937**

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**JOURNEAUX ASSOC.**

DIVISION LAB JOURNEAUX INC.

801 BANCROFT, POINTE-CLAIRE, QC H9R 4L6

**T (514) 630-4997 F (514) 630-8937**



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**JOURNEAUX ASSOC.**

DIVISION LAB JOURNEAUX INC.

801 BANCROFT, POINTE-CLAIRE, QC H9R 4L6

**T (514) 630-4997 F (514) 630-8937**

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**JOURNEAUX ASSOC.**

DIVISION LAB JOURNEAUX INC.

801 BANCROFT, POINTE-CLAIRE, QC H9R 4L6

**T (514) 630-4997 F (514) 630-8937**

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801 BANCROFT, POINTE-CLAIRE, QC H9R 4L6

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