MADRID-BOSTON PROJECT
FINAL ENVIRONMENTAL IMPACT STATEMENT

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Glossary and Abbreviations

ADCP	Acoustic Doppler Current Profiler
CTD	Oceanography instrument for measuring conductivity, temperature, depth. Conductivity is a measure of salinity.
Current velocity	By convention, the direction of a current (degrees) is given as the direction towards which the current is heading. Currents are generally represented as a magnitude and a direction. However, they are often separated in their eastern and northern components for ease of interpretation. A positive (+) eastern component corresponds to the East direction; a negative (-) eastern component corresponds to the West direction. Similarly, a positive (+) northern component corresponds to the North direction; a negative (-) eastern component corresponds to the South direction.
Density	Weight of water per unit volume (kg/m^3); calculated from temperature, salinity and pressure.
DHI	Danish Hydraulic Institute
EIS	Environmental Impact Statement
EZD	Euphotic zone depth
LSA	Local Study Area
NIRB	Nunavut Impact Review Board
NSIDC	National Snow & Ice Data Center
NTKP	Naonaiyaotit Traditional Knowledge Project
NU	Nunavut
ppt	Parts per thousand
the Project	Madrid-Boston Project
Pycnocline	Depth zone where density changes sharply; in inlets and estuaries, the pycnocline is usually mirrored by the halocline.
RSA	Regional Study Area
sp.	Species
Thermohaline	Pertaining to temperature and salinity
VEC	Valued Ecosystem Component
Wind velocity	By convention, the direction of a wind (degrees) is given as the direction from which the wind is blowing.

7. Marine Physical Processes

Marine physical processes include the ocean currents, tides, ice, waves, and storm surges that affect the chemical, geological, and biological aspects of the marine environment. Marine physical processes are considered to be Subjects of Note in this final Environmental Impact Statement (EIS) as they were not identified as potential Valued Ecosystem Components (VEC) in the EIS Guidelines (NIRB 2012) and Madrid-Boston Project (the Project) activities are not expected to affect the physical components mentioned above.

The objective of this section is to describe the physical marine processes of specific interest to the Madrid-Boston Project and its brief overlap with the Doris Project (approximately 3 years). This section provides the information requested in the EIS Guidelines (NIRB 2012) related to marine physical processes and supports other marine VEC sections such as water quality, sediment quality, marine fisheries, and marine mammals. Section 7.1 specifically addresses the Inuit Traditional Knowledge relevant to the study site and marine physical processes, while Section 7.2 presents an overview of the physical processes around Roberts Bay and builds on the high quality physical oceanographic data collected in the Roberts Bay/Melville Sound area in 2011 (Rescan 2012c; Appendix V5-7F). Section 7.3 details how the marine processes section is treated as a Subject of Note in the EIS.

7.1 INCORPORATION OF TRADITIONAL KNOWLEDGE

7.1.1 Incorporation of Traditional Knowledge for Existing Environmental and Baseline Information

The *Inuit Traditional Knowledge for TMAC Resources Inc. Proposed Hope Bay Project, Naonaiyaotit Traditional Knowledge Project (NTKP)* report (Banci and Spicker 2016) was reviewed for information related to marine physical processes.

From the NTKP report, most interviewees discussed the decline in ocean levels and river estuaries.

> *"We went back home over a week ago for about a week. We went to Arctic Sound (Katimanak) where my wife was born. We noticed that anywhere we go boating you have to be careful where you go because the water levels were so low. In the past where we used to go boating fast, and anywhere you want to go, you can't anymore because it's shallow all over the place now… There will be a lot of spots there that were very deep before won't be as deep now."*

> *"Not only rivers, everywhere is really changed. Since we know, we have been here (in Kugluktuk) now for 17, 18 years. When we travel home (Omingmaktok and Bathurst Inlet area), every area that we went through, there is about… that much missing, that water level had dropped. The water level was higher. You could see where… the lines, the lines where the water level has dropped over the years. It's only in the rivers, but the whole ocean. That's how much water has been gone since 17 years have passed."*

> *"It has changed a lot. A lot of people have noticed the water. The scientists are saying that the water will be rising due to ice melting. But what we are seeing at this stage in time we're noticing that the water levels are going down, even in the big ocean. We are home about over a week ago, for a week. There's one little island, way back when we're still living in Bay Chimo, Omingmaktok, we always used to go boating by it, in between the point and the little island. The island was about this big when it was*

> *showing, as big as this table (the boardroom table), now that island is as big as the whole building itself."*

> *"We've noticed over the years in Bathurst Inlet area it's been dry, really dry, over all those years."*

There was also a keen awareness of the changes in sea ice. Generally, the ice is regarded as thinner and has different surface characteristics.

> *"Lake and ocean ice are not the same. The lake has really brittle ice. You have to wait until its four or five inches to be really comfortable to be walking on freshwater ice. But for ocean water, it can be no more than two inches. It's denser. And it's spongy, just like a sponge. The salt content makes it just like a fibrous water, the salt content. There is no fiber in lake water."*

> *"The ice is thinner than many years ago. Both in lake and the ocean."*

> *"Both, but especially the ocean. It used to take maybe a month for the ice to go away from the area, and now it only takes two days sometimes."*

7.1.2 Incorporation of Traditional Knowledge for VEC Selection

The results of the NKTP report (Banci and Spicker 2016) were used for scoping and refining the potential VEC list for the EIS. The NTKP report presents clear maps of valued animal species, environmental components, and traditional land use activities. This information was used to determine if these valued aspects have the potential to interact with the Project, and if so, they were included in the VEC list.

There were few comments related to physical marine physical processes in the NTKP report. Those that were (Section 7.1.1) were related to changing ocean water levels and sea ice thickness which are affected by global climatic patterns. No Project-related effects to ocean circulation or other marine physical processes were identified that could affect the water levels or sea ice thickness in Roberts Bay; thus, marine physical processes were classified as a Subject of Note in this EIS.

7.2 EXISTING ENVIRONMENT AND BASELINE INFORMATION

The Hope Bay Development is comprised of existing and approved projects and the Madrid-Boston Project. All Madrid-Boston infrastructure and activities associated with the marine environment, including laydown areas, the marine port and jetty, shipping, and effluent discharge will be within or proximate to Roberts Bay (Figure 7.2-1). Thus, the presentation of existing environment and baseline information in the following section will focus largely on this bay.

