LA GRANDE ALLIANCE

PRE-FEASIBILITY STUDY – PHASES II & III – TRANSPORTATION INFRASTRUCTURE

TECHNICAL NOTE 13A

DEEP-WATER PORT –

PHYSICAL ENVIRONMENTAL CONDITIONS

FINAL VERSION

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EXECUTIVE SUMMARY

This Technical note 13 has been split in two parts:

- 13A: Physical Environmental Conditions;
- 13B: Concept Port Design.

This current Technical Note 13A of the Deep-Water Port Study covers the description and evaluation of the Physical Environmental Conditions along the coastline of Whapmagoostui/ Whapmagoostui/Kuujjuarapik thus, to eventually identify an area that is most appropriate for the construction of a port.

At the time of the redaction of this document the size of the port and its purpose were not known yet (pending Market Survey completion), and all port options are being considered ranging from a seasonal Small Craft Harbour for vessels requiring a water depth of maximum 6.0 m only to year-round operation for a deep-water port requiring vessels with a water depth of maximum 18 m.

Physical environmental conditions which are favourable for a Small Craft Harbour are not necessarily favourable for a Deep-Water Port and vice versa.

The key physical conditions studied are:

- Ice dynamics;
- Oceanography (bathymetry, wind, waves, currents and water levels, both operational and extreme);
- Coastal and river geomorphology.

After studying the data obtained to define the physical environmental conditions, we have selected areas that pose less risk for a physical environmental phenomenon (which could damage the structures, cause important maintenance or hamper the operations for both types of ports), promise better operability and/or have less capex associated with them.

Coincidentally, but governed by different physical phenomena, the location selected for the Small Craft Harbour option is the same location as the location selected for the deep-water port. This now opens possibilities to expand the Small Craft Harbour to a Deep-Water Port if required whilst minimising capex and even keeping a potential future Small Craft Harbour together with a potential future Deep-Water Port. The chosen location does not seem to pose any particular challenges with road access to Whapmagoostui/Kuujjuarapik, rail access and/or rail yard from the newly to be constructed rail line, land access (elevation differences), geotechnical and permafrost conditions, land area available to build the terminal(s) and areas potentially of cultural importance. All the latter parameters are being studied as part of other work areas for the Grande Alliance study and will require careful consideration in future phases.

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1 INTRODUCTION

The purpose of this Technical Note 13 Part A is to provide a description of the physical environment including coastal processes (wind, waves, water levels, currents), coastal and marine morphology and ice dynamics at a wider coastal area that could be suitable for a proposed port infrastructure foreseen to be included in the Phase III of La Grande Alliance study, namely a port at Whapmagoostui/ Whapmagoostui/Kuujjuarapik.

1.1 PURPOSE AND SCOPE

The purpose of this report is to evaluate the local physical environmental conditions of the coast adjacent to Whapmagoostui/ Whapmagoostui/Kuujjuarapik and establish the most favourable location for a port. Coastal systems are evaluated within the context of three main parameters:

- Ice dynamics;
- Oceanography;
- Coastal and river geomorphology.

Ice dynamics are described in Section 2. Conditions through the annual ice cycle were examined for the coast near Whapmagoostui/Kuujjuarapik from satellite images and observation cameras. These data were compiled to provide a spatio-temporal picture of sea ice conditions to determine ice catch and release periods.

The physical oceanography description includes eastern Hudson Bay and the estuary of Great Whale River and can be found in Section 3. The oceanographic data required to develop maritime infrastructure, assess impacts and define mitigation measures includes the following:

- Bathymetry and nature of the seabed and rivers;
- Tides, water level and currents;
- Wind, wave and storm surges.

A fluvial and coastal geomorphological characterization describing the state of the shorelines and the risks of erosion and marine submersion is provided in Section 4. The study describes the main sources of sediment (Great Whale River, coastal erosion) and river-marine sedimentary processes in order to assess areas at risk of significant sedimentation that may require significant maintenance dredging.

Each of the main physical environment parameters were also analyzed within the scope of coastal systems in a changing climate. An understanding of how climate change affects coastal stability, and the nature of coastal response, provides a basis for assessing implications for port infrastructure.

Key sources of information have been consulted to provide a comprehensive picture, including:

- Nautical charts of the area;
- Satellite imagery;
- Provincial surficial geology maps;
- Environment Canada data:
  - Meteorology: Whapmagoostui/Kuujjuarapik Airport;
  - Tides and water level data.
- Data from studies on the development of Great Whale River hydroelectric project (Hydro-Québec);
- Previous research studies covering the study area.

1.2 LOCATION

The study site is located on the Hudson Bay along the shoreline near Whapmagoostui/Kuujjuarapik, Quebec, at the mouth of the Great Whale River. This report assesses the suitability of four study areas for the implementation of either a Deep-Water Port (18 m depth) or a Small Craft Harbour (SCH) (6 m depth). The four study zones (A, B, C, and D) are shown in Figure 1-1.

Figure 1-1 Study Zones A, B, C, and D near Whapmagoostui/Kuujjuarapik

2 ICE CONDITIONS NEAR WHAPMAGOOSTUI/KUUJJUARAPIK

2.1 ICE REGIME IN HUDSON BAY AND STRAIT

This section presents the general ice conditions in Hudson Bay and Strait. The specific ice regime along the east coast near Whapmagoostui/Kuujjuarapik is described in the following Section 2.2.

Figure 2-1 illustrates the median ice concentration in Hudson Bay and Strait, on the period 1981-2010, compiled by Environment Canada (EC).

The ice cover formation typically starts in late October in the coastal zones in the North-West of the Hudson Bay and in the Hudson Strait (Figure 2-1 a). The cover progresses towards the south-east in the bay and then into James Bay (Figure 2-1 b-c). The bay and strait are completely covered by ice (100% coverage) in early January (Figure 2-1 d). The ice in the bay is non-consolidated except along the coasts where it typically forms a solid ice cover (MPO, 1996). Thaw and breakup in the bay usually starts in May. In June (Figure 2-1Fig. e), the ice coverage along the east-coast of the bay is typically ranging between 0 and 30%. At the same time in June, the strait is still covered by ice with coverage ranging between 30 and 100%. In mid-July (Figure 2-1f), an ice-free passage is typically available in the strait. There is typically no more ice in the bay and strait in August, except for rare icebergs originating from the Foxe Basin which drift thought the strait (Percy, 1990).

Based on EC ice observations on the period 1981-2010, the typical ice-free season is:

- Hudson Strait: Mid-July to mid-November (~4 months);
- Hudson Bay (East coast): Early July to end of November (~5 months).

Maps show that the ice cover on the East coast forms later and break earlier in comparison with the West. Thus, a marine infrastructure at Whapmagoostui/Kuujjuarapik (East coast) would experience a longer ice-free season compared to one located along the West coast; for example, the existing Port of Churchill (Manitoba).

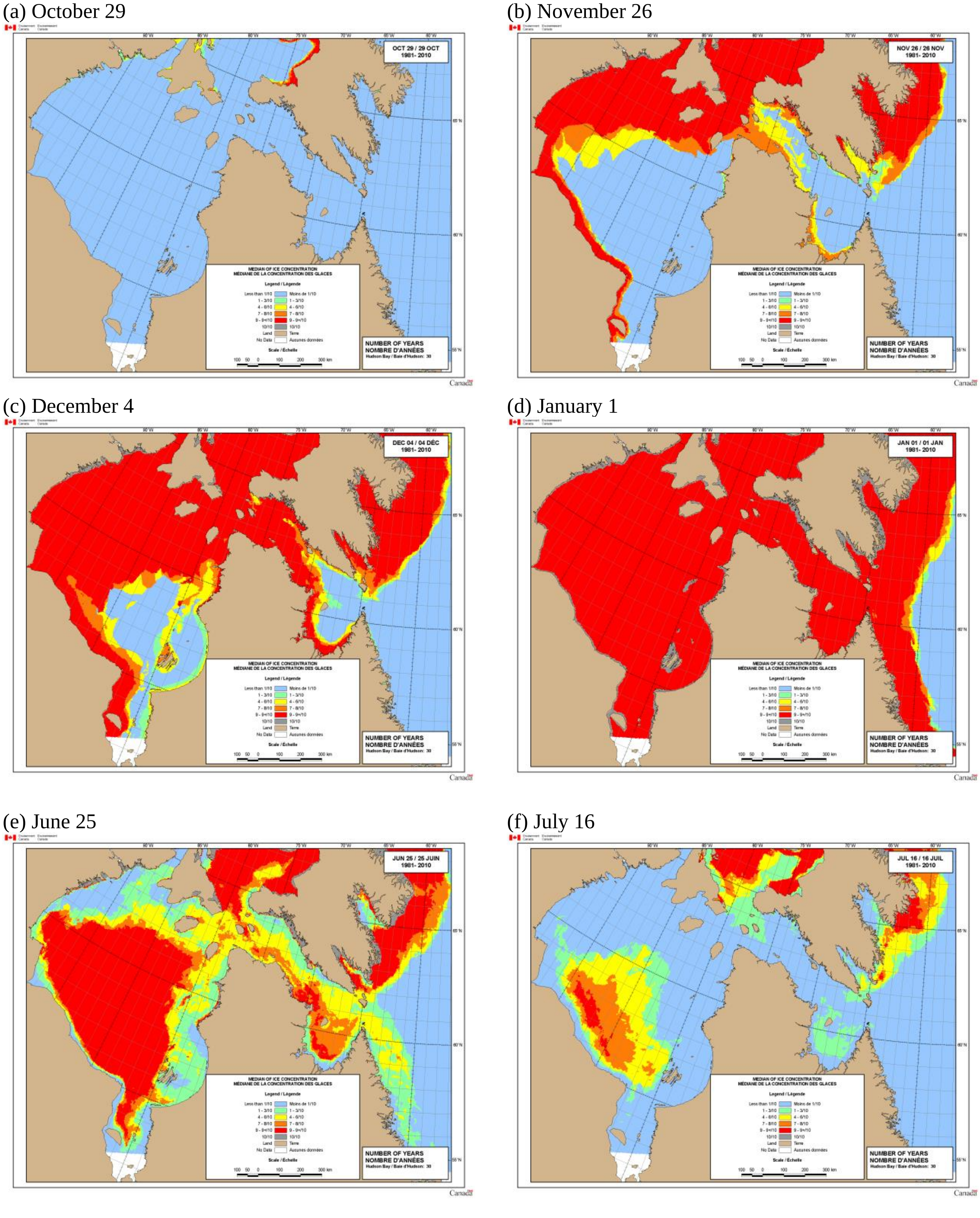


Figure 2-1 Median of ice concentration in Hudson Bay and Hudson Strait, on the period 1981-2010 (EC, 2021)

2.2 ICE REGIME ALONG THE COAST NEAR WHAPMAGOOSTUI/KUUJJUARAPIK

This section describes the ice regime along the coast near Whapmagoostui/Kuujjuarapik. The ice conditions in Zones A, B, C and D (Figure 1-1) are described with the objective of identifying the preferred location to implement port infrastructure.

2.2.1 OVERALL APPROACH

The comparison between Zones A, B, C, and D is subdivided into four ice seasons corresponding to the full annual cycle, as shown below. This breakdown generally holds true for the ice cycle although there are some differences and inconsistencies.

- Freeze-up;
- Mid-winter;
- Break-up;
- Summer.

The comparison was focused on the past five winters as this period is considered to be most relevant for the study. Also, the available ice information is most extensive and detailed for this period (described subsequently). However, for completeness, satellite imagery dating back to the 2004-05 winter was also reviewed.

2.2.2 INFORMATION SOURCES

The information sources were limited to the ones capable of showing detailed ice conditions, as this is necessary to meet the study objectives. They included the following, as summarized in Table 2-1.

Sentinel 2 satellite images – because this provided the most detailed information, this source was the primary information source for 2017-18 and later.

- Landsat satellite images – these were used to supplement the information set, and to extend it back further in time. Landsat images were examined as far back as the 2004-05 winter;
- Observation cameras placed onshore facing the Manitounuk Channel and Islands and at Gillis Island. The shootings are available at http://www.caiman.ete.inrs.ca/. These provided local ice information, but they were not able to provide overall, regional-scale ice information.

Table 2-1 Summary of Ice Regime Information Sources near Whapmagoostui/Kuujjuarapik

Winter	Satellite Images		Continuous Camera Photos (every hour)	
	Sentinel 2 Images[1]	Landsat Images[1]	Facing Manitounuk Channel	On Gillis Island
2020-21	89 images	-	n/a	√
2019-20	67 images	-	√	√
2018-19	96 images	-	√	√
2017-18	108 images	-	√	√
2016-17	28 images	77 images	√	√
2015-16	11 images	74 images	√	√
2014-15	n/a before 2015	32 images	n/a before 2015	n/a before 2015
2013-14		59 images		
2012-13		14 images		
2011-12		19 images		
2010-11		27 images		
2009-10		16 images		
2008-09		9 images		
2007-08		23 images		
2006-07		39 images		
2005-06		40 images		
2004-05		54 images		

Note: Only images with useful ice information are included in the above totals. Note that not all of the available satellite images provided usable ice information due to cloud cover

2.2.3 2020-21 ICE CYCLE

The ice cycle is discussed in detail for the 2020-21 winter to illustrate the patterns. Note that these same general patterns were seen for the other winters as well. Key satellite images for 2020-21 are referred to in the text here.

Freeze-up commenced in about mid-November with new ice growth along shore (Figure 2-2 a). This progressed over the next 2 weeks with new ice first being seen in the north end of Manitounuk Channel on Nov. 30 (Figure 2-2 c). Note that all zones were essentially ice-free during this period.

On Dec. 3, new ice (as evidenced by its coloration) was present over all of Zone D and Manitounuk Channel (Figure 2-2 c), although Zones A, B and C were ice-free, as well as the areas offshore of them. On Dec. 13, new ice was evident offshore, although Zones A, B and C were still ice-free (Figure 2-3 a).

On Dec. 25, Zones A and B were still ice-free although Zone C had a partial ice cover, with an ice edge running at an angle of about 45° through it (Figure 2-3 b). On Dec. 28, all zones were ice-covered. The ice cover on Zones A and B consisted of new ice (based on coloration) with ice floes (probably from offshore) frozen into the matrix (Figure 2-3 c).

On Jan. 17, a shore lead was present, which caused Zone A to be practically ice-free. The other zones (i.e., B, C and D) were ice-covered as the ice edge ran through Zone B (Figure 2-3 d). The ice offshore of the shore lead was clearly dynamic as leads and areas of open water were present.

On Feb. 1, the ice cover was essentially solidified over the whole area (including Zones A, B, C and D), and a shore lead had been established that ran south of the Manitounuk Islands (Figure 2-4 a).

The ice cover was partially broken up on Feb. 21, as newly-frozen areas (based on coloration) can be seen in the ice pack (Figure 2-4 b). The ice cover for Zone A consisted mainly of new ice, whereas the ice cover for the other zones was still intact.

This pattern was repeated soon after as:

— The ice cover solidified, and a shore lead running south of the Manitounuk Islands became established along the whole shoreline on Feb. 28 (Figure 2-4 c), and;
— The ice cover became broken up such that Zone A was covered with new ice on Mar. 3 while the ice cover for the other zones was still intact as a solid ice sheet (Figure 2-4 d).

After March 3, the shore lead gradually became larger as seen by the images on Mar. 25, Apr. 4, Apr. 9, and Apr. 12 (Figure 2-5 a, b, c and d, respectively). During this period, Zone A was essentially ice-free while the ice cover for the other zones was still intact as a solid ice sheet.

On April 17, the offshore area was ice-free (Figure 2-6 a). Zone A was essentially ice-free while the ice cover for the other zones was still intact. On April 22, ice floes (originating further offshore) had drifted into Zone A (Figure 2-6 b), while the ice cover for the other zones was still intact as a solid ice sheet.

This general pattern persisted for about six weeks, as seen by the images on April 29, May 19, May 22, and May 24 (Figure 2-6 c, d and Figure 2-7 a, b, respectively). Zone A was exposed to ice floes drifting in from offshore while the ice cover for the other zones was still intact as a solid ice sheet. The ice cover was clearly becoming deteriorated, (based on coloration), especially for Zone D, as seen on May 19.

All zones were ice free on June 13 and June 18 (Figure 2-7 c and d, respectively).

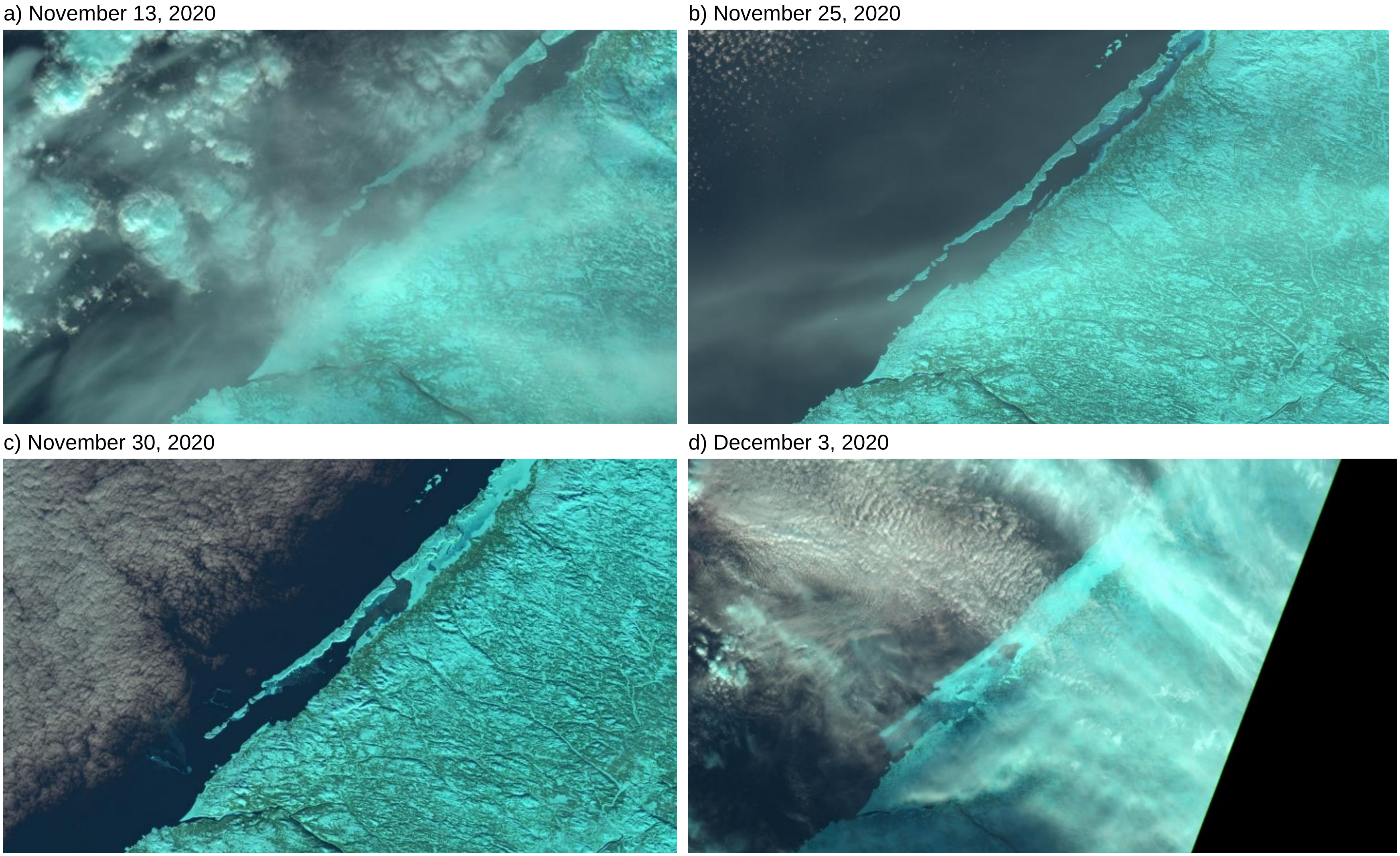


Figure 2-2 **Sentinel 2, Natural-Colour, Satellite Images for the 2020-21 Ice Season (November-December)**

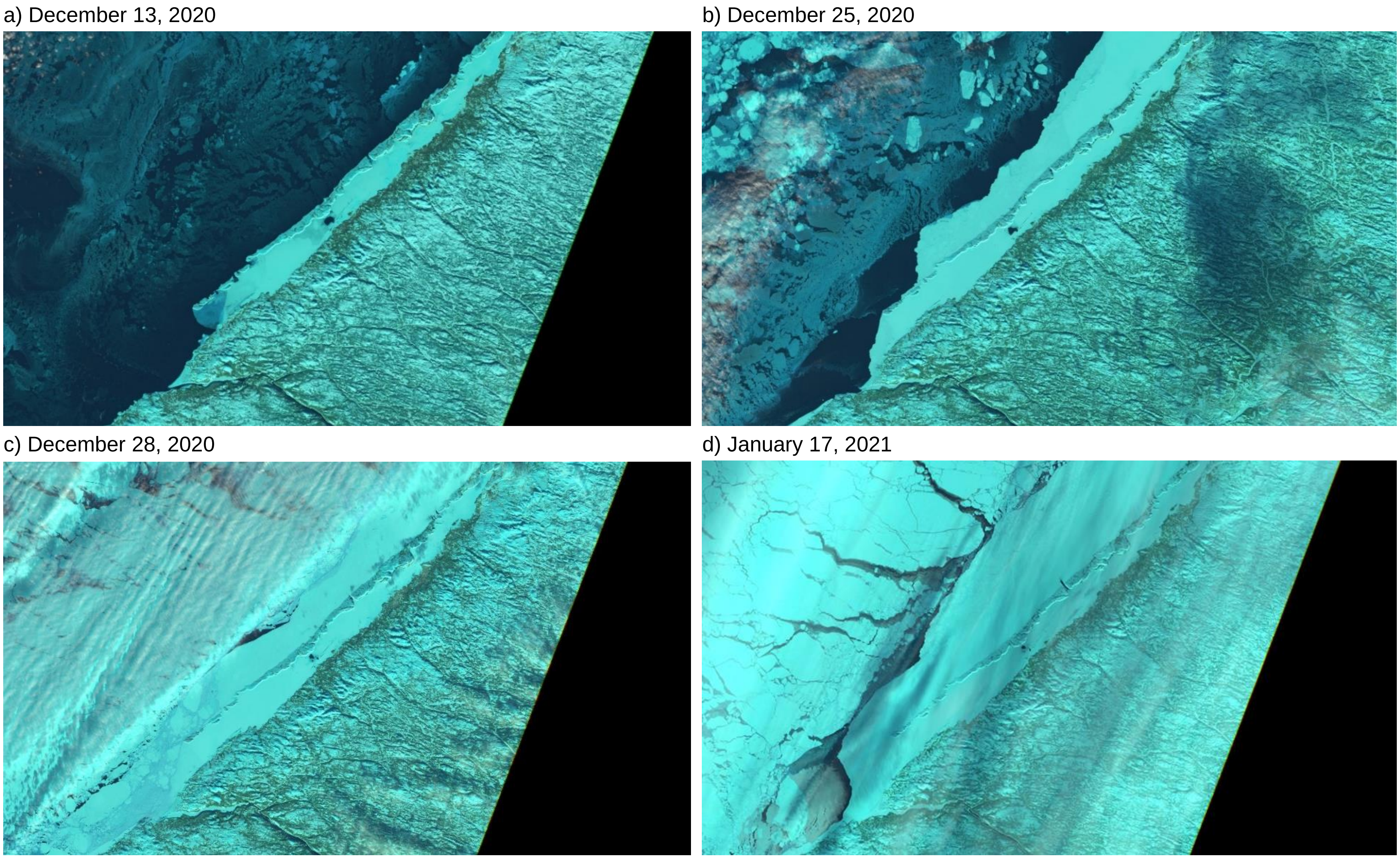


Figure 2-3 Sentinel 2, Natural-Colour, Satellite Images for the 2020-21 Ice Season (December-January)

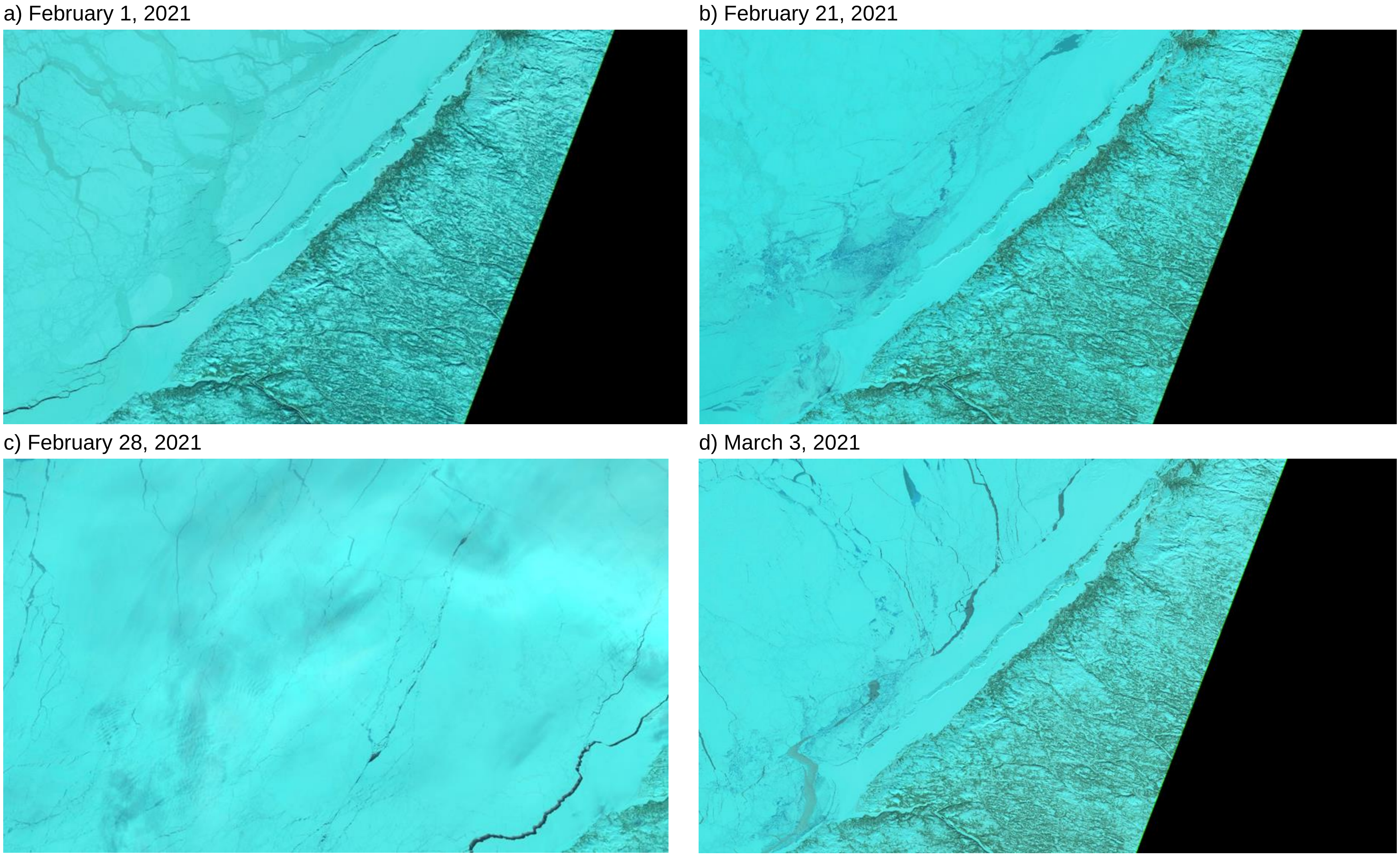


Figure 2-4 Sentinel 2, Natural-Colour, Satellite Images for the 2020-21 Ice Season (February-March)

a) March 25, 2021
b) April 4, 2021
c) April 9, 2021
d) April 12, 2021

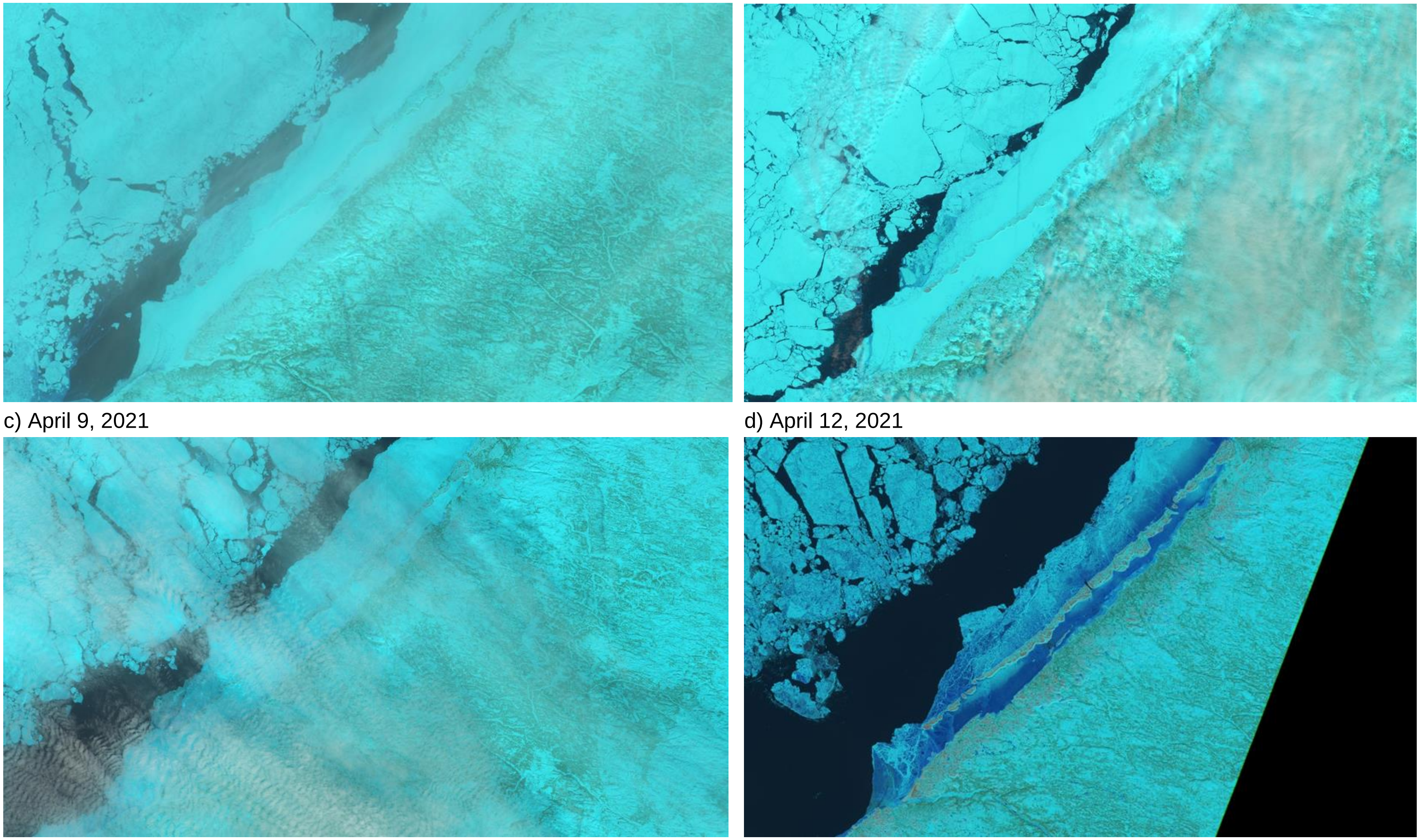
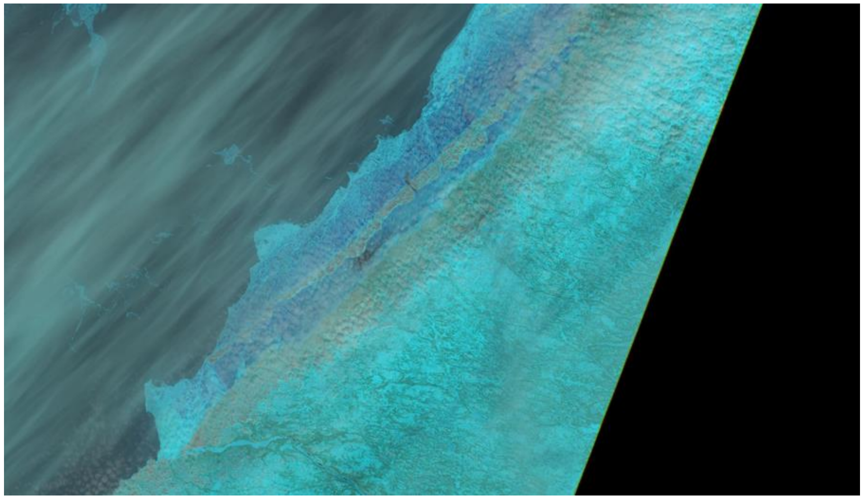
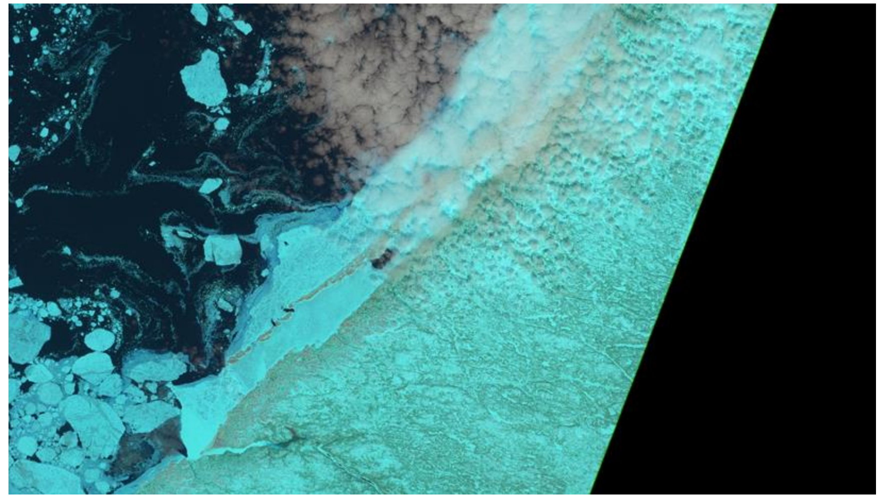


Figure 2-5 Sentinel 2, Natural-Colour, Satellite Images for the 2020-21 Ice Season (March-April)

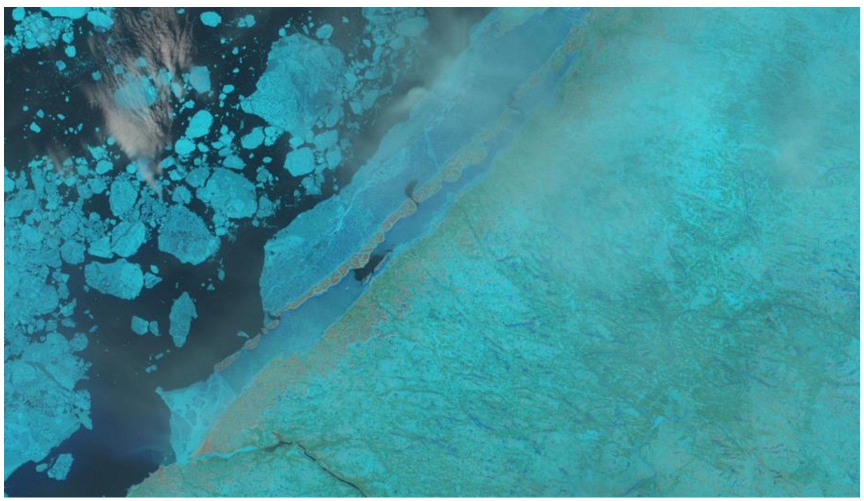
a) April 17, 2021



b) April 22, 2021



c) April 29, 2021



d) May 19, 2021

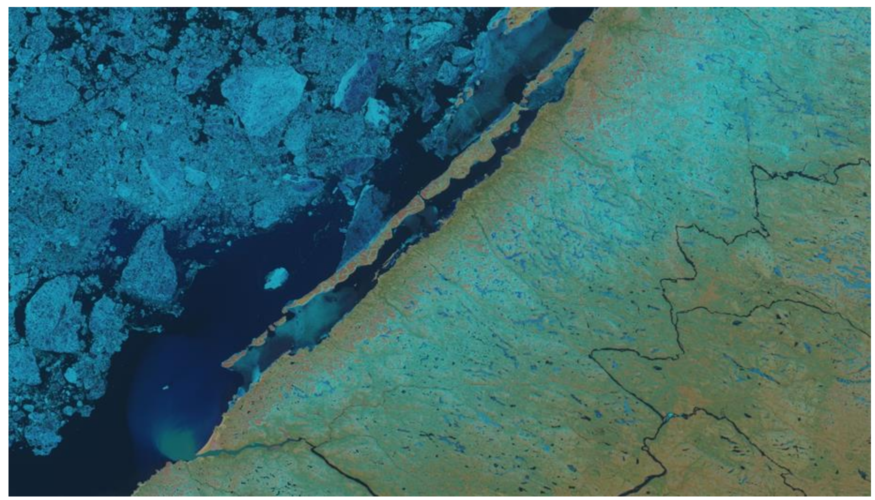


Figure 2-6 Sentinel 2, Natural-Colour, Satellite Images for the 2020-21 Ice Season (April-May)

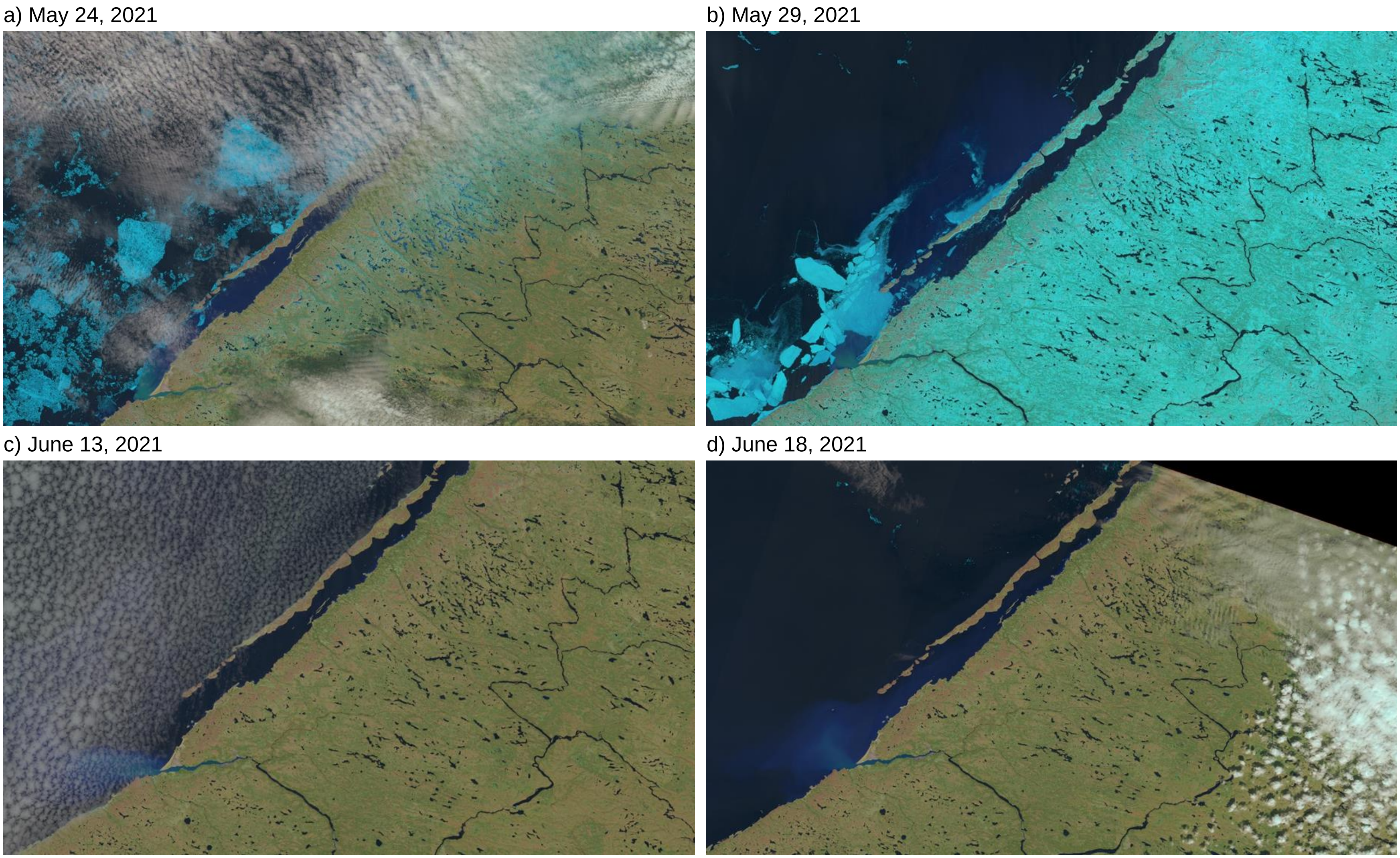


Figure 2-7 Sentinel 2, Natural-Colour, Satellite Images for the 2020-21 Ice Season (May-June)

2.2.4 VARIATIONS IN ICE BREAKUP

As expected, variations could be seen among the winters studied (2004-2021). Generally, the range of variation in ice breakup dates was about 1 month.

Early breakups in 2004-05 and 2016-17 are shown in Figure 2-8 a-b, and c-d respectively. These images show a case where all zones were ice-free before June 1. However, Zones A, B and C would have been potentially exposed to ice incursions involving very large ice floes. Zone D was protected from ice incursions, being located in the Manitounuk Channel.

A late breakup occurred in 2017-18 as shown in the sequence for June 2 to June 12 (Figure 2-9 a-d). In this case, only Zone A was ice-free by June 12, while Zones B, C and D were still ice-bound.

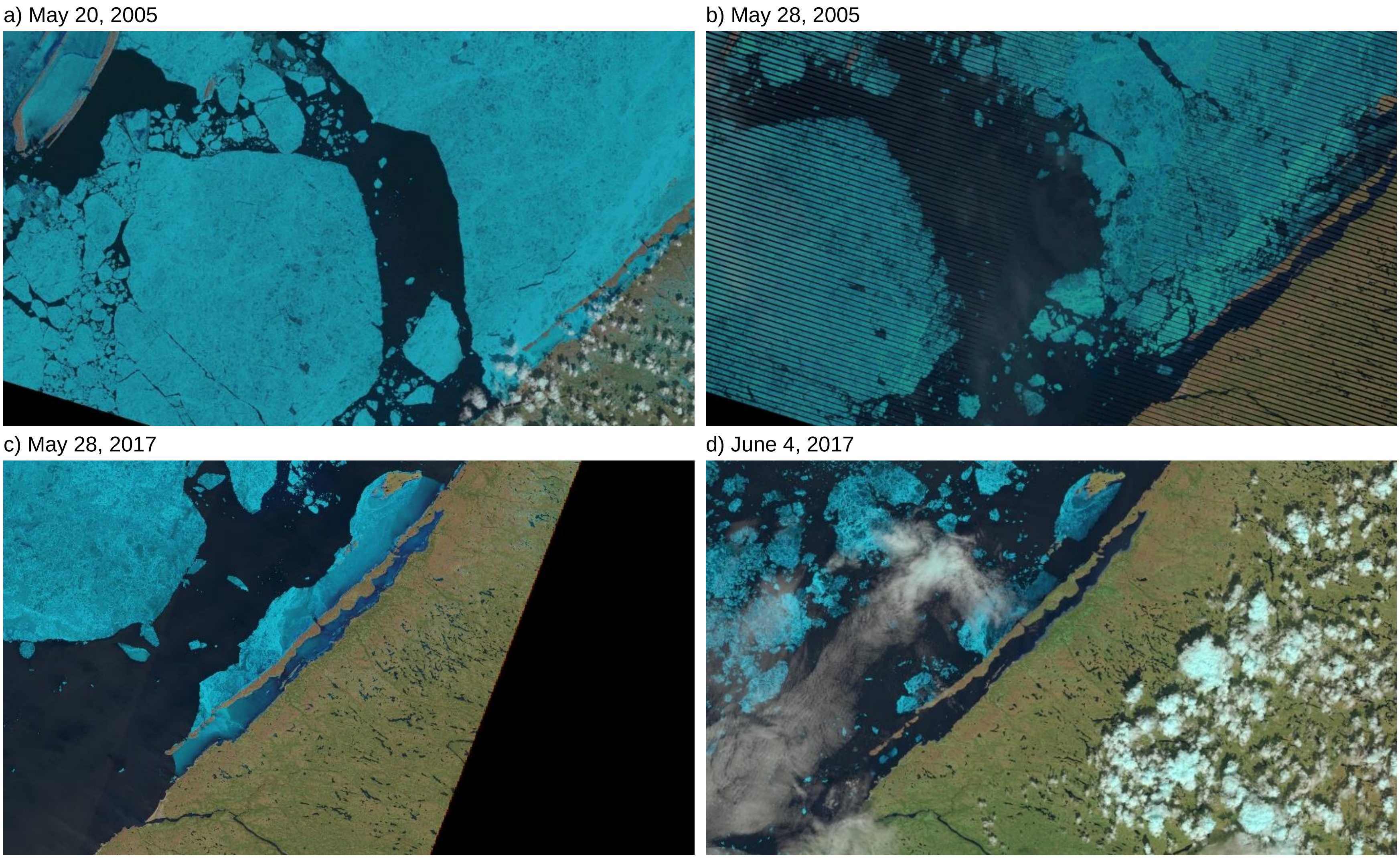


Figure 2-8 Examples of Early Breakup – Landsat Images

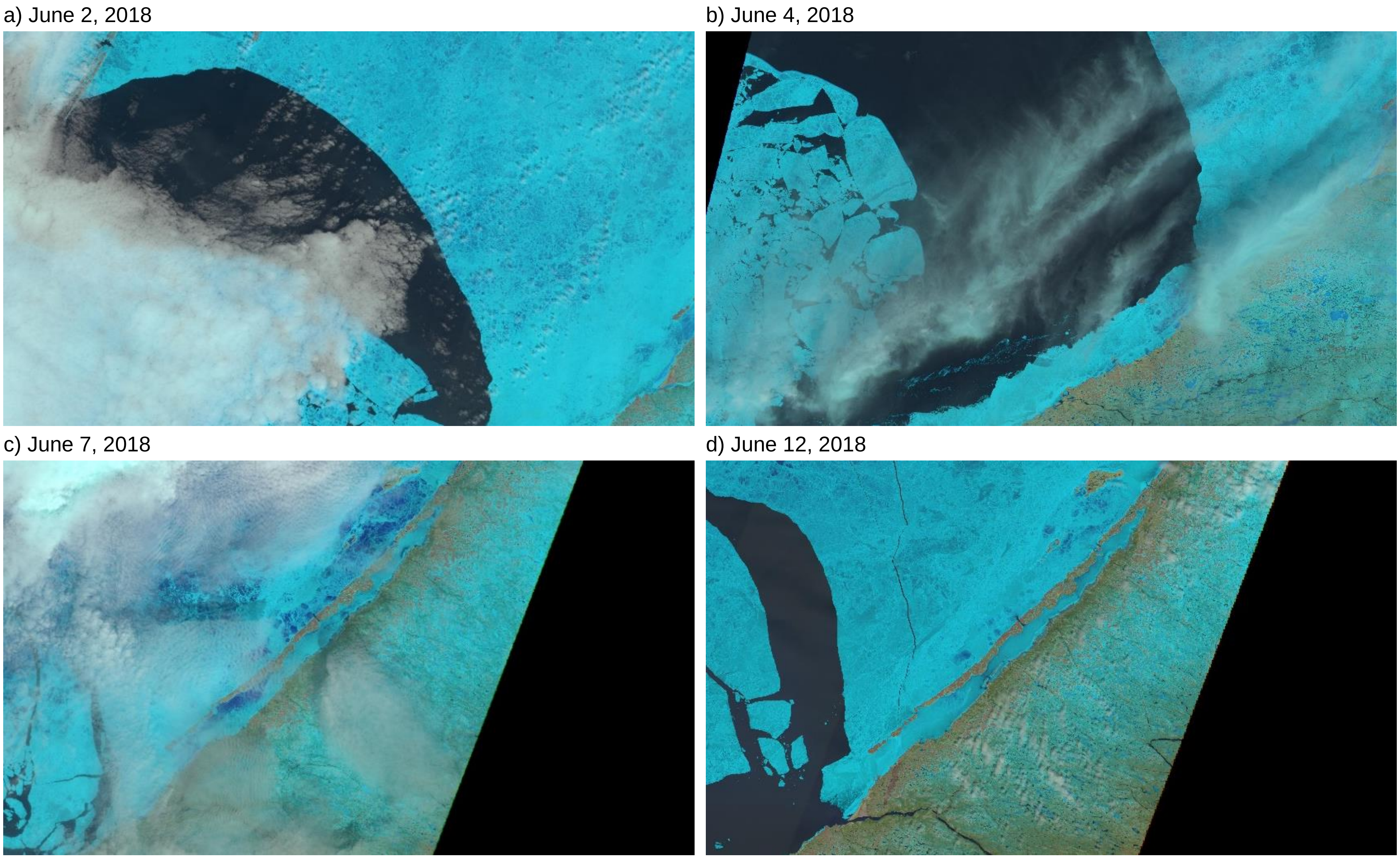


Figure 2-9 Examples of Late Breakup – Sentinel 2 Images

2.2.5 ICE JAMMING AND ICE PROCESSES AT THE MOUTH OF GREAT WHALE RIVER

Ice breakup on the Great Whale River and potential jamming at its mouth might impact an infrastructure located in Zone A (Figure 1-1). For instance, the installations might get caught up in an ice jam or get impacted by moving river ice floes.

An ice jam would affect the two general port options (i.e. SCH or a deep-water port) differently. A SCH would be located in relatively shallow water (probably about 6 m) so it would be closer to shore and the ice jam as well. However, all of the boats and floating jetties in a SCH would probably be removed for the winter. Therefore, the only structures likely exposed to an ice jam would be the rock breakwaters expected to form the exterior sides of the SCH. These would probably be capable of withstanding the forces from an ice jam, but they might get affected by hydraulic scour caused by the ice jam.

A deep-water port would be located in deeper water (probably 18 m or more) so it would be farther away from the immediate effects of an ice jam. Nevertheless, an ice jam could potentially be of concern for the port structures. Also, an ice jam would likely affect ship access to the port, if it were a year-round port.

Overall, it is desirable to avoid locating the port or SCH at a location where it would be exposed to ice jams.

Figure 2-10 shows satellite images of the ice conditions at the mouth of the Great Whale River. Images show that that the ice cover on the river can either breakup before the landfast ice along the coast (Figure 2-10 a) or after (Figure 2-10 b).

No evidence of ice jam at the mouth of the river nor ice jam flooding in Whapmagoostui/Kuujjuarapik were found in the literature. Despite the possible breakup timing (i.e., river can break before mouth), it appears that the river has no tendency of developing a large ice jam at Whapmagoostui/Kuujjuarapik.

Ice accumulations could form upstream of Whapmagoostui/Kuujjuarapik, as in April 2021 (Figure 2-10 c). This accumulation occurred in conjunction with a massive landslide, which has brought significant amount of sediment and trees in the river (Figure 2-10 d). Authorities are currently investigating this event. It is not clear at this point if the ice accumulation occurred before landslide or was triggered by it.

Infrastructures in Zone A could induce changes to the river ice dynamics during breakup, for example partial blockage of the ice transport. Additional river ice analysis would be required if Zone A is selected.

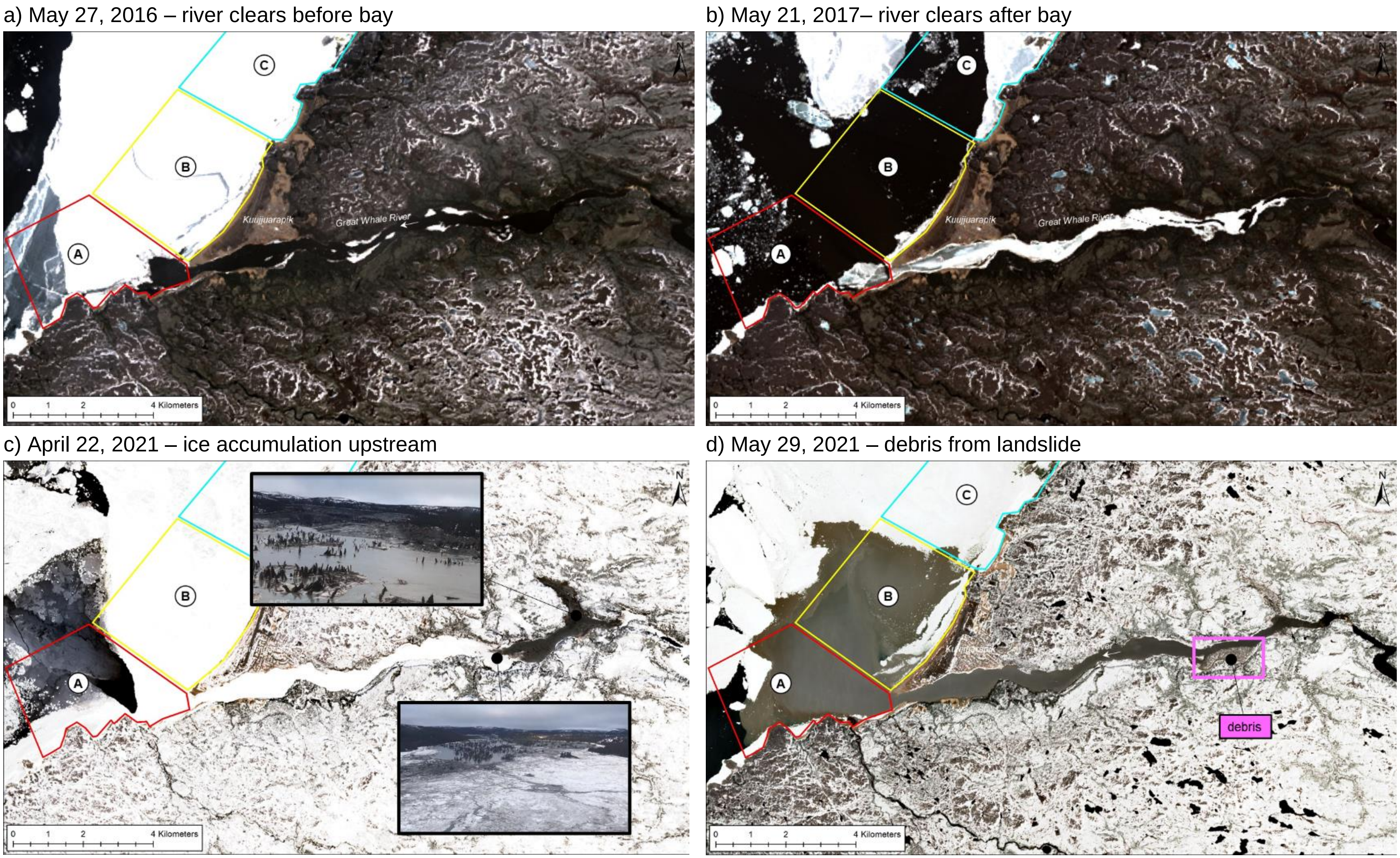


Figure 2-10 Ice conditions at the mouth of the Great Whale River on May 27, 2016 (a), May 21, 2017 (b), April 22, 2021 (c) and May 29, 2021 (d).

2.2.6 OVERALL SUMMARY AND COMPARISONS OF THE ICE REGIME

The following is evident regarding the ice regimes for the four zones:

Zone A - This is the most exposed site. The ice cover forms latest in Zone A, and often gets removed through the action of the ice pack, followed by new ice growth. It is the latest to freeze up and the earliest to break up. A dock in Zone A would be exposed to ice incursions involving large floes over a large part of the winter. Zone A is also exposed to breakup and potential ice jam at the mouth of the Great Whale River. Zone A is ice free an average of 7-8 months every year, with frequent breakup and ice incursion episodes.

Zone B – The ice exposure for Zone B is intermediate, between Zone A (which is the most exposed) and Zone D (which is the most protected). Zone B freezes up later than Zone D, but earlier than Zone A. The ice tends to break up later at Zone B at than at Zone A. In contrast to Zone D, ice breakup occurs by ice being transported away from the area (probably by winds and currents) rather than by thermal decay and melting as occurs at Zone D. A dock in Zone B would be exposed to ice incursions involving large floes during the break-up part of the ice cycle. Zone B is ice free an average of 7-8 months every year.

Zone C – Zone C is somewhat less exposed to ice action than Zone B, as it freezes up before Zone B, and breaks up later. Zone C is ice free an average of 7-8 months every year.

Zone D – This is the most protected site. Ice forms earliest in Zone D and persists latest. The ice thickness would be controlled by thermal growth over the full winter. Ice breakup occurs thermally, as the ice mainly melts in place. Zone D is not exposed to incursions of ice floes from offshore. Zone D is ice free an average of 6-7 months every year.

2.3 ICE THICKNESS

Ice thickness is a prime parameter when assessing ice loading and interaction with marine infrastructures. This section provides an overview of the ice thickness in the study area.

The Government of Canada (GC, 2022) has measured ice thicknesses near Whapmagoostui/Kuujjuarapik, at the mouth of the Great Whale River, for 19 winter seasons between December 1972 and April 1991. The ice thickness database includes 329 measurements. The measurements are deemed to be representative of the conditions in the four study zones: A, B, C and D.

Figure 2-11 illustrates the maximum annual ice thickness measurement on the period 1973-1991. The maximum ice thickness measurement was 2.2 m, on April 4, 1983. The average maximum annual ice thickness is 1.4 m. Figure shows the natural variability of the ice thickness. Ice evolves and thicken differently from one year to the other under the influence of climatic and hydraulics conditions.

Ice thickness can be estimated using the Stefan equation:

$$h = \propto \sqrt{AFDD}$$

where h is the ice thickness (m), α is the ice growth coefficient (m °C-½ d-½) and AFDD is the accumulated freezing degree-day (°C-d). AFDD was computed based on daily air temperature recorded at Whapmagoostui/Kuujjuarapik Airport by Environment Canada (station ID no. 6083).

AFDD is calculated by summing the daily air temperature below zero degree Celsius (<0°C). Days above 0°C are not considered in the calculation. In accordance with the approach used by the Canadian Ice Service, counting starts on the day when the 30-day average air temperature becomes negative.

The ice growth coefficient (α) varies based on the conditions of exposure and surface insulation. The theoretical maximum of α is 0.034 m °C-½ d-½. Typical value for a windy lake with no snow is 0.027 m °C-½ d-½ (CRIPE, 1996).

Figure 2-12 shows the ice thickness curves based on GC's measurements. Blue circles show the actual measurements (329 data points) and the black dashed lines show the estimated curves (minimum, average and maximum) based on the Stefan with growth coefficients α of 0.019, 0.027 and 0.034 m °C-½ d-½, respectively.

The maximum curve (α = 0.034) captures all data, except for winter 1982-1983. For that winter (black crosses on Figure 2-12), a fast thickening of +0.6 m occurred between December 24 (0.6 m) and January 14 (1.2 m).

Figure 2-13 show the ice thickness curve for winter 1984-85. The curve shows the gradual growth of the cover throughout winter and the beginning of decay in late-April and May. Ice thickness curve for winter 1984-1985 roughly follows the average curve (α = 0.027).

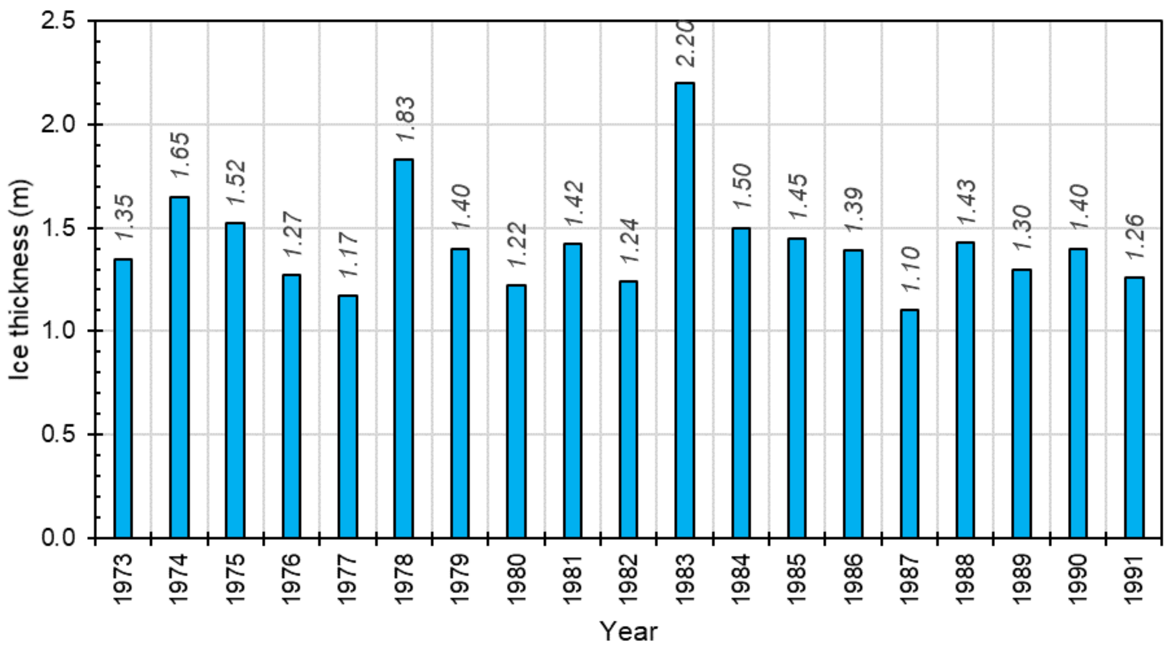


Figure 2-11 Maximum annual ice thickness measurement on the period 1973-1991. Based on measurements by the GC (2022)

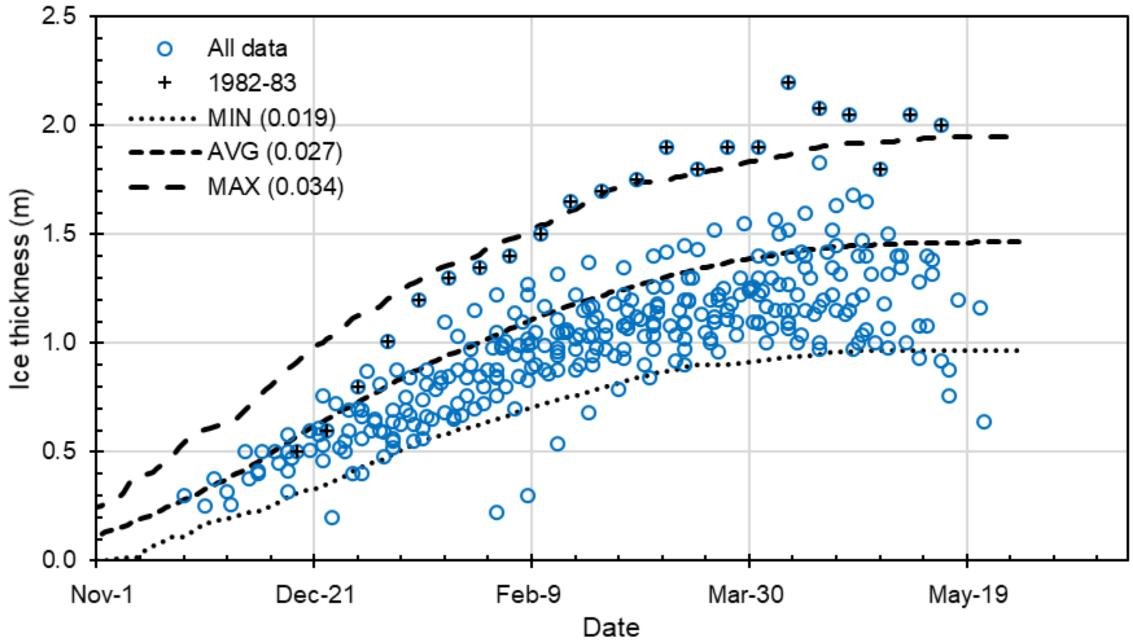


Figure 2-12 Ice thickness curves: Measured ice thickness between December 1972 (GC, blue circles) and 1982-83 (blue circles with black crosses), estimated curves based on Stefan equation with values 0.019, 0.027 and 0.034 m °C-½ d-½ (black dashed lines)

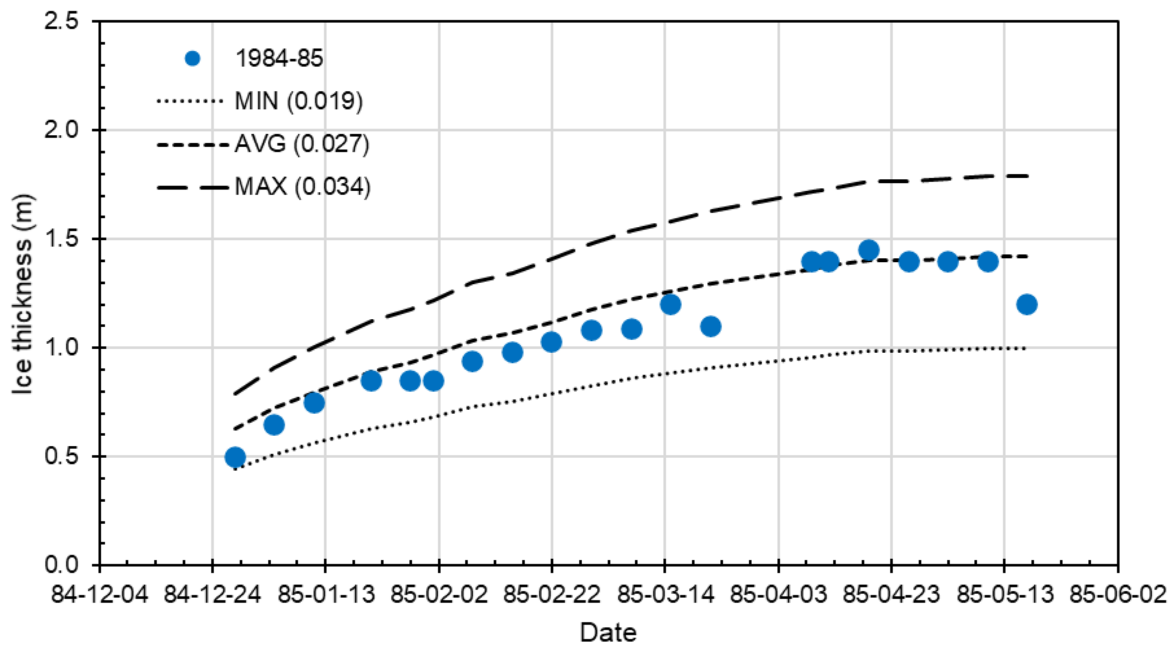


Figure 2-13 Ice thickness curve for winter 1984-85

2.4 ICE LOADING AND INTERACTION SCENARIOS

2.4.1 GENERAL

Ice loading and interaction scenarios are important considerations for the port. Because the study is at the pre-feasibility stage, only general comments are possible at present. The ice action scenarios likely to be significant vary greatly between the two general port options (i.e., a SCH versus a deep-water port).

2.4.2 SMALL CRAFT HARBOUR

The ice actions for a SCH are affected by many factors:

- Water depth – the water depth for a SCH would likely not exceed about 6 m, which would generally place the SCH within the landfast ice zone. This would tend to protect it against ice incursions from offshore. Furthermore, the low water depth would prevent deep-draft ice features (e.g., ridge keels) from reaching the SCH.
- The type of structures comprising the SCH – most likely, the exterior of the SCH (which would "see" ice) would consist of rock breakwaters:
  - Ice loads - rock breakwaters typically have high lateral resistance which gives them good capabilities to resist ice forces, so ice loads are not expected to be a major issue for them. For this reason, ice loading scenarios for rock breakwaters are not discussed further here;
  - Ice actions on armour stones – the armour stones must be sized to avoid ice-induced damage. Ice action scenarios for armour stones in rock breakwaters are discussed further below;
  - Ice ride-up and encroachment – the significance of this ice action depends on whether or not any facilities would get damaged by an ice encroachment. For an isolated rock breakwater, it is doubtful that any facilities would be present on the breakwater. Hence, it would have low vulnerability to ice damage caused by ice encroachment. For this reason, ice encroachment scenarios for rock breakwaters are not discussed further here;
  - Ice-out – the layout of the breakwaters for the SCH may retard ice clear-out in the spring, thereby preventing small craft from exiting the SCH and shortening the operating season for the SCH.
- The vessels calling at the SCH and the SCH's operating basis – By definition, the SCH would be limited to small craft which would have no capability to operate in ice. Thus, the operating season for a SCH would be limited to the open water period.

Ice actions on armour stones can generally be divided into the following processes:

- Bulldozing - In this case, horizontal ice action "bulldozes" the armour stones. Because the interface is sloping, the ice tends to push the armour stones up slope. The sloping face also leads to ice flexural failure, ride up and rubble formation on, or at the top of, the slope;
- Plucking – this refers to the case where individual armor rocks get moved or carried away by ice. This type of ice action is of most concern for cases where vertical ice movements are predominant, which could occur due to tides or water level changes. "Plucking" is unlikely unless large, steady, cyclic, water level changes occur. This type of water level fluctuation pattern occurs regularly at hydro-electric dams; and not surprisingly, these are the sites where "plucking" has been primarily observed. With regular tidal action, a stationary "ice foot" is usually generated on the slope/ice interface. The vertical ice motion then occurs outboard of the ice foot at a tidal crack. This is expected to occur at a SCH at Whapmagoostui/Kuujjuarapik;

- Sliding - this refers to large-scale failure planes developing in a rock berm as a result of ice forces, which could include "decapitation" of the berm. Sliding failures are unlikely in our opinion, as typically, rubble berms have high sliding resistance.

Rock armour can be designed to resist all three above mentioned processes.

2.4.3 DEEP-WATER PORT

The ice actions for a deep-water port are affected by many factors:

- Water depth – the water depth for a deep-water port would likely be about 18 m, which would make it much more exposed to dynamic ice conditions, such as ice incursions from offshore which might bring large ice floes and deep-draft ice features (e.g., ridge keels) in contact with the port.
- The type of structures comprising the port – a deep-water port would be larger than a SCH and it would be comprised of more complex permanent structures, requiring a detailed evaluation of the ice actions. This would include the following:
  - Ice loads – the design must ensure that the structures have adequate structural integrity against ice loads for a prescribed return period. Ice loading scenarios are discussed further below;
  - Ice ride-up and encroachment – the design must ensure that all structures (e.g., ship loaders) would not be negatively affected by potential ice ride-up and encroachment on to the deck. Ice encroachment scenarios are discussed further below.
- The vessels calling at the port and the port's operating basis – the operating season for a deep-water port may vary over the following range:
  a. Port open only in open water – of course, this would provide the shortest operating season, but vessels calling at the port would only need to have minimal ice class. In this case, the ice cover would develop naturally without being affected by ship transits, and tactical ice management vessels would probably not be required as the port would only operate in open water. It is expected that from time to time, the port might need to call upon the Canadian Coast Guard (CCG) for icebreaker assistance, say for clearing ice resulting from an ice incursion. However, it is not expected that the port's requests would be more excessive than those of the other open-water ports in the Arctic that the CCG supports in summer operations.
  b. Port open in open water and the "shoulder" freeze-up season – this is a common approach used to extend the operating season for arctic ports. In this case, vessels calling at the port would need to have an ice class appropriate for early-winter operation in ice. For this scenario, the ice regime may be affected by ship transits in early-season, but it would develop naturally after the ship transits cease. Of course, vessels calling at a port operating in open water and the "shoulder" freeze-up season would have to have sufficient ice-capability to transit through the ice conditions along the routes to and from the port, e.g., in Hudson Bay and Hudson Strait. However, because these vessels would probably not be equipped for tactical ice management at the port, it is expected that some icebreaker support would be required at the port for the shoulder season, e.g., to keep the port open and to clear the access lanes to the terminal. Because the port would only operate in the shoulder season, the tactical ice support vessel(s) would only need to be capable of operating in relatively thin ice, up to about 0.3-0.5 m thickness, depending on the port's operating schedule.
  c. Port open year-round – Of course, this would provide the longest operating season, but vessels calling at the port would need to be classed for year-round ice transit. Regular ship transits would affect the ice regime, likely retarding or preventing the establishment of landfast ice. Regular ship transit would also lead to brash ice being formed near the port and in the shipping lanes. The same comments made in b. above also apply for a year-round port. However, for a year-round port, the required tactical ice support vessel(s) would need to be more ice-capable as they would have to operate in ice up to the maximum ice thickness for the winter.

Ice loads may get exerted by various mechanisms:

- Impacts by ice floes originating offshore that get driven into the dock, say by winds – this scenario may occur during two general time periods as described below. The governing ice loads may be produced by either case, depending on the parameters of the interaction (e.g., ice thickness, ice strength).
  - Freeze-up: ice movements are possible until freeze-up is complete, which stabilizes the ice and prevents further movements;
  - Break-up: ice incursions may occur bringing large floes, and possibly ice ridges as well, into contact with the dock.
- Thermal ice loads – these will be the dominant loading during the mid-winter period when the ice is essentially stable.
- Vertical ice loads – vertical loads will get exerted due to tidal action. Tidal action will also affect the horizontal ice loads through the formation of an ice bustle on the structures.

Ice encroachment may occur during either freeze-up or break-up. Basically, ice movements are required to produce ice encroachments (bringing ice onto the top of the structures), depending on the parameters of the interaction (water depth, slope of structure, amount of movement, ice thickness, etc.).

2.5 CLIMATE CHANGE

Climate change will modify future sea ice characteristics (e.g., presence, duration, thickness) in Nunavik, including along the coast of Hudson near Whapmagoostui/Kuujjuarapik. These changes could, in turn, have impact on coastal infrastructures.

Nunavik’s coastline has been exposed to significant warming, especially during the period from 1987 to 2016, which show an increase in winter temperatures of +1.5°C per decade (Ouranos, 2020). The increase in winter air temperature will be a major driver to the anticipated changes to the ice conditions. In Nunavik, on the horizon 2046--2064, the average winter air temperature (DJFM) is projected to increase by +5.5°C under the scenario RCP4.5 and by +5.8°C for scenario RCP8.5 (Ouranos, 2020).

Future anticipated changes to the ice conditions are described by Ouranos (2020) based on the works of other scientists. Main findings are the followings:

- The rapid increase in winter temperatures above Hudson Bay and Nunavik will lead to later ice freeze-up and earlier ice breakup;
- In spring, warmer temperatures will accelerate the ice degradation processes, which will lead to ice floes mobility;
- The increased mobility of the ice could lead to a higher probability of ice-related erosion and ice impact on marine infrastructures;
- According to the original simulations conducted by Senneville (2018a), by 2040-2070, the ice is expected to be 15 cm thinner in November and 80 cm thinner in June. The thinner ice cover could break if strong winds and higher water levels occur simultaneously. In spring and autumn, the coasts could therefore be more exposed to erosion through ice pushes;
- The duration of the ice season in the bodies of water surrounding Nunavik could be reduced by more than six weeks by 2041-2070, according to the SRES-A2 scenario (Senneville and St-Onge Drouin, 2013), and by more than two months by 2100, according to the same scenario (Joly et al. 2011).

Figure 2-14 shows the average concentration of sea ice in Nunavik in December 1980-2010 (a) and 2040-2070 (b). From this figure, it appears that the ice coverage near Whapmagoostui/Kuujjuarapik could be reduced from 40-50% (1980-2019) down to 10-20% (2040-2070), approximately. The ice coverage in Hudson Strait is also reduced significantly: from 80-90% to 30-40%, approximately. Sea ice model are currently being improved to refine their horizontal resolution (currently 10 km).

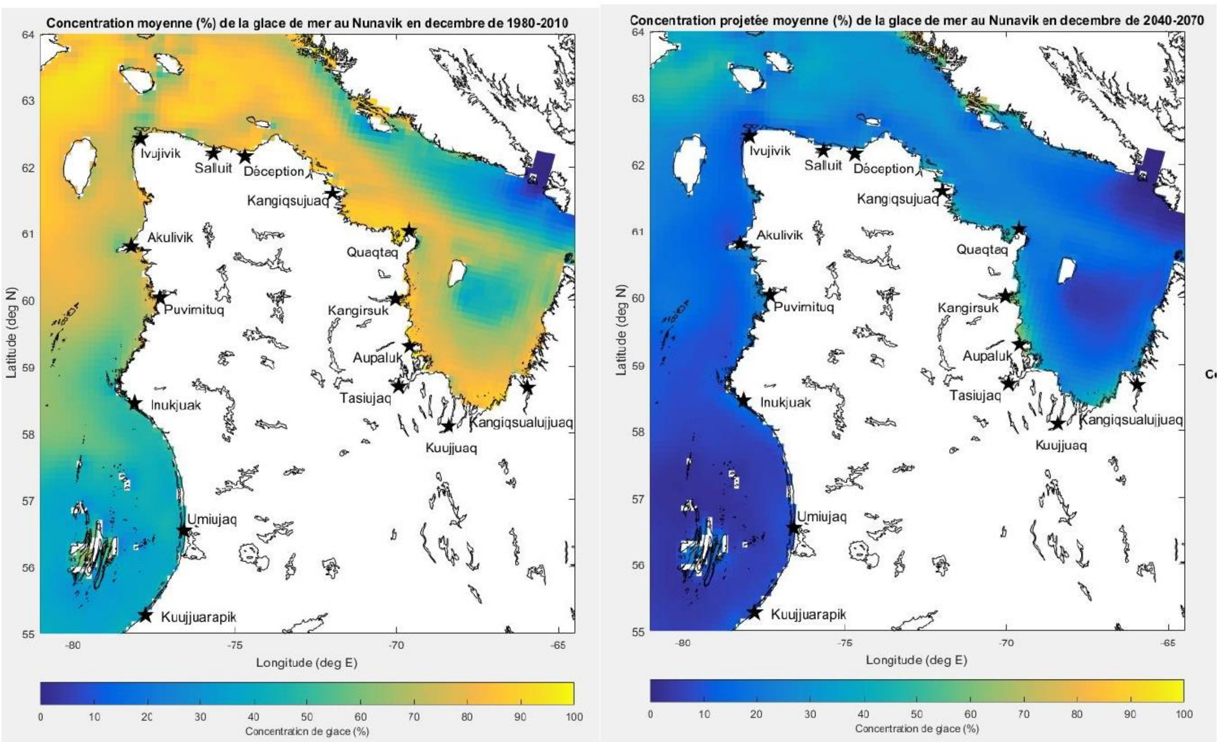


Figure 2-14 Average concentration of sea ice in Nunavik in December 1980-2010 (a) and 2040-2070 (b) (Senneville, 2018b) – excerpt from Ouranos (2020)

With climate change, all zones (A, B, C, and D) will experience later ice freeze-up, earlier ice breakup and thinner ice cover. Frequency of ice incursion will increase for Zones A, B and C but not for Zone D, which is protected within the Manitounuk channel.

The Great Whale River will also be impacted by climate change, which may lead to more frequent ice breakup and increased river ice floes movement at the mouth of the river. Zone A will be influenced by these changes to the river ice regime.

Climate change will extend the duration of the ice-free period. The route from Whapmagoostui/Kuujjuarapik to the Hudson Strait will stay open longer, which will be favorable for shipping.

The anticipated impacts of climate change do not affect the preferred zone for a port.

2.6 SUMMARY

The ice regime in the Hudson Bay (global) and along the East coast near Whapmagoostui/Kuujjuarapik has been analysed using the available information, including ice charts, satellite images, ice thickness measurements and climate data.

Results show that the typical ice-free season along the East coast of Hudson Bay last for about 5 months, from July to November. Based the climate change projections, the duration of the ice-free season could increase by more than six weeks by 2041-2070 (Ouranos, 2020). The ice cover on the East coast forms later and break earlier in comparison with the West, which could be an advantage for a marine infrastructure in Quebec (East) compared to one in Nunavut, Manitoba, or Ontario (West).

The ice regime in four (4) study Zones (A, B, C and D) near Whapmagoostui/Kuujjuarapik were analysed based on satellite observations. The major finding are the followings:

- Zone A is the most exposed site. The ice cover forms latest in Zone A, and often gets removed through the action of the ice pack, followed by new ice growth. It is the latest to freeze up and the earliest to break up. A dock in Zone A would be exposed to ice incursions involving large floes over a large part of the winter. Zone A is also exposed to breakup and potential ice jam at the mouth of the Great Whale River.
- Zone B shows intermediate ice exposure; between Zone A (which is the most exposed) and Zone D (which is the most protected). Zone B freezes up later than Zone D, but earlier than Zone A. The ice tends to break up later at Zone B at than at Zone A. In contrast to Zone D, ice breakup occurs by ice being transported away from the area rather than by thermal decay and melting. A dock in Zone B would be exposed to ice incursions involving large floes during the break-up part of the ice cycle.
- Zone C is somewhat less exposed to ice action than Zone B, as it freezes up before Zone B, and breaks up later.
- Zone D is the most protected site. Ice forms earliest in Zone D and persists latest. The ice thickness would be controlled by thermal growth over the full winter. Ice breakup occurs thermally, as the ice mainly melts in place. Zone D is not exposed to incursions of ice floes from offshore.

Based on our general ice assessment, the preferred zone for both a SCH and a Deep-Water Port are Zone B and the western part of Zone C. More detailed analyses as appropriate should follow to identify the optimal location of the infrastructure. This is explored further in Section 5.

3 METEOROLOGICAL AND OCEANOGRAPHIC (MET-OCEAN) CONDITIONS

3.1 WIND

Wind speeds in the area of interest are recorded at Whapmagoostui/Kuujjuarapik Airport, located at 55°17'00" N, 77°45'00" W, approximately 1.2 km east of the shore of Hudson Bay in the village of Whapmagoostui/Kuujjuarapik. The Whapmagoostui/Kuujjuarapik airport is most closely located to area B, but due to the lack of available data at the other locations (A, C and D) it can be assumed the wind conditions at all sites are similar because of their relative proximity and the topographic similarity among sites. Wind records at the airport station are available between 1957 and present day. The wind rose below shows the overall wind environment from 1957-2022 recorded at the Whapmagoostui/Kuujjuarapik airport, Figure 3-1. During the entire length of records, most winds prevail from Southeast through Northeast. The predominant direction in the wind rose is southeasterly but stronger winds occur from westerly and northwesterly sectors. The average wind speed over the record is approximately 5.1 m/s.

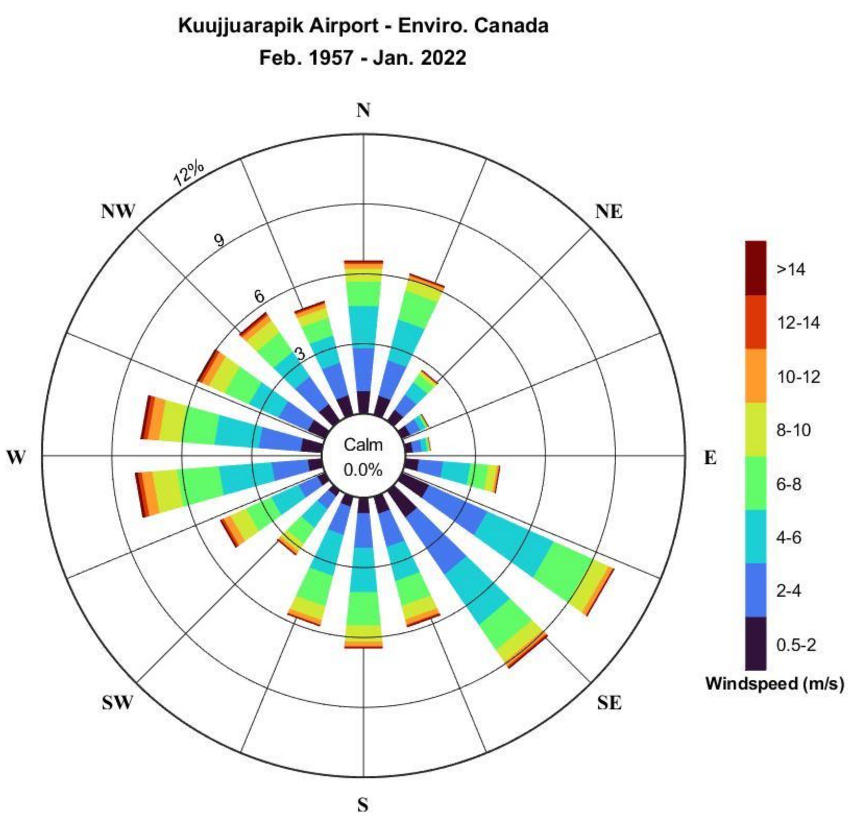


Figure 3-1 Windrose Whapmagoostui/Kuujjuarapik Airport 1957-2022

The wind data from the ice season and ice-free seasons was compared over the full time period of available data (1957-2022). From a comparison of the two wind roses, Figure 3-2 and Figure 3-3, during the winter ice season there is an increase of winds prevailing from the southeast and east-southeast, whereas in the open water summer months the most frequent winds prevail from the west. The southeasterly winds are from overland and do not influence the wave climate at the site.

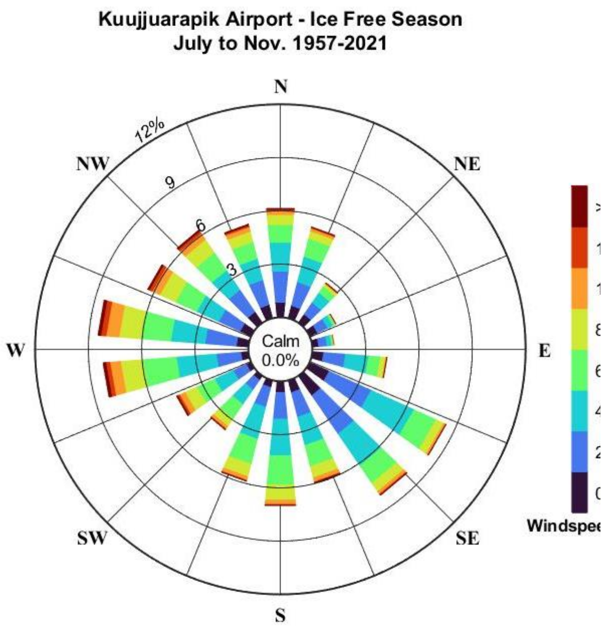


Figure 3-2 Windrose Whapmagoostui/Kuujjuarapik Ice Free Season

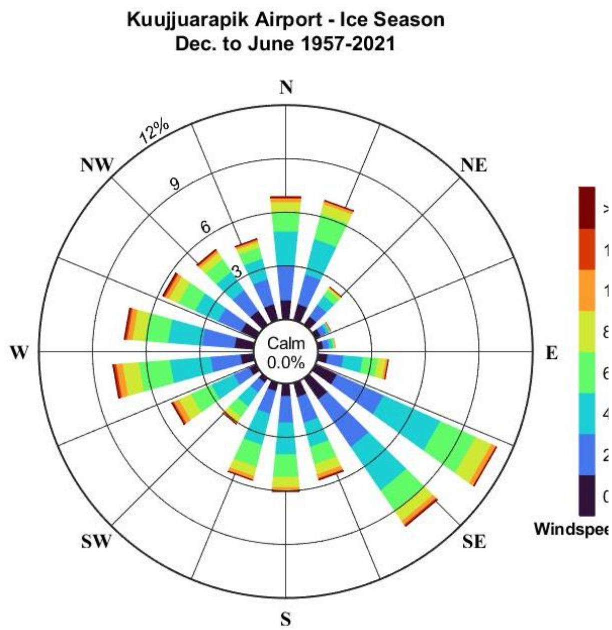


Figure 3-3 Whapmagoostui/Kuujjuarapik Windrose Ice Season

3.2 WATER LEVELS

The water levels near Whapmagoostui/Kuujjuarapik are subject to fluctuations due to tides and during storm surge events. Water level also change on longer times scales as a result of relative sea level (RSL) change.

3.2.1 TIDES

In this region of Hudson Bay, the tide dominates short term fluctuations of the water level, although meteorological conditions and storm surges can also influence water levels. General water level data for the mouth of the Great Whale River, provided by the Canadian Hydrographic Service (CHS), are shown in Table 3-1.

Tides near Whapmagoostui/Kuujjuarapik are semidiurnal and the tide range varies from a mean of 1.5 m to a high range of 2.0 m. The tides from Canadian tide and current tables 2021 Volume 4, for the Arctic and Hudson Bay, are presented in Table 3-1. Note that the tides for Whapmagoostui/Kuujjuarapik use Churchill as a reference port which is approximately 1000 km to the northwest.

Table 3-1 Whapmagoostui/Kuujjuarapik Tides (Canadian Tides and Current Tables 2021. Volume 4, Arctic and Hudson Bay)

Region	Whapmagoostui/Kuujjuarapik		
Reference Port	Churchill		
Index Number No.	4645		
Tide Type	Semidiurnal		
Range	Mean Tide		1.5 m
	High Tide		2.0 m
Tide Height	Higher High Water	Mean Tide	1.7 m
		Large Tide	2.0 m
	Lower Low Water	Mean Tide	0.2 m
		Large Tide	0.0 m (Chart Datum)
Mean Water Level			1.0 m

**Note: Heights are compared to chart datum*
Fs73-4-2021.pdf (publications.gc.ca)

It should be noted that there are seasonal variations to the tides due to annual ice cover. During the ice-covered season Hudson Bay experiences smaller tidal variations in addition to a tidal advancement (Freeman, 1986).

3.2.2 STORM SURGE

Storm surges resulting from low atmospheric pressure and westerly winds can induce an extra sea-level increase above mean sea level and tide fluctuations. In the fall of 1999, a study at the mouth of the Great Whale River was conducted by *Université du Quebec, Institut des Sciences de la Mer* which included the measurements of waves, currents, and suspended sediments in 10 m of water depth conducted over 15 days, which included a four-day storm event. During this storm event wave heights over 3 m for 15 hours and a storm surge of over 1 m height was recorded. During fair weather days of the data collection only local waves with significant heights less than 1 m were recorded (Hill et al., 2003). The latter is consistent with storm surge of more than 1 m reported by Hydro-Quebec (Hydro-Quebec, 1980).

3.2.3 SEA LEVEL

Projections of climate change in the marine environment indicate that rising sea level and declining sea ice will cause changes in extreme water levels, which will impact Canada's coastlines and the infrastructure. Understanding these changes is essential for developing adaptation strategies that can minimize the harmful effects that may result.

The relative sea level (RSL) is defined as the sea level that is observed with respect to a land-based reference frame. RSL changes because of sea level rise, and due to vertical motion of the land. This is discussed in further in Section 4.3.

Values of projected RSL change from 2006 to 2020, 2050 and 2100 are presented in Table 3-2 based on three greenhouse gas pathways: RCP 2.6 for a low emissions scenario, RCP 4.5 for intermediate emissions scenario, and RCP 8.5 for a high emissions scenario, which also includes an enhanced scenario for RCP 8.5. A graphical representation of the sea level change scenario is also shown in Figure 3-4.

RSL is anticipated to be lower than present based on the scenarios presented due to isostatic rebound. RSL change projections range from -109 cm by 2100 for RCP 2.6 Median scenario to -6 cm by 2100 RSL change for RCP 8.5 Enhanced scenario (climatedata.ca, 2022).

Table 3-2 Projected Sea-Level Change (Pointe Tikiraq Ungalliq, Whapmagoostui/Kuujjuarapik, QC) (climatedata.ca, 2022)

	2020	2050	2100
RCP 2.6 Median (50%) (cm)	-23	-52	-109
RCP 2.6 Upper (95%) (cm)	-21	-50	-103
RCP 4.5 Median (50%) (cm)	-23	-50	-98
RCP 4.5 Upper (95%) (cm)	-21	-48	-84
RCP 8.5 Median (50%) (cm)	-22	-47	-80
RCP 8.5 Upper (95%) (cm)	-21	-36	-48
RCP 8.5 Enhanced (cm)	N/A	N/A	-6

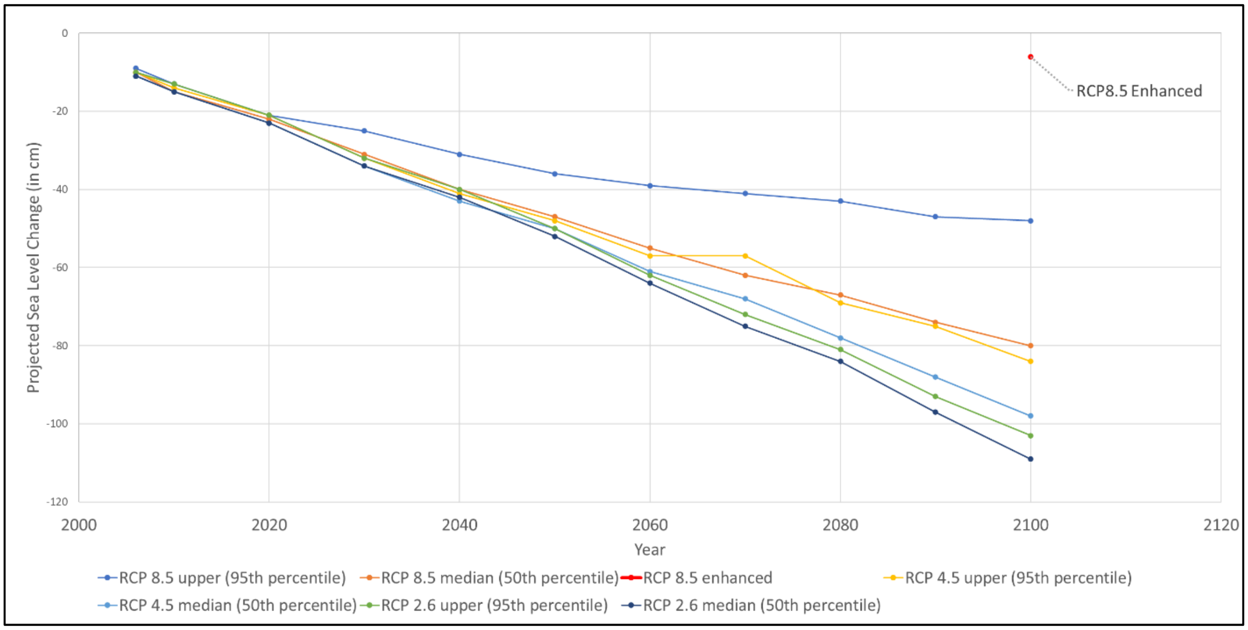


Figure 3-4 Projected sea-level change for Whapmagoostui/Kuujjuarapik based on emissions scenarios RCP 2.6, RCP 4.5, and RCP8.5 (climatedata.ca, 2022)

3.3 WAVE CLIMATE

Published wave data for the southeastern area of Hudson Bay is sparse. Limited observations during the summers of 1991 and 1992 of Whapmagoostui/Kuujjuarapik beach estimate wave heights at 0.2 – 1.2 m with wave periods of 2 – 5 seconds with a median wave height of 50 cm (Ruz, 1994a).

Long fetch lengths of approximately 1000 km combined with strong W and NW winds during storms lead to the development of large wind generated waves. The wave climate, previously referenced in the Ropars 2011 report, was generated using wind data collected from the Whapmagoostui/Kuujjuarapik airport. The analysis generated significant wave heights exceeding 4.8 m on average during one hour per navigation season and 6.0 m for a 25-year return period at the entrance to the Manitounuk Strait, which is closest to area D. Nearer to the shoreline the significant wave height of 1.7 m and 2.2 m for a 25-year return period was reported.

During the summer months the Whapmagoostui/Kuujjuarapik area is dominated by westerly waves (Ruz, 1994a), which is expected due to the increase of westerly winds during the ice-free season.

The mouth of the Great Whale River, adjacent to areas A and B is a wave-dominated environment with a low tidal influence (Hill et al. 2003). These waves are most often wind generated.

The waves experienced at areas A, B and C will all be fairly similar to one another due to a lack of sheltering. Area D is fairly well sheltered from strong waves from the west and northwest and would make a favourable location for a deep-water terminal. Areas A, B and C may be sheltered from waves from the north in varying degrees due to the presence of the Manitounuk Islands.

3.4 CURRENTS

Currents may be driven by a combination of winds, waves and tides. A major portion of the current energy is associated with the tides and winds in the region. Nearshore currents in the surf zone will also be driven by waves.

Ropars (2011) summarizes the currents for the considered areas near Whapmagoostui/Kuujjuarapik (A, B and C) to be of little significance and according to CSSA 1992 are approximately 30 cm/s. However, area D may be impacted by stronger tidal and sometimes wind induced currents due to its location in the Manitounuk Strait (Ropars, 2011).

3.5 SUMMARY

- The wind data from the ice season and ice-free season was compared over the full time period of available data (1957-2022). During the winter ice season there is an increase of winds prevailing from the southeast and east-southeast, whereas in the open water summer months the most frequent winds prevail from the west.
- Water levels near Whapmagoostui/Kuujjuarapik have an average mean tide of 1.5 m, and an average high tide of 2.0 m above chart.
- RSL is projected to fall for Whapmagoostui/Kuujjuarapik based on studies of three greenhouse gas pathways, which indicate potential range of change of -109 cm by 2100 for RCP 2.6 Median scenario to –6 cm by 2100 for RCP 8.5 Enhanced scenario.
- Long fetch lengths of approximately 1000 km combined with strong W and NW winds during storms lead to the development of large wind generated waves. An analysis generated significant wave heights exceeding 4.8 m on average during one hour per navigation season and 6.0 m for a 25-year return period. Nearer to the shoreline the significant wave height of 1.7 m and 2.2 m for a 25-year return period was reported.

4 GEOMORPHOLOGY

The study area is characterized by landforms shaped by remnants of glacial processes as the coastline was reworked while the land slowly emerged from the sea. The Great Whale River is the dominant source of sediment to the coast in the study area. To the northeast of the study area erosion of tidal flats is a major contributor to sediment in Manitounuk Sound. The modern coastline consists of bedrock and sediment deposits acted on by hydrodynamic processes, such as tides, tidal currents and sea ice, in context of relative sea-level fall. Climate change is anticipated to generate multiple impacts on geomorphic processes in the study area, driven by sea-ice dynamics, water level changes, precipitation and temperature changes.

This section reviews the elements of geomorphology for eastern Hudson Bay coastline in the vicinity of Whapmagoostui/Kuujjuarapik, Manitounuk Sound, including the mouth of the Great Whale River. Consideration is given to bathymetry, topography and the process of deglaciation in providing the framework for development of present-day morphology.

4.1 BATHYMETRY

The bathymetry, as shown in Figure 4-1, is characterized by general trends that reflect the underlying bedrock morphology, including discontinuous ridges and troughs running northeast-southwest. The ridges form cuestas, steeply sloping on the east, and with shallow slopes on the west. The cuestas extend offshore for 40 km west of Great Whale River.

West of Great Whale River the depth increases to 60 m within 3 km of the shore but rarely exceeds 100 m relative to chart datum. Approximately 8 km west from the river mouth the seafloor rises to depths less than 20 m. The discontinuous rises trend northeastward and are contiguous extensions of the Manitounuk Islands. Southwest of Great Whale River, the trend of the ridges is cut by a west-southwest oriented trough, generally aligned with Great Whale River channel.

Manitounuk Sound is located ~10 km northeast of Great Whale River and is bounded by the northeast trending mainland coast and the Manitounuk Islands. The sound is 58 km long, a minimum of 1 km wide and maximum width of 5.7 km. The mouth of Manitounuk Sound is 3.5 km wide and opens to the southwest. Waters progressively deepen westward from the mainland. Maximum water depth is >100 m near the mouth of the sound, and shallower toward the northeast. Near the head of Manitounuk Sound maximum water depth is >30 m. Intertidal flats are present in the shelter of promontories or headlands and are generally <100 m wide in the southeast of the sound, and widen to 1 km near the head of the Manitounuk Sound.

Great Whale River delta bathymetry has a shoal margin (<5 m) with shallow sand bars (<2 m). The delta extends 2 km from shore near the mouth of Great Whale River with a slope break between 5 and 10 m water depth. The shoal margin narrows toward the northeast. In general, the coastal margin has a slope break at 5-10 m depth within 150 m from shore. In places the slope of the coastal margin is steeper, such as southwest of the mouth of Great Whale River and in the northeast of the study area, opposite Manitounuk Island, with depths in the range of 10-20 m within 50 m from shore.

Bathymetry is an important consideration for a SCH or Deep-Water Port within the study area. The nearshore water depth is shallow with a relatively wide margin in Zone B and Zone C, which includes the estuary of Great Whale River and northeast of the river delta. Water depths are greater in the nearshore in the southwest part of Zone A and in the northeast part of Zone D.

The offshore does not pose a major concern to navigation except for isolated small shoals near Gillies Island, and at the eastern side of the entrance of Manitounuk Sound.

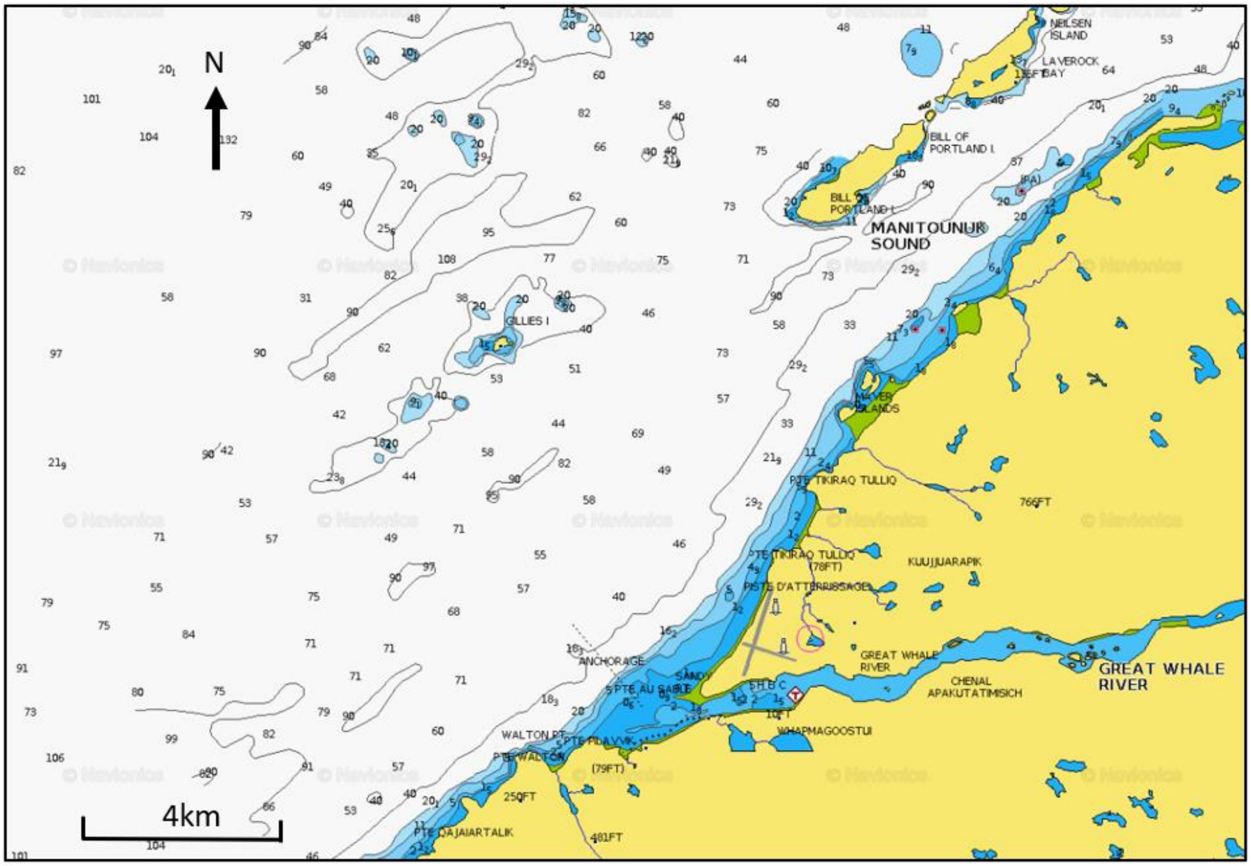


Figure 4-1 Bathymetry of study area (Navionics ChartViewer)

4.2 TOPOGRAPHY

The general topography of the study area is a northeast trending coastline. The nearshore coastal zone has a low relief, with elevations generally less than 20 m above mean sea level. The profile of the coastal terrain located northeast of Great Whale River has gradual seaward dipping slope - the elevation decreases 70 to 90 m over a distance of about 2 km. The coastline is also fringed by bedrock ridges, behind which there are subtidal flats. Southwest of the mouth of Great Whale River terrain has a steep seaward dipping slope - over a distance of 1.5 km the elevation decreases 150 m.

To the northeast of the study area there are a series of low-elevation northeast trending cuesta shaped islands that form the western edge of Manitounuk Sound. The islands have steep slopes on eastern shoreline, and gentle slopes on western shore. The islands include Bill of Portland Island and Neilsen Island. Bill of Portland Island is ~3 km long, has maximum width of 0.8 km and elevation of 45 m above MSL. Neilsen Island is located to the north, it is ~3 km long, has a maximum width of ~1km and a maximum elevation of 30 m above MSL. Both islands are ~3 km long.

The nearshore coastal zone topography of the study area is generally not steep in Zone B and Zone C, with gentle gradients near the shoreline (< 5º). However, south of the Great Whale River, in Zone A, there is steeper gradient nearshore coastal topography (<15º), which is a more challenging terrain for building infrastructure, and may require rock blasting to grade the potential site.

4.3 DEGLACIATION

Most sediments on the coast are a legacy of deposition since the last glacial cycle when the Laurentian ice sheet was present in the Hudson Bay region. As described by Lochte et al. (2019) and shown in Figure 4-2, deglaciation proceeded in the following stages:

i. Development of Lake Agassiz/Ojibway, a massive proglacial lake south of the ice sheet, in southern Hudson Bay between 13,000 and 8,700 years ago

ii. Deglaciation of Hudson Bay began between approximately 8,700 and 8,400 years ago (Lochte et al. 2019), and from Great Whale River approximately 8,100 years ago (Hillaire-Marcel, 1976).

iii. Drainage of Lake Agassiz/Ojjibway from southern Hudson Bay.

iv. Tyrrell Sea incursion into newly deglaciated isostatically depressed areas. The Tyrrell Sea is defined as the late glacial and postglacial sea in Hudson Bay region (Lee, 1960).

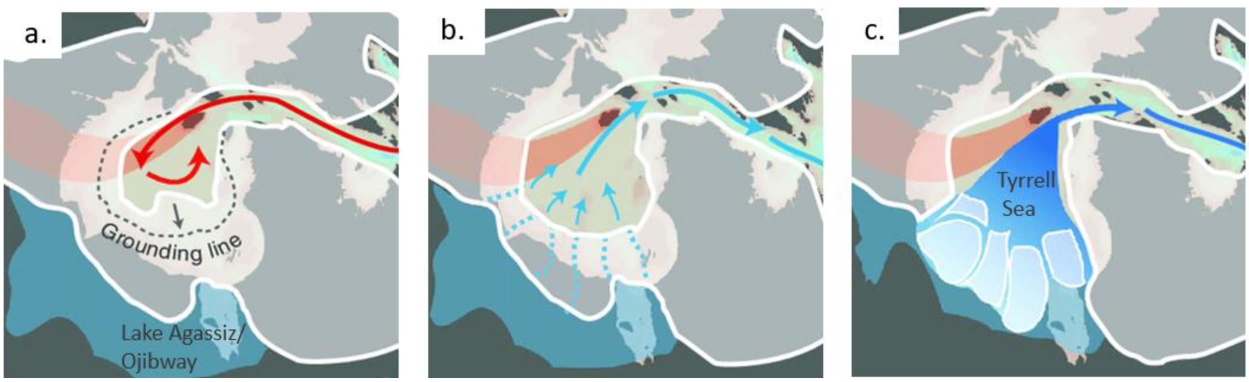


Figure 4-2 Schematic plan views of Hudson Bay between 8,700 – 8,400 years ago showing initial stages of deglaciation.

a.) The extent of the Laurentian Ice Sheet and Lake Agassiz/ Ojibway
b.) The drainage of Lake Agassiz
c.) Inundation of the Tyrrell Sea (modified from Lochte et al, 2019)

The weight of the ice isostatically depressed the landmass making Tyrell Sea much larger than modern Hudson Bay. However, the size of the new sea was governed by two opposing processes: the eustatic rise of sea level and isostatic fall of the sea caused by rebound of the land. Eustatic sea level rise, caused by continued melting of the ice and thermal expansion of the ocean, was dominant until deglaciation approximately 8,500 years ago. Thereafter, isostatic rebound became very rapid. The combination of eustatic and isostatic components is defined as RSL (Relative Sea Level).

Emergence of eastern Hudson Bay coastline resulted in multiple forms of erosion and uplifted littoral accumulations which have been used to measure rates of RSL change. As shown on Figure 4-3, the rate of emergence on the eastern Hudson Bay coastline was initially very rapid, on the order of 9-10m/ century and decreased to a rate of approximately 1m/ century as of 2,800 years ago (Lavoie et al., 2012).

Isostatic adjustment continues to cause uplift of the Hudson Bay coastline, resulting in land emergence (negative RSL). Recent sea level projections for Whapmagoostui/Kuujjuarapik are discussed in Section 3.2.3. Projections indicate that the rate of emergence of the coast could potentially be equal to or less than long-term RSL rise for the past 2,800 years.

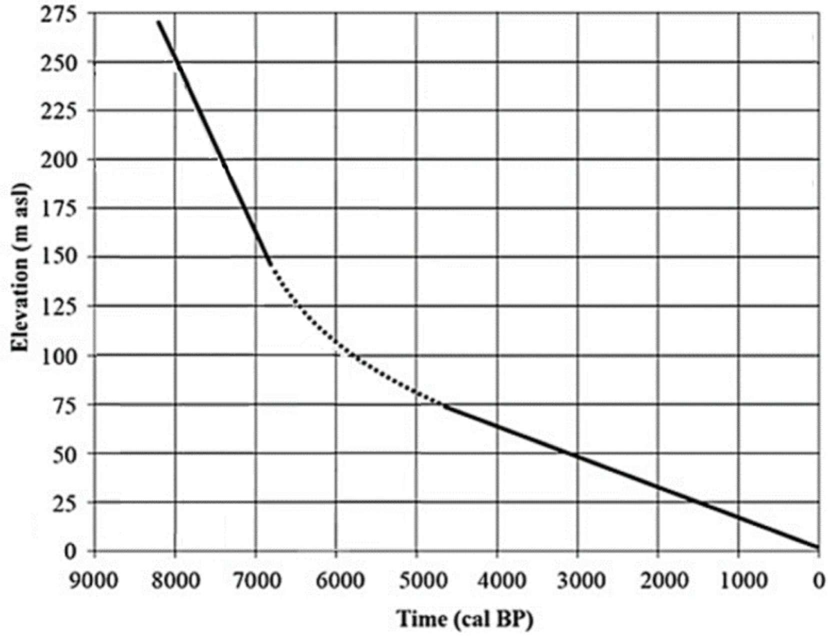


Figure 4-3 Inferred postglacial RSL elevation for the east coast of Hudson Bay in calendar years before present (cal BP). Dashed section of curve represents uncertainty due to lack of datum material used for constraining RSL (modified from Lavoie et al., 2012)

4.4 SURFICIAL GEOLOGY

A morphology map from the study area shown in Figure 4-4 was produced by Le Bureau de la Connaissance géoscientifique du Québec (BCGQ) (Brouard et al., 2020). According to the map, the shoreline of the study area is mainly composed of prodeltaic deposits and sediments deposited into the nearshore of the ancient Tyrell Sea (Unit Mb) and bedrock (R and Rp) (see descriptions of morphological in Table 4-1.

Within the estuary section of the Great Whale River, soil deposits are mainly composed of deltaic, prodeltaic, and deep water fine glaciomarine sediments (Md and Ma), consisting of clay, silt and gravel. Landslides are recurring in these soils, often initiated by river processes and contribute to sediment yield into the study area (Owczarek et al. 2020).

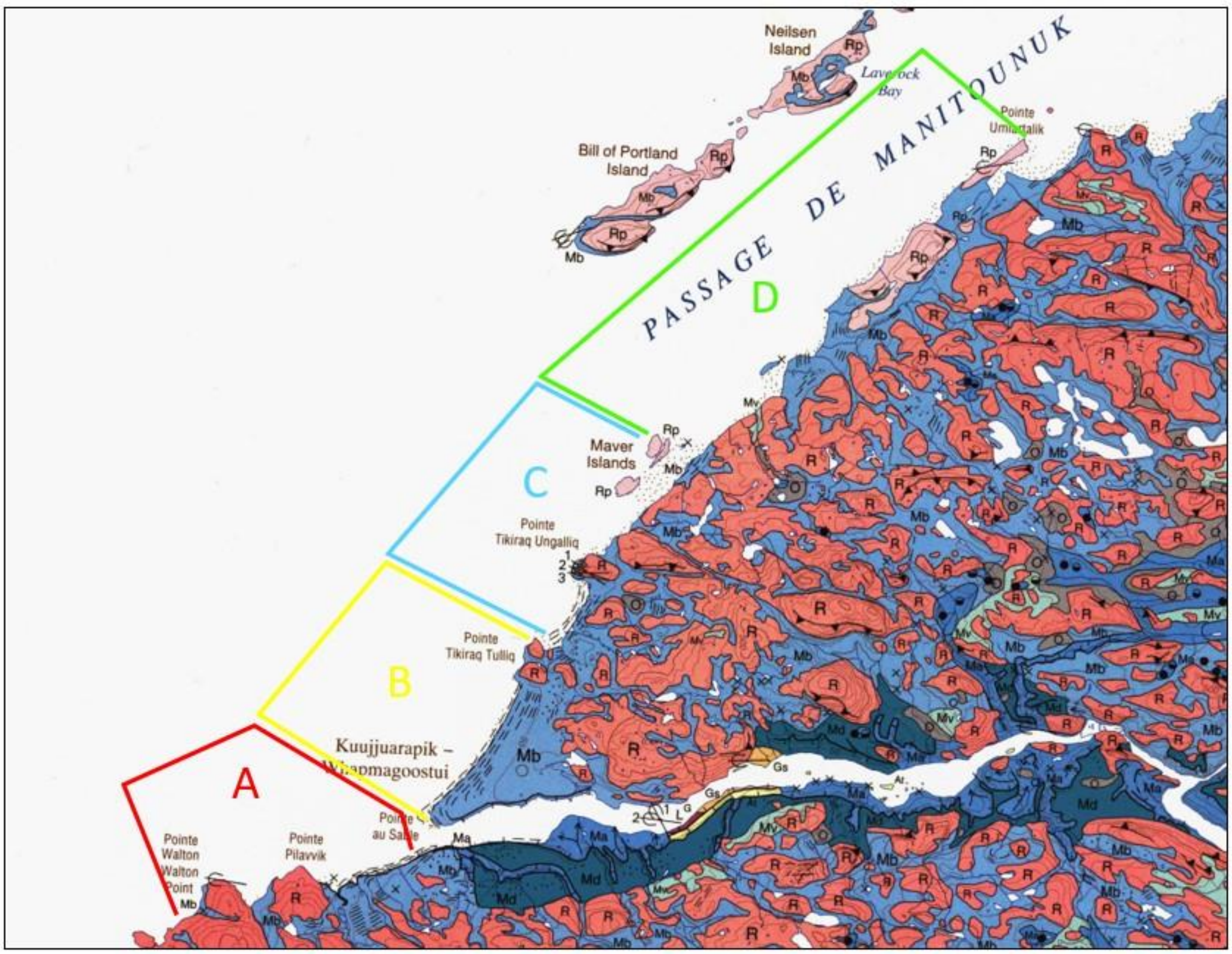


Figure 4-4 Distribution of morphology around the zones of interest (Brouard et al., 2020).

Table 4-1 Coastal Morphological Unit Legend

CLASSIFICATION	CODE	GROUP	DESCRIPTION
Rock	Rp	Proterozoic Bedrock	Volcanic and sedimentary rocks of Proterozoic
	R	Archean Bedrock	Metasedimentary, metavolcanic and intrusive rocks of the Archean
Sand, Gravel Pebbles, Blocks	Mb	Coastal and pre-coastal sediments	0.5 to 5 m thick; deposited along the relict shores of the Tyrell Sea; also including prodeltaic sediments close to large deltaic complexes; surface generally marked by beach ridges and sometimes modified by wind action.
	Mv	Thin prelittoral and reworked till	<0.5 m or till reworked on a thickness of <0.5 m deposited in shallow water deep in the Tyrell Sea; surface controlled by the bedrock topography of the underlying till.
Sand, Gravel	Md	Marine and Glaciomarine deposits	1 to 40 m thick; deposited at the mouth of rivers flowing into the Tyrrell Sea; surface generally marked by abandoned channels and sometimes modified by wind action
Clay, Silt	Ma	Deep Water Marine Sediments	0.5 to 20 m thick; deposited by streams, gully and mass movements; surface generally covered with a thin peat layer and modified by the presence of palses

4.5 PERMAFROST

The four prospective port sites (A, B, C, D) at Whapmagoostui/Kuujjuarapik are located along the shoreline of Hudson Bay. Adjacent to the prospective sites, onshore is broadly classified as discontinuous scattered permafrost where less than 50 % of the land surface is permafrost, the temperature of permafrost for ice rich clay soils and peat is estimated at the melting point, and the permafrost temperature is estimated to be between 0°C and -1°C (Allard et al. 2012). More specifically, the upland areas adjacent to the port sites are "characterized by palsas overlying fine Tyrrell Sea sediments and scattered permafrost under exposed bedrock hills in the wind-blown rocky hills along the coast" (Bhiry et al. 2011) as shown in Figure 4-5. Locally, permafrost may vary over short distances depending on topography, vegetation and snow cover. However, Bhiry et al. (2011) note the absence of permafrost at elevations less than 20 m along the coast that is attributed to the moderating effects of Hudson Bay.

Permafrost is not expected to extend offshore according to GRID-Arendal (2020). Shoreline deposits include sandy rocky beaches, as well as dunes and other eolian features affected by frost processes and coastal dynamics.

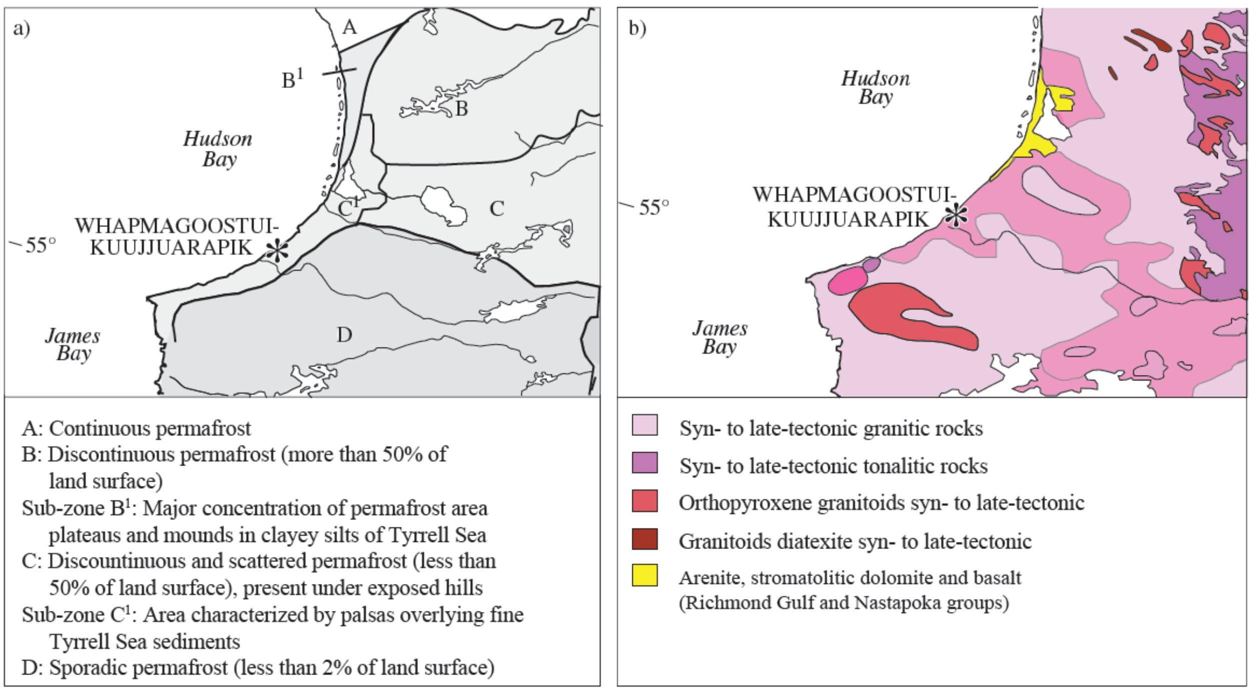


Figure 4-5 a) Permafrost conditions on the coast in context of b) bedrock geology (Bhiry et al. 2011).

The geomorphology and surficial geology of the onshore includes glacially-scoured bedrock either exposed at the surface or overlain by sediments along the Hudson Bay shore (NRCan 2020). Inland of prospective port sites C and D, bedrock is overlain by offshore sediments containing silt and clay, plus larger clasts. Inland of prospective port sites A and B, bedrock is overlain by littoral and nearshore sediments including sand and gravel deposits. The Great Whale River enters Hudson Bay at approximately the boundary between prospective port sites A and B.

ONeil et al. (2019) provide estimates of excess ground ice (percent ice by volume) in the top five metres of permafrost. For the area inland of prospective port sites C and D, the total estimated excess ice content in permafrost is greater than 10-20%. For the area inland of prospective sites A and B, the total estimated excess ice content in the permafrost is greater than 0-5%. These excess ground ice estimates correlate in general with the surficial geologic unit designations– silt and clay deposits have a greater potential for excess ground ice than sand and gravel deposits.

4.6 COASTAL AND FLUVIAL GEOMORPHOLOGY

The erosional depositional dynamics on the coastline of the study area are conditioned in context of hydrodynamics, physiography, and coastal emergence due to uplift. Coastal emergence has preserved specific landforms and geomorphic features, and a legacy of paleo-shorelines remain, consisting of boulder strewn shores, uplifted marine terraces, paleodeltas, and flights of raised beaches and dunes. A general classification of the shoreline for the study area is provided in Figure 4-6 using a mapping classification developed by Wynja et al. 2015.

Most of the unlithified shoreline features in the study area are progradational, such as sand spits, beaches, tombolos and deltas. Though short sections of the coast to the north of the study area are retreating. Part of the study area is in Manitounuk Sound, a coast sheltered by a string of cuesta islands (ie. Manitounuk Islands) - within these areas there are tidal flats which are retreating due to coastal permafrost thawing and erosion. Also, sections of the Great Whale River valley have landslide terrain eroding by way of mass movements.

The Great Whale River discharges into the study area from a drainage basin of approximately 42,735 km^2 (Hülse and Bentley, 2012). Surface currents are setting to the northeast at mean velocities of 0.6 to 0.7 m/s (Hydro-Quebec, 1993), and are strongly dependant on freshwater discharge, which averages 700 m^3s^{-1}, ranging from <200 m^3s^{-1} in March to >1,300 m^3s^{-1} in June (Ingram, 1981). Winds contribute to northeasterly circulation, the most frequent wind direction being from the west between July and November, during ice-free conditions. Figure 4-6 shows the dominant direction of longshore transport during ice-free conditions.

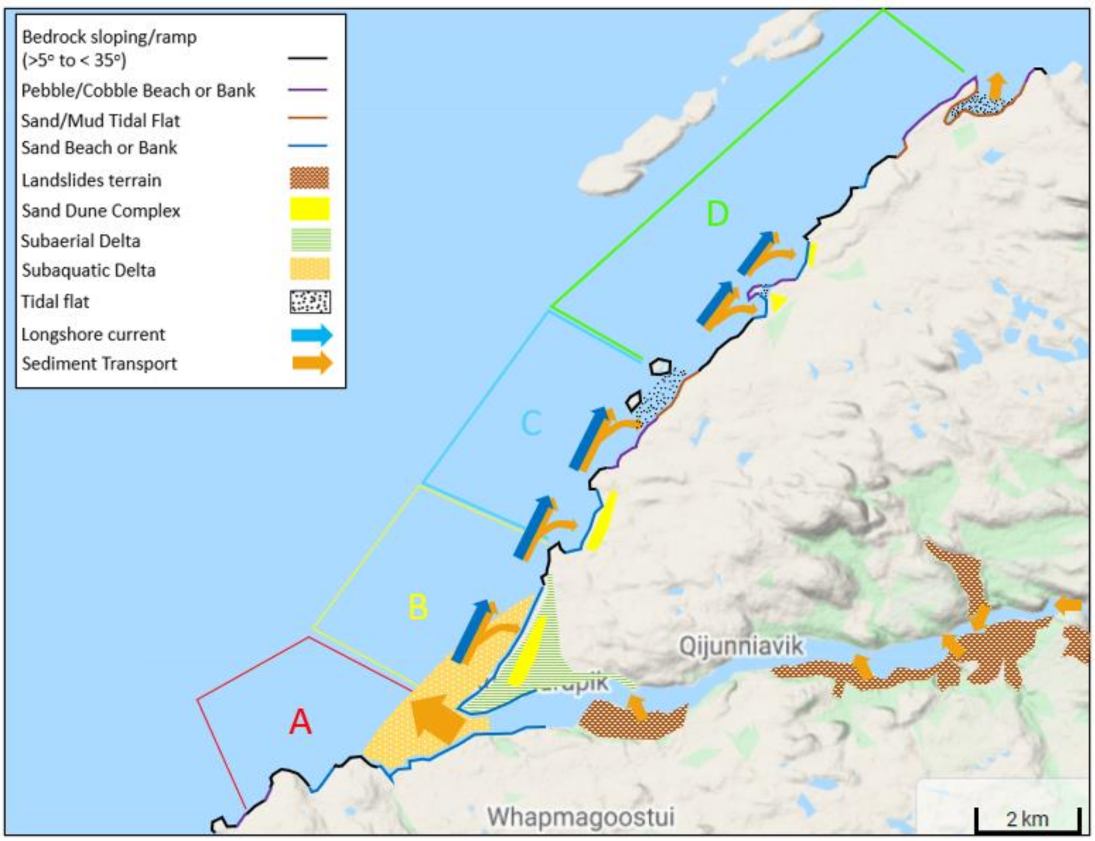


Figure 4-6 A coastal classification map for the shoreline of study area, including geomorphic features and directions of sediment transport based on dominant wind directions during ice-free conditions (Boisson and Allard, 2015; Hill et al., 2003; Owczarek et al., 2020)

4.6.1 BEDROCK

The bedrock shoreline generally consists of low lying rocky outcrops that have gentle gradients (< 5º), except southwest of the mouth of Great Whale River which has steeper slopes (<15º). The bedrock coasts are intensely wave washed, scoured by floating ice and have been affected by frost weathering since the withdrawal of the Laurentide Ice Sheet and the subsequent regression of the Tyrrell Sea (Boisson and Allard, 2018, Fournier and Allard, 1992). The lithified coasts are stable with little to no retreat.

4.6.2 SUBAQUATIC DELTA

The mouth of Great Whale River flows into the sea on the southwest side of a terrace (subaerial delta) and across a nearshore platform, ~1 km wide. The river channel shoals across a shallow (<2m) mouth bar (Hill et al. 2003, Longuepee 2000). Offshore of the mouth bar, a single offshore bar, 2.5 m high, with its crest having a minimum water depth of 3.5 m, extends along the outer edge of the subaqueous delta platform, subparallel to the beach, and converges with the shoreline near the distal (northeastern) extent of the beach. The slope break occurs between 5 and 10 m water depth, and the prodelta slope extends to approximately 40 m water depth, where it merges with the basin floor.

The progression of the Great Whale River can be seen nearshore sediments of the river valley, as remnants of a series of down-stepping incisions into older deltaic deposits caused by isostatic rebound, has left exposures of older deltas in the valley walls (Hill et al. 2003).

4.6.3 SUBAERIAL DELTA

The sandy triangular shaped terrace with its shoreline bound to the south by the mouth of Great Whale River is a subaquatic delta, deposited when sea level was higher, which have since become subaerial because of isostatic rebound. Ruz and Allard (1994) describe the terrace, characterized by a seaward-dipping surface, sloping at 1º from 25 m elevation to sea level. This feature has an extent of 3.6 km from the river mouth to a bedrock outcrop to the northeast. Sandy ridges on the surface of the subaerial delta are parallel to the present-day shoreline and curve near the estuary mouth, marking the former position of the river mouth. There are approximately 20 ridges, progressing to 20-25 m elevation, developed between 2000 years ago and present. Aerial photo analysis by Ruz and Allard (1994) indicate 100 to 150 m of progradation between 1972 and 1990 at the southern tip of the beach. Comparison with satellite imagery from 2021 shows continued progradation southward (Figure 4-7).

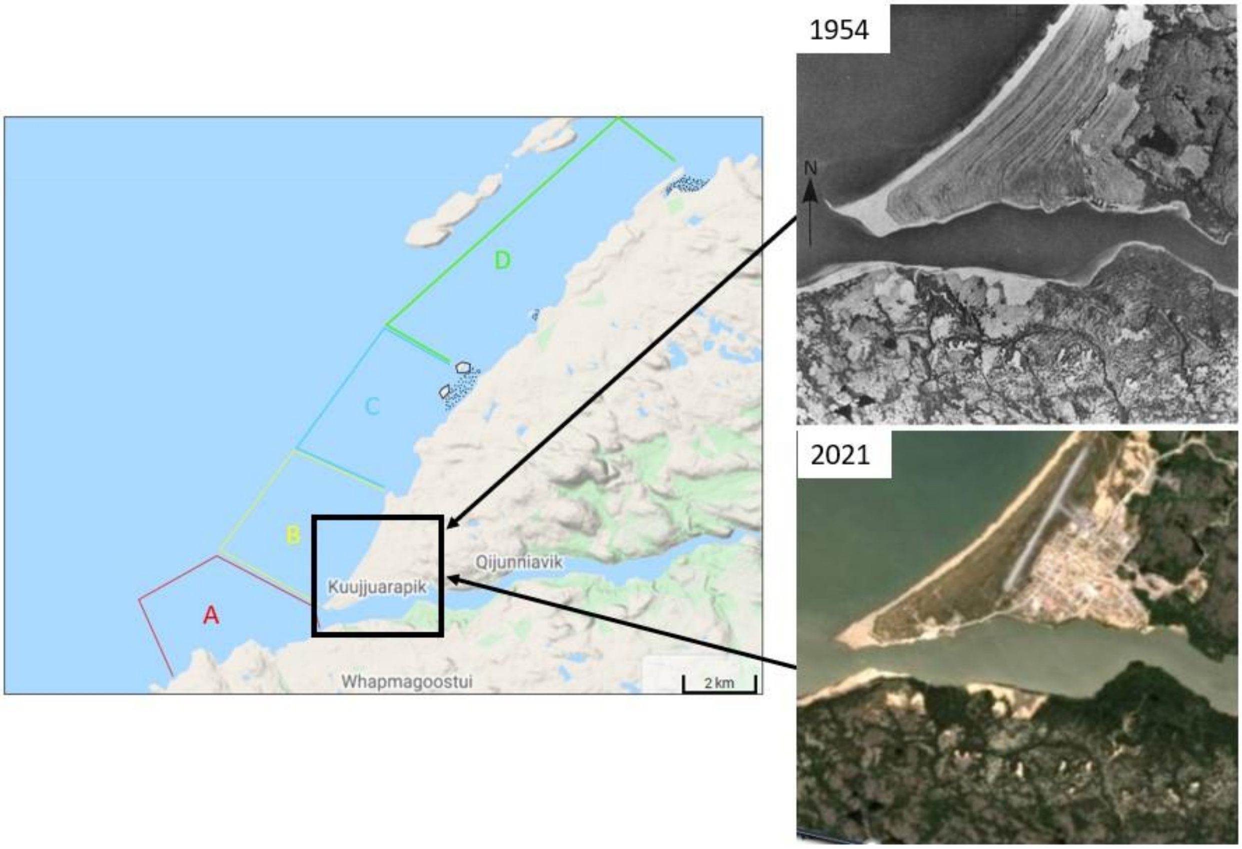


Figure 4-7 **Subaerial delta located at the mouth of Great Whale River. Top right image is an aerial photograph from 1954 (from Ruz and Allard, 1994), bottom right is a satellite image from 2021**

4.6.4 BEACHES & DUNES

Sandy pocket beaches are present between bedrock headlands and pebble/cobble banks in site B and site C. Examples of beaches in the study area are in Figure 4-8. Because of local water circulation, the Great Whale River freshwater plume tends to extend northeastward, acting as a source of sediment for beach deposition in the study area (Hequette and Tremblay, 2009). A 1.6 km long beach located 4 km east of the mouth of Great Whale River was characterized by Hequette and Tremblay (2009). The intertidal zone is approximately 100 m wide, with an average foreshore slope of 5%, decreasing to about 2% on the lower beach. The nearshore zone is characterized by a parallel longshore bars and troughs that dissipate the energy of the incoming waves. The main parameters responsible for sediment movement along beaches are wave energy and velocity of longshore currents induced by obliquely incident waves (Hequette and Tremblay, 2009).

Low dunes (<5 m high) have formed landward of the sand beaches. Progressively raised dune ridges are also present, interpreted as relict dunes raised to higher elevations by isostatic uplift (Ruz and Allard,1994b). Dunes on the eastern Hudson Bay coast tend to form on open-ocean coasts with large fetch lengths (hundreds of kilometers) (Boisson and Allard, 2018). To the northeast, because of more sheltered conditions within Manitounuk Sound, dunes are absent from the coastline.

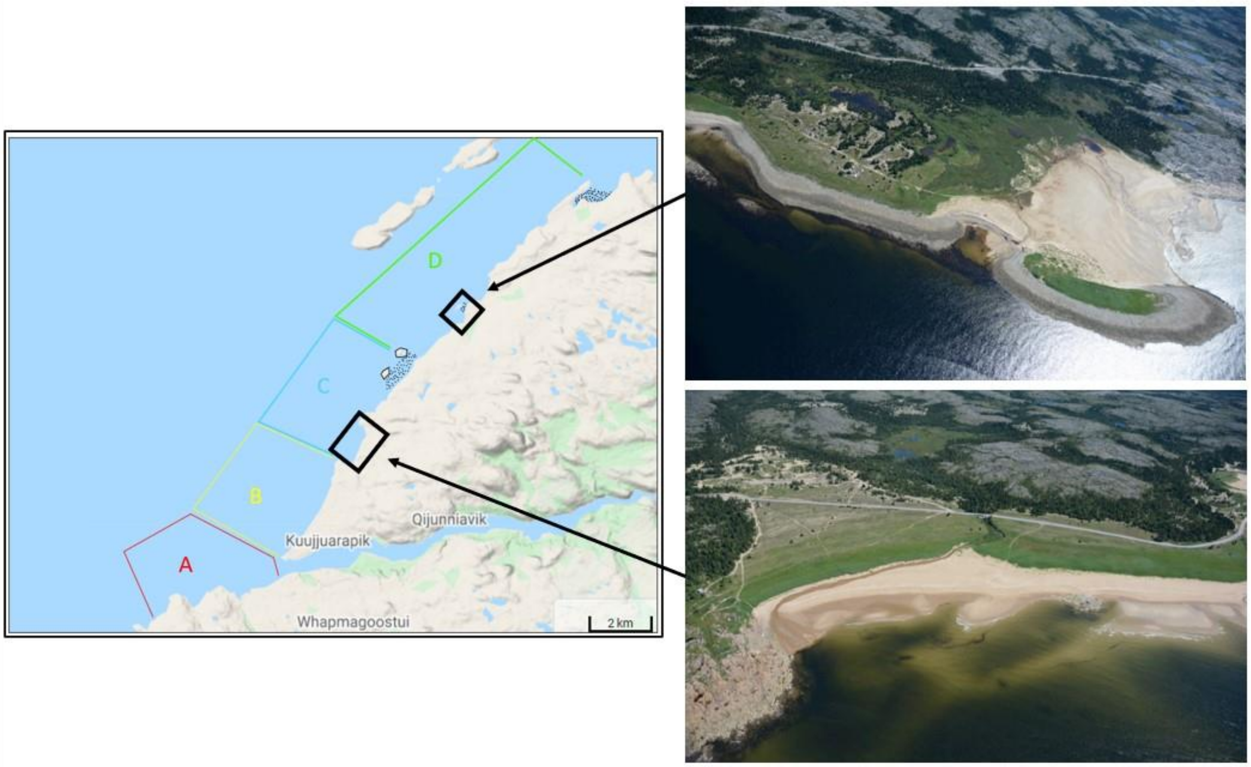


Figure 4-8 Examples of pocket beaches located in the study area (images from Boisson et al. 2015)

4.6.5 LANDSLIDE TERRAIN

Landslides have been reported within 12 km upstream from the mouth of Great Whale River (Belanger and Filion, 1991). The landslide terrain is limited to fine grained silty marine clays from the Tyrrell Sea, which is primarily located on the south bank of the river. The landslides result in episodes of high sediment load and cause constrictions in the river. A potential concern is the impact of high sedimentation rates, which may result in a clogged waterway or navigation hazard for a SCH installed within the estuary of Whapmagoostui/Kuujjuarapik or near the mouth of the river.

There are examples of both gradual and rapid mass movements of active landslide terrain. Owczarek et al. (2020) used air photos to analyze landforms within the landslide and river valley to evaluate gradual slope failures and constriction to the river between 1969 and 2020. Analysis indicates triggering mechanisms are interacting processes, the most important being summer rainfall intensity and high river discharges. Uplifted marine clays are exposed and unstable resulting in a relatively low rainfall/river discharge threshold for landslide initiation or activation in comparison to other sub-arctic Canadian landslide areas.

An example of a rapid mass transport landslide occurred 8 km upstream from the mouth of Great Whale River in April 2021 (Figure 4-9). The landslide covers a 1.8 km section of a tributary to Great Whale River and is approximately 500 m wide. The tearing scar and disturbed area below it are identifiable in the image in Figure 4-9, and the sediment transported from the tributary can be seen on the banks of Great Whale River from satellite images.

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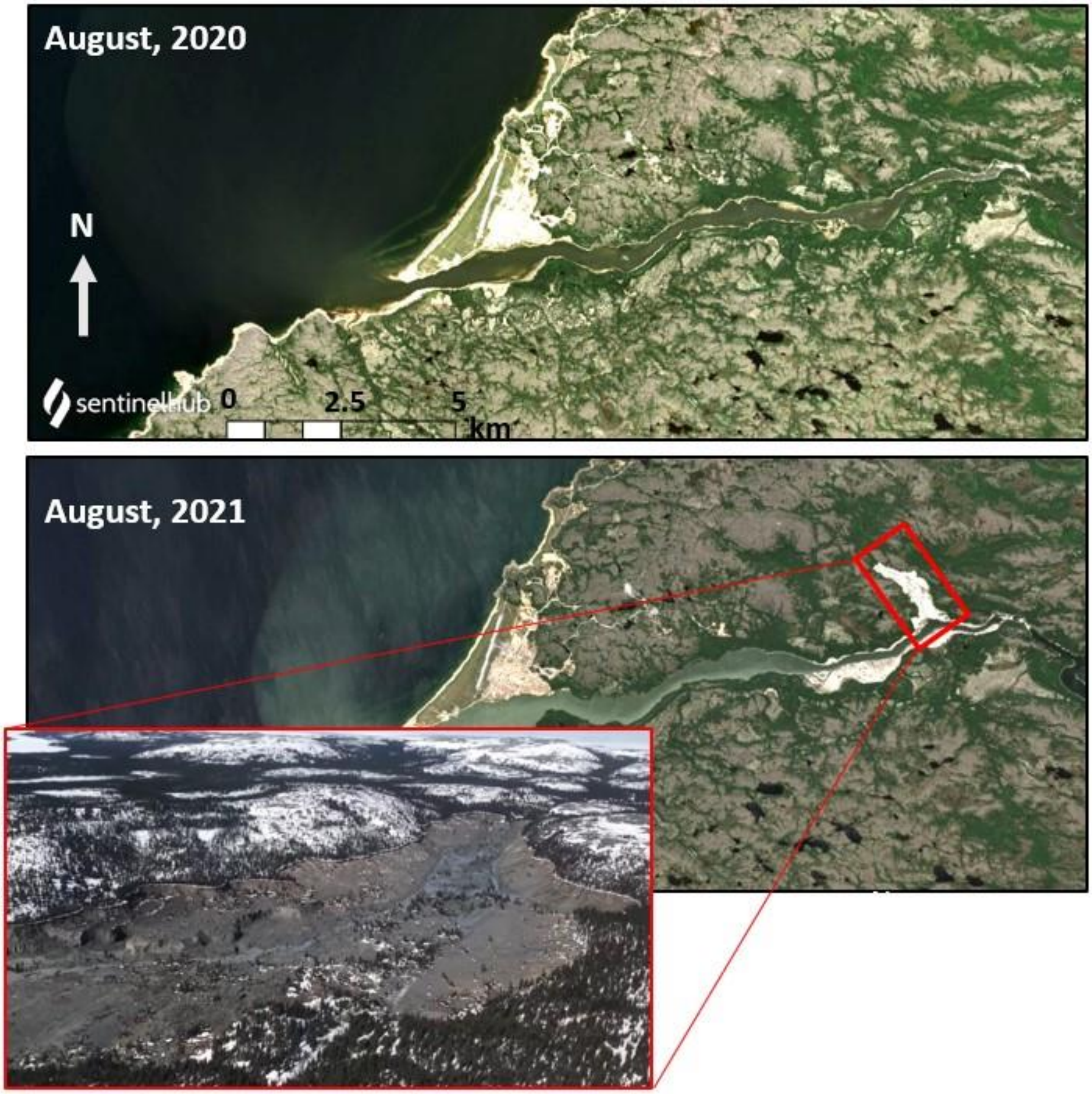

Figure 4-9 Satellite imagery showing before and after of April, 2021 landslide located 8km upstream from the mouth of Great Whale River (inset image by the Whapmagoostui First Nation, via Nunatsiaq News)

4.6.6 TIDAL FLATS – MANITOUNUK SOUND

Tidal flats within Manitounuk Sound are retreating due to coastal permafrost thawing and erosion. The tidal flats in Manitounuk Sound are marine clays derived from post-glacial Tyrrel Sea deposited when sea level was much higher than today and have emerged due to isostatic uplift. They are an erosional platform now graded to the local tidal regime (Allard et al, 1998). Based on inspection of satellite imagery and observations from coastal video (Michaud and Frobel, 1994), narrow tidal flats are present just north of the study area, located in embayments between low and narrow promontories, and becoming progressively wider (up to 1km wide) toward the head of sound.

Landfast ice forms over tidal flats and freezes down into the seabed and incorporates up to 3 m of sediment (Allard et al., 1998). Volumes measured along mudflats in April, 1993, indicate average 28% sediment composition within the ice per unit volume at the ice base (Zevenhuizen, 1994). The combined effects of sediment incorporation into the sea ice and subsequent meltout alters geotechnical properties by reducing cohesion of the sediments making them more susceptible to erosion (Zevenhuizen, 1994, Allard et al., 1998).

4.7 SEDIMENT BUDGET

4.7.1 GREAT WHALE RIVER

A study by Hulse and Bentley (2012) evaluated sediment load in Great Whale River and used marine sediment core samples to estimate sediment accumulation rates. Average sediment accumulation rates measured from 8 marine core samples were used to estimate total accumulation in a nearshore basin, a 25 km^2 area bound by an offshore northeast trending seafloor ridge, that aligns with Manitounuk Islands. The total accumulations were then compared with an estimate of sediment input from Great Whale River. Findings describe sediment load from Great Whale River, marine accumulation rates, and distribution:

- A sediment load study by Hydro-Quebec (1993) measured a fluvial sediment load of 176,000 t/yr from Great Whale River.
- Sediment accumulation rates from core samples measured between 0.09 and 0.26 cm/yr (Figure 4-10). Based on the average of these accumulation rates and evaluated over the 25 km^2 proximal basin, a calculation of 40,000 t/yr of sediment load is deposited within the 25 km^2 proximal basin. This accounts for 23% of deposition of sediment input from the Great Whale River. The remaining sedimentation bypasses the proximal basin.
- Freshwater plume dynamics are discussed to explain deposition of the other 77% of sediment input from Great Whale River. Ingram (1981) describes the freshwater plume covering an area ~100 km^2 and extends ~8 km offshore. Below the freshwater plume the currents are shore parallel towards the northeast. Therefore, it is likely that most of the sediment plume is deposited within the 100 km^2 plume area, with some also deposited along the coast.

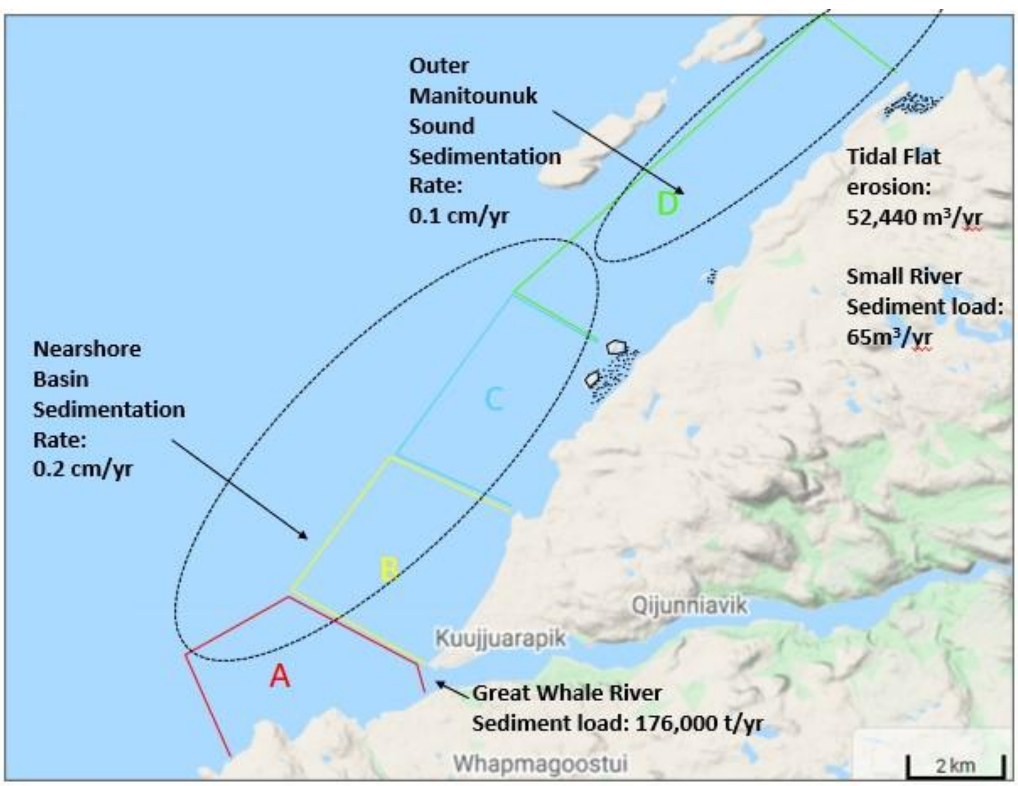

Figure 4-10 Seafloor sedimentation accumulation rates and sediment budget for the Study area.

4.7.2 MANITOUNUK SOUND

Most information on sediment budget for Manitounuk Sound comes from Zevenhuizen (1994) and is summarized as follows:

- Tidal flats are eroding due to isostatic uplift and subsequent exposure to tidal currents, wave action and episodic storm surges, and reduced cohesion caused by landfast ice. Survey measurements of tidal flat elevations approximate annual erosion on the order of 1-2 cm/yr (Zevenhuizen, 1994; Allard et al., 1998). These numbers are approximate and would benefit from long term studies (Allard et al., 1998).
- Most sediment input to Manitounuk Sound comes from erosion of tidal flats located on the eastern coast of Manatounuk Sound. Based on CHS (Canadian Hydrographic Service) field sheets, total shallow subtidal and tidal flat area of Manitounuk Sound is 14.164 $x10^6m^2$, and the volume removed is 141,640 m^3/yr. Total volume of sediments into the sound from cliff erosion induced by melting of ground ice is 2880 m^3/yr. Only 370 m^3/yr of sediment comes from fluvial input.
- In the outer section of Manitounuk Sound, total shallow tidal flat area is 5.244 x 10^6 m^2, and the volume removed is 52,440 m^3/yr. 65m^3/yr of sediment comes from fluvial input.
- Landfast ice disappears principally by melting in situ. After breakup, moving ice floes are pushed by winds and carried by tidal currents, but because tidal range is about equal to floe thickness, the rafts are too large to float over the tidal flat (Allard et al., 1998). Thus, very little ice scour takes place therefore not contributing to overall sediment budget (Zevenhuizen, 1994; Allard et al., 1998).
- The mean deposition rate for the sound's inner, central and outer parts are 0.3, 0.2 and 0.1 cm/yr, based on the sediment budget and the area of Manitounuk Sound. The trend demonstrates a steady diminution in deposition rate from the head to the mouth of the sound.

This sediment budget by Zevenhuizen (1994) suggests there is little sediment received into Manitounuk Sound from outside sources, including from Great Whale River. This suggestion is based on the course of the plume indicated by Ingram (1981) to deviate offshore south of Manitounuk Sound. As a result, minimal sediment is likely received in Manitounuk Sound sourced from Great Whale River.

4.8 ENVIRONMENTAL CHANGE

The impacts of climate change are affecting the nature of change along the coast in the study area. Climate change will likely lead to increased water levels, waves, and extreme winds leading to increased rates of submersion and potentially erosion of the Whapmagoostui/Kuujjuarapik coastline.

Some of the main anticipated impacts of climate change on the coast include:

- Water levels and high/low storm surge levels

  Extreme positive storm surges could be up to 29 cm higher toward the end of the 21^{st} century based on calculations by Masse and Gallant (2016). Negative storm surges are not likely to change with respect to the recent past.

  Conversely, based on RSL projections (refer to Section 4.2), there is potential for slower rates of RSL change, which will likely result in a higher degree of reworking of unlithified shoreline. Prolonged exposure to hydrodynamic conditions will likely influence the development of both prograding and erosional features on the coast. However, this hypothesis has not yet been validated with geomorphological mapping.

— Sea ice formation/ disappearance dates

  As the climate is warming, break-up is occurring earlier and freeze-up later (Joly et al., 2010; Tivy et al., 2011). Summer sea ice concentrations are also decreasing (Tivy et al., 2011). The length of the sea ice season in Hudson Bay could be reduced by more than 6 weeks by 2041-2070 (Senneville and St-onge Drouin, 2013).

  The coast is protected by sea ice from wave action in winter. However, as the extent and duration of sea ice decreases, fetch increases, resulting in larger waves and increased wave energy reaching the coast, leading to increased erosion. Sea ice impact includes ice-scouring and ice rafting in tidal flats. Ice can move against the coast under wind stress or stress transmitted through the ice pack, scouring the seabed and driving sediment onshore.

— Ice Push

  An ice-push occurs when sheets of ice are pushed and piled onto shorelines caused by ocean currents, strong winds, or temperature changes. Once onshore, the ice pushes and scours sediments to form mounds or ridges. Thus, an ice-push event can erode sedimentary environments (ie. Beaches, tidal flats). In context of climate change, ice-push could be more intense and frequent due to longer period of mobile sea ice.

— Landslides

  Climate models indicate that extreme precipitation events will increase in the future for this region, coinciding with rapid increases in air temperature (Climate Atlas of Canada, 2019). Research by Owczarek (2020) predicts increased precipitation events will lead to increased risk of landslides. The increased sediment yield will likely cause changes in river channel architecture and an increase in sediment rates in Hudson Bay and coastline from river input.

4.9 ARCHAEOLOGY

For millennia, Indigenous Peoples have travelled, lived and settled along the shores of the Hudson Bay. In Nunavik, coastal settlements are often found in places such as rocky outcrops, emerged beaches, field blocks and on a prograding sand spits in Whapmagoostui/Kuujjuarapik. Many Indigenous archeological sites have been identified along the coast of Hudson Bay, which include tent rings, caches, hunting blinds, kayak stands, semi-subterranean houses, waste areas, and graves. Non-Indigenous sites are more recent and include notably fur trading posts and shipwrecks (Boisson and Allard, 2018). The earliest archaeological sites may reach several meters above current sea levels and lie away from present-day shores because of marine regression and isostatic rebound that took place over the millennia. Some sites may not have survived shoreline conditions, where waves and ice would have disturbed archaeological material. Other sites may lie at the surface of the ground, exposed to weathering, or may be buried by accretionary processes involved in sand dune formation. Additional archaeological mitigation would be required for any selected area. Refer to Technical Note 4 for more detailed information regarding the coastal archeology.

4.10 SUMMARY

— The shoreline in the study area is composed mainly of exposed bedrock, deltaic deposits and postglacial sediment deposits. Most of the unlithified shoreline features in the study area are progradational, such as sand spits, beaches, tombolos and deltas. Tidal flats are present in short sections of the coast to the north of the study area and are retreating due to coastal permafrost thawing and erosion. Sections of the Great Whale River valley have landslide terrain eroding by way of mass movements, often initiated by river processes and contribute to sediment yield into the study area. The main supply of sediment to the coast is from the Great Whale River. However, within Manitounuk Sound the dominant sediment supply is from erosion of tidal flats.

- Adjacent to the prospective sites, onshore is broadly classified as discontinuous scattered permafrost where less than 50% of the land surface is permafrost. For the area inland of prospective port sites C and D, the total estimated excess ice content in permafrost is greater than 10-20%. For the area inland of prospective sites A and B, the total estimated excess ice content in the permafrost is greater than 0-5%.
- The main source of sediments to beaches in Zone B and Zone C and Zone D is from Great Whale River, which is transported by longshore currents. An important concept to consider is sediment accretion in the lee of offshore breakwaters and erosion down coast. A breakwater has the potential to create a new static equilibrium, with accretion in the lee at the expense of beach erosion downcoast. Because longshore currents primarily transport sediment northeast from Great Whale River, beaches in Zone B and Zone C are most susceptible to potential changes in equilibrium. Pocket beaches in Zone A are small, and likely fed by small streams and would likely not be as vulnerable to changes in longshore sediment transport. Zone D has the advantage that there are fewer sandy beaches than in Zone B or Zone C.

5 PREFERRED ZONE FOR PORT

5.1 OBJECTIVES

The work was aimed at identifying the pros and cons of a port located in Zones A, B, C or D. Because the important considerations vary significantly between the two general port options (i.e., a seasonal SCH versus a deep-water port), evaluations are provided for each port option.

It should be further noted that because the study is at the pre-feasibility stage, only general assessments are possible at present. These should be followed up with more detailed analyses as appropriate.

5.2 SMALL CRAFT HARBOUR

The key considerations for a SCH are summarized in Table 5-1.

Table 5-1 Key Considerations for a SCH

GENERAL FACTORS		SIGNIFICANCE
Ice Conditions	Water Depth	The water depth for the SCH would be 6 m or less; so most likely, the SCH would be in the landfast ice which would generally protect it from ice actions originating offshore.
	Ice Thickness	This is not expected to be a major discriminator among the four zones, as the design ice thickness will likely not be greatly different for all four Zones.
	Ice Jamming and breakup	Zone A is located at the mouth of the Great Whale River where breakup and potential jamming can occur. Additional river ice analysis would be required if Zone A is selected.
	SCH Structures, and Ice Actions of Concern	Most likely, the SCH will have rock breakwaters along its exterior, which will affect the ice actions are significant and not significant. The most significant ice actions are expected to be: (a) the SCH's effect on ice-out; and (b) ice actions on armour stones.
Coastal Geomorphology	Topography	The gradient of shoreline topography is a consideration for development as steeper locations may require grading and bedrock blasting, making lower gradient topography more favourable.
	Bathymetry	Less than 6 m water depth is required for a SCH. The depth of nearshore bathymetry is less than 6m throughout the nearshore of either zone. However, water depth should be maximized to avoid shoal hazards and to maximize access for vessels. Thus, gradient and water depth of the nearshore is a consideration for design of SCH port structures.
	Permafrost	This is not expected to be a major discriminator for the nearshore among the four zones, as there is an absence of permafrost within 20 m of sea level. Above 20 m elevations permafrost is a consideration, but not a major discriminator as percentages of inland permafrost is similar throughout the area. Additional permafrost analysis would be required for any selected area.
	Coastline composition	The location should consider shoreline stability from the effects of an eroding / prograding shoreline.
	Sediment Transport Processes	The design of SCH should take into consideration the potential for longshore sediment transport.
	Archaeology	The port location should take into consideration the potential for archaeology sites on the coast. Additional archaeology analysis would be required for any selected area.
Wind/Waves/Currents		Impact of meteorological and hydrodynamic conditions are minimized at favorable SCH locations.
Accessibility		The distance of the local community to the port site is essential for accessibility. Also, the distance to transportation infrastructure from the port site is a consideration for reducing infrastructure costs for building new roadways.

The pros and cons for a SCH and deep-water port at Zones A, B, C or D are summarized below:

5.2.1 ZONE A

The key points for Zone A are summarized below:

ICE CONDITIONS

a. Ice regime - This is the most exposed site among the four zones. The ice cover forms latest in Zone A, and often gets removed during the winter through the action of the ice pack, followed by new ice growth. It is the latest to freeze up and the earliest to break up. A dock in Zone A would be exposed to ice incursions from offshore involving large floes over a large part of the winter.

b. Ice regime – Zone A is located at the mouth of the Great Whale River where breakup and potential jamming can occur. Additional river ice analysis would be required if Zone A is selected.

c. Ice thickness - The design ice thickness (for structures comprising the SCH) would be controlled by the thickness of ice floes brought to the site from offshore by ice incursions. On a conservative basis, the design offshore ice thickness will be the same for all zones.

d. Operating season – A SCH in Zone A would probably have the longest operating season among the four zones. However, further evaluation is required to assess this definitively, because the boats using the SCH would have no ice transiting capability. Should ice incursions bring ice from offshore to the SCH, the boats would not be able to enter or exit the SCH until the ice cleared.

e. Ice loads and ice actions on the SCH structures – Because Zone A is exposed and often, the landfast ice clears out, a SCH located there would experience the most severe ice loads and ice actions.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Most of the shoreline south of the mouth of Great Whale River is composed of bedrock, which is stable in context of erosional processes.

b. Accretionary processes – The mouth of Great Whale River in Zone A is susceptible to accretionary processes. However, it is likely that there is less sediment from Great Whale River driven southward by longshore currents than to the northeast, thus there is less potential for accretionary processes around a SCH structure in Zone A south of the river delta.

c. Topography – There is steeper topography along the coast in Zone A than any of the other zones, which may require bedrock grading for infrastructure.

d. Bathymetry - South of the Great Whale River in Zone A, the nearshore bathymetry is steeper than zones to the northeast, thus accommodates <6 m water depth for SCH.

e. Permafrost – For area of land above 20 m elevation landward of coastal Zone A, the total estimate permafrost content is greater than 0-5%, which is similar to Zone B, and lower than for Zone C and Zone D.

f. Archaeology – There is low-moderate potential for archaeology artifacts near the shoreline considering predominant bedrock shoreline exposure, however further investigation is necessary.

WIND/WAVES/CURRENT

a. Exposure – Lack of shelter from seasonally dominant westerly wind present during ice-free conditions indicates greater wind/wave exposure in Zone A, B and C than in Zone D.

ACCESSIBILITY

a. There is presently poor accessibility as no roads exist near the shoreline south of Great Whale River.

5.2.2 ZONE B

The key points for Zone B are summarized below:

ICE CONDITIONS

a. Ice regime - The ice exposure for Zone B is intermediate, between Zone A (which is the most exposed) and Zone D (which is the most protected). Zone B freezes up later than Zone D, but earlier than Zone A. The ice tends to break up later in Zone B than in Zone A. In contrast to Zone D, ice breakup occurs by ice being transported away from the area (probably by winds and currents) rather than by thermal decay and melting, as occurs in Zone D. A dock in Zone B would be exposed to ice incursions involving large floes during the break-up part of the ice cycle.

b. Ice regime – No ice jamming is anticipated in Zone B.

c. Ice thickness - The design offshore ice thickness (for structures comprising the SCH) would be controlled by the thickness of ice floes brought to the site from offshore by ice incursions. On a conservative basis, the design offshore ice thickness will be the same for all zones.

d. Operating season – A SCH in Zone B would probably have an operating season similar to that for Zone A. However, further evaluation is required to assess this definitively, because the boats using the SCH would have no ice transiting capability. Should ice incursions bring ice from offshore to the SCH, the boats would not be able to enter or exit the SCH.

e. Ice loads and ice actions on the SCH structures – Because Zone B is exposed, a SCH located there would experience severe ice loads and ice actions.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Shoreline is composed mostly of deltaic sediment and is potentially susceptible to erosional processes.

b. Accretionary processes – The mouth of Great Whale River in Zone B is susceptible to accretionary processes, also it is likely that most sediment from Great Whale River is driven northeast by longshore currents, thus there is significant potential for accretionary processes around a SCH structure anywhere in Zone B.

c. Topography – There is low gradient topography along the coast in Zone B, similar to Zone C and D.

d. Bathymetry - The nearshore bathymetry is most shallow in Zone B than in either of the other zones of interest with river mouth bars of less than 2 m water depth, which may be a navigational hazard for small vessels.

e. Permafrost – For areas of land above 20 m elevation landward of coastal Zone B, the total estimate permafrost content is greater than 0-5%, which is similar to Zone A, and lower than for Zone C and Zone D.

f. Archaeology –In context of geomorphological considerations, archaeological sites might exist, however further investigation is necessary. Potential archaeological artifacts may be buried near the shoreline considering accretionary processes involved in sand dune formation in the area.

WIND/WAVES/CURRENT

a. Exposure – Lack of shelter from seasonally dominant westerly wind present during ice-free conditions indicates greater wind/wave exposure in Zone A, B and C than in Zone D.

ACCESSIBILITY

a. Transportation infrastructure exists in the adjacent community of Whapmagoostui/Kuujjuarapik; there is good accessibility for the community of Whapmagoostui/Kuujjuarapik.

5.2.3 ZONE C

The key points for Zone C are summarized below:

ICE CONDITIONS

A key point is that the ice regime depends on the exact location of the SCH within Zone C. During freeze-up, an ice edge tends to form, running roughly diagonally N-S through Zone C. Sheet ice tended to form to the east of the ice edge, whereas the ice conditions to the west of it were more dynamic. Comparisons are made below:

a. Ice regime – A SCH east of the ice edge would experience an ice regime similar to that of Zone D. Conversely, a SCH to the west of the ice edge would experience an ice regime similar to that for Zone B.

b. Ice regime – No ice jamming is anticipated in Zone C.

c. Ice thickness – A SCH east of the ice edge would have a landfast ice thickness similar to that for Zone D. Conversely, a SCH to the west of the ice edge would have a landfast ice thickness similar to that for Zone B. On a conservative basis, the design offshore ice thickness will be the same for all zones.

d. Operating season – A SCH east of the ice edge would have an operating season similar to that for Zone D. Conversely, a SCH to the west of the ice edge would have an operating season similar to that for Zone B.

e. Ice loads and ice actions on the SCH structures – A SCH east of the ice edge would be similar to Zone D. Conversely, a SCH to the west of the ice edge would be similar to Zone B.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Most of the shoreline of Zone C is composed of bedrock and pocket beaches. The bedrock shoreline is stable in context of erosional processes, whereas beaches may potentially be susceptible to erosional processes.

b. Accretionary processes – It is likely that most sediment from Great Whale River is driven northeast by longshore currents, thus there is significant potential for accretionary processes around a deep-water port structure in Zone C.

c. Topography – There is low gradient topography along the coast in Zone C, similar to Zone B and Zone D.

d. In general, the nearshore bathymetry is shallow in Zone C, with a margin of about 0.5 km to the 20 m bathymetry contour. However, in the northeast portion of the zone C (on the border of Zone D), Maver Islands, a low-lying bedrock outcrop connected to the mainland by a tidal flat, has a higher gradient nearshore bathymetry.

e. Permafrost – For areas of land above 20 m elevation landward of coastal Zone C the total estimate permafrost content is greater than 10-20%, which is similar to Zone D, and lower than for Zone A and Zone B.

f. Archaeology – In context of geomorphological considerations, there is potential for undisturbed archaeology sites to exist in the area, however further investigation is necessary. Potential archaeological sites may be buried near the shoreline considering accretionary processes involved in sand dunes formation in the area.

WIND/WAVES/CURRENT

a. Exposure – Lack of shelter from seasonally dominant westerly wind present during ice-free conditions indicates greater wind/wave exposure in Zone A, B and C than in Zone D.

ACCESSIBILITY

a. Transportation infrastructure exists near the shoreline. Based on aerial imagery there is a roadway within 0.3 km to 0.7 km of the shoreline in Zone C. The community of Whapmagoostui/Kuujjuarapik is within 2 km to 6 km of any site location in Zone C.

5.2.4 ZONE D

The key points for Zone D are summarized below:

ICE CONDITIONS

a. Ice regime - This is the most protected zone. Ice forms earliest in Zone D and persists latest. Ice breakup occurs thermally, as the ice mainly melts in place. Zone D is not exposed to incursions of ice floes from offshore.

b. Ice regime – No ice jamming is anticipated in Zone D.

c. Ice thickness - The landfast ice thickness would be controlled by thermal growth over the full winter, so among the four zones, it is in Zone D that it would reach the greatest thickness .

d. Operating season – A SCH in Zone D would have the shortest operating season, due to: (i) early freeze-up, and; (ii) the likelihood that ice breakup would mainly occur through ice melting.

e. Ice loads and ice actions on the SCH structures – Because Zone D is protected, the ice loads and ice actions would be least severe on a SCH located there.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Most of the shoreline of Zone D is composed of bedrock and with smaller pocket beaches in the southwest portion of Zone D. The bedrock shoreline is stable in context of erosional processes, whereas beaches may potentially be susceptible to erosional processes.

b. Accretionary processes – It is likely that most sediment from Great Whale River is driven northeast by longshore currents, though less than in Zone A or Zone B because of the sheltered conditions from dominant westerly wind conditions during ice-free conditions.

c. Topography – There is low gradient topography within the coastal zone in Zone D, similar to Zone B and Zone C.

d. Bathymetry - The nearshore bathymetry has a higher gradients in Zone D than in Zone B or Zone C, with a margin of about 0.1 - 0.2 km to the 20 m bathymetry contour.

e. Permafrost – For areas of land above 20 m elevation landward of coastal Zone D the total estimate permafrost content is greater than 10-20%, which is similar to Zone C, and lower than for Zone A and Zone B.

f. Archaeology –In context of geomorphological considerations, there is potential for undisturbed archaeology sites to exist in the area, however further investigation is necessary. Potential archaeological sites may be buried near the shoreline considering accretionary processes involved in sand dunes formation in the area.

WIND/WAVES/CURRENTS

a. Exposure – Zone D is most sheltered from seasonally dominant westerly wind present during ice-free conditions, which indicates less wind/wave exposure in Zone D than in either of the other zones of interest.

ACCESSIBILITY

a. Transportation infrastructure exists near the shoreline. Based on aerial imagery there is a roadway within 0.3 km to 1.0 km of the shoreline in Zone D. The community of Whapmagoostui/Kuujjuarapik is within 6 km to 14 km of any site location in Zone D.

5.3 DEEP-WATER PORT

The key considerations for a deep-water port are summarized in Table 5-2.

Table 5-2 Key considerations for a deep-water port

GENERAL FACTOR		SIGNIFICANCE
Ice Conditions	Water Depth and Ice Regime	The water depth for the deep-water port would be 18 m or more; As a result, the port would be exposed to ice features and ice actions originating offshore. – Note that the significance of the ice regime varies with the type of port and the type of ships calling at the port. For a year-round port, ships calling at the port would have to be able to transit the ice year-round. In this case, ship transits at the port would break up the ice cover, likely causing more dynamic ice conditions depending on the frequency of transits. – For a seasonal port, ship transits would be limited to the open water season, or perhaps the "shoulder" season at freeze-up as well. In this case, the ice cover would form naturally for the most part.
	Ice Thickness	This is not expected to be a major discriminator among the four zones, as the design ice thickness will likely not be greatly different for all four zones.
	Ice Jamming and breakup	Zone A is located at the mouth of the Great Whale River where breakup and potential jamming can occur. Additional river ice analysis would be required if Zone A is selected.
	Port Structures and Ice Actions of Concern	– Only general comments can be made because the port parameters are not yet specified (deep-water, type of operation – seasonal vs year-round, etc.). The port structures affect which ice actions are significant and not significant. – The most significant ice actions for the port structures are expected to be: (a) the ice loads and actions on the port structures; and (b) ice ride-up and encroachment onto the deck, which might threaten facilities such as a ship loader.
Coastal Geomorphology	Topography	The gradient of shoreline topography is a consideration for development as steeper locations may require grading and bedrock blasting.
	Bathymetry	The distance from shoreline to the 18 m water depth required for deep-water port should be minimized. Thus, the gradient and depth of nearshore bathymetry is a consideration for design of port structures.
	Permafost	This is not expected to be a major discriminator for the nearshore among the four zones, as there is an absence of permafrost within 20 m of sea level. Above 20 m elevations permafrost is a consideration, but not a major discriminator as percentages of inland permafrost are similar throughout the area. Additional permafrost analysis would be required for any selected area.
	Coastline composition	The port location should consider shoreline stability from the effects of an eroding/ prograding shoreline.
	Sediment Transport Processes	The design of the deep-water port should take into consideration the potential for longshore sediment transport.
	Archaeology	The port location should take into consideration the potential for archaeology sites on the coast. Additional archaeology analysis would be required for any selected area.
Wind/Waves/Currents		Impact of meteorological and hydrodynamic conditions are minimized at favorable deep-water port locations.
Accessibility		The distance of the local community to the port site is essential for accessibility. Also, the distance to transportation infrastructure from the port site is a consideration for reducing infrastructure costs for building new roadways.

5.3.1 ZONE A

The key points for Zone A are summarized below.

ICE CONDITIONS

a. Ice regime – This is the most exposed site among the four zones, which affects the natural ice regime as discussed previously. However, this may or may not be significant depending on the type of port (year-round vs seasonal) and of course, the type of ships calling at the port.

b. Ice regime – Zone A is located at the mouth of the Great Whale River where breakup and potential jamming can occur. Additional river ice analysis would be required if Zone A is selected.

c. Ice thickness – The design offshore ice thickness (for structures comprising the port) would be controlled by the thickness of ice floes brought to the site from offshore by ice incursions. On a conservative basis, the design offshore ice thickness will be the same for all zones.

d. Operating season – This depends on the type of port (year-round vs seasonal). For a year-round port, ships calling at the port would have to be capable of transiting all ice conditions so the operating season would be unaffected. A seasonal port in Zone A would probably have the longest operating season among the four zones. However, further evaluation is required to assess this definitively, as it might be affected by ice incursions from offshore.

e. Ice loads and ice actions on the port structures – Because Zone A is exposed and often, the landfast ice clears out, a port located there would experience the most severe ice loads and ice actions.

f. Icebreaker support – The icebreaker requirements are governed much more by the port's operating season (i.e., open-water only vs open water with an extension into freeze-up vs year-round) than by the geographic location of the port (i.e., Zone A vs B vs C vs D). Consequently, many of the points made below regarding the icebreaker requirements for Zone A apply to the other zones as well.

g. Zone A is the most exposed site so it is likely to be affected by ice incursions, which might require icebreaker support to re-open the port. Because the site is exposed, extensive icebreaker support would likely not be needed to open the port (say at breakup), or at freeze-up.

h. The requirement for tactical icebreaker support at a port in Zone A will depend on the port's operating season as summarized below:

- Port limited to open-water – The port would have minimal need for icebreaker support. It is expected that should a need for ice management arise (say due to an ice incursion), the port could probably operate by calling upon the CCG for icebreaker assistance.
- Port limited to open-water and the shoulder season at freeze-up – This type of port would have a requirement for "light-duty" icebreaker support, as the port's operating schedule would probably lead to vessels calling at the port in ice thicknesses up to about 0.3 m-0.5 m, depending on the port's schedules.
- Port with year-round operation – This type of port would have a requirement for major icebreaker support over the whole winter, as the port's operating schedule would probably lead to vessels calling at the port in ice thicknesses up to the maximum for the winter.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Most of the shoreline south of the Great Whale River delta is composed of bedrock, which is stable in context of erosional processes.

b. Accretionary processes – The mouth of Great Whale River in Zone A is susceptible to accretionary processes. However, it is likely that there is less sediment from Great Whale River driven southward by longshore currents than to the northeast, thus there is less potential for accretionary processes around a deep-water port structure in Zone A south of the river delta.

c. Topography – There is steeper topography along the coast in Zone A than either of the other zones, which may require grading for infrastructure.

d. Bathymetry - South of the Great Whale River, in Zone A, the nearshore bathymetry has a steeper gradient than the zones to the northeast – nearshore margin is approximately 0.1 km to 20 m bathymetry contour based on navigational charts.

e. Permafrost – For area of land above 20 m elevation landward of coastal Zone A, the total estimate permafrost content is greater than 0-5%, which is similar to Zone B, and lower than for Zone C and Zone D.

f. Archaeology – In context of geomorphological considerations, there is potential for undisturbed archaeology sites to exist in the area, however further investigation is necessary.

WIND/WAVES/CURRENT

a. Exposure – Lack of shelter from seasonally dominant westerly wind present during ice-free conditions indicates greater wind/wave exposure in Zone A, B and C than in Zone D.

ACCESSIBILITY

a. There is presently poor accessibility as no roads exist near the shoreline south of Great Whale River.

5.3.2 ZONE B

The key points for Zone B are summarized below:

ICE CONDITIONS

a. Ice regime - The ice exposure for Zone B is intermediate, between Zone A (which is the most exposed) and Zone D (which is the most protected). However, as for Zone A (discussed above), the significance of this depends on the type of port. For a year-round port, the ice regime would be of minor significance because ships calling at the port would have to be capable of transiting all ice conditions. For a seasonal port, the ice regime would develop more-or-less naturally which would affect the parameters below.

b. Ice regime – No ice jamming is anticipated in Zone B.

c. Ice thickness - The design offshore ice thickness (for structures comprising the port) would be controlled by the thickness of ice floes brought to the site from offshore by ice incursions. On a conservative basis, the design offshore ice thickness will be the same for all zones.

d. Operating season – The operating season for a port in Zone B would depend on the port parameters (deep-water, ships calling at the port, whether the port is year-round or seasonal, etc.). These issues have been discussed previously.

e. Ice loads and ice actions on the port structures – Because Zone B is almost as exposed as Zone A, and often the landfast ice clears out, a port located there would experience severe ice loads and ice actions.

f. Icebreaker support – The same comments made above regarding icebreaker support for Zone A generally apply to Zone B as well as Zone B is also relatively exposed. Icebreaker support, if required, would mainly result from ice incursions, as opposed to being required to maintain a channel in sheet ice. The icebreaker requirements would depend on the port's operating season, as described for Zone A.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Shoreline is composed mostly of deltaic sediment and is potentially susceptible to erosional processes.

b. Accretionary processes – The mouth of Great Whale River in Zone B is susceptible to accretionary processes, also it is likely that most sediment from Great Whale River is driven northeast by longshore currents, thus there is significant potential for accretionary processes around a deep-water port structure anywhere in Zone B.

c. Topography – There is low gradient topography along the coast in Zone B, similar to Zone C and D.

d. Bathymetry - The nearshore bathymetry is most shallow in Zone B than in either of the other zones of interest with river mouth bars of less than 2 m water depth. The margin between the shoreline and the 20 m bathymetry contour based on navigational charts is up to 1 km. Zone B would require extensive seaward development for deep-water port infrastructure.

e. Permafrost – For areas of land above 20m elevation landward of Zone B the total estimate permafrost content is greater than 0-5%, which is similar to Zone A, and lower than for Zone C and Zone D.

f. Archaeology – In context of geomorphological considerations, there is potential for undisturbed archaeology sites to exist in the area, however further investigation is necessary. Potential archaeological sites may be buried near the shoreline considering accretionary processes involved in sand dunes formation in the area.

WIND/WAVES/CURRENTS

a. Exposure – Lack of shelter from seasonally dominant westerly wind present during ice-free conditions indicates greater wind/wave exposure in Zone A, B and C than in Zone D.

ACCESSIBILITY

a. Transportation infrastructure exists in the adjacent community of Whapmagoostui/Kuujjuarapik; there is good accessibility for the community of Whapmagoostui/Kuujjuarapik.

5.3.3 ZONE C

The key points for Zone C are summarized below:

ICE CONDITIONS

The key point is that the ice regime depends on the exact location of the port within Zone C. During freeze-up, an ice edge tended to form which ran more-or-less diagonally N-S through Zone C. Sheet ice tended to form to the east of the ice edge, whereas the ice conditions to the west of it were more dynamic. Comparisons are made below:

a. Ice regime – A port east of the ice edge would experience an ice regime like that for Zone D. Conversely, a port to the west of the ice edge would experience an ice regime like that for Zone B.

b. Ice regime – No ice jamming is anticipated in Zone C.

c. Ice thickness – A port east of the ice edge would have a design landfast ice thickness like that of Zone D. Conversely, a port to the west of the ice edge would have a landfast ice thickness like that for Zone B. On a conservative basis, the design offshore ice thickness will be the same for all zones.

d. Operating season – the operating season for a port in Zone C would depend on the port parameters (cargo, ships calling at the port, whether the port is year-round or seasonal, etc.). These issues have been discussed previously.

e. Ice loads and ice actions on the port structures – A port east of the ice edge would be like Zone D. Conversely, a port to the west of the ice edge would be like Zone B.

f. Icebreaker support – A mix of ice conditions occur in Zone C as described previously. West of a N-S diagonal, the area is relatively exposed, so ice incursions would likely be the event leading to a need for icebreaker support. The area east of a N-S diagonal is more protected so sheet ice would likely be the reason for icebreaker support, if needed. However, the icebreaker requirements would depend on the port's operating season in the same general way described for Zone A.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Most of the shoreline of Zone C is composed of bedrock and pocket beaches. The bedrock shoreline is stable in context of erosional processes, whereas beaches may potentially be susceptible to erosional processes.

b. Accretionary processes – It is likely that most sediment from Great Whale River is driven northeast by longshore currents, thus there is significant potential for accretionary processes around a deep-water port structure in Zone C.

c. Topography – There is low gradient topography along the coast in Zone C, similar to Zone B and Zone D. The nearshore bathymetry is shallow in Zone C, with a margin of about 0.5 km to the 20 m bathymetry contour.

d. Bathymetry - In general, the nearshore bathymetry is shallow in Zone C, with a margin of about 0.5 km to the 20 m bathymetry contour. However, in the northeast portion of the zone C (on the border of Zone D), Maver Islands, a low-lying bedrock outcrop connected to the mainland by a tidal flat, has a higher gradient nearshore bathymetry. West of Maver Islands there is a margin of about 0.1 - 0.2 km to the 20 m bathymetry contour based on navigational charts.

e. Permafrost – For areas of land above 20 m elevation landward of coastal Zone C the total estimate permafrost content is greater than 10-20%, which is similar to Zone D, and lower than for Zone A and Zone B.

f. Archaeology – In context of geomorphological considerations, there is potential for undisturbed archaeology sites to exist in the area, however further investigation is necessary. Potential archaeological sites may be buried near the shoreline considering accretionary processes involved in sand dunes formation in the area.

WIND/WAVES/CURRENTS

a. Exposure – Lack of shelter from seasonally dominant westerly wind present during ice-free conditions indicates greater wind/wave exposure in Zone A, B and C than in Zone D.

ACCESSIBILITY

a. Transportation infrastructure exists near the shoreline. Based on aerial imagery there is a roadway within 0.3 km to 0.7 km of the shoreline in Zone C. The community of Whapmagoostui/Kuujjuarapik is within 2 km to 6 km of any site location in Zone C.

5.3.4 ZONE D

The key points for Zone D are summarized below:

ICE CONDITIONS

a. Ice regime - This one is the most protected among the four zones. Ice forms earliest in Zone D and persists latest. Ice breakup occurs thermally, as the ice mainly melts in place. Zone D is not exposed to incursions of ice floes from offshore.

b. Ice regime – No ice jamming is anticipated in Zone D.

c. Ice thickness - The landfast ice thickness would be controlled by thermal growth over the full winter, so it would reach the greatest thickness in Zone D among the four zones.

d. Operating season – The operating season for a port in Zone D would depend on the port parameters (cargo, ships calling at the port, whether the port is year-round or seasonal, etc.). These issues have been discussed previously. A seasonal port in Zone D would have the shortest operating season of the four zones, due to: (i) early freeze-up, and; (ii) the likelihood that ice breakup would mainly occur through ice melting. A year-round port would be unaffected as the ships calling at the port would have to have enough ice capability to transit all ice conditions.

e. Ice loads and ice actions on the port structures – Because Zone D is protected, the ice loads and ice actions would be least severe on a port located there.

f. Icebreaker support - Zone D is sheltered, being inside the Manitounuk Channel. As a result, a port in Zone D will not experience ice incursions but it will have to deal with steady ice growth throughout the winter. Icebreaker support would be required to open up the access channel to a port in it (through the sheet ice), and to maintain it, throughout the winter. The icebreaker requirements would depend on the port's operating season, as described for Zone A.

COASTAL GEOMORPHOLOGY

a. Shoreline stability – Most of the shoreline of Zone D is composed of bedrock and with smaller pocket beaches in the southwest portion of Zone D. The bedrock shoreline is stable in context of erosional processes, whereas beaches may potentially be susceptible to erosional processes.

b. Accretionary processes – It is likely that most sediment from Great Whale River is driven northeast by longshore currents, though less than in Zone A or Zone B because of the sheltered conditions from dominant westerly wind conditions during ice-free conditions.

c. Topography – There is low gradient topography along the coast in Zone D, similar to Zone B and Zone C.

d. Bathymetry - The nearshore bathymetry has higher gradients in Zone D than in Zone B or Zone C, with a margin of about 0.1 - 0.2 km to the 20 m bathymetry contour.

e. Permafrost – For areas of land above 20 m elevation landward of Zone D, the total estimate permafrost content is greater than 10-20%, which is similar to Zone C, and lower than for Zone A and Zone B.

f. Archaeology – In context of geomorphological considerations, there is potential for undisturbed archaeology sites to exist in the area, however further investigation is necessary. Potential archaeological sites may be buried near the shoreline considering accretionary processes involved in sand dunes formation in the area.

WIND/ WAVES/ CURRENTS

a. Exposure – Zone D is most sheltered from seasonally dominant westerly wind present during ice-free conditions, which indicates less wind/wave exposure in Zone D than in either of the other zones of interest.

ACCESSIBILITY

a. Transportation infrastructure exists near the shoreline. Based on aerial imagery there is a roadway within 0.3 km to 1.0 km of the shoreline in Zone D. The community of Whapamagoostui/Kuujjuarapik is within 6 km to 14 km of any site location in Zone D.

5.4 PREFERRED LOCATION FOR SMALL CRAFT HARBOUR

To evaluate the most appropriate site for a SCH each zone was ranked based on the criteria presented in Section 5.2: i) Ice conditions, ii) Coastal Geomorphology, iii) Vicinity of required water depth to shoreline, iv) Wind, waves, currents, v) Accessibility. Each zone is ranked a scale of 1 to 4 and presented in Table 5-3. A rank of 1 is the most favorable zone for a SCH and 4 is considered least favorable. An overall score is presented, with lowest score representing the most favorable zone. The four main criteria are weighted equally in this evaluation.

Table 5-3 Ranking of each Zone for SCH.

RANKING FOR EACH ZONE OF STUDY AREA FOR SCH				
CRITERIA	ZONE A	ZONE B	ZONE C	ZONE D
Ice Conditions	4	2	2	4
Coastal Geomorphology	3	4	2	1
Vicinity of required water depth to shoreline	1	4	2(1*)	1
Wind, Waves, Currents	4	3	2	1
Accessibility	4	1	2	3
Overall Score	16	14	10 (9*)	10

**Score of 1 is only valid if Maver Islands are used as a landbridge to get to deep water.*

Based on the examination the Maver Islands in Zone C has the best overall score and is considered the most favorable location for a SCH.

5.4.1 SUMMARY OF MAIN CRITERIA

- In context of ice conditions, either Zone C or Zone B (i.e., west of the ice edge) would be the preferred location for a SCH. The disadvantages with the other zones are as follows:
  - Zone A – This is the most exposed one of the four zones, so a SCH there would be most vulnerable to offshore ice actions, which may interfere with boats trying to exit and enter the SCH. Zone A is also exposed to the Great Whale River ice dynamics.
  - Zone D and the eastern part of Zone C – These areas are the most protected of the four zones, which will cause a SCH located there to have the shortest operating season.
- In context of geomorphology the most favourable location is Zone D because the influence of longshore currents on sediment transport is likely to be less than in either Zone B or Zone C. Also, on the border between Zone C and Zone D, bedrock outcrops in the nearshore at Maver Islands act as a natural breakwater that can be used in the port design.
- For bathymetry, the vicinity to required water depth is closest in Zone D, and sufficient in Zone C. The exception in Zone C is Maver Islands, as shown in Figure 5-1, a low-lying bedrock outcrop connected to the mainland by a tidal flat. The nearshore bathymetry of Maver Island is in closer vicinity to required water depths than in other portions of Zone C.
- In context of wind, waves and currents, there is some shelter from dominant westward wind during ice free conditions in Zone D. Zone A, Zone B and Zone C are more exposed during ice-free conditions.
- Accessibility is most favourable near Whapmagoostui/Kuujjuarapik, however proximity to road access northeast of Whapmagoostui/Kuujjuarapik is favourable over Zone A, which has poor accessibility. In general, road access is further from the shoreline in Zone D than in Zone C.

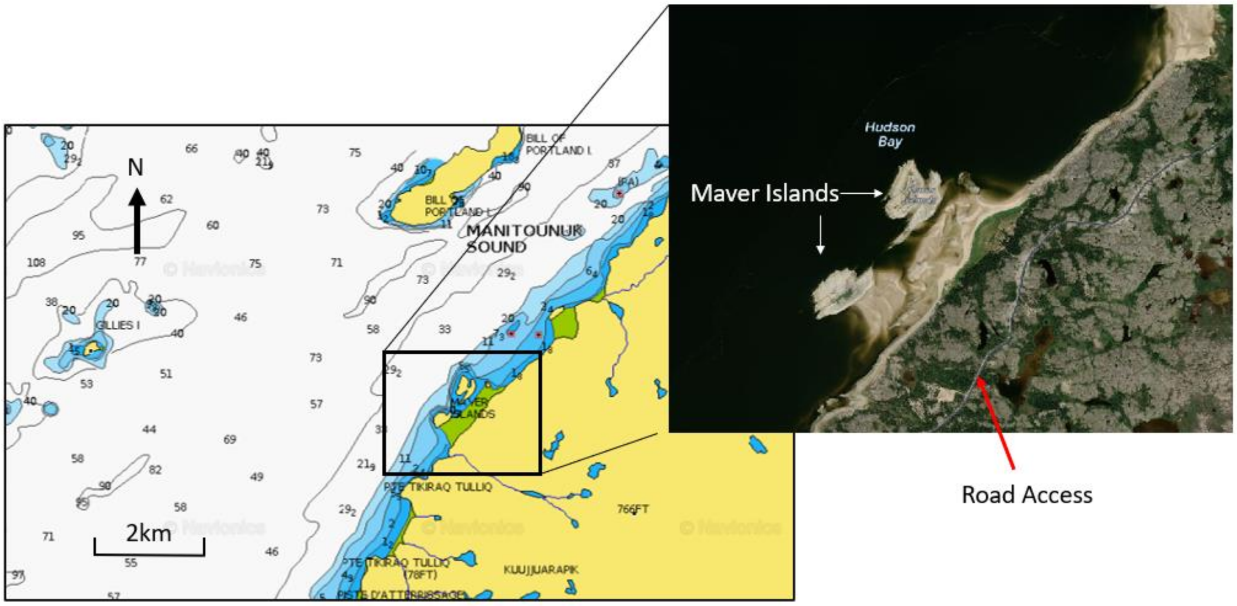

Figure 5-1 Location of Maver Islands on bathymetric chart and satellite imagery.

5.5 PREFERRED LOCATION FOR DEEP-WATER PORT

To evaluate the most appropriate site for a deep-water port, each zone was ranked based on the criteria presented in Section 5.3: i) Ice conditions, ii) Coastal Geomorphology, iii) Wind, waves, currents, iv) Accessibility. Each zone is ranked a scale of 1 to 4 and presented in Table 5-4. A rank of 1 is the most favorable zone for a deep-water port and 4 is considered least favorable. An overall score is presented, with lowest score representing the most favorable zone. The four main criteria are weighted equally in this evaluation.

Table 5-4 Ranking of each Zone for deep-water port.

RANKING FOR EACH ZONE OF STUDY AREA FOR DEEP-WATER PORT				
CRITERIA	ZONE A	ZONE B	ZONE C	ZONE D
Ice Conditions	4	2	1	3
Coastal Geomorphology	3	4	2	1
Vicinity of required water depth to shoreline	2	4	3 (1*)	1
Wind, Waves, Currents	4	3	2	1
Accessibility	4	1	2	3
Overall Score	15	10	10 (8*)	9

**Score of 1 is only valid if Maver Islands are used as a landbridge to get to deep water.*

Based on the examination the Maver Islands in Zone C has the best overall score and is considered the most favorable location for a deep-water port.

5.5.1 SUMMARY OF MAIN CRITERIA

- In context of ice conditions, Zone D should be avoided; although because it is the most protected site, the ice loads and actions on a port there (e.g., ice ride-up and encroachment) will be least severe for it. However, ice management and port operations will be probably most difficult for a port in Zone D because the ice does not clear out naturally.
  - Also, it is felt that Zone A should be avoided because this zone is most vulnerable to ice dynamics due to ice originating offshore. Pack ice incursions are most likely to interfere with port operations in Zone A.
  - Probably either Zone B or Zone C would be the preferred location for a port. These sites are somewhat sheltered from pack ice incursions, while at the same time, they are exposed enough that pack ice dynamics would help to keep the port open.
  - Navigation charts (Figure 5-2) shows that deep water is closer to shore in Zone C compared to Zone B. The 60 ft (18.3 m) is about 0.5 km away from the shoreline in zone C and 1.1 km in Zone B. This feature could be an advantage for Zone C.

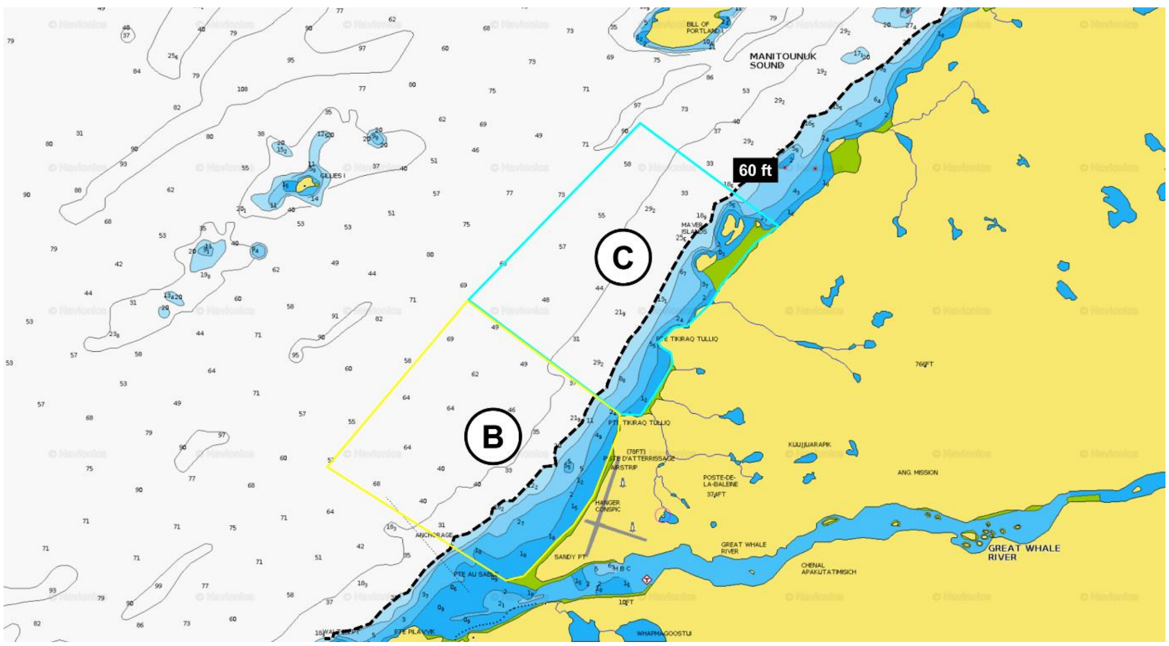

Figure 5-2 Navigation chart near Whapmagoostui/Kuujjuarapik

- In context of geomorphology the most favourable location is Zone D because the influence of longshore currents on sediment transport is likely less than in either Zone B or Zone C. Also, on the border between Zone C and Zone D, bedrock outcrops in the nearshore at Maver Islands could potentially act as a natural breakwater that can be used in the port design, and potentially as a land bridge for deeper water access.
- In context of bathymetry, the most favourable location for a deep-water port is Zone D because of the vicinity of required water depth to shore is closer than in either Zone B or Zone C. The exception in Zone C is Maver Islands, a low-lying bedrock outcrop connected to the mainland by a tidal flat, which have a higher gradient in nearshore bathymetry as shown in Figure 5-1. West of Maver Islands there is a margin of about 0.1 - 0.2 km to the 20 m bathymetry contour based on navigational charts.
- In context of wind, waves and currents, there is some shelter from dominant westward wind during ice free conditions in Zone D. Zone A, Zone B and Zone C are more exposed during ice-free conditions.
- Accessibility is most favourable near Whapmagoostui/Kuujjuarapik and to the northeast because of proximity to road access.

6 CONCLUSIONS AND ADDITIONAL CONSIDERATIONS

The preferred location for both a Small Craft Harbour and a Deep-Water Port are an area just North East of the Maver Islands (border of areas C and D) for the following reasons:

- The Islands act as a natural barrier for ice floes coming from the SW for a Small Craft Harbour, tucked in behind the islands;
- The Manitounuk Islands start to provide an important degree of shelter for waves coming from the North;
- The breakwater structure for a Small Craft Harbour will need less rock since the shape of the islands partially be used as a natural harbour;
- The breakwater for the Small Craft Harbour can be expanded in the future to a causeway for a Deep-Water Port, and bring the 18 m contour close to the shore due to a higher gradient bathymetry just off the rock outcrop;
- Sediment regime (infill) is believed to be minor, especially with extra protection of a breakwater for Small Craft Harbour;
- The ice cover on the East coast appears to form later and break earlier in comparison with the West; therefore, the proposed Small Craft Harbour is expected to experience a longer ice-free season (likely 7 months) compared to marine infrastructures located along the West coast; for example, the existing Port of Churchill (Manitoba);
- No ice jamming is expected in the north part of Zone C;
- Road access going north of the Great Whale River maybe favourable;
- Rock for quarrying (breakwater) is likely to be available in close proximity;
- Lower elevation land on the land side of the port seems available for the construction of terminal(s) on rocky soil (not on deltaic depositions);
- In context of geomorphological considerations, there is potential for undisturbed archaeology sites to exist in the area, however further investigation is necessary. Potential archaeological sites may be buried near the shoreline considering accretionary processes involved in sand dunes formation in the area;
- A few small buildings (likely community) can be seen on Google Earth in the area. Their function is not clear and further consultation is needed to verify their purpose does not interfere with the intended port use.

Further investigations, environmental, and geotechnical studies and community consultation will be required to confirm the above findings and conclusions.

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