ENGINEERING CHALLENGES FOR COASTAL INFRASTRUCTURE/DOCKS WITH REGARD TO CLIMATE CHANGE IN NUNAVUT

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1 INTRODUCTION

"In September 2011, JOURNEAUX ASSOC., a division of LAB JOURNEAUX INC., was awarded a contract to outline the potential hazards on the coastal infrastructure, specifically docks, in Nunavut up to the year 2100 as a result of the projected climate changes and sea level rise."

Coastal infrastructure will be subject to several potential hazards due to climate changes. Although, houses, office buildings, garages, roads and other infrastructure along the coast will be affected by climate change, this report's main focus is on ports and docks. This paper addresses particular conditions for dock design across Nunavut considering future climate change. Furthermore, the construction, operation and maintenance associated with climate change and the Arctic environment in Nunavut are addressed.

Given the long operational life of ports, new ports or upgrades to existing ports must incorporate the long-term effects of climate changes on the marine and inter-tidal physical environment. Notable climate change considerations relating to port design include sea-level rising, increased wind/wave action, changing currents or tides and coastal erosion. A review of these climate effects and related climate predictions, including temperature and precipitation change, is presented. This is followed by an overview of typical dock types, construction methods (e.g. open and closed construction) and design considerations.

2 GEORGRAPHIC LOCATION AND COASTAL GEOLOGY

The Nunavut territory (see Figure 2-1) extends westward from Hudson Bay to the eastern boundary shared with the Northwest Territories. It extends northwards from the southern border, shared with Manitoba (60^{o} N latitude), to the North Pole. More than half of the territory is composed of islands; all the eastern Arctic Ocean islands including Baffin Island, Victoria Island and Ellesmere Island are within Nunavut. Nunavut’s coastline accounts for 40% of Canada’s entire coast. The majority of Nunavut’s coastline was previously covered by sea (light blue region in Figure 2-2; Glacial Geology of Canada). This area contains stratified deposits of clay, silt, sand and gravel. Further north, coastal regions may be composed of ground moraines (white region in Figure 2-2) or existing glaciers (dark blue region in Figure 2-2). Ground moraines are unsorted materials deposited at the base of glaciers. They include most ice-contact stratified material and outwash (e.g. till, gravel and sand).

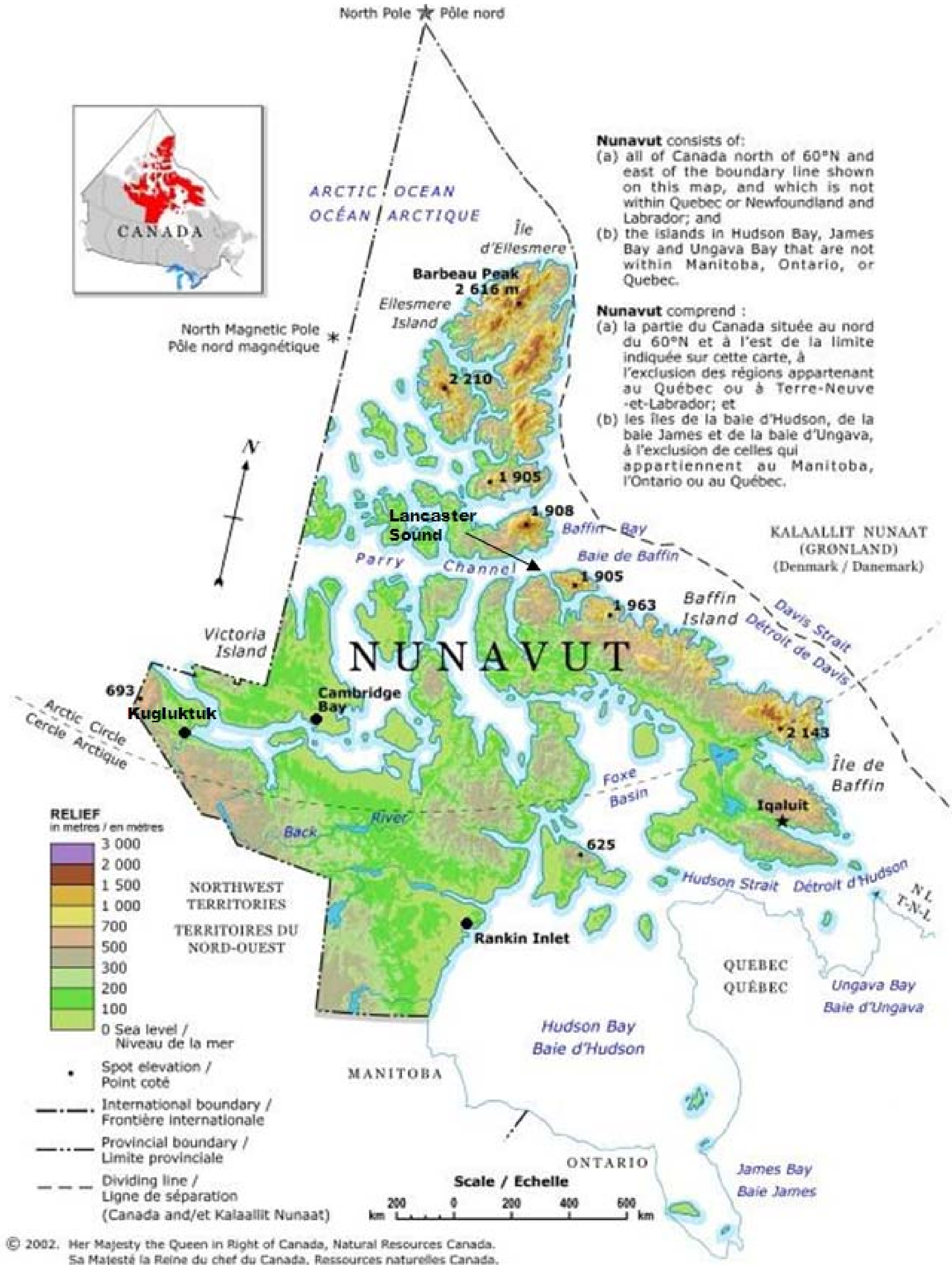

Figure 2-1: Nunavut Territory and Relief Details (NRCan, 2002).

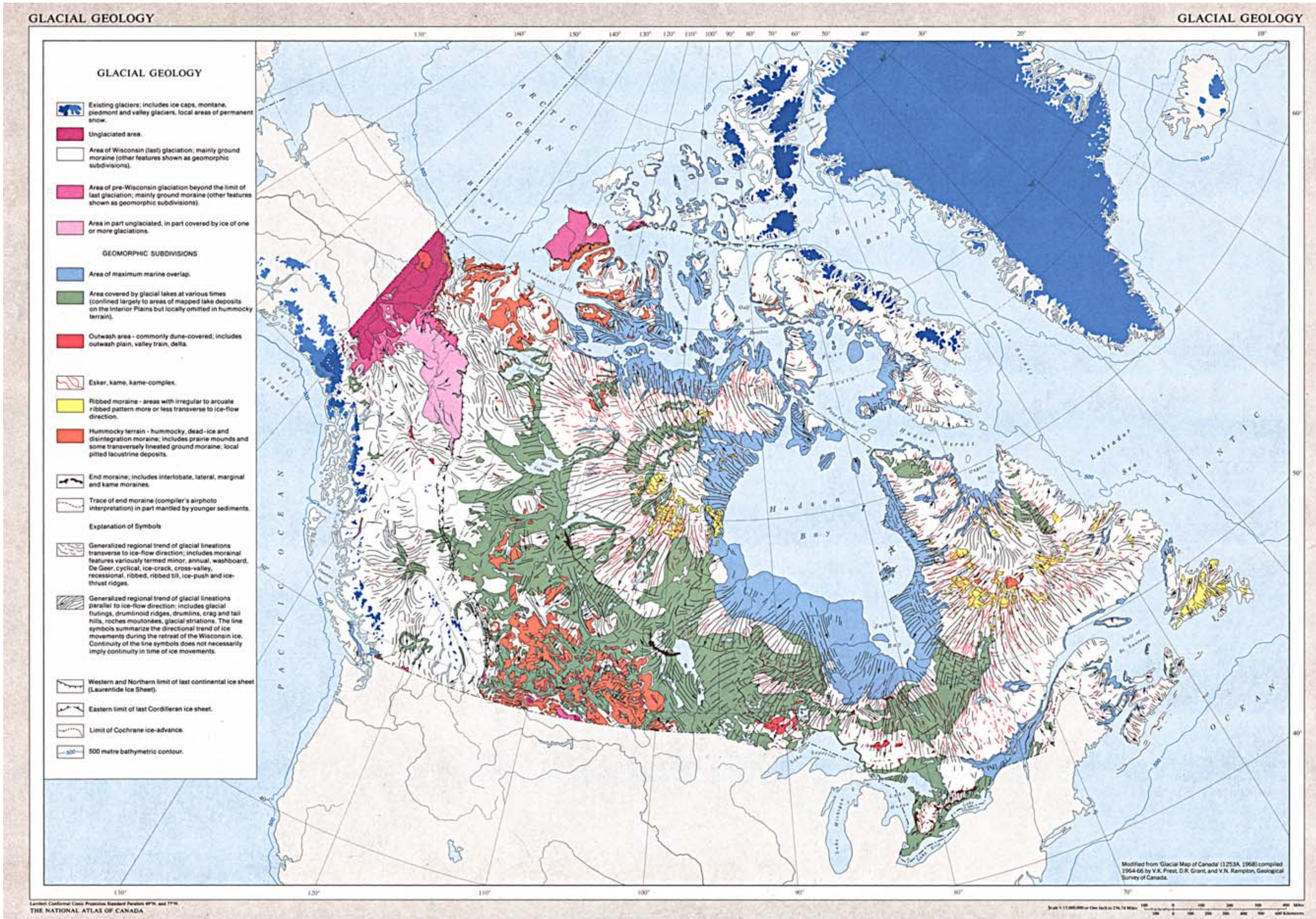

Figure 2-2: Glacial geology of Canada (Atlas of Canada, 1972).

3 CLIMATE CHANGE AND NUNAVUT'S COASTLINE

3.1 Introduction – Impacts on Coastal Infrastructure

As defined by the US Environmental Protection Agency (EPA), climate change is:
"major changes in temperature, rainfall, snow, or wind patterns lasting for decades or longer" that may result from "natural factors, such as changes in the Sun's energy or slow changes in the Earth's orbit around the Sun; natural processes within the climate system (e.g., changes in ocean circulation); human activities that change the atmosphere's makeup (e.g., burning fossil fuels) and the land surface (e.g. cutting down forests, planting trees, building development in cities and suburbs, etc.)" (US EPA, 2011)

Future and current coastal infrastructure in the Arctic will be affected by climate change. All future coastal infrastructure projects will require research relating to climate change. Climate data available for the past century can be used to predict possible expected changes, but uncertainties relating to climate change are inevitable. Engineers are able to provide solutions with growing technologies, but future projects must expect additional capital cost. (ACIA, 2005)

Climate changes will have important implications for maritime operations and facilities which likely will be impacted (directly and indirectly) by various climate change factors such as:

- Predicted changes in wind and current patterns.
- Rising temperature.
- Sea level rise (which could be up to one meter by the year 2100).
- Increased storm magnitudes and frequency.
- Thermal erosion of coastal permafrost.
- Increased wave action and destructive ice forces.
- Inundation of lowlands and wetlands.

- The retreat of beaches.
- Reduction of ice sheet, etc.

All of these items, many of which are directly related to one another, must be carefully taken into consideration in the design of the coastal infrastructure. Sea level changes and associated subsidence of permafrost shore lines due to thaw aggravate the impacts of increased wave energy. Extended periods of ice-free passages, caused by higher temperatures and changes in wind intensity and patterns, increase the magnitude and frequency of storm surges. This will in turn result in greater energy waves and increased coastal erosion and inundation. Direct impacts may affect maritime transport infrastructure, operations, maintenance, dredging and shipping patterns. Indirect impacts could result from changes in demand for maritime transport services, such as trade (merchandise) and energy or mineral exploration activities.

Some of the effects of climate change are beneficial to maritime facilities and operations, such as:

- Less sea ice reduces dangers to maritime traffic and extends the shipping season;
- Fewer days below freezing temperature reduce ice accumulation on vessels, docks and associated facilities, as well as ice jams in ports and frequency of ice fogs.

3.2 Climate Change in Nunavut

3.2.1 Temperature and Precipitation

Environment Canada's website provides historical meteorological data across Nunavut. Table 3-1 presents an overview of the mean annual air temperatures (MAAT) and mean annual precipitation (MAP) recorded at sixteen stations across Nunavut (a total of twenty-three stations exist). Figure 3-1 shows the location of stations and other hamlets in Nunavut.

Table 3-1 : 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
Station	Lat., N	Long, W	El., m	MAAT	MAP	MAAT	MAP	Warming
Alert	82 31	62 16	30	-18.2	154	-18	154	0.2
Baker Lake A	64 17	96 04	18	-12.2	235	-11.8	270	0.4
Cambridge Bay A	69 06	105 08	27	-15.1	136	-14.4	139	0.7
Cape Dyer A	66 35	61 37	393	-10.3	663	-11	602	-0.7
Cape Hooper	68 28	66 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	68 31	27	-12.2	206	-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 56	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	16	-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 3-1 : Hamlet locations throughout Nunavut (Environment Canada, 2012).

3.2.1.1 Temperatures in Nunavut

Nunavut has mean annual average temperatures between -9 ºC in the southeast (Iqaluit) and -20 ºC in the far north (Ellesmere Island). Figure 3-2 summarises the yearly average temperature variation for the 1971 to 2000 period for the villages of Iqaluit, Rankin Inlet, Cambridge Bay and Eureka. These four villages give a representative distribution of the weather over Nunavut (refer to Figure 3-1 for geographical locations). (Environment Canada, 2011)

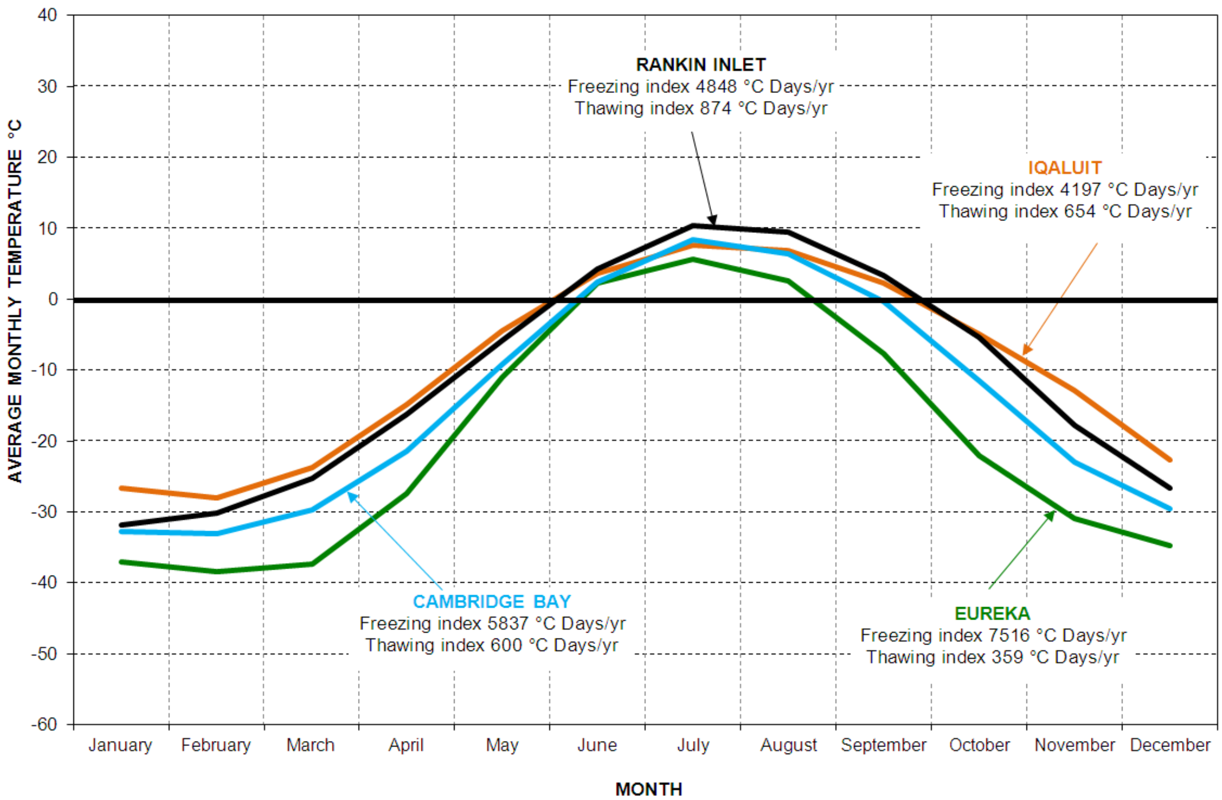

Figure 3-2 : Comparison of average monthly temperatures and air freezing/thawing indices between 1971 and 2000 – Hamlets in Nunavut.

From Figure 3-2, 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 ºC to -34 ºC) by December and last until the end of February (into March in the far north). This represents a three month (or four month) period of intense cold.

Figure 3-2 also provides the air freezing and thawing indices given in degree-days. [<u>*Note:*</u> *air freezing index = degree-day freezing (DDF) and air thawing index = degree-day thawing (DDT)*]. Air freezing/thawing indices are basically calculated by summing the number of days with temperatures below zero/above zero multiplied by the average temperature during that day.

Boyd (1976) presents a paper summarizing how the air freezing and thawing indices are calculated based on normal monthly temperatures. The freezing/thawing indices are used in foundation design (e.g. assessing frost heave), but can also be used to assess thermal regimes in permafrost conditions by correlating the air indices to the ground indices and performing a variety of geothermal analyses. Nevertheless, the values given in Figure 3-2 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 in the southeast to 20:1 in the north.

Table 3-1 (pg. 7) shows a warming trend between the periods 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 a warming average of 0.04 °C/year. Recent events and research indicate that the Arctic warming will continue in the future and should be taken into 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 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. (ACIA, 2005)

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 3-3 shows the difference in the longer period of above-zero average monthly temperatures (thawing) and the corresponding shorter freezing period.

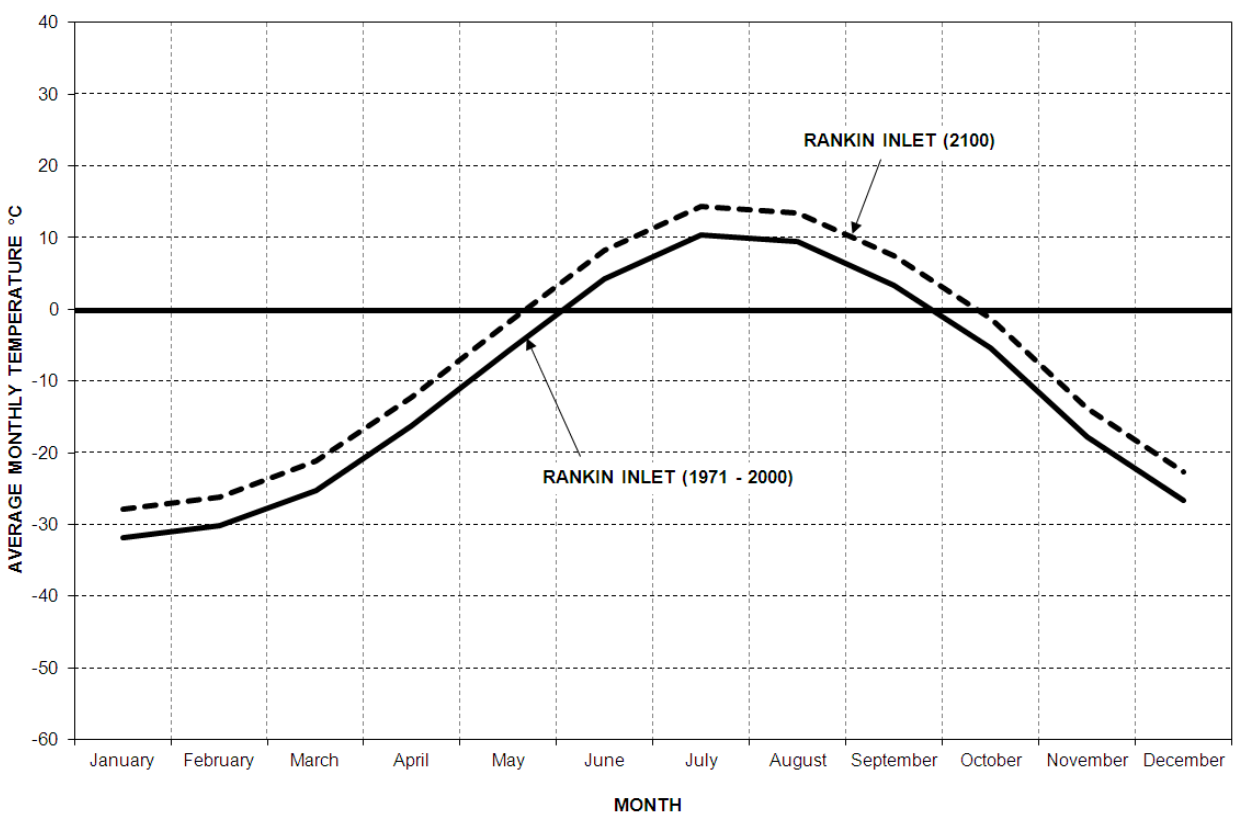

Figure 3-3 : Comparison of average monthly temperature conditions between (1971-2000) and (2100) – Rankin Inlet, Nunavut.

3.2.1.2 Precipitation in Nunavut

The mean annual precipitation for stations in Nunavut is shown in Table 3-1 (pg. 7). 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 is found in the southeast (over 600 mm) and the minimum precipitation in seen in the far north (below 100 mm) on Ellesmere Island. The snow and ice cover over the land and water prevent evapotranspiration and therefore result 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 of Canada with the thinnest active layer. Under these temperature conditions, the active layer in Nunavut should not exceed about 1 metre in ice-rich soils and perhaps 1.5 metres in relatively dry sands or sand and gravel in late summer (August-September).

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; therefore resulting in increased precipitation. Figure 3-4 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).

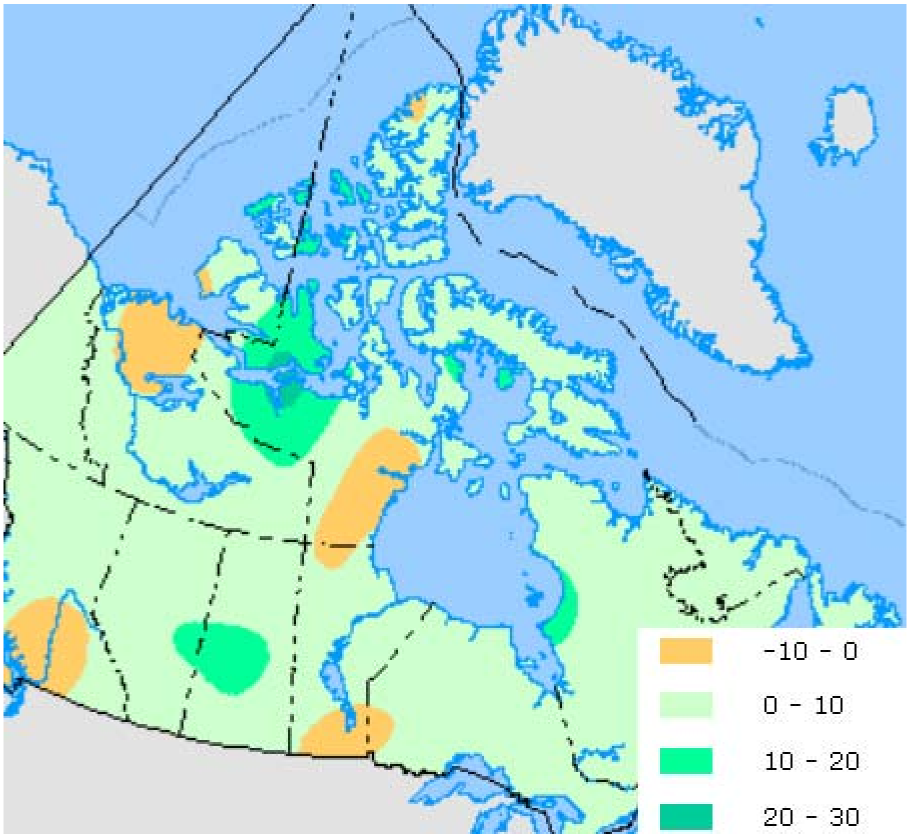

Figure 3-4 : Annual precipitation change (%) from 1961 – 1990 to 2040 – 2050 (Atlas of Canada, 2003).

3.2.2 Shoreline Permafrost and Sub-sea Permafrost

Nunavut is located in the continuous permafrost zone (see Figures 3-5 and 3-6). The depth of permafrost in Nunavut generally extends several hundred meters below the ground surface. Knowing the physical state and thermal conditions is the first step for design engineers to implement mitigation strategies to reduce the negative impacts of climate change.

When sea levels are low, permafrost aggrades in the exposed shelves under cold subaerial conditions. When sea levels are high, permafrost degrades in the submerged shelves under relatively warm and salty boundary conditions. The presence and characteristics of sub-sea permafrost must be considered in the design, construction, and operation of coastal facilities.

Figure 3-5 displays ground monitoring stations over Canada. Figures 3-5 and 3-6 show no known sub-sea permafrost in Nunavut. However, the scarcities of direct data (probing, drilling, sampling, temperature measurements) make the map highly speculative. Most of the distribution comes from indirect measurements; primarily water temperature, salinity, and depth (100 m depth contour). Sub-sea permafrost has been reported, by various authors and designers, to exist in near shore regions throughout Nunavut's coast (see, for example, Rykaart, 2005). Sub-sea permafrost also exists near the eroding coasts of the Arctic islands, mainlands, and where seabed temperatures remain negative.

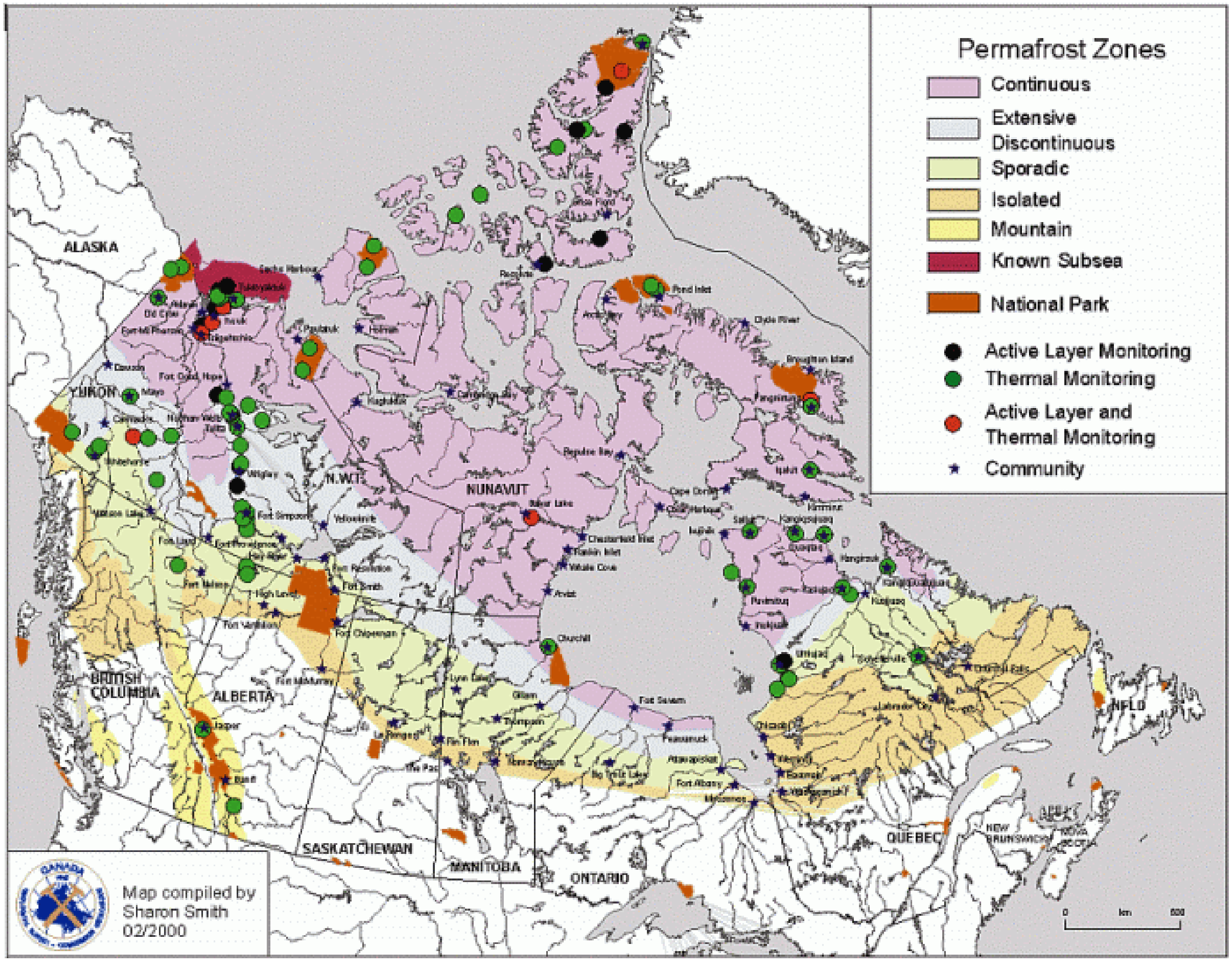

Figure 3-5: Permafrost zones and thermal monitoring stations within Canada (Courtesy S. Smith – GSC, 2000).

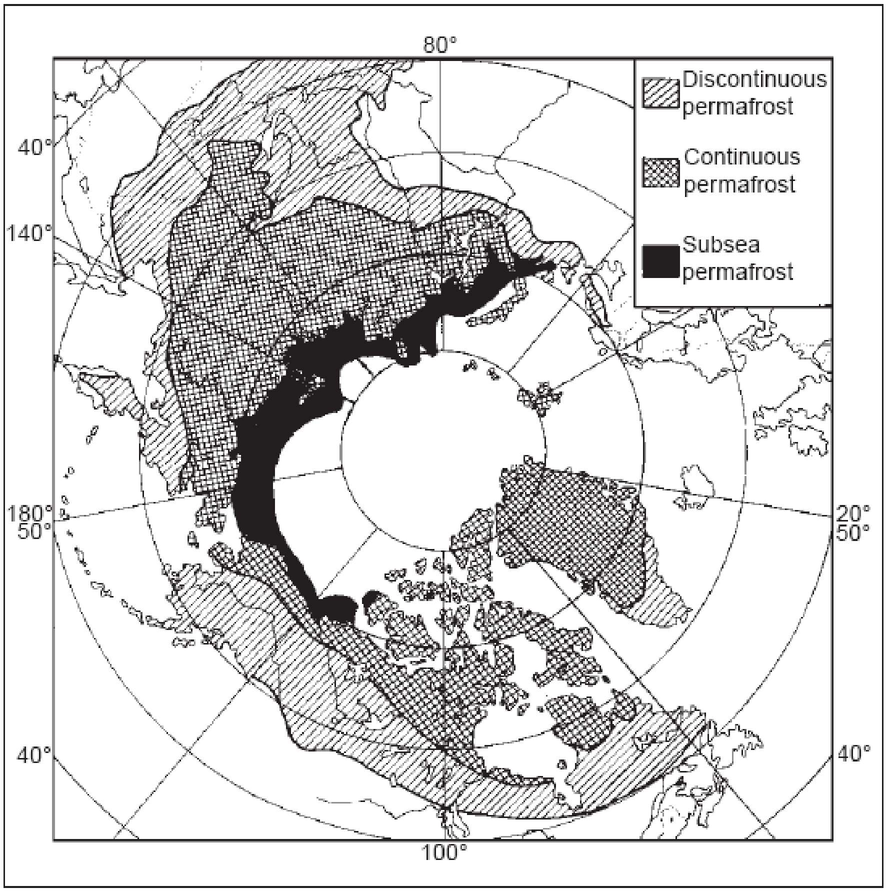

Figure 3-6: Map showing the approximate distribution of sub-sea permafrost in the continental shelves of the Arctic Ocean (Osterkamp, 2001).

3.2.3 Sea Ice Cover

The change in sea ice cover is directly correlated to the surface temperature. Comiso (2012) reported that the analysis of the monthly anomalies of the sea ice extent showed an overall declining trend. Figure 3-7 presents the overall trend in sea ice extent over a given year and the 10-year averages for the last three decades excluding certain years.

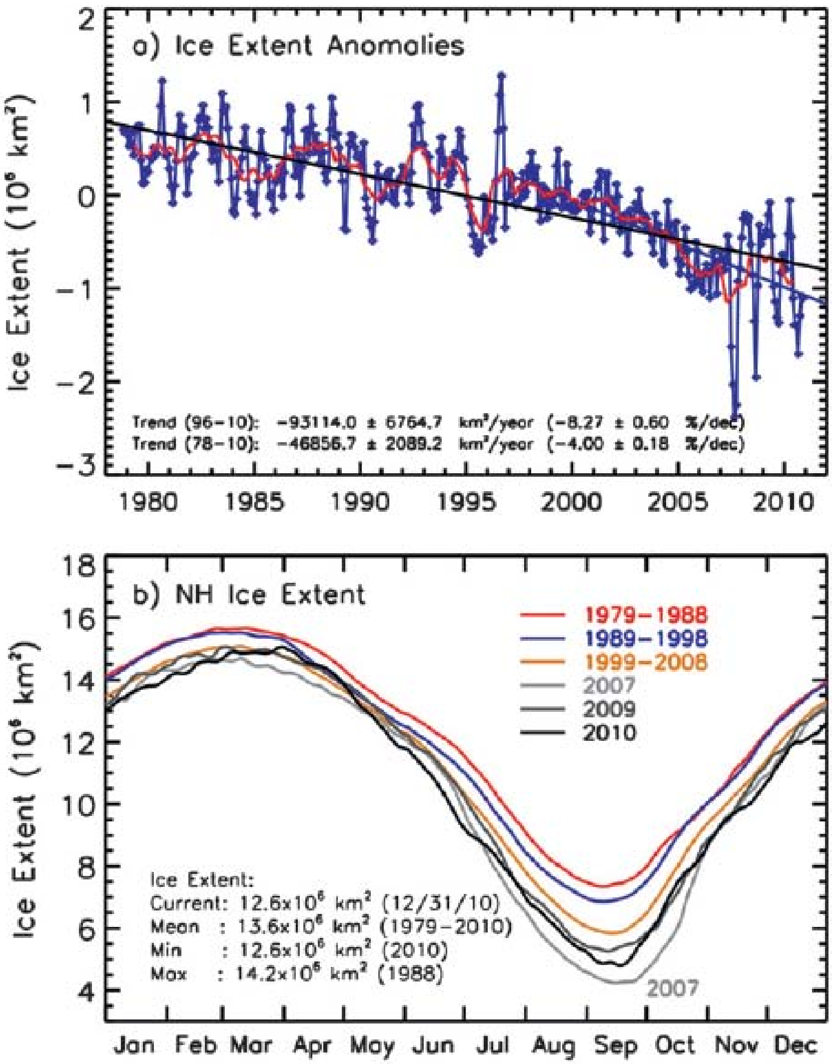

Figure 3-7: Sea ice extent (a) monthly anomalies and (b) 10-year average (Comiso, 2012).

The following conclusions can be deduced from this figure:

(a) A dramatic decline in sea ice extent was recorded in 2007.

(b) The highest extent occurs in February or March while the lowest extents occur at the end of the summer melt period taking place in September.

(c) The changes in the Arctic ice cover are more pronounced in the summer than in the winter period.

(d) The change from the first to the second decade of recordings was significant mainly in spring and summer while the change from the second to the third decade was significant in all seasons.

Under scenarios of climate warming, sea ice cover is expected to retreat further into the Arctic Basin to breakup earlier and freeze-up later, and to become thinner and more mobile (ACIA, 2005). Figure 3-8 presents the projected changes in sea ice distribution as predicted by the five different global climate models conducted by ACIA (2005). This is expressed in terms of the number of models out of five that project the presence of sea ice during the specified month for at least 50% of the years in the time slice. An overall projected reduction in sea ice trend can be noticed from the presented figures. September values for all of the time slices are less than the maximum of five over much of the Arctic Ocean. On the other hand, the projected reduction in sea ice extent in winter is less than in summer. Figure 3-9 shows observed and projected Arctic sea ice extent (ACIA, 2004, 2005).

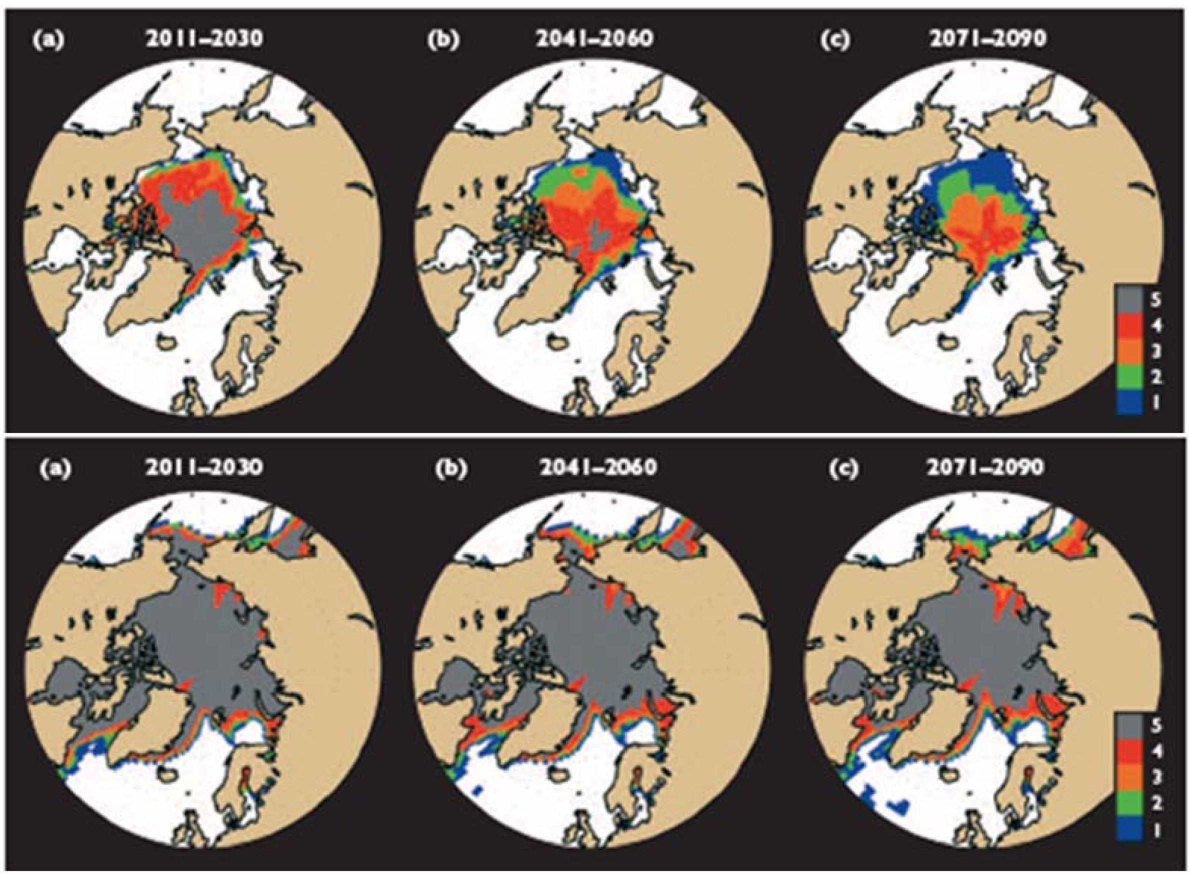

Figure 3-8: Projected changes in sea ice distribution (ACIA, 2005).

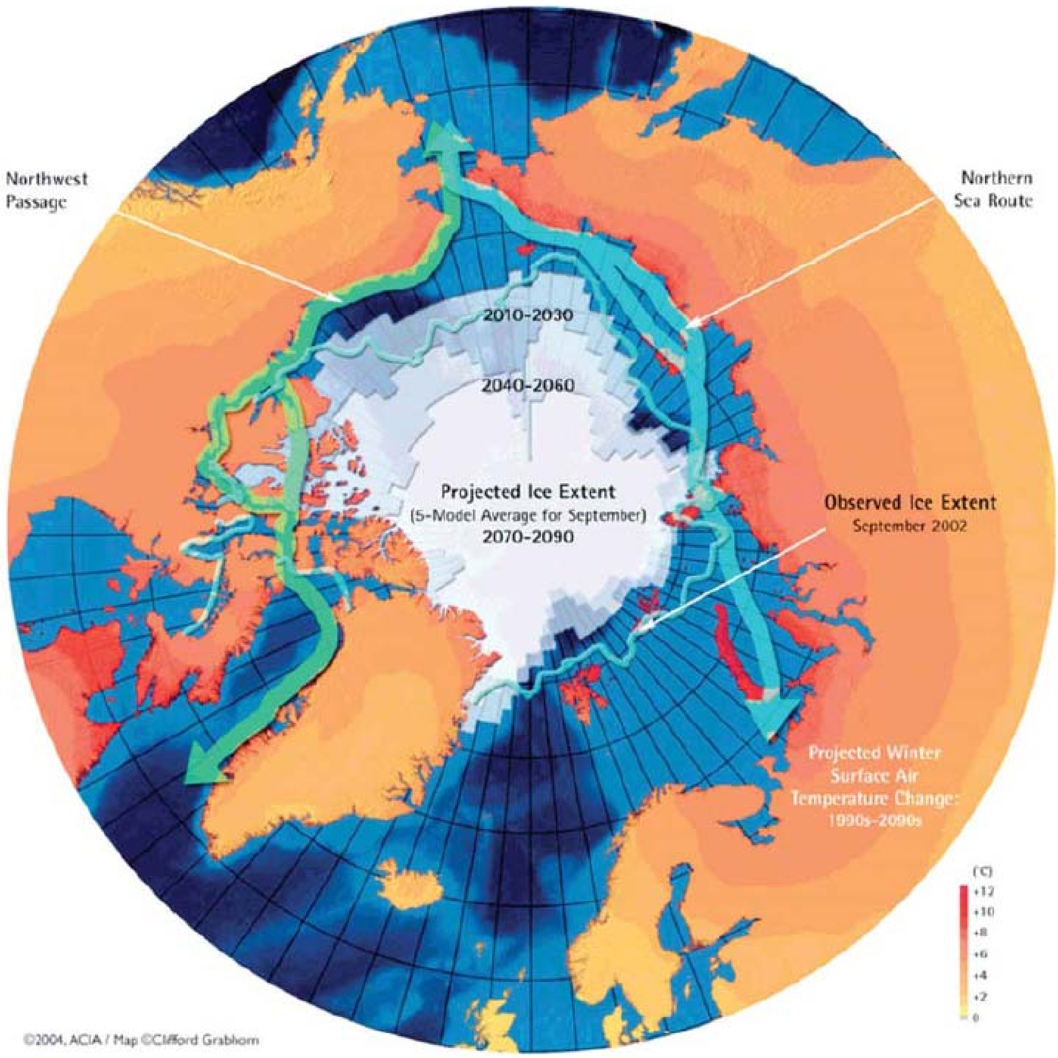

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Figure 3-9: Observed and projected Arctic sea ice extent (PIANC, 2008).

3.2.4 Sea Levels Rise

Predictions on sea level rise on the land surface, due to melting land-based ice sheets, thawing of permafrost and sediment deposition, are complicated by the daily tidal fluctuations caused by the moon and the fact that the earth's crust, which is the reference, has been moving upward. Figure 3-10 shows the coastal sensitivity to sea level rise for the Canadian Arctic. In Nunavut, the sensitivity varies from low to moderate.

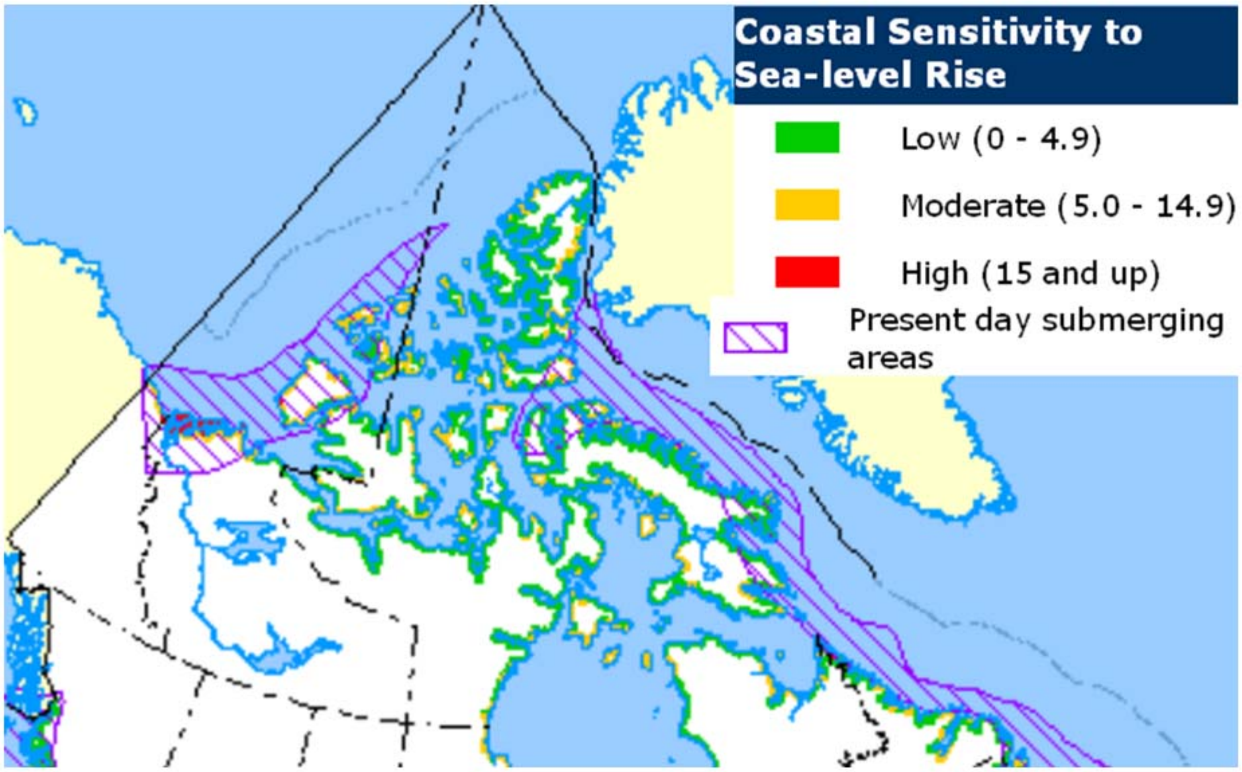

Figure 3-10: Coastal sensitivity to sea-level rise (Atlas of Canada, 2007).

The land surface was compressed at the beginning of the retreat of the Laurentide continental ice sheet, about 20,000 years ago. At that time, the land was more than 100 metres below today's ground levels. With isostatic rebound, the earth's crust rose at varying rates which are evidenced by the numerous beach or strand lines visible in all Arctic locations. A recent article published in PEG magazine (Jacobs, 2011) reported that, during the latest 8000 years, the average rate of increase in sea level is about 1.5 mm/year. However, with recent warming trends, climate prediction simulations expect an overall increase in sea level that ranges between 0.5 and 1.0 metre by the year 2100.

3.2.5 Coastal Erosion

Coastal erosion or shoreline erosion in Nunavut generally occurs by wave action at high tides and littoral currents. However, the process is complicated by several factors. Figure 3-11 provides a schematic of the processes surrounding coastal erosion. More details and references related to coastal erosion in the Arctic can be found in Chapter 16 (ACIA, 2005).

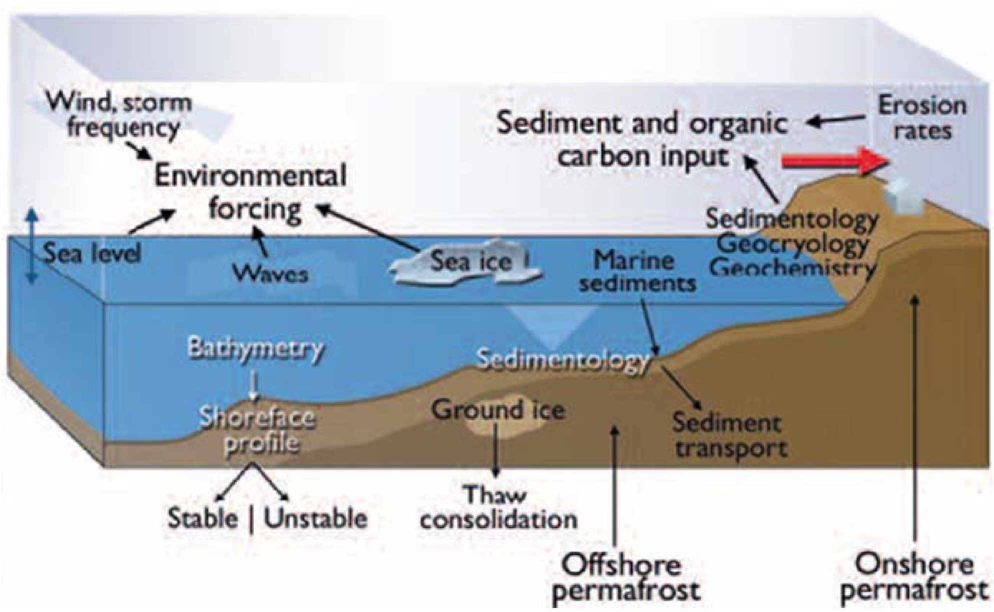

Figure 3-11: Schematic representation processes affecting coastal erosion in the Arctic (ACIA, 2005).

The Arctic Coastal Dynamics (ACD) project has been adapted to address coastal change over the Arctic, and extensive work has been done through this program; however, much of the work is focused on other more sensitive regions than Nunavut. Environmental forces that effect erosion will be affected by climate change. Sea level rise can play a role in increasing erosion simply by raising the water levels. With increased storm frequency, increased wave action will create more potential for erosion in the future.

Ground ice, found within permafrost, is a unique feature of Arctic coastal systems. The ice content within the frozen ground along the coast (either within the sub-aerial or sub-marine part of the shore profile) will affect the erosion rates. Aré (1988) termed the combined action of waves and the thawing of permafrost as "thermal abrasion". Ice rich coastal cliffs, particularly in the Western Arctic, and the presence of thermokarst are some notable areas that are well-documented to be affected by ice content. In nearshore zones, the presence of thawing of ice within the permafrost influences the shoreline profile, thereby modifying the course of erosion.

Lantuit et al. (2008) presented a study on 545 shoreline segments across the Arctic Region to investigate the statistical relationship between erosion and ground ice content. A weak correlation was found between shoreline retreat and ground ice content, indicating that ice content is a major factor affecting erosion, but other processes, such as hydro-dynamic forces, are contributing factors as well. It should be noted that no data was taken from the Arctic Archipelago (all the Islands north of the Canadian mainland), since sea ice is present throughout the summer, which hampers erosion rates. (Lantuit et al., 2008)

Thermal erosion is the result of degrading permafrost along the near shore coastline due to wave action. Permafrost of marine origin (clay and other marine-derived sediments) is common along the coastline. Permafrost may be located between patches of exposed bedrock or over widespread areas. Case studies have been and are being carried out to assess permafrost degradation conditions in localized areas in Nunavut. For example, Fortier et al. (2007) has reported thermal erosion of ice wedges on Bylot Island, Nunavut.

3.2.6 Current

The Department of Fisheries and Oceans in Canada provides nautical charts and services. DFO has also began a project called the Canadian Arctic Through-flow study (CAT) that is being undertaken in order to better understand the Arctic Ocean current, which is a key element in climate change. The project hopes to make future predictions on Arctic climate change. Figure 3-12 displays the prevailing surface flows (red arrows); the red circles indicate areas where CAT is performing studies and the black arrows show major river flow. Figure 3-13 displays major currents (left) and warm and cool currents (right) through the Arctic Region. Figure 3-13 (right), also shows the Baffin Island current, which runs south down the along the north coast of Baffin Island.

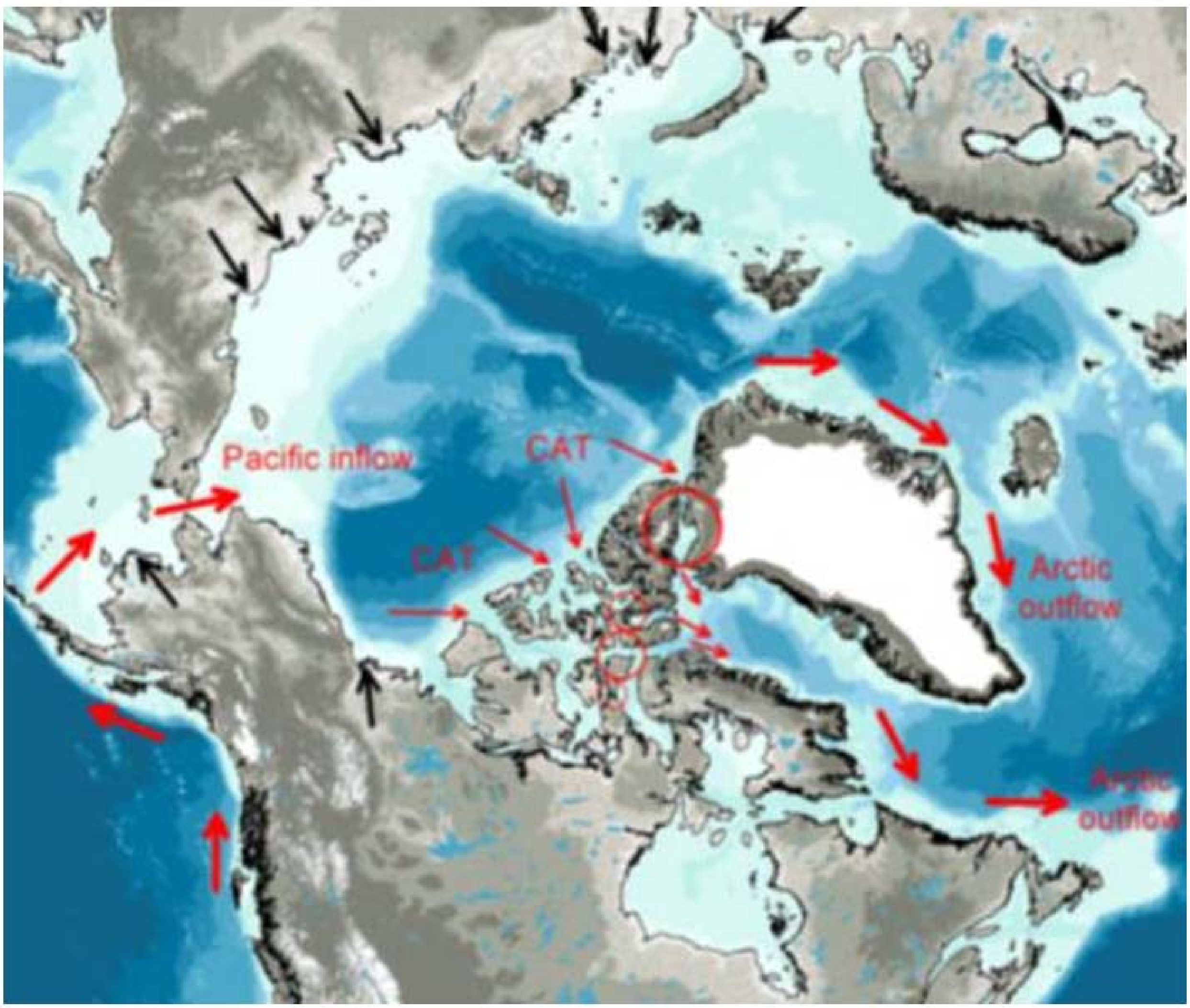

Figure 3-12: Prevailing surface flow of Arctic waters – West to East (Atlas of Canada, 2007).

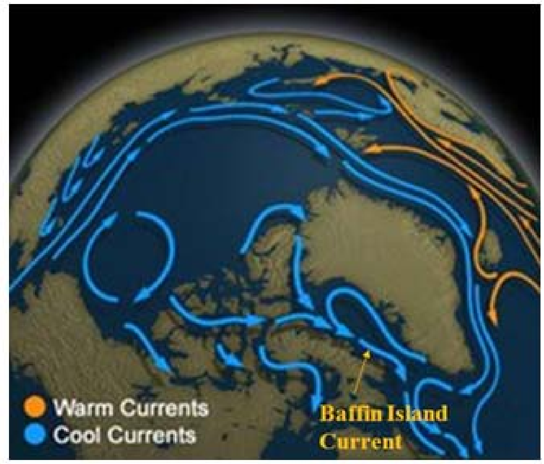

Figure 3-13: Main currents (left) and warm and cool currents (right) in the Arctic (BIO, 2012).

3.2.7 Wind, Storms and Waves

In recent years, changes in storm tracking, intensity and durations have been observed on low pressure systems shifting northwards, and summer thunderstorms systems and winter freezing rain is observed further north (Figure 3-14). The rising frequency and intensity of Arctic storms have forced acceleration of the rate of sea ice drift. Historical conditions (1953 to 1997) record more than 350 blizzard hours in Nunavut (Figure 3-15) with associated potential intensity changes in the future.

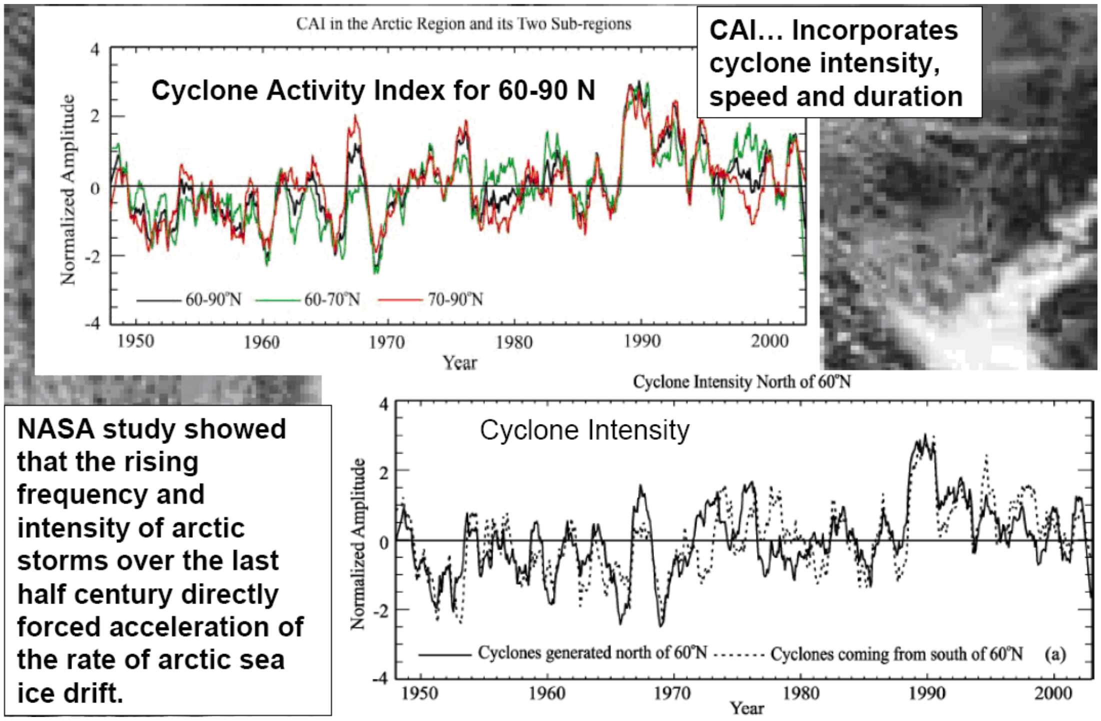

Figure 3-14: Shifting storm tracks and increasing storm intensities (Zhang et al., 2004).

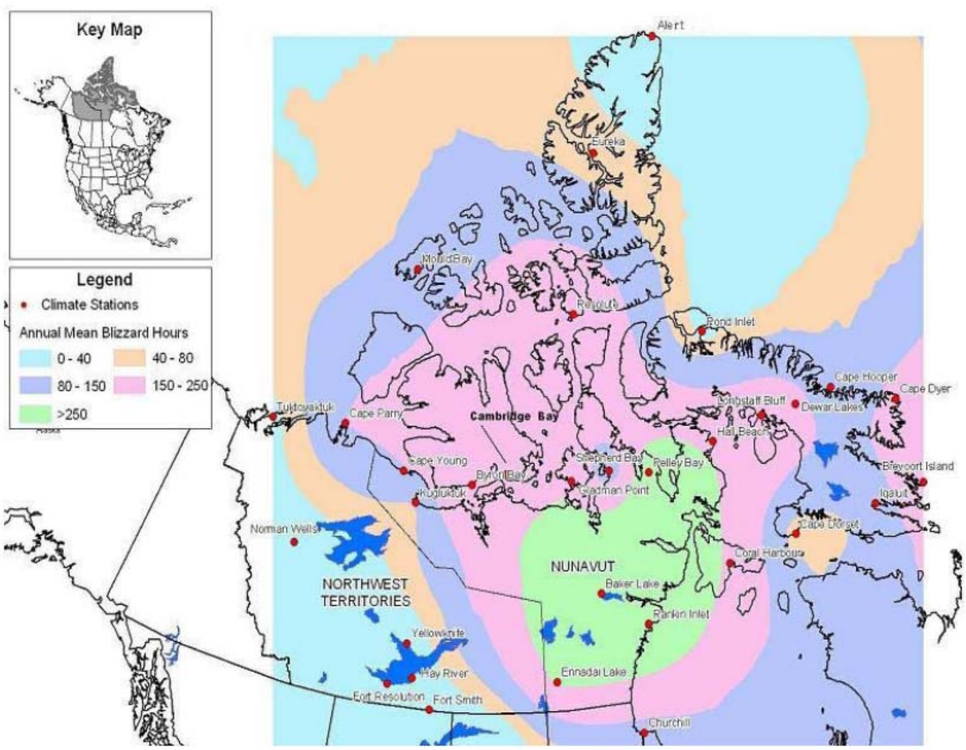

Figure 3-15: Mean annual blizzard hours in the Canadian Arctic between 1953 and 1997 (CAHN, 1997).

3.2.8 Tides

Some regions of the Arctic experience strong tidal flows, up to 3 m/s, especially in shallow seas such as the Barents Sea or along the Siberian shelf break; tidal dissipation yields enhanced vertical mixing, helping the Arctic lose global heat to the atmosphere and to space. Upward mixing of oceanic heat contributes also to sea ice melt. Tides have other effects on ice, creating cracks which allow ocean heat to escape and mobilise the ice.

The eastern portion of Nunavut has some of the highest tides in the world, with a tidal range of about 13 metres. The western part has very low tides. Tidal information is available through the Department of Fisheries and Oceans website (http://www.dfo-mpo.gc.ca/) for hydrographic stations across Nunavut.

Generally, the sea ice cover dampens the tidal amplitude and affects the phase of the tidal wave. The decreased water level is due to the damping mechanism used to dissipate the tidal energy that also induces friction at the ice-ocean interface. Considerable variability of the ice cover effect to the tides between geographic locations in the Canadian Arctic has been reported in literature. This subject is not completely understood and research is on-going.

Climate change is expected to reduce the sea ice cover in thickness and extent which will attenuate tidal conditions. Tidal currents generally reduce the expansion of sea ice cover, speed up the retreat process and alter the evolution of sea ice. Consequently, a change in tidal currents and amplitude will further affect the sea ice cover and will help accelerate the change of present conditions, thus affecting future design and operation of near shore and shore infrastructures.

3.3 Overall Effects of Climate Change in Nunavut

Based on the short presentation of the climatic changes projected to the end of the present century, it is deduced that the Arctic may slowly resemble parts of the globe located at more southern latitudes today. While the same climatic changes may prove detrimental to parts of the globe located nearer to the equator, proper engineering design can overcome and adapt port infrastructures and operations in the Arctic due to the expected new, mostly detrimental, conditions resulting from climate change. As a reminder, the present report does not discuss environmental and socioeconomic changes due to climate change.

As a prerequisite, engineering design requires reasonable projections of climate changes for producing feasible and economically acceptable solutions. Much research is still required to provide input into engineering design so that new, unedited, economically and environmentally accepted methods can be developed instead of reinforcing existing materials and structures to withstand harsher weather conditions.

4 DOCKS

4.1 Introduction

A dock is a general term used to describe a marine structure for mooring or tying up ships or vessels as may be needed to load/unload cargo or embark/disembark passengers. Factors affecting dock design are topography, subsoil conditions, water depth, shore profile, tidal range, current, wind, waves, protection, and, of course, the type of function the dock will be used for. Dock location is also an important consideration. Design is mainly governed by the function or use of the dock. For an industrial or mining operation, transatlantic ship size can be up to 300,000 DWT and requires deep draft conditions with up to 25 metres of water at low tide.

These operations may require an approach channel, turning circle and parking area, as well as protection from high winds and ice. Normally in remote areas, a dock location is selected and finalized by extensive map examinations of shoreline profiles and water depths, and exploratory trips by experts to various potential sites, followed by preliminary soil investigation at the selected sites. With this information the most suitable location and economical dock design can be arrived at.

As a result, selecting a suitable dock location in a remote area requires an understanding of some basic principals of dock design and dock types, as well as the type of terrain and soil conditions that they are most suited to. The purpose of this section is to identify the different factors that have an influence on the design and operation of a dock, and to correlate visible site conditions with the corresponding suitable types of dock structure so that, upon arriving at the site, and observing shoreline and topographic conditions, it may be possible to approximately identify the type or types of dock that would most likely suit the location. The results are however intended to provide rough guidelines only, and in all cases will have to be confirmed or revised to suit actual conditions at the site by experts.

The main difference between Arctic ports and ports elsewhere in North America is that for an Arctic port there are two main additional design features to be considered, these are, ice and low temperatures. It should be noted that the eastern Canada seaboard shares very similar ice conditions to the Arctic. The force of ice exerted on a dock in the Arctic can be very high and can equal or exceed the combination of berthing forces imposed by a ship. Therefore, this additional force must be taken into account in the dock design. Temperature is also an important factor, since the extremely low temperatures combined with wind chill can make operations very difficult if not impossible. In the case of industrial or mining operations, where dockside shiploading and unloading mechanical equipment must operate, extremely low temperatures combined with high winds can cover dockside equipment with thick ice layers making operations hazardous.

For Arctic ports with thick ice cover nearly 8 months of the year and usually shallower water depth, smaller ships are used, in the range of 40,000 to 100,000 DWT. These may become important considerations depending on the amount of traffic expected, and therefore the berth occupancy that is estimated. For lighter functions such as fishing boats or local village commerce, and the use of supply ships, if no natural protection for the dock exists, it is usually sufficient to provide an entrance channel protected by a breakwater. This will enable the barges to come and go to prepared loading areas during most types of weather conditions. Finger piers can also be built to accommodate the operations. Such structures are usually built of timber cribs usually filled with natural rocks. Blasted rock can also be used if available. If severe ice conditions exist, steel plates can be attached to the face of the cribs for ice protection.

In zones affected by the exceptionally high tides of eastern Baffin Island (Iqaluit), providing deep sea access in 100% of the navigation season, docks must be located well beyond the low tide bed, which can be more than 1 km from the hamlet or the mine site. If for technical or economic reasons a dock structure cannot be provided inside a breakwater protected area, barges will have to be used to receive supplies and a suitable shore embankment built to enable the barges to be unloaded. In some cases where the topography and ocean bottom is suitable, a steel sheet pile bulkhead dock may be a practical solution. Also, timber cribs can be sunk in a suitable area, filled with stone and used either as protection or as mooring for fishing boats. This type of solution, however, lacks the necessary safety features, water supply, electricity, and cargo handling capabilities. In these cases, the required draft is usually not more than 3 or 4 metres and the tide usually less than 2.5 metres. Floating barge docks are another type of temporary dock; barges are pinned together and connected to steel post by an o-ring that allows the dock to float with the tide level.

4.2 Need for Port Development in Nunavut

In Nunavut, ports and harbours are relied on by local fisherman, commerce, and recreation. The current and growing mining industry also rely on ports to bring equipment and supplies in and out. Although, in some cases, mines will build docks with short lifespans, which are not subject to long-term climate change (see, for example, Rykaart, 2005). Regardless, there are very few docks in Nunavut and the need for improvements to marine infrastructure is well overdue. Peter Taptuna, the minister of economic development and transportation, noted that Newfoundland and Labrador have approximately 370 docks, while Nunavut, with 40 % of Canada's coastline, has just one, in Pangnirtung, which is under construction (Windeyer, 2009).

4.3 Types of Docks

The most common types of docks are the following:

- Wharf/Quai: A dock which parallels the shore.
- Steel sheet pile bulkhead wharf: Similar to a wharf but backed up by land.
- Gravity Quai wall: Same as a bulkhead wharf but built of concrete blocks.
- Pier or Jetty: A dock which projects into the water (also known as finger piers).
- Breakwater pier: A pier or jetty, with one side as a breakwater.

- T-head pier: A pier parallel to shore with the approach connected to it at the centre.

- L-shaped pier: A pier parallel to shore with the approach to it at one end.

- Breasting Dolphins: A marine structure designed to take the impact of a ship when docking, and to hold the ship against broadside winds.

- Mooring Dolphins: Additional dolphins located in back of the dock face, at the front and back of the dock to hold the ship against broadside wind blowing in a direction away from the dock.

- Fixed Mooring Berth: A marine structure consisting of breasting and mooring dolphins for tying up the ship, and a platform for supporting the cargo handling equipment.

- Excavated Basin Dock: A basin excavated into the shoreline, and containing a dock structure of timber cribs, concrete caissons, steel sheet piling or built-up rock face.

- Dike Protected Basin: A basin enclosed by a rock dike with a built-up shore embankment for unloading barges.

See Appendix for schematic cross-sections of typical dock construction options for Nunavut, which includes: steel sheet piles or tubular steel piles driven into sand or clay, or to refusal on bedrock or till, concrete caissons on sand, till, or shallow bedrock, timber rock cribs on solid bay bottom, steel sheet pile cells driven to bedrock, and floating dock behind break water protection.

4.4 Types of Dock Construction

The construction of wharves, piers, bulkheads, and fixed mooring berths, falls generally into two broad categories.

- Docks of open construction are those which contain a working deck usually of reinforced concrete supported by a network of timber piles, tubular steel piles, or concrete piles, equally spaced and driven into the ocean bottom to a predetermined penetration.

- Docks of closed or solid construction are structures such as steel sheet pile cells, steel sheet pile bulkheads, timber cribs, concrete caissons and gravity quay walls.

The most common types of dock foundations are summarized Sections 6.4.1 and 6.4.2. The choice of which depends on soil and bedrock conditions at the site.

4.4.1 Dock of Open Construction

Most common types of open construction docks are jetties or piers, both T-shaped and L-shaped. A fixed mooring berth dock is also usually of the open type construction. The piles are usually tubular steel piles. Timber piles were used in the past, but have now been replaced by heavy steel pipes. Due to the presence of ice in the Arctic, large diameter steel piles are preferred as they can more adequately resist the ice forces. Timber piles may still be used on rare occasions for mainly temporary structures such as for an equipment unloading dock for a mining project while the main dock is under construction. Concrete piles are not recommended because of durability problems (see Figure 4-1). Open construction docks are suitable in areas where there is deep sand, or shallow sand overlaying hard material or rock. The piles are designed to act in friction, or end-bearing (or a combination of both). The steel pile diameter will usually vary from 600 mm to 1000 mm. A common construction difficulty with piles is when the sand material contains boulders, which makes driving or drilling the piles more complicated. It should be noted that the vibrations associated with pile driving can be detrimental to fish (Popper et. al, 2006). However, strategies such as pile installation during slack tides (high or low tide), when fish activity is low, and wave attenuation by cofferdams or air bubble curtains can be used (see, for example, Hardyniec and Skeen, 2005).

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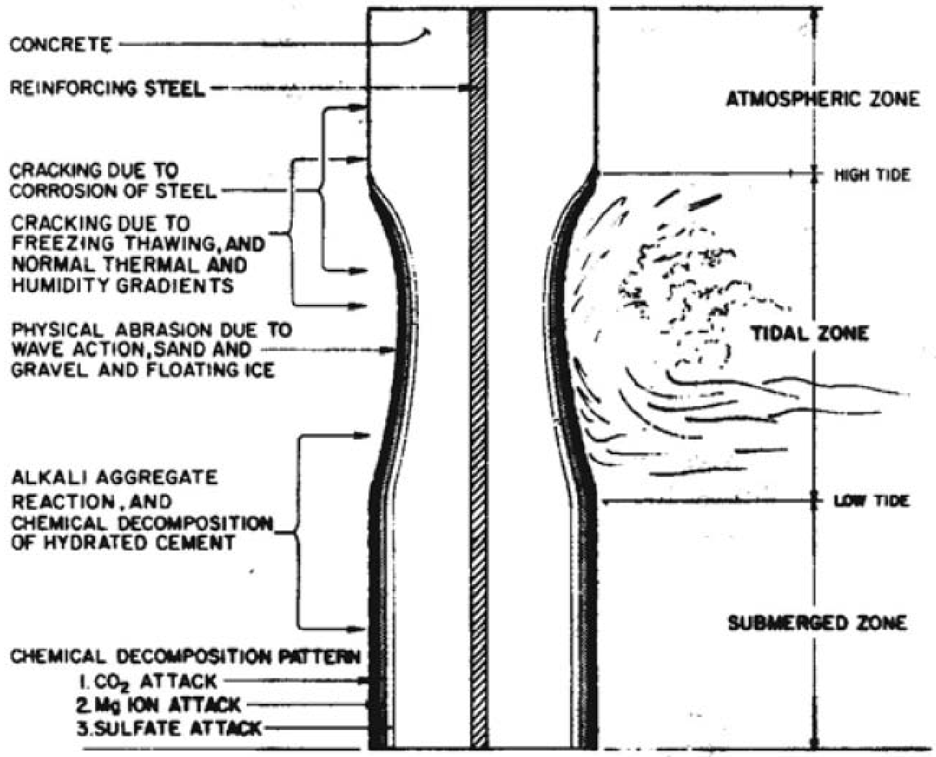

Figure 4-1: Factors affecting concrete durability in seawater environments.

4.4.2 Dock of Closed construction

This type of structure is economical for shallow draft docks such as those used for fishing boats, and local trade, as well as for more industrial and mining uses, especially where there is a need for heavy loading/unloading equipment to travel along the surface near the dock face. Closed construction docks are also used in Quai wall structures, where the backup land becomes useful for handling and storage purposes. Deep sand or shallow sand underlaid with hard material or even flat/gently sloping rock surface can accommodate a closed construction type dock.

- For fishing boats and local trade, a suitable and economical type of dock (topography permitting) would be timber cribs or the steel sheet pile bulkhead type wharf.

- A dike enclosed basin and barge unloading is particularly suitable in an area where the bay bottom consists of soft, compressible soils which cannot support breakwaters. A dike enclosed basin may also have a dock structure. In the Arctic, rock filled timber cribs are the most economical structures.

- Shallow draft dock structures such as timber cribs or (topography permitting) steel sheet pile bulkhead type docks are used. These can be located inside a sheltered harbour, or a breakwater protected area, or an excavated basin, all depending on the topography, soil conditions and the cost of providing protection.

- For a quai wall structure of steel sheet piling, the supporting material would have to be deep granular or silty sand so that the steel sheet piles could be driven to fixity.

- The presence of boulders in the sand always creates difficulties, but this can only become known after borings have been taken. At any rate the depth of sand would have to be sufficient to ensure the required sheet pile penetration.

- For timber cribs, concrete caissons, and gravity quay walls, the supporting material may be sand, hard material or gently sloping rock.

- For concrete caissons or cribs, the supporting material would require a mattress of crushed stone or gravel to ensure adequate bearing pressure, uniform load distribution, and in the case of gently sloping or irregular rock, a horizontal surface upon which the structure may sit. Gravity concrete caissons are the most practical type of dock for large ore carriers in the Arctic.

- For local village operation, in sandy conditions and with a relatively low tidal range, both a steel sheet pile wall and a timber crib dock structure would be suitable and economical. In terms of constructability, however, the timber cribs could be more economical for smaller docks as it is a labour intensive operation requiring mainly hand tools and unskilled labour. A steel sheet pile wall dock on the other hand is equipment intensive requiring fairly heavy construction equipment (e.g. crane, pile driver, compressors, welders, skilled, labour, etc.)

- Steel sheet pile circular cells are most commonly constructed in areas where the sand depth is shallow or non-existent and the ocean bottom contains areas of exposed bedrock and is otherwise covered with varying depths of overburden material consisting of sand, silt, clay, or a mixture of each interlaced with boulders.

- The steel sheet piles are usually driven to refusal and filled with crushed stone or gravel. Stability of the cell structure is provided by its mass, depth to width ratio and friction along the bottom surface. These structures are more suitable for industrial or mining purposes where a deep draft is required to accommodate bulk carriers, container ships or oil tankers having drafts that may exceed 22 metres.

- In areas where the ocean bottom is steeply sloping solid rock, or very soft silt or clay over steeply sloping rock, it may at times be necessary to expose the rock by clamming away the overburden, then drilling and blasting a supporting ledge into the rock on which either caissons or cells may be placed to form the dock structure.

4.5 Breakwater

In selecting a dock location, two important considerations are: adequate water depth close to shore and protection against high winds, and if possible, ice. If these two conditions do not occur naturally, they can be created; however, the cost may be significant. Additional water depth is created by dredging, and protection is created by a breakwater. A breakwater is usually a mound of quarried rock deposited on the ocean bottom of different predetermined sizes having a specified cross-section and a specific horizontal orientation and length. They serve to break oncoming waves from the seaward side to create calm conditions on the shoreward side. In some areas a breakwater will not only protect the dock from high waves but it may also serve to prevent floating ice from entering the protected area during the winter period. In the event that the dock cannot be located in a sheltered area, whether or not a breakwater is required, is determined by the maximum wave height that can be expected along with the most severe ice conditions.

For fishing boats and small commercial vessels, natural protection can take the form of a small harbour or cove or the inside of a bay. Local residents can usually provide valuable information regarding exposure to winds, waves, and ice of the selected site. This can often confirm whether or not a breakwater is necessary and what orientation it should have.

For large industrial, bulk, oil, and mining ships, the protection requirement is more complicated and will involve soil investigation and specialized calculations and design. Currents, ice movements and dominating wind direction will have to be identified. Due to the size of the vessels involved, and depending on the wave heights that can be expected, along with the space required for the ships to approach, berth and leave the dock, a breakwater design in terms of cross-section and horizontal shape can become an important and costly structure. It will be either built of various sizes of quarried rock, with the final wave dissipating surface of fabricated concrete shapes or large quarried stone weighing several tons each. The cross-section area of the breakwater, the slope of its seaward face and the overall length are used to determine the volume of material required and hence the cost. The flatter the seaward face, the greater will be the cross-section area and capital cost. But also, the flatter the seaward face, the lower the erosion and the maintenance cost.

4.6 Design Factors

The main factors affecting the design of docks can be divided into two general categories.

- Technical: This would include the dock function, ship size, draft requirements, berthing and other forces, live loads, dock dimensions to accommodate operations and ship approach.

- Geographical: This would include wind, ice, waves, current, tide fluctuation, rock protection.

4.6.1 Technical

These factors are determined by the design consultant and are generally based on the users' basic requirements.

4.6.2 Geographical

These are generally site conditions that must be taken into account during the design of the dock structure.

4.6.2.1 Shoreline Permafrost and Sub-sea Permafrost

Permafrost in the nearshore area where docks are to be built is rather rare in Nunavut, however when encountered it can provide a stable foundation for dock foundations if the underlying ground remains frozen; the high strength and lack of settlement are key benefits. With the risks of climate warming and permafrost degradation, artificially freezing the underlying ground using thermosyphons can be used. Thermosyphons are may be required to counter balance the heat transfer occurring along steel piles during installation Thermosyphons can be installed to prevent differential settlement and to ensure the strength of the underlying frozen soil is maintained. Thermosyphons can also be installed if required on an inclined angle into a potential slip surface beneath a dock to stabilize the underwater slope leading to a deep berth area. Steel sheet pile walls, cells or piled foundations would be undesirable foundation options in regions directly overlying permafrost/sub-sea permafrost due to the difficulties in penetrating to a sufficient depth into the frozen soil during installation.

4.6.2.2 Sea Ice

In all Arctic operations the presence of ice greatly shortens the shipping season. The length of the shipping season could vary from location to location. It may be as short as two months, or as long as six months. This is mainly due not only to the temperature, but also to the currents and wind which move the drifting ice. These may become important considerations depending on the amount of traffic expected and also the estimated berth occupancy.

Ships travelling in northern and Arctic waters have to be ice reinforced. The effect of ice on the dock and the ship may be quite significant. Ice at the dock during ship berthing may require tugs or even the ship itself to manoeuvre back and forth to break and remove the ice and permit berthing. Similarly, when leaving the dock, the ship may have to loosen the ice by manoeuvring back and forth at high throttle. This situation requires that scour pads be installed on the ocean bottom in front of the dock to prevent erosion of the ocean bottom material by the ships propeller. Large ice fields may be blown against the dock and a condition called rafting may take place. Large mass of concrete caissons, cells, or large diameter steel piling are usually used to resist this force. Breakwater protection is useful to prevent heavy ice presence inside the breakwater area. If the breakwater creates an inner harbour with a narrow opening, the movement of heavy ice fields will be limited to outside the area.

4.6.2.3 Sea Level Rise

The effects of future sea level rises on the shore lines can only be based on the extreme water levels occurring during the highest tides. These occur under extreme storm conditions at full moon periods and during high intensity on-land winds. Sea level rise combined with increased temperatures lead to longer periods of open water and shorter periods of land-fast ice. Under this condition, continual attack by waves, storms and ice flows will expose the shoreline at similar levels experienced during the period of isostatic rebound. Headlands and coarse boulder beaches will be affected the least. Sandy beaches will continue to be affected by littoral current erosion and movement of sand along the shoreline beaches toward narrow estuaries and river outlets. Land-based installations, such as oil storage reservoirs, ore storage facilities or administrative buildings, must be built well above the highest autumn or spring tides under surging conditions and protected with high rock berms to avoid damage by ice rafting during periods of severe off-shore winds.

In the case of docks with rock fill dikes providing access to the mooring structures, the sands will be deflected to the berth area and the water depth at low tides will be diminished. Only an open free flowing section at the shoreline or a longer deflector dike, which moves the sands to deeper water beyond the berth area, will avoid costly dredging requirements.

4.6.2.4 Coastal Erosion

Areas that are highly susceptible to coastal erosion processes should be avoided (e.g. areas with high ground ice content, degrading permafrost). Erosion control protection measures for the north include: offshore breakwaters, groynes, revetments, sea walls, dikes, gravel bags, concrete mats, gabions, rock protection (stone riprap protection), steel sheet pile bulkhead, thermosyphons to stabilize slopes, and beach nourishment. Examples of coastal protection case studies in cold regions can be found through Coastal Frontiers', website (www.coastalfrontiers.com/).

4.6.2.5 Current

A ship's berthing and departure is affected by current. For most favourable berthing and departure conditions, the dock alignment should parallel the current direction. This makes it easier to control the ship during berthing and departure. It also helps move the ice away from the dock face.

4.6.2.6 Wind, Storms and Waves

The effect of the wind is the force it exerts on the ship, while docking or leaving the dock, and the broadside force it exerts on the ship while tied up at dock. In addition, a wind blowing over a long stretch of ocean can generate waves which will disrupt operations. This potential wind effect however can be taken into account by means of a breakwater during the design of the dock.

A wind blowing broadside against a ship towards the sea, while it is tied up at the dock, is at a maximum when the ship is light at high tide. This force may equal or exceed the bollard capacity at the dock and at such times it may become necessary to release the ship from the dock. When the wind is blowing against the dock, the resulting force is transmitted to the dock structure through the fendering system. When the ship is leaving the dock or berthing, tug assistance may be necessary during high winds.

Whether the dock functions as a local or an industrial operation, heavy winds and large waves will halt the operation and may even force the ship to leave the dock, anchor in deep water and ride out the rough weather. If such occurrences are frequent, the construction cost of a breakwater may be justified. For a dock facility, it is important to gather data on wind velocity and direction. This is usually available through Environment Canada. Increased frequency and associated winds will create wave conditions of higher significant height, duration and fetch as the extent of sea ice cover will be diminishing, thus creating:

- Greater horizontal forces on docks and on structures;
- Greater loads on mooring;
- Greater horizontal loads on bollard or mooring dolphins.

4.6.2.7 Tides

An extremely high tide, (e.g. 10 metres or more), together with a draft requirement of 15 meters, would make certain dock structures less practical or economical than others. For example, steel sheet pile bulkhead docks would become gradually impractical as their height increases beyond 25 metres, mainly due to the excessive length of the sheet pile required, the difficulty in achieving the required penetration, and the many levels of tie backs that would be necessary. For such heights, a more practical and cost-effective solution would be steel sheet pile cells or caissons, and large diameter steel piles.

For low tide levels and little draft requirements (e.g. where the total dock height would not exceed 10 meters), the most suitable and cost-effective dock for fishing boats and village commerce would be timber cribs. However, ground conditions, exposure, and other factors could alter this significantly. Timber cribs are still quite cost-effective especially in remote areas because they can be built with local labour and require minimal construction equipment, which is available in the Hamlet. In many cases, the timbers (typically with a cross-section of 12 in. x 12 in., 12 in. = 0.3048 m) can be handled with light equipment using unskilled labour to do the fastening.

Most Arctic villages are located near the high tide level at the head of long inland bays or fjords. At low tide conditions, the sea can be up to 1 kilometre from the villages. Access to the seas can only be provided by long breakwaters extending to the low tide level or to a point where access to the water is available only 50 percent of the time (half tide). Alternatively, the port must be relocated where deep water is present, which is sometimes several kilometres further down the inlet.

4.6.3 Dock Location Determination

For mining projects in the Arctic, selecting the most suitable and economical dock location will involve consideration of several factors as discussed below.

4.6.3.1 Deep Draft Dock for Mining Projects in Nunavut

A first consideration should be the volume of materials to be shipped. This will establish the maximum and minimum size of vessel that will be required. The second consideration is the depth of water available and the tidal fluctuation involved since this will establish the distance to the dock facility from the shoreline. Adequate water depth (either existing or available) and proximity to the plant and storage areas are the main considerations. Several locations may have to be examined, and possibly preliminary comparative cost estimates made to determine the most suitable and economical location. Turning circle, parking areas and available wind and wave protection must also be considered. If protection in the form of a breakwater has to be provided, it may become quite costly, as a source and distance to a suitable rock and quarry site may be quite far. At such times it may be more advantageous to select a costlier dock site that has natural protection. Surface topographic information may provide an indication of the types of dock structure suitable for the selected location. A detailed geotechnical investigation is required to determine the most suitable dock for the site and size of ships involved.

4.6.3.2 Shallow Draft Dock for Fishing Boats and Local Hamlet Use in Nunavut

Access by an existing road is a main consideration and bathymetric information to determine the location of the harbour with the most suitable water depth and protection against rough weather is another. On this basis the visible site topography will provide a guide as to the most suitable type of dock structure for that particular location. For Arctic villages, the rock filled timber crib docks are usually the most economical. It may be that other locations are suitable, if a natural protection exists at one of the locations. This would be a considerable factor in the selection process. Otherwise, protection by means of a rock dike may have to be provided. After the above has been reviewed and discussed, the findings should be further examined by experts and a detailed list of site investigation requirements drawn up in order to finalize the location and other details.

4.6.4 Compatibility Table

Table 4-1 : Compatibility Table for Docks.

SITE	DRAFT		TIDE		FUNCTION		DOCK TYPES
	Shallow	Deep	Small	Large	Local	Industry	
Deep sand		√	√			√	2 3
		√		√		√	2 3
	√		√		√		1 2 3 6B
	√			√	√		1 2 3 6B
Shallow sand rock		√	√			√	4 5 5A 6B
		√		√		√	4 5
	√		√		√		4 5 5A 6B
	√			√	√		4 5 5A 6B
Rock flat		√	√			√	5A 5C 7
		√		√		√	5C 7
	√		√		√		5A 5C 7
	√			√	√		5A 5C 7
Rock steep		√	√			√	5E 6A
		√		√		√	5E 6A
	√		√		√		5E 6A 6B
	√			√	√		5E 6A 6B
Soft silt / clay rock		√	√			√	2 4 5
		√		√		√	2 4 5
	√		√		√		2 4 5 5A
	√			√	√		2 4 5 5A
Soft silt / clay no rock							2 3

5 ENGINEERING CHALLENGES FOR DESIGN, CONSTRUCTION AND MAINTENANCE OF LARGE SCALE PORTS IN NUNAVUT WITH REGARD TO POTENTIAL CLIMATE CHANGE

The design lifetime for dock structures in permafrost regions is typically 30 to 50 years, but could be over 100 years for large iron ore docks. During this period, the structure must function according to design with normal maintenance procedures and costs. The effects of climate change on Arctic infrastructure are difficult to quantify. Structural damage will not be exclusively attributed to climate change, but climate change can have considerable effects on the structure which will affect operation and maintenance requirements during the service life. In some coastal areas, shore protection measures have to some extent reduced local erosion rates. However, thawing and erosion of ice-rich coastal sediments is a process that has been ongoing since the last glaciation and will not be reversed given present climate trends. Nunavut faces the challenge of increased coastal erosion rates with increased wave action, sea level rise, thermal erosion that can result in problems which require innovative engineering solutions.

Fortunately, projected climate change is not likely to pose an immediate threat to infrastructures designed with adequate factors of safety in Nunavut. Exceptions would be found in regions located on ice-rich terrain or along coastlines highly susceptible to erosion. Projected climate change is very likely to have a serious effect on existing infrastructure in vulnerable areas; therefore protective measurements should be implemented in highly susceptible areas. Maintenance costs will increase, but it should be feasible to gradually adjust the infrastructure over time to a warmer climate.

Future design of engineering structures in coastal zones should be based on actual meteorological observations and a risk-based method reflecting trend analyses related to projected climate change. The sensitivity of a particular infrastructure project to climate change is a function of various factors, including the initial conditions, the project lifetime, and the over-design or safety margin that is included in the design. Bush et al. (1998) proposed a procedure for categorizing these effects and determining the climate sensitivity of a project (based on a scale from high to low) considering potential damages, as well as socioeconomic or cultural impacts (the present report does not address socioeconomic or cultural impacts). After all possible scenarios are evaluated and categorised, the impacts due to climate-change are determined and incorporated to the final design.

Table 5-1 presents, in tabular form, the impacts of the various parameters affected by climate change on design, construction, maintenance and dredging of ports in Nunavut, as well as suggestions on engineering design items and operational approaches.

TABLE 5-1. EFFECTS OF CLIMATIC CHANGE ON DESIGN, CONSTRUCTION AND MAINTENANCE OF LARGE PORTS (MINING AND MERCHANDISE) IN NUNAVUT				
CLIMATE CHANGE EVENT		**IMPACTS AND GENERAL RECOMMENDATIONS ON**		
PARAMETER	**PROJECTED CHANGE TO NATURAL ENVIRONMENT**	**DESIGN IMPACTS AND MITIGATION STRATEGIES**	**CONSTRUCTION**	**MAINTENANCE AND OPERATION**

A. Air temperature	• Projected increase 4 ^{o}C/100 years (worst case scenario).
	• More open water over longer period.
	• Degradation of permafrost table, particularly along the shore line.
	• More material accumulating in berth area.
	• Increased availability of the ports, more frequent traffic to manage over long period of time.
		• Potential for land slides of soft clay deposits along steep slopes. This could endanger dock support structures.
		  o Installation of thermosyphons along slopes at risks of failure in areas where existing docks are located.
		  o Avoid these regions for new port construction.
		  o Reinforce slopes with embankments.
		• Increased settlements of heavy dikes and caisson type structures carried on soft sea bottom.
		  o Structures should be supported on heavy piles.
		  o Installation of thermosyphons in underlying foundation at risk of thaw.
		• See also section below for steel, concrete and reinforcement steel deterioration.
			• Longer period of ice free sea.
			  o Less downtime in construction.
				• Costly removal of sloughing.
				• Shore material flowing into berth area.

B. Sea water temperature	• Increased sea water temperature.
	• Fewer sea ice/icebergs.
	• See also "sub-sea permafrost" in Section I of this table.
		• Increased and accelerated corrosion of metal structures
		• Faster deterioration of concrete exposed to sea water and corrosion of reinforcement bars (chloride attack).
		  o Design for increased corrosion of steel structures;
		    o Use galvanized steel.
		    o Cathodic protection.
		    o Corrosion resistant steels.
		  o Stronger horizontal welds at steel pile extension joints.
		  o Design concrete to account for increased degradation;
		    o Increase concrete cover.
		    o Lower permeability concrete.
		      • Lower water/cement (w/c) ratio
		      • Longer curing times
		      • Well distributed aggregate size
		      • Admixtures
		    o Larger diameter steel reinforcement with corrosion protection.
		    o Air-entrainment to reduce freeze-thaw effects.
		  o Design with wood, which is very durable in Nunavut climate.
			• High capital costs.
			  o Increased cost for steel and concrete, but improved durability.
				• More frequent maintenance; corrosion and damages to steel and concrete components.
				  o Remove, Clean, Replace.
				  o Corrosion Inhibitors, Cathodic Protection, Sacrificial Anode, Cancellation Current.
				  o Protective Overlay: Waterproof Membrane, Watertight Concrete Overlay.
				• Increased availability of the ports, more frequent traffic to manage over long period of time.

<table>
<tr><th colspan="5">TABLE 5-1. EFFECTS OF CLIMATIC CHANGE ON DESIGN, CONSTRUCTION AND MAINTENANCE
OF LARGE PORTS (MINING AND MERCHANDISE) IN NUNAVUT</th></tr>
<tr><th colspan="2">CLIMATE CHANGE EVENT</th><th colspan="3">IMPACTS AND GENERAL RECOMMENDATIONS ON</th></tr>
<tr><th>PARAMETER</th><th>PROJECTED CHANGE TO NATURAL ENVIRONMENT</th><th>DESIGN IMPACTS AND MITIGATION STRATEGIES</th><th>CONSTRUCTION</th><th>MAINTENANCE AND OPERATION</th></tr>
<tr><td>C. Precipitation</td><td>• More rainfall along coast lines, particularly the west coast of Hudson Bay and western shore of region of Nunavut.
• Changes in sedimentation process; bank erosion, local scour, etc.</td><td>• More icing on overhead structures, wiring and light standards.
  o Design for heavier loads on overhead structures.
• Provide suitable drainage design.
• Provide for more runoff erosion.
  o More protection of roadways.
• Reduce permeability of concrete to resist leaching and efflorescence (from soft rain water):
  o Lower water/cement (w/c) ratio
  o Longer curing times
  o Well distributed aggregate size
  o Admixtures</td><td>• More costly construction for geosynthetics and erosion protection.</td><td>• More frequent control/ maintenance of structures and drainage, better flood protection.
• Costly dredging of berth area possible.</td></tr>
<tr><td>D. Wind velocity, extreme weather events, storm surge level, and high tidal wave energy</td><td>• Increase in intensity, duration and frequency.
• Higher onshore waves and lower offshore waves.
• Higher tides and higher surge effects if wind direction is blowing up narrowing bays during rising high tide period (Bay of Fundy effects).</td><td>• More bay bottom scour at edges of caissons and around piles.
• Increased vulnerability of dock structures, possible overtopping of dock, thicker ice accumulation on structures and higher loads.
• More ice abrasion of steel marine surfaces and exposing fresh metal leading to accelerated corrosion processes on steel.
• Severe ice abrasion of concrete in tidal range.
  o Choose protected area if possible and orientate structure into predominant wind direction to minimize wind, waves and floating the effects on dock structure.
  o Stricter design of structures for erosion and scour protection.
  o Design superstructure for higher winds for hurricane and severe ice coating over more extended periods of extreme weather events.
  o Design for higher water levels during surging at high tides.
  o Design for higher ice forces on marine structures and larger rip-rap on flatter underwater slopes to minimise overtopping and damages to rock dikes and jetties, dock facilities, superstructures, lights, higher capacity bollards on docks and mooring dolphins with enclosed weather protected associated access man-ways. More robust bumper protection.
  o For near shore wave conditions and shore protection structures, apply a 10% increase of deep water wave height that break before reaching the shore according to water depth at the particular location.
  o Design structures for extreme events and apply stricter safety standards. Increased loads on structures; for new ports, limitations on choice of location.
  o When soft offshore bay bottom conditions do not offer sufficient</td><td>• Increased vulnerability of construction equipment.
• Higher capital costs.
  o More costly protection for floating equipment during construction
  o More downtime for marine construction equipment and ship demurrage during storms.
  o More costly scour protection.
  o More costly rip-rap protection.
  o More costly breakwaters.
  o Provide for replacement equipment and materials for construction.</td><td>• Increased maintenance and repair of port infrastructures and overhead services.
• More costly maintenance for damage repairs to local failures of breakwater rip-rap and scouring at sea bed.
• More frequent sand accumulation in berth area from shore line erosion: costly storage.
• Increased maintenance of coastal protection infrastructure, seawalls, breakwaters, etc.
• More robust emergency procedures required.
• More frequent control/ maintenance of structures and drainage, better flood protection required.
• Reduced availability of the ports.
• Avoids costly ship standby charges (demurrage).</td></tr>
</table>

TABLE 5-1. EFFECTS OF CLIMATIC CHANGE ON DESIGN, CONSTRUCTION AND MAINTENANCE OF LARGE PORTS (MINING AND MERCHANDISE) IN NUNAVUT				
CLIMATE CHANGE EVENT		**IMPACTS AND GENERAL RECOMMENDATIONS ON**		
PARAMETER	**PROJECTED CHANGE TO NATURAL ENVIRONMENT**	**DESIGN IMPACTS AND MITIGATION STRATEGIES**	**CONSTRUCTION**	**MAINTENANCE AND OPERATION**
		hold for ship anchors, provide mooring structures to secure vessels when laying offshore in open waters to ride out severe storm conditions. (70 km/h winds and 6 m waves) o Oversized tethering lines to secure ships to suitable anchorages. o Include higher surcharge loads on structures design – structural frames and foundations. o Stricter structural and drainage design standards. o Breakwaters: design height and weight of armour unit block for orientation according to projected conditions for overtopping and stability. o Shoreline protection design with flexible mechanically stabilized earth (MSE) walls or large size armours with filter layers (geosynthetics, filter rock layers).		
E. Mean sea level	• Rise by 500 mm by 2100. • More shoreline erosion and sediment into berth area.	• Decrease of water levels increases exposure of docks, wharfs and jetties and results in higher corrosion rates. o Mitigate corrosion design. • Higher static water pressures on structures o Design for higher predicted sea levels. o At zones where the sea level is expected to rise, docks and other affected port structures need to be higher to withstand overtopping during design life. o If the sea level is expected to drop due to high erosion, sufficient draft needs to be allocated for large vessels access and manoeuvring over the design life of the project. o In the absence of site-specific projections, use an allowance of 5mm/yr sea level rise.	• Higher capital costs.	• Increased water levels will provide better draft conditions. • Decreased levels will have to be corrected with dredging, change of port location or configuration of longer docks to permit ships to dock in deeper water. • Corrosion of reinforcing steel in concrete. o Remove, Clean, Replace, o Corrosion Inhibitors, Cathodic Protection, Sacrificial Anode, Cancellation Current. o Protective Overlay: Waterproof Membrane, Watertight Concrete Overlay. • Decrease of water levels increases exposure of docks, wharfs and jetties and results in higher corrosion rates. o Higher maintenance of steel structures.

TABLE 5-1. EFFECTS OF CLIMATIC CHANGE ON DESIGN, CONSTRUCTION AND MAINTENANCE OF LARGE PORTS (MINING AND MERCHANDISE) IN NUNAVUT				
CLIMATE CHANGE EVENT		**IMPACTS AND GENERAL RECOMMENDATIONS ON**		
PARAMETER	**PROJECTED CHANGE TO NATURAL ENVIRONMENT**	**DESIGN IMPACTS AND MITIGATION STRATEGIES**	**CONSTRUCTION**	**MAINTENANCE AND OPERATION**
F. Sea currents	• Worst case: higher velocity and frequency. • More sedimentation in berth area.	• Longer and stronger attacks by floating ice. o Protective measures: move into deeper waters offshore. o Protect sensitive shorelines with armour stones. o See mitigation strategies concrete and steel mentioned in above sections.	• Longer and stronger forces on floating construction. equipment and temporary formworks. • Organize construction for ice free construction period and install temporary barges to deflect waves and ice around work area. • Higher capital costs.	• Repairs of damaged equipment during storms and strong currents. • More shoreline erosion at high tides accumulation of sediments in berth area.
G. Tides and tidal surcharges	• Increase in intensity and frequency.	• High forces will develop on large size concrete caissons carried on the seabed, particularly during iceberg season and high tides and are violent on shore winds. o Design structures at higher elevations. o Locate structures at higher elevations: quays, sea wall structures, etc. to overcome overtopping and low land flooding. o Piles structures that allow free water flow through the structure are preferable to bulk-type structures to reduce water pressure effects on design – structural frames • Increased degradation of concrete structures due to increased freeze/ thaw intensity and frequency. o Use air-entrainment admixtures to reduce freeze/thaw effect on concrete structures.	• Higher capital costs. • More downtime.	• Increased maintenance and replacement costs of port, coastal and sea infrastructures.
H. Days with frost, sea ice cover	• Decrease	• Less ice load on structures. o Adapt design accordingly.	• Low capital costs. • Less downtime.	• Reduction of days with working restrictions; less ice load-related damage • Increased regularity of ports – longer operating season. • Port management to be designed to handle larger traffic.

TABLE 5-1. EFFECTS OF CLIMATIC CHANGE ON DESIGN, CONSTRUCTION AND MAINTENANCE OF LARGE PORTS (MINING AND MERCHANDISE) IN NUNAVUT				
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PARAMETER	**PROJECTED CHANGE TO NATURAL ENVIRONMENT**	**DESIGN IMPACTS AND MITIGATION STRATEGIES**	**CONSTRUCTION**	**MAINTENANCE AND OPERATION**
I. Sub-sea permafrost	• Decrease	o Design for a lower permafrost horizon. o Place foundations deeper in the permafrost layer and/or bear on till or rock – pile foundations to be considered.	• Higher capital costs.	
J. Land submergence	• Lowering of land mass relative to sea level.	o For new ports, select sites not subject to severe land submergence.		
K. Isostatic rebound	• Rise of land masses relative to sea level	o If isostatic rebound outweighs sea level rise, design must account for lower draft conditions.		

6 CONCLUSION AND GENERAL RECOMMENDATIONS

Recognition of climate change and associated present and future impacts provides an opportunity for Nunavut ports and navigation authorities to shape polices, adaptation strategies and mitigation measures for inland and maritime navigation. This report summarises climate change parameters and impacts, and explores potential responses to port infrastructure and operation in an effort to create a continuing communication for consideration and adaptation of our current and future systems and infrastructure to account for a changing climate. Although sustainable development is required to adapt successfully to climate change, costs could render some resource projects uneconomical and may prohibit some adaptation alternatives.

Port designers must incorporate climate change projections in their plans as new docks and piers usually have a lifespan, during which time significant changes in climate may occur. Although present design process and construction standards for port infrastructures typically include historical data, climate change should be addressed with appropriate forecast models and high safety factors, as well as leading edge technology to ensure durability. These data should be compared to present design methods that allow for occurrence of events with return periods of 50 or 100 years.

Existing Nunavut ports should reconsider their current design, while future ports should account for some or all of the items presented here (and on Tables 5-1 and 5-2 in greater detail).

- Adjust heights of infrastructures, if current infrastructures are lower than future anticipated rising sea levels;
- Anticipate future rising sea levels for new infrastructure;
- Anticipate new containment methods for existing ports with contaminated land on their premises;

- Investigate the navigability under the anticipated future sea levels;
- Reinforce or design infrastructures to withstand impacts from stronger wave action and higher storm surges;
- Reinforce or design drainage facilities to respond to anticipated storm water flows and associated erosion;
- Adjust/design dredging requirements;
- Anticipate larger port traffic, as well as possible longer delays and suspension of operations due to more severe weather events;
- Relocate existing port facility or optimise location with the climate change in mind when designing new port facilities;
- Enhance or design for increased security equipment, strategies and personnel.

Finally, other indirect impacts should be considered such as changes in the concentrations of populations (increased population, relocation, etc.) changes on patterns of goods and energy consumption, insurance coverage and premiums, as well as shipping prices.

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APPENDIX – Schematic Cross-sections of Typical Dock Structures

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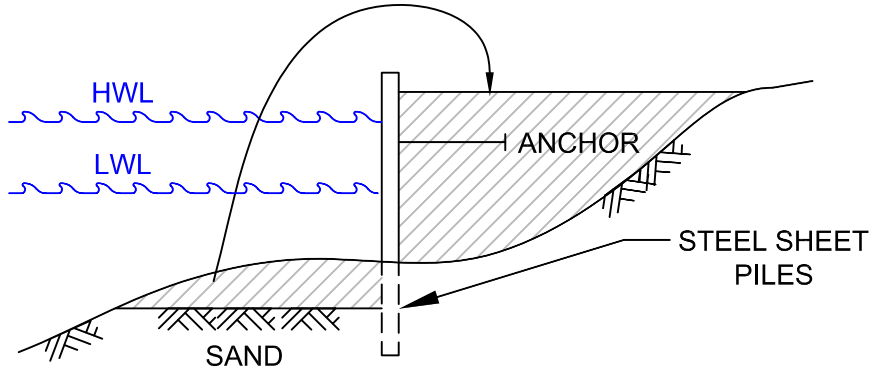

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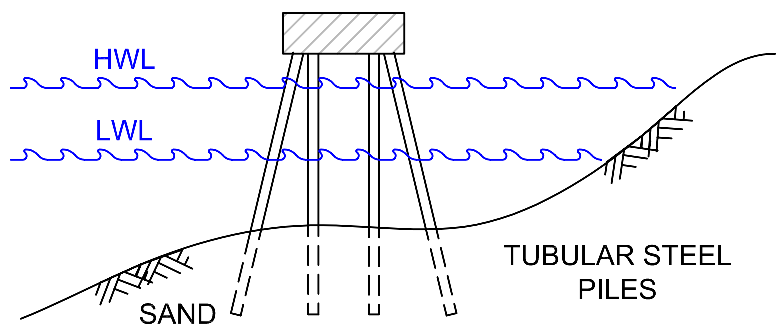

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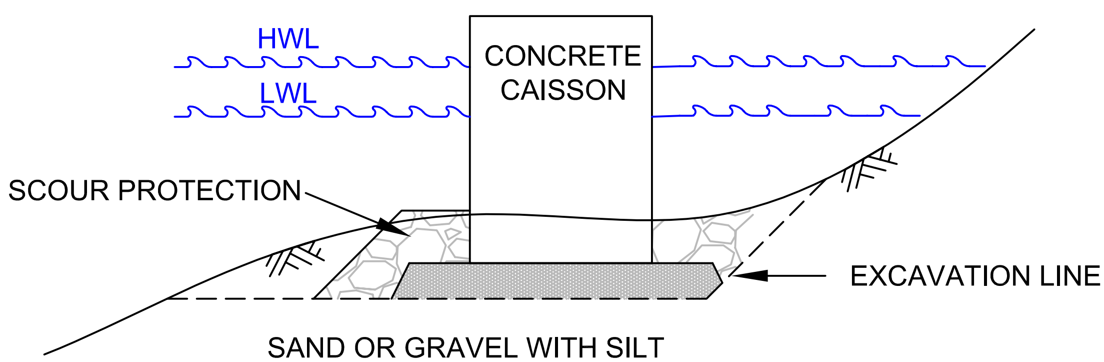

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		ENGINEERING CHALLANGES IN THE NORTH NUNAVUT REGIONAL ADAPTATION COLLABORATIVE PORT FACILITIES	DRAWN BY: A.B.			
			PROJECTED BY: N.J.			
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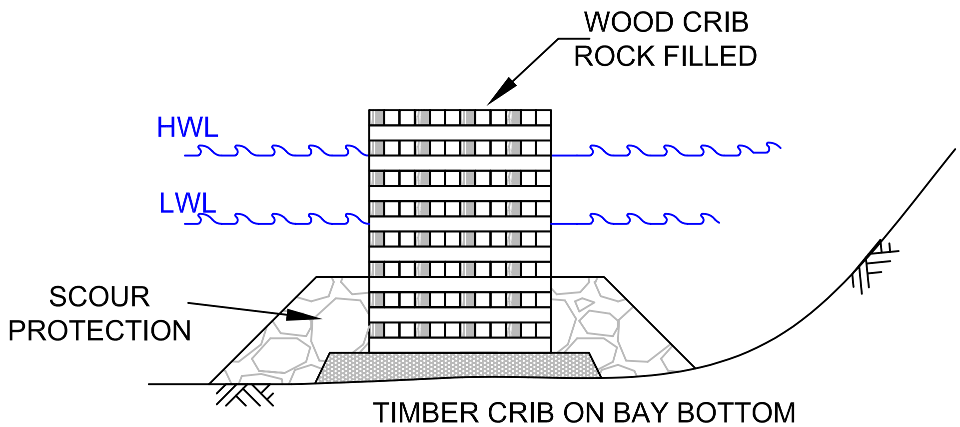

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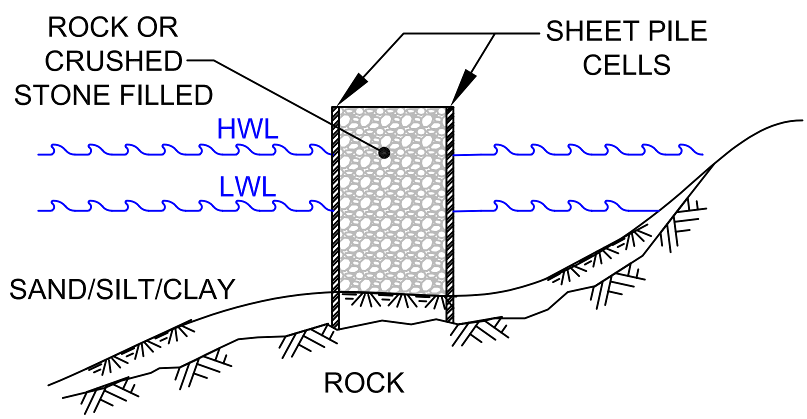

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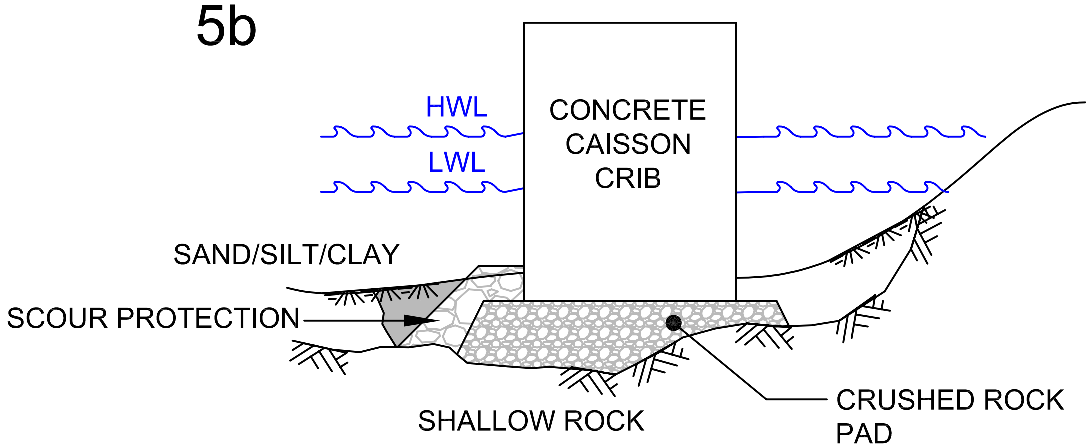

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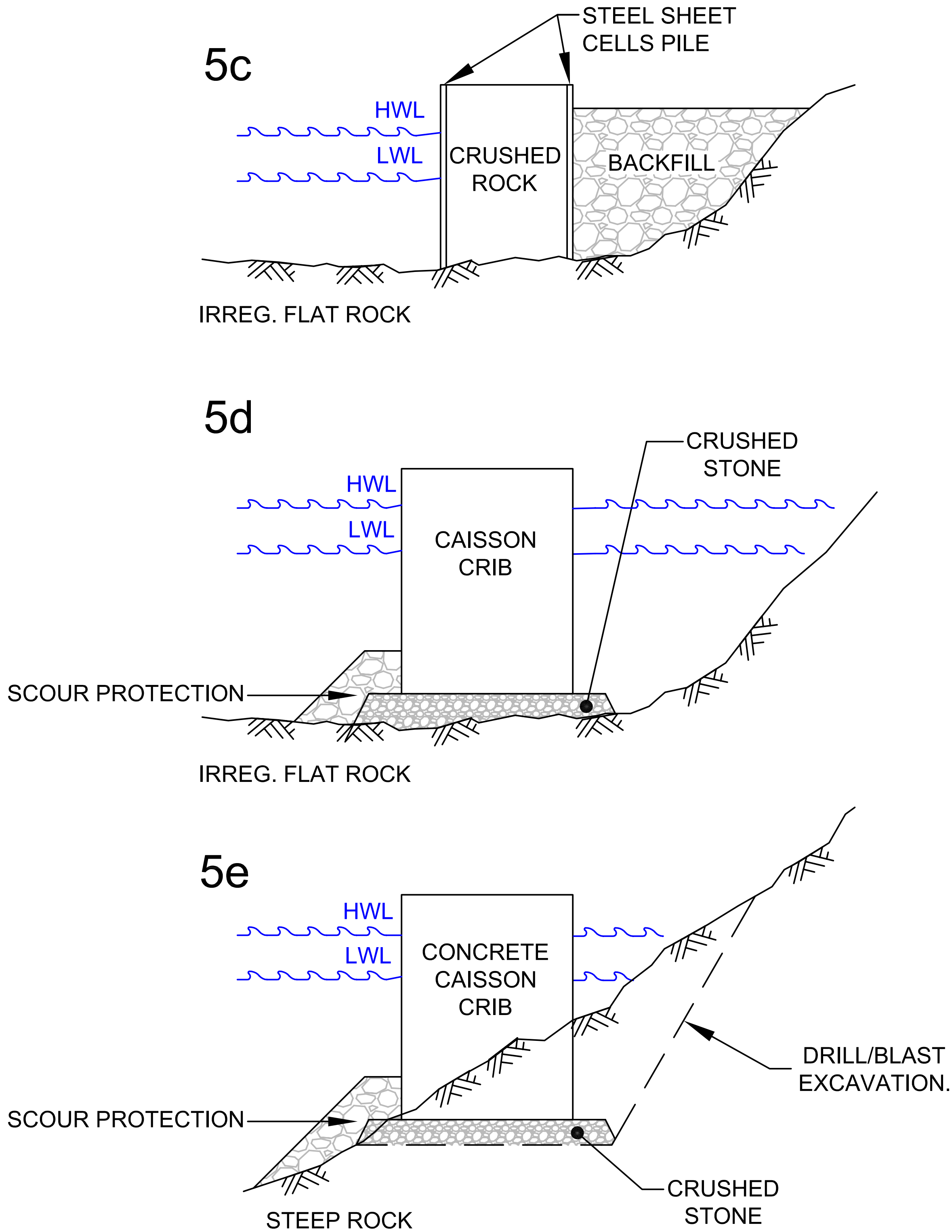

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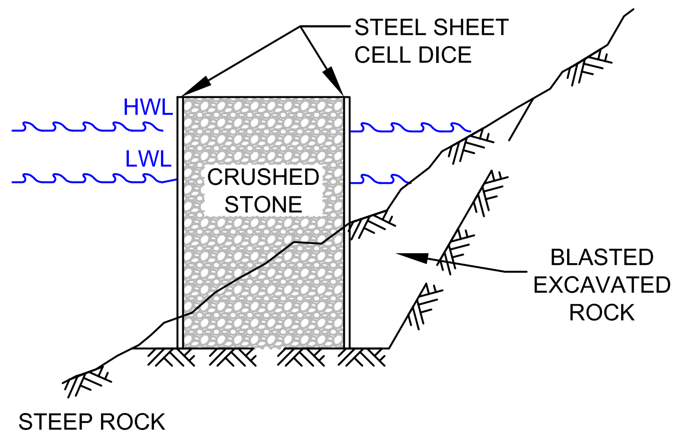

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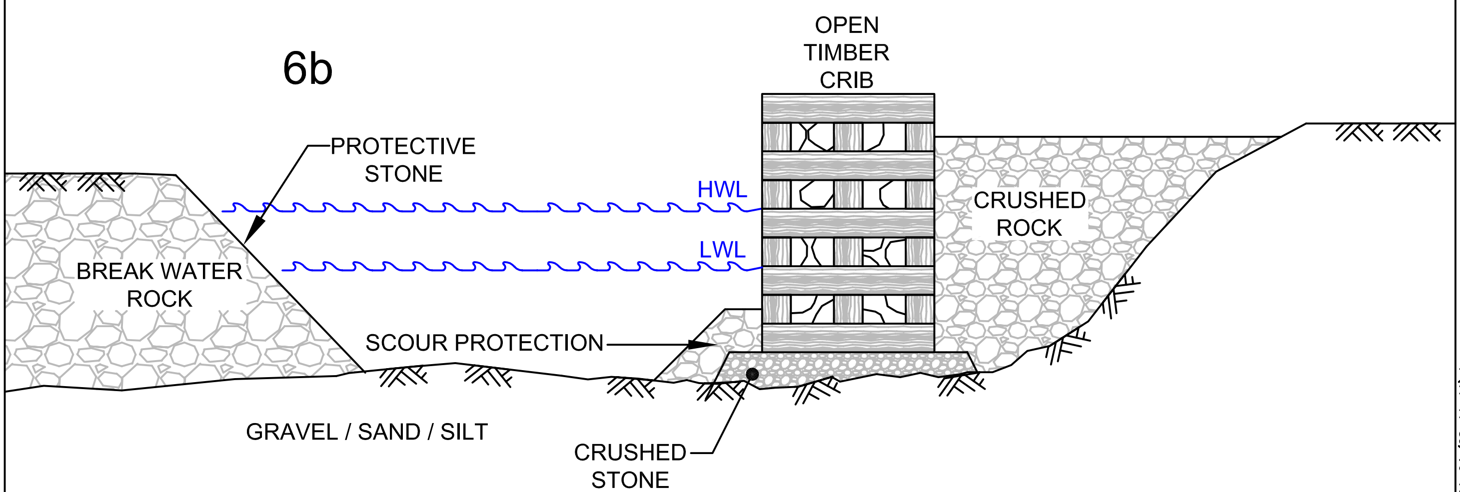

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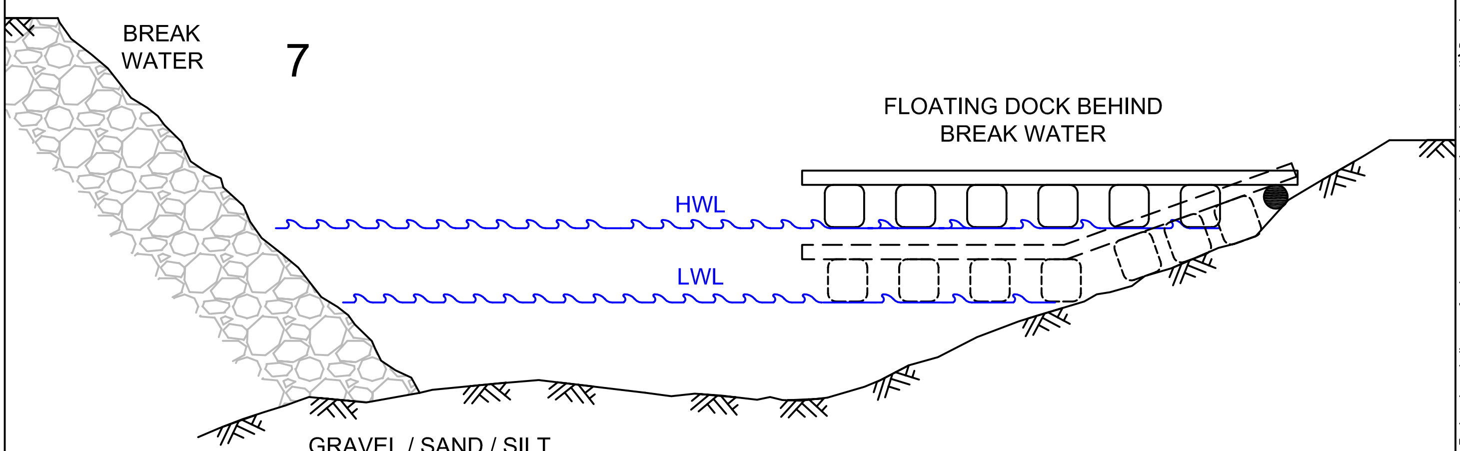

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