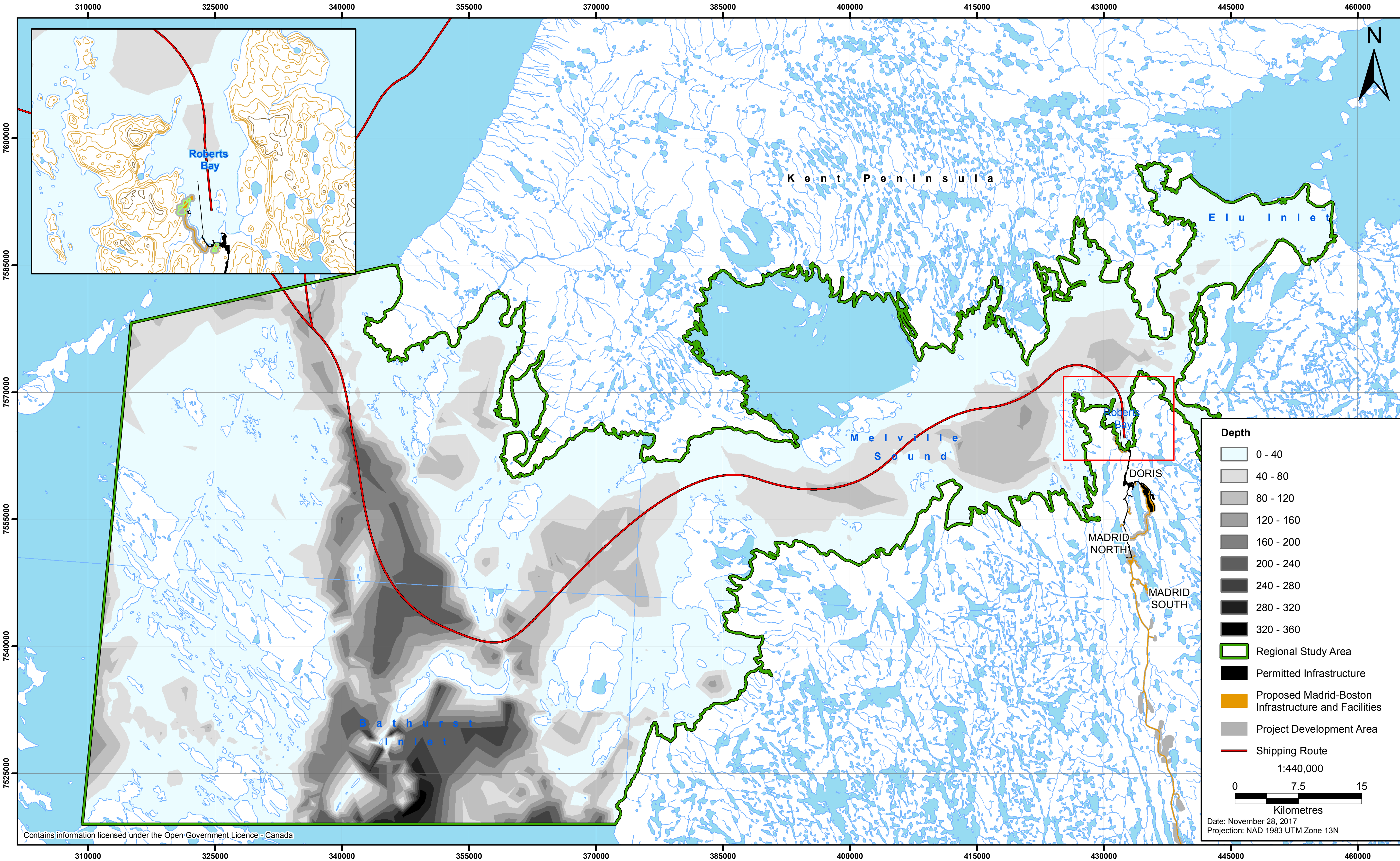
7.2.1 Roberts Bay Overview

7.2.1.1 Geographic Setting

The Project is within the Hope Bay Project development area that is located in the Kitikmeot Region of Nunavut (NU) on the southern shore of Melville Sound bounded by the Nunavut mainland (north) and the Kent Peninsula (south). The Hope Bay Project is approximately 705 km northeast of Yellowknife, Northwest Territories and 153 km southwest of Cambridge Bay, NU. The nearest settlements are Omingmaktok, 62 km to the west, and Kingaok (Bathurst Inlet), 130 km to the southwest. Other communities within the Kitikmeot Region are Gjoa Haven (approximately 447 km away), Kugaaruk (approximately 694 km away), and Taloyoak (approximately 558 km away).

Figure 7.2-1

Roberts Bay, Regional Marine Setting, and Bathymetry along Shipping Route



Infrastructure associated with the Madrid-Boston Project will be along the southern and western shorelines of Roberts Bay (68º 12' N, 106º 38' W; Figure 7.2-1), a small broad estuary bordered by Hope Bay to the west and Ida Bay to the east. Hope Bay is dotted with small islands and islets approximately 4 km west of Roberts Bay, and Ida Bay (i.e., Reference Bay) is a true fjord with a sill at its entrance and is more than 7 km east of Roberts Bay. Melville Sound is the large marine system that receives and contributes water to Roberts Bay and connects to the Bathurst Inlet.

Shipping access to the Project is via the Arctic Ocean and will terminate at a port site in southwestern Roberts Bay (Volume 3, Chapter 1). Shipping occurs along an existing shipping route through the Northwest Passage beginning in Nunavut at Lancaster Sound, and passing through Barrow Strait, Peel Sound, Victoria Strait, and the Queen Maud Gulf. Ships will travel south into northern Bathurst Inlet, and will enter Melville Sound from the west before terminating in Roberts Bay. The Bathurst Inlet to Roberts Bay shipping route and associated bathymetry is presented in Figure 7.2-1.

Roberts Bay has a maximum north-south length of 5 km and an east-west width of 4 km giving a total surface area of 14.3 km^2. The total volume of Roberts Bay is approximately 5.1×10^8 m^3 with a mean depth of 36 m. The southernmost section of the inlet is shallow (less than 20 m), and deepens to between 40 m and 90 m towards Melville Sound (Figure 7.2-2). The physiography of the surrounding area is represented by broad, sloping uplands that reach approximately 300 m in elevation in the south, and subdued undulating plains near the coast. The region’s vegetation is characterized by shrub tundra vegetation such as dwarf birch (*Betula nana*), willow (*Salix* sp.), Labrador tea (*Ledum decumbens*), avens (*Dryas* sp.), and blueberries (*Vaccinium* sp.; Volume 4, Chapter 8).

Water from Roberts Bay has free access to Melville Sound as there is no sill present in the inlet. Water exchange between the two waterbodies occurs primarily during the summer months when winds drive the upper freshwater layer towards the shoreline of Roberts Bay, and deeper waters move into Melville Sound (Rescan 2012c). The bay is typically ice covered from October to June, most of that time with land-fast ice that is about 1.5 m thick. During ice cover, the waters of the bay are isolated from wind stress and the exchange of waters between Roberts Bay and Melville Sound is minimal.

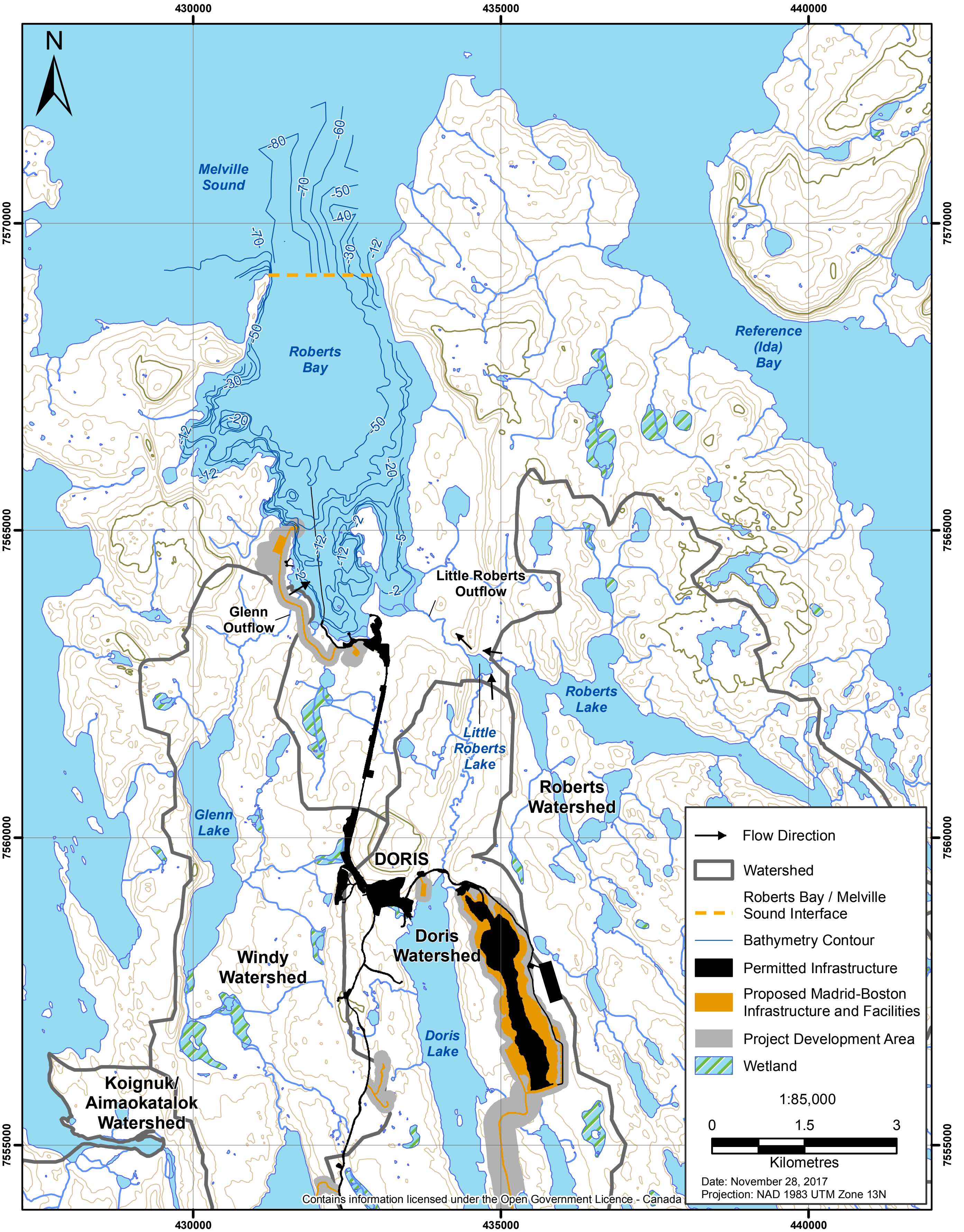
Freshwater enters Roberts Bay from Little Roberts Outflow, Glenn Outflow, and smaller tributaries (Figure 7.2-2), with Little Roberts Outflow being the primary source. These inputs contribute to vertical stratification by forming a two-layer system with less dense water overlying denser bottom water, which can reduce the vertical mixing from wind stress.

7.2.1.2 Proximity to Designated Environmental Areas

There are currently no existing or proposed parks or conservation areas near proposed Madrid-Boston Project activities. The nearest conservation area is the Queen Maud Gulf Migratory Bird Sanctuary, approximately 50 km east of Roberts Bay by air and over 300 km by water (as Melville Sound is isolated from the Queen Maud Gulf by the Kent Peninsula).

The Draft Nunavut Land Use Plan (Environment Canada 2014) has designated northern Bathurst Inlet, Melville Sound, and Elu Inlet as a key bird habitat site, and thus the Madrid-Boston marine Local Study Area (LSA; Roberts Bay) and Regional Study Area (RSA; Hope Bay and Ida Bay) are contained within this area (see Volume 5, Chapter 8 for study area delineations). The Madrid-Boston Project area has also been designated as a High Mineral Potential area. The proposed Hiukitak River Cultural Area is on the eastern shore of northern Bathurst Inlet and is outside of the marine RSA, approximately 120 km northeast of Roberts Bay (by water).

Figure 7.2-2
Roberts Bay and Surrounding Freshwater Catchments



Historically, consolidated first-year ice covers Roberts Bay and its adjacent waters from October to June and measured ice thickness ranges from 1.5 to 2.0 m. Ice break-up usually occurs during the first few weeks of July, with ice floes moving in and out of the bay with the prevailing winds. Ice floes are usually removed from Roberts Bay within a week or two of initial break-up and no ice damming occurs given the broad entrance to Roberts Bay. Following the break-up and removal of ice, open waters prevail until thin new ice forms around mid-October. Figure 7.2-3 from Environment Canada (2013b) displays the average sea ice freeze-up and break-up dates within the Canadian Arctic for the past 30 years. There has been significant temporal and spatial variation in the timing of break-up and freeze-up around Melville Sound, as well as in the amount of ice present year-to-year. This can be seen in Figure 7.2-4 from Environment Canada (2013a), which shows recent ice coverage data collected between 2005 and 2013 for Barrow Strait, Franklin Strait, and the area between Queen Maud and Coronation Gulfs. The bar graphs show the percent of ice coverage expressed as a percent of the total sea area on a weekly basis compared to the 30-year average of 1981 to 2010.

Observational evidence from the last few decades indicates that sea ice in the Arctic has been thinning and retreating earlier than historical reports (Stroeve et al. 2012). Figure 7.2-4 illustrates this by showing that most ice concentration records between 2005 and 2013 have been lower than historical averages. The strongest changes have occurred in the summer for the more northern straits, with several ice-free periods recently recorded where ice used to be present year-round. In 2012, Arctic sea ice was at the lowest recorded levels since ice monitoring by satellite began three decades ago (NSIDC 2012). Arctic ice concentrations rebounded during the 2013 summer with over 60% more ice cover than the previous year, although the coverage was still much lower than historical averages (NSIDC 2013).

7.2.1.3 Winds and Riverine Discharge

Winds are typically a dominant forcing mechanism in the water circulation of open-water estuaries (Li and Li 2012), and this was observed in Roberts Bay as currents were mostly influenced by winds compared to freshwater inputs or tidal forcing (Rescan 2012c). Winds in the Project area typically blow from the west-northwest quadrant year round, with winds from the east and southeast also common especially during the summer. Average annual wind speed at the Doris meteorological station was 5.8 m/s (20.9 km/h), and gusts of up to 22.0 m/s (79.3 km/h) were recorded. The maximum wind gust recorded since compliance reporting began in 2011 was 28.9 m/s (104 km/h) in August 2013 (ERM Rescan 2014b).

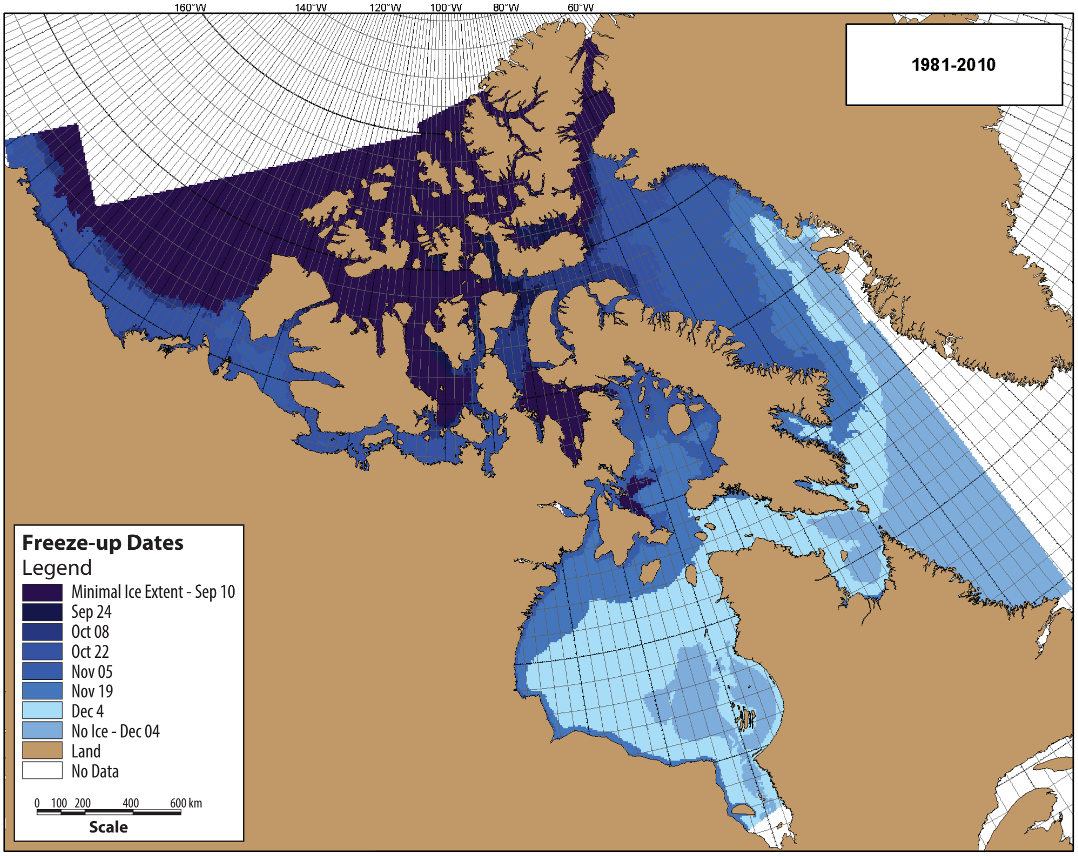
Freshwater enters Roberts Bay through two main watersheds: Windy-Glenn (48 km^2) and Doris-Roberts (194 km^2; Rescan 2011b; Appendix V5-1E; ERM Rescan 2014a; Appendix V5-1J). The two largest streams are Doris and Roberts outflows, which discharge into Little Roberts Lake before flowing into Roberts Bay via the Little Roberts Outflow. All creeks and rivers follow the same general pattern of other Arctic watersheds (Woo 1990), that is peak flows occur during the spring freshet after the ice melt and are followed by low flows in summer that are punctuated with occasional high–flow events from storms before the surface waters begin to freeze.

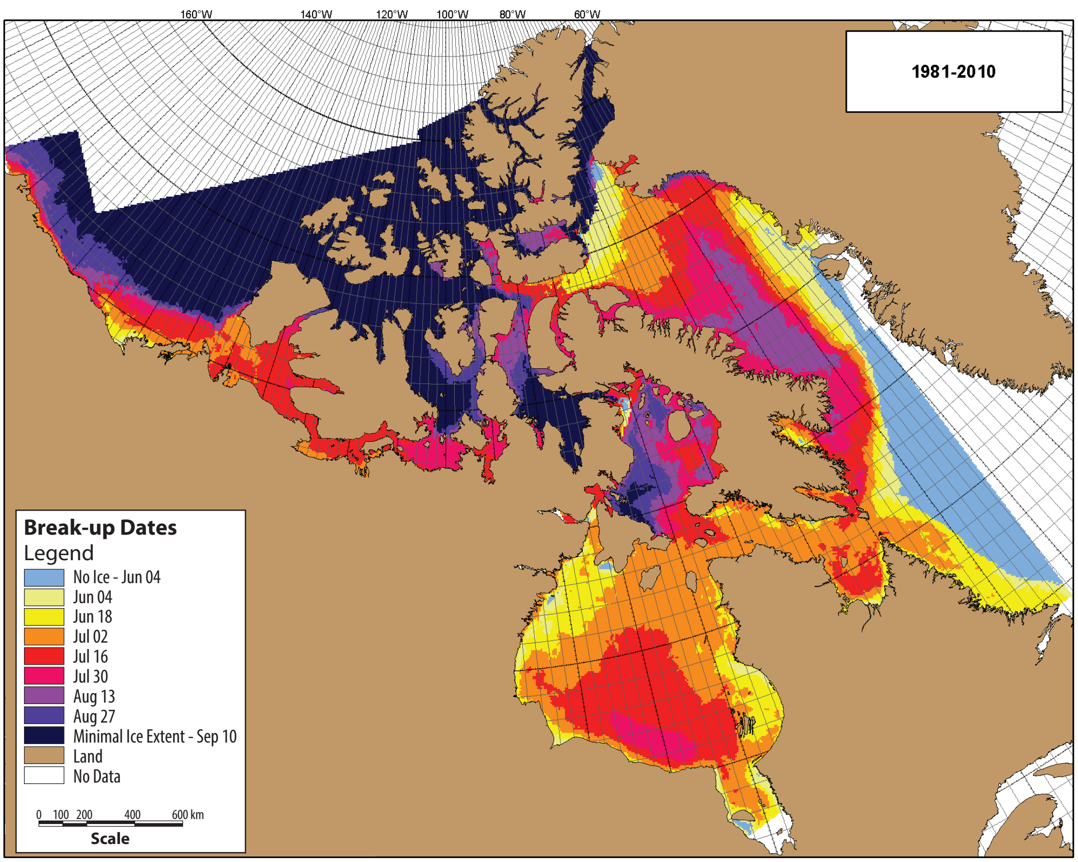
7.2.2 Data Sources

Baseline information on ocean currents and circulation, physical water column structure, water quality, sediment quality, and biological communities (phytoplankton, zooplankton, benthic invertebrates, fish, seabirds, and marine mammals) have been collected in Roberts Bay since 1996. Comprehensive, basin-scale sampling has been carried out in Roberts Bay since 2009. Additional baseline data have been collected sporadically in Hope Bay since 1997 and consistently in Ida Bay since 2009. Marine surveys were conducted within Melville Sound and the southern portion of the Coronation Gulf in 2010 to understand the regional marine environment far outside of Roberts Bay.

Figure 7.2-3

Average Canadian Arctic Ice Freeze-up and Break-up Dates, 1981 to 2010

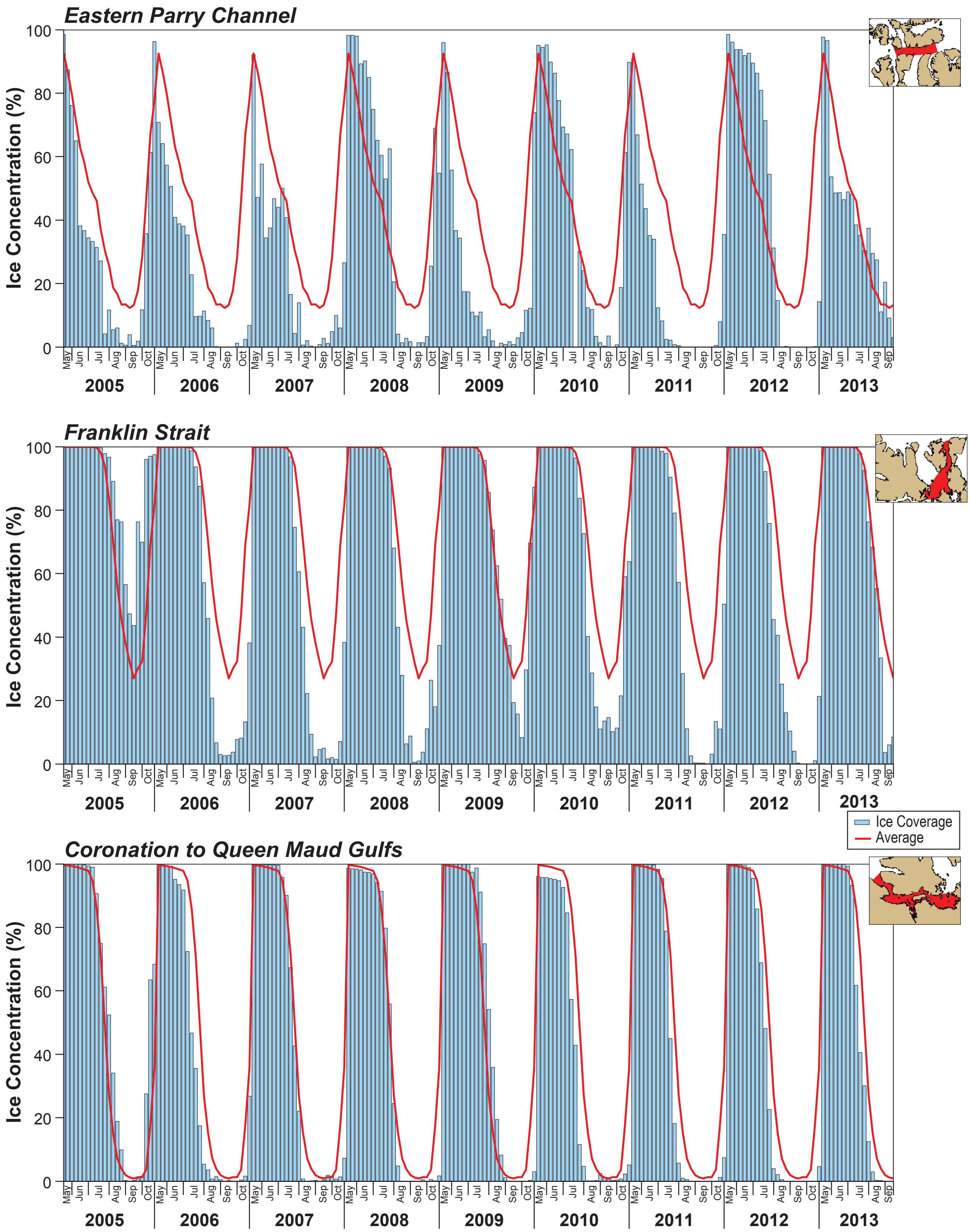




Source: Environment Canada (2013b).

Figure 7.2-4

Historical Weekly Ice Coverage in Selected Canadian Arctic Marine Waters, 2005 to 2013



Note: Red line indicates 1981 to 2011 average
Source: Environment Canada (2013a).

The data presented in the following sections are mainly from 2009, 2010, 2011, and 2016 because of the intensive spatiotemporal sampling that was conducted in Roberts Bay during these years. Sources of baseline physical oceanographic information include the following reports:

- Hope Bay Belt Project: 2009 Marine Baseline Report (Rescan 2010; Appendix V5-7A);
- Hope Bay Belt Project: 2010 Marine Baseline Report (Rescan 2011c; Appendix V5-7B);
- Hope Bay Belt Project: 2010 Regional Marine Baseline Report (Rescan 2011d; Appendix V5-7C);
- Doris North Gold Mine Project: 2011 Aquatics Effects Monitoring Program (AEMP) Marine Expansion Baseline Report (Rescan 2011a; Appendix V5-7D);
- Doris North Gold Mine Project: 2011 Aquatic Effects Monitoring Program Report (Rescan 2012a);
- Doris North Gold Mine Project: 2011 Numerical Simulation of Roberts Bay Circulation (Rescan 2012b; Appendix V5-7E);
- Doris North Gold Mine Project: 2011 Roberts Bay Physical Oceanography Baseline Report (Rescan 2012c; Appendix V5-7F); and
- Doris Project: 2016 to 2018 Roberts Bay Marine Baseline Report (ERM in preparation).

7.2.3 Methods

7.2.3.1 Water Column Structure

Water column structure within Arctic estuaries such as Roberts Bay is defined principally by vertical stratification, which is driven by the freezing and melting process of surface ice (Rudels, Larsson, and Sehlstedt 1991) and is directly related to flow patterns and the strength of mixing. Stratification precludes mixing of nutrients throughout the water column which contributes to the low summer primary productivity observed in the region (Rescan 2010, 2011c, 2011d). The physical characteristics involved in assessing water column structure include vertical profiles of water temperature and salinity, which allow profiles of density and stratification to be calculated.

Discrete temperature and salinity profiles have been collected at several locations in Roberts Bay during the ice-covered winter and ice-free summer seasons (Rescan 2010, 2011c, 2011a, 2011d, 2012c). All vertical profiles were taken using an internally-logging *in situ* conductivity-temperature-depth (CTD) probe. The units were deployed either through an augured ice hole in winter or lowered over the side of a boat in summer, and were lowered at roughly 0.5 m/s. Sampling stations varied from year to year according to the various work plans, and a map of locations sampled between 2009 and 2016 is shown in Figure 7.2-5.

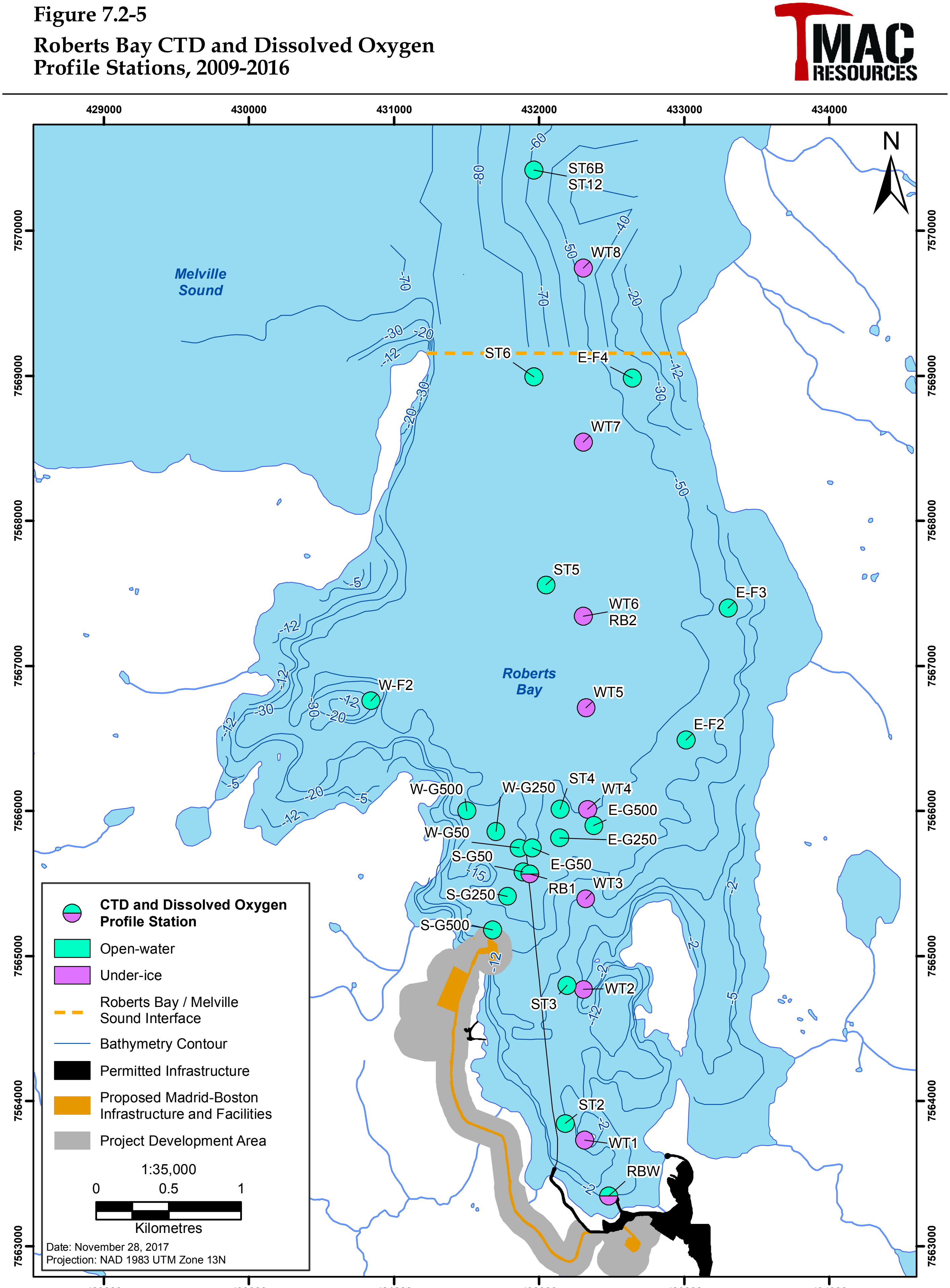
7.2.3.2 Water Level and Tides

Water level changes in marine waters come from a combination of tidal (i.e., caused by the gravitational pull of the moon and sun) and non-tidal (i.e., precipitation, river discharges, drought, etc.) inputs. To accurately assess those inputs in Roberts Bay, a tidal gauge station was installed and operated along the southern shore of during the open-water season from 2009 to 2014.

The station consisted of a Levelogger M-10 (Solinst Canada Ltd.) pressure transducer/data logger combination. The Levelogger was attached to a floating marker and anchored to the ocean bottom. The unit recorded water levels every 10 minutes. A Barologger (Solinst Canada Ltd.) was installed on shore and recorded atmospheric pressure to correct the Levelogger absolute pressure readings. The elevation of the tide gauge at Roberts Bay (relative to a geodetic benchmark) was determined using a local station surveying instrument (Appendix V5-1E).

Figure 7.2-5

Roberts Bay CTD and Dissolved Oxygen Profile Stations, 2009-2016



7.2.3.3 Light Attenuation and Euphotic Zone

The transmission of light in seawater is essential to phytoplankton productivity, and thus influences the dissolved oxygen levels within the water column. Light attenuation primarily occurs due to turbulence or turbidity from suspended particles and biological organisms. Baseline information on light attenuation has been gathered at several sites in Roberts Bay during open-water marine surveys from 2005 to 2011. Measurements of light attenuation were collected using a 30 cm, white Secchi disk that was lowered over the shaded side of a boat until it disappeared from sight. The depth of disappearance was identified as the Secchi depth (D_S). Secchi depths were used to calculate the euphotic zone depth (EZD), which is defined in this section as the depth in the water column at which 1% of surface radiation occurs. This generally represents the zone in a water column where integrated photosynthesis equals the integrated respiration (i.e., compensation depth). Above this depth net primary production is possible given sufficient nutrients. The EZD was calculated as follows:

$$k' = 1.7/D_S\ ;$$

where k' = light extinction coefficient, D_S is the Secchi depth, and 1.7 is a constant derived from experimental data (Parsons, Maita, and Lalli 1984);

$$EZD = 4.6/k'$$

7.2.3.4 Marine Currents

Marine currents are continuous, directed movements of seawater generated by a variety of forces acting on the water column. In estuaries like Roberts Bay, the important forcings include winds, breaking waves, river flow, density differences, tides, and shoreline configurations.

Ocean currents were measured at two different sites within Roberts Bay from February 10 to October 3, 2011 using a moored Acoustic Doppler Current Profiler (ADCP), including a station in the southern portion of the bay just beyond the shelf break (38 m deep), and a station at the Roberts Bay/Melville Sound border (85 m deep; see Rescan (2012c) for details). The 38 m station deployment consisted of top-ice mounted instrumentation that only measured velocities, and was operational from February 10 to April 16. The 85 m station deployment began as a similar top-ice deployment from April 21 to May 11, and to accommodate the eventual ice melting, was switched to a bottom, taut-line deployment from May 22 to October 4 (Rescan 2012c).

7.2.3.5 Marine Circulation

The Roberts Bay summer circulation and flushing rate was modeled using the Danish Hydraulic Institute (DHI) MIKE3 hydrodynamic model (DHI 2012). MIKE3 is a three-dimensional baroclinic fluid model that can simulate unsteady discretized flows while accounting for density variations, bathymetry, and external forcings such as tides, boundary currents, and meteorological inputs. The simulation methods and results are detailed in Rescan (2012b).

7.2.4 Characterization of Existing and Baseline Conditions

7.2.4.1 Water Column Structure

Water column structure was measured in Roberts Bay during the winters and summers of 2009, 2010, 2011, and 2016 (summer only). Figure 7.2-5 shows the sampling locations where these measurements were collected. Due to the inter-annual variability in wind strength and direction, climate, and freshwater inputs, natural variability in the water column structure of Roberts Bay is to be expected.

Figure 7.2-6 shows the water column temperature and salinity over a cross-section of Roberts Bay in April 2010 when the bay was ice covered. The winter water column structure in Roberts Bay consisted of two distinct layers. The upper mixed layer depth was approximately 10 m deep, with a temperature of approximately -1.5ºC and salinity that ranged from 23.9 ppt at the nearshore site WT2 to 26.5 ppt at the more seaward sites. The deeper layer was weakly stratified with an upper pycnocline transitioning down to stable bottom waters, where water temperature and salinity approached -0.5ºC and 27.3 ppt. The pycnoclines in April 2009 and April 2010 were approximately 10 m thick (Rescan 2010, 2011c); however, the pycnocline in April 2011 reached considerably deeper at 30 m (Rescan 2011a). Measurements obtained in Ida Bay in 2009, 2010, and 2011 (Rescan 2010, 2011c, 2012a) had very similar characteristics than Roberts Bay. Hence, the changes between 2009/2010 and 2011 were region-wide.

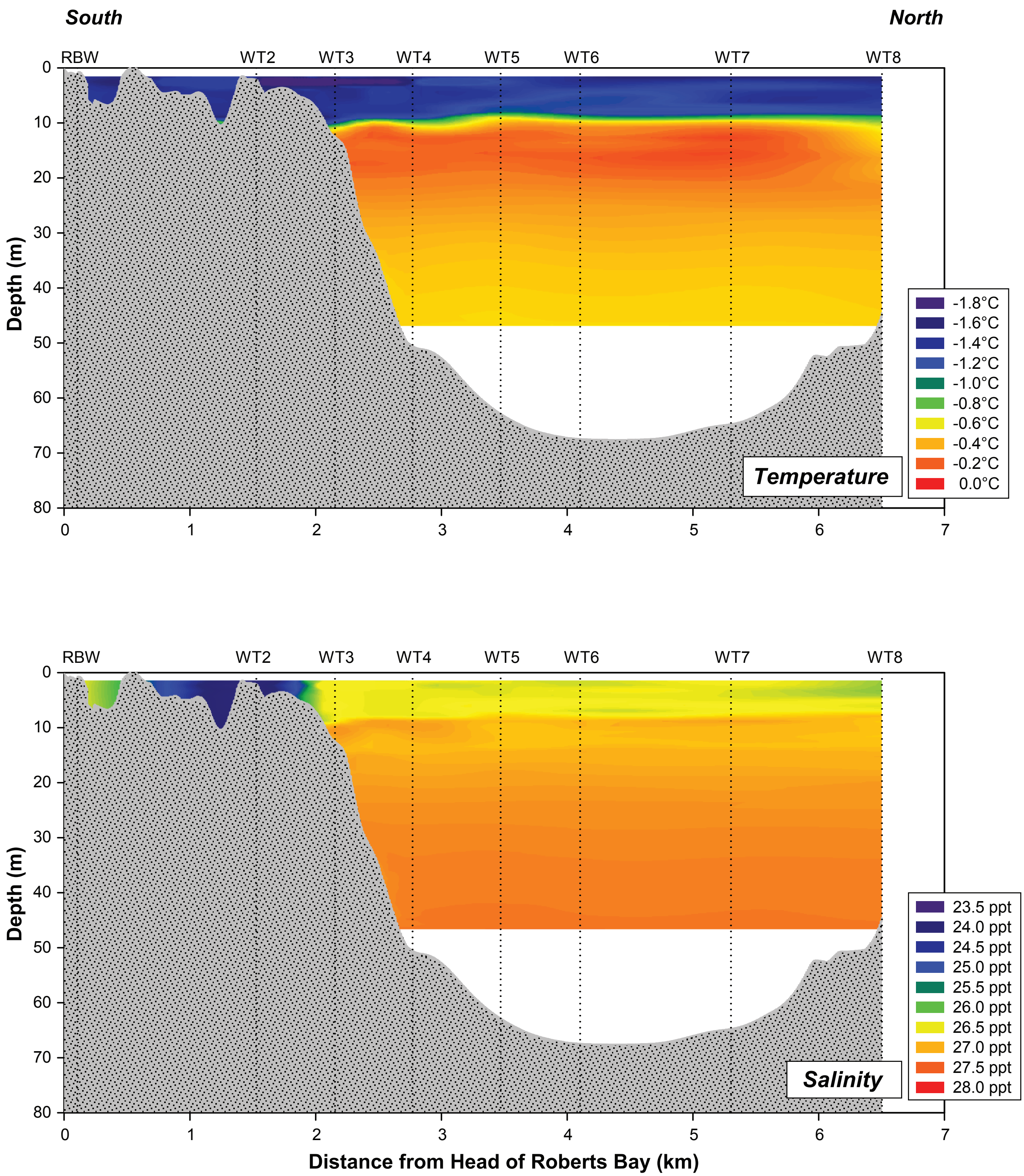
Under-ice, deep-water column profiles were also measured in nearby Hope Bay (Rescan 2010) and Melville Sound (Rescan 2011d). Overall, Hope Bay surface salinities (26.6 to 26.8 ppt) and temperatures (-1.4°C) were similar to Roberts Bay. The main difference between the two inlets was the less-defined vertical stratification in Hope Bay. Pycnocline depths in Hope Bay were near 10 m, but isohaline (constant salinity) conditions were generally not attained until 20 m below this depth. This likely resulted from the increased mixing caused by water flowing through the network of islands and raised bathymetries that are present in Hope Bay. Similarly, all sites sampled in Melville Sound had broad pycnoclines, with warmer and less saline waters in the surface, and colder, saltier water at depth. While surface waters between Roberts Bay and Melville Sound had similar characteristics, the deeper waters of Melville Sound had greater salinities (28.1 ppt) than those recorded in Roberts Bay.

Figure 7.2-7 shows a cross-section of the temperature and salinity in Roberts Bay during the open-water season (August 2010). During this time the water column was strongly stratified with a pycnocline at approximately 10 m depth. Surface temperatures ranged from 10 to 13ºC and salinities ranged from 20 to 24 ppt. At 60 m depth, temperature and salinity approached -0.7ºC and 27.4 ppt. In August 2009, the depth of the pycnocline and the deep water conditions were similar to 2010, although, the upper layer was less well-mixed and less saline in August 2009 than in August 2010 (Rescan 2010, 2011c). Data from August 2011 showed a much shallower pycnocline at around 5 m depth, with strongly stratified bottom waters that implies less wind mixing had occurred than previous years (Rescan 2011a). In 2016, the upper mixed layer depth extended to 20 m during August, with a colder than usual (6°C), saline (22 ppt) surface layer overlying the bottom layer (ERM in preparation). This suggests greater entrainment of the colder, saltier deep waters into the surface layer in 2016 due to greater wind mixing.

Temperature, salinity, and dissolved oxygen were also logged continuously near the mouth of Roberts Bay at approximately 81.5 m depth between May 22 and October 4, 2011 to study the dynamics of the bottom water masses in conjunction with the current measurements. Strong variations in temperature and salinity were recorded during the end of the ice-covered period (i.e., in the first two weeks of the deployment). These changes were coupled with an increase in dissolved oxygen concentrations as colder, oxygen-rich deep waters from Melville Sound (see example profiles in Rescan (2011d)) were advected into the Roberts Bay waters(Rescan 2012c). From July to October, the bottom waters showed a progressive increase in salinity, temperature, and density indicating that the incoming Melville Sound waters within Roberts Bay were progressively mixed with the warmer surface layer. The continuous wind mixing combined with the lack of freshwater discharges and increased evaporation during the summer months lead to a slow homogenization of the water column.

Figure 7.2-6

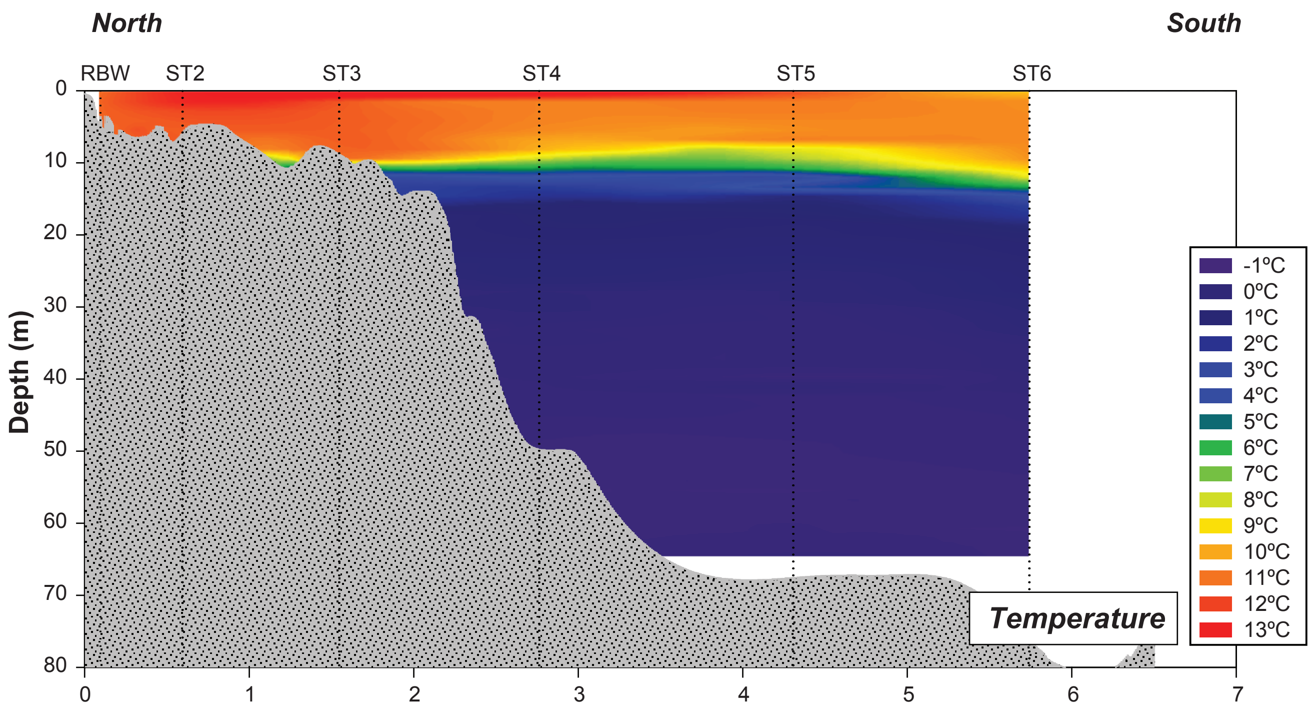
Temperature and Salinity Contours in Roberts Bay, April 2010

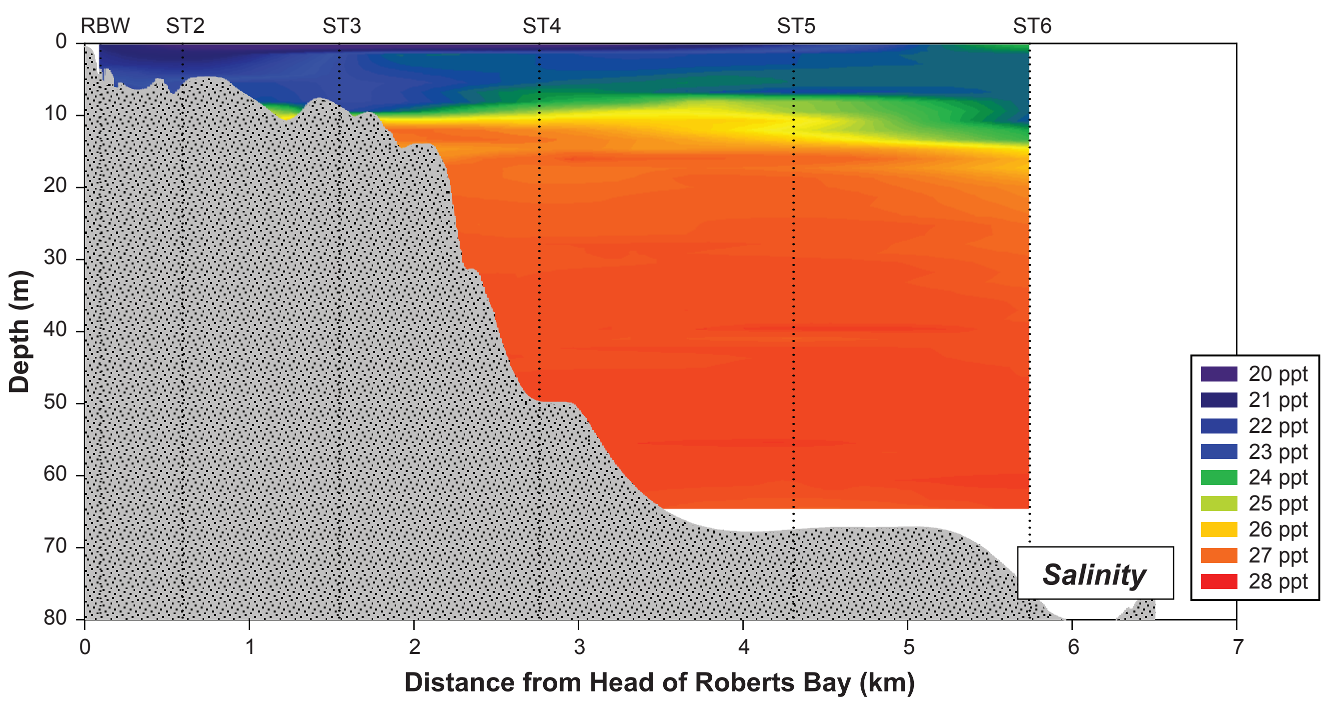


Note: Vertical exaggeration is 44:1

Figure 7.2-7

Temperature and Salinity Contours in Roberts Bay, August 2010





Note: Vertical exaggeration is 44:1

7.2.4.2 Water Level and Tides

Results from the gauge have shown that there are the two main tidal cycles in Roberts Bay: 1) the fortnightly spring-neap cycle, and 2) the daily diurnal high-low tidal cycle (Rescan 2012c). Overall, the tidal levels in Roberts Bay are small, with only minor differences between the daily tidal ranges of the spring and neap cycles; the spring tidal (new and full moon period) levels rarely exceed 0.4 m, while neap tidal levels (1st and 3rd quarter moons) are typically between 0.2 and 0.3 m. Tidal ranges at regional stations monitored by the Canadian Hydrographic Service (Cambridge Bay, Omingmaktok, Kugluktuk) are similar to those measured in Roberts Bay.

Figure 7.2-8 shows the time series of measured water levels in Roberts Bay for 2010. A tidal eliminator filter was applied to the measured levels to yield the residual, non-tidal signal, which represents water level fluctuations occurring in response to wind stress or other meteorological factors. Meteorological forcing (i.e., direct wind stress) account for changes in water level up to 0.5 m in this record, indicating that water levels in Roberts Bay are more readily influenced by winds rather than by tides.

7.2.4.3 Light Attenuation and Euphotic Zone

Secchi depths in Roberts Bay during the 2009 and 2010 sampling programs ranged from 0.3 to 15 m, and the estimated euphotic zone depth ranged from 5.7 to 40.6 m (Rescan 2010, 2011c) . The euphotic zone reached the seabed at most stations with depths less than 10 m (Table 7.2-1); therefore, benthic production (periphyton) would be possible in these shallower areas. At the deeper stations (greater than 10 m), the euphotic zone depth ranged from 16.2 to 38.7 m and was always deeper than the pycnocline in the well-mixed surface layer. Overall, water clarity was high for all sites (i.e., low light attenuation with depth) and the primary producer communities were typically suspended in optimal light regimes to support growth (pending available nutrients). Measurements in Ida Bay tended to have shallower Secchi and euphotic depths in the deep waters compared to Roberts Bay, with shallower water euphotic depths also reaching the sediment surface. A summary of the average depth characteristics for both bays is shown in Table 7.2-1.

Table 7.2-1. Summary of Secchi and Euphotic Depths in Roberts Bay and Ida Bay Sites

Waterbody	Sample Size (n)	Mean Secchi Depth*, D_S (m)	Mean Euphotic Depth*, EZD (m)	% of Sites with EZD Greater than Bottom Water Depth
Roberts Bay (LSA)				
Shallow sites (<10 m)	13	2.1	5.7	92.3
Deep sites (>10 m)	15	10.2	27.6	0
Ida Bay (RSA)				
Shallow sites (<10 m)	6	7.4	21.2	100
Deep sites (>10 m)	13	8.1	21.8	0

**Calculations included only those measurements that did not reach the sediment surface. Twelve of 13 Secchi measurements reached sediment surface in shallow region of Roberts Bay (<10 m).*

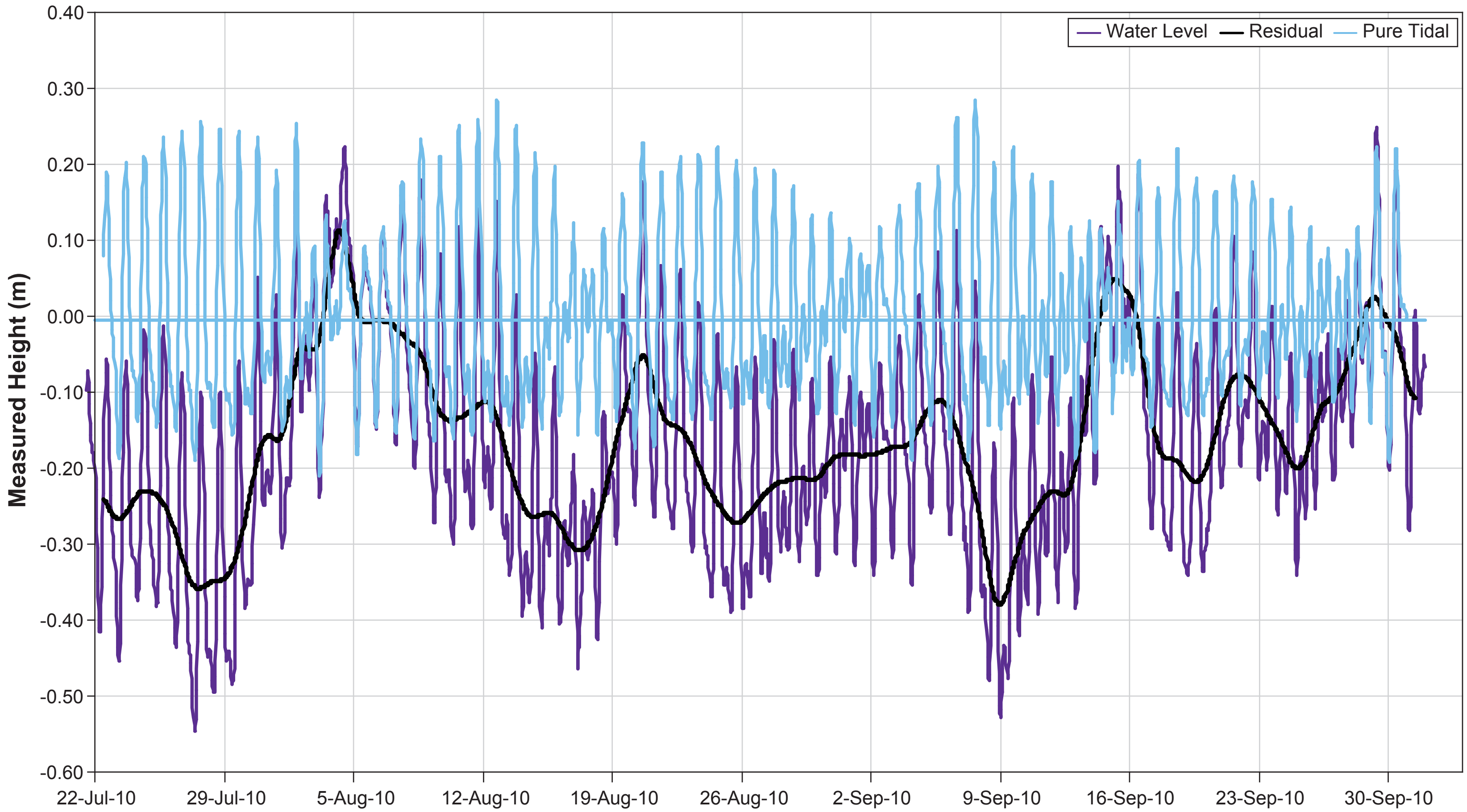
7.2.4.4 Marine Currents

Ice-covered Conditions

A 1 to 2 m thick ice layer forms in Roberts Bay during the ice-covered season and shelters the water from wind. Over time, the under-ice convection generated from the ice growth leads to the formation of a two-layer thermohaline structure with weak stratification, and a colder, fresher layer atop a warmer, more saline layer. The thickness of the top layer during ice cover varied from 10 to 30 m depending on the climactic condition at the time of sampling (Rescan 2010, 2011c, 2011a).

Figure 7.2-8

Water Level Measurements in Roberts Bay Showing Tidal and Non-tidal Oscillations



Note: The Pure Tidal component is modelled as the sum of a finite set of sinusoids at specific frequencies related to astronomical parameters. The Residual component, which refers to water height changes due to physical processes other than tides (e.g., wind waves, freshwater discharges, etc.), is obtained by subtracting the Pure Tidal component from the total Water Level.

During the 2011 current meter deployment, under-ice currents were generally very weak with mean horizontal current velocities between 1 and 2 cm/s. Tidal ebb and flow currents were found across the bay but they had very low velocities around 0.1 cm/s. Deep currents that were driven either by density gradients formed through ice formation/brine release or advection of waters from Melville Sound had generally stronger velocities. This was particularly apparent for the more southern, 38-m station near the shelf break that recorded mean currents between 4 and 5 cm/s with a maximum of 7.91 cm/s. These greater currents were likely due to the extrusion of salt generating density currents down the shelf break. A summary of the mean north velocity component and the mean and maximum current speed magnitudes observed for the 2011 winter deployments from Rescan (2012c) is shown in Table 7.2-2.

Table 7.2-2. Summary of the Mean North Velocity Component and the Mean and Maximum Current Speeds in Roberts Bay, Winter 2011

Site and Depth		Mean North Velocity Component (cm/s)*	Mean Speed (cm/s)	Maximum Speed (cm/s)
Feb 10 – Feb 22, Shelf-break site (38 m)	9 m	0.20	1.80	5.02
	21 m	0.51	1.19	4.56
	30 m	4.79	4.88	7.91
Feb 22 – Apr 16, Shelf-break site (38 m)	9 m	0.17	1.69	4.63
	21 m	0.37	0.98	4.61
	30 m	3.96	4.02	7.72
Apr 21 – May 11, Deep-water site (85 m)	12 m	0.24	1.05	3.08
	36 m	-0.21	0.99	3.64
	66 m	-0.62	1.23	4.10
	78 m	0.02	0.78	2.41

**Northern velocities are positive.*

The weak convectively driven flow and tidal currents combined to gently stir Roberts Bay during the winter ice-covered season tending to laterally homogenize the density-stratified bay. The overall circulation pattern in the surface waters indicated a sluggish clockwise flow. There were occasional larger currents recorded directly under the sea ice particularly in shallow areas where brine rejection flows were likely to occur. A schematic interpretation of the general winter circulation in Roberts Bay can be found in Figure 7.2-9.

<u>Open-water Conditions</u>

Water circulation in Roberts Bay during the summer ice-free months is dominated by wind-driven flows rather than freshwater discharge, with the direction and strength of flow depending on the prevailing wind conditions. Mean horizontal current velocities in the deep layer ranged from 1 to 5 cm/s, but had recorded maximums near 30 cm/s during periods of large flow. Similarly, horizontal currents in the upper water column had mean velocities between 1 and 6 cm/s, with maximum values of over 30 cm/s sometimes recorded above 10 m depth. A summary of the mean north velocity component and the mean and maximum current speed magnitudes observed for each summer deployment is shown in Table 7.2-3.

Figure 7.2-9

Example of Roberts Bay Circulation during the 2011 Winter: Vertical Side View

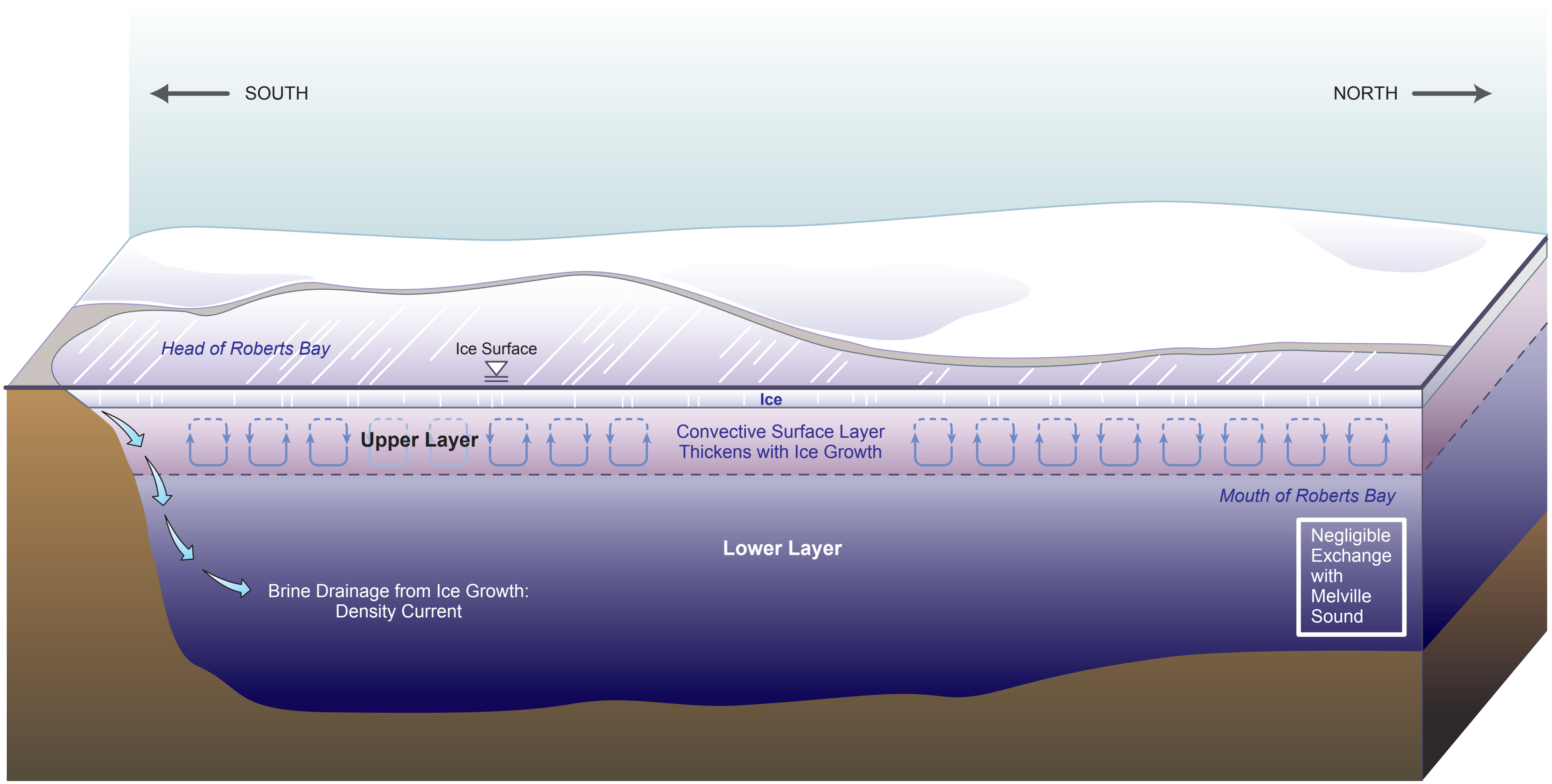


Table 7.2-3. Summary of the Mean North Velocity Component and the Mean and Maximum Current Speeds in Roberts Bay, Summer 2011

Site and Depth		Mean North Velocity Component (cm/s)	Mean Speed (cm/s)	Maximum Speed (cm/s)
May 22 – Jul 17, Deep-water site (85 m)	16 m	0.17	1.46	6.24
	34 m	-0.15	1.10	4.11
	58 m	-0.23	1.02	5.50
	76 m	-0.45	1.11	5.03
Jul 17 – Oct 04, Deep-water site (85 m)	17 m	-0.38	5.38	22.89
	34 m	-0.18	2.83	17.14
	58 m	-0.81	3.22	23.94
	66-72 m	-1.26	3.74	29.81

**Northern velocities are positive.*

As displayed in the current measurements, the combination of southern/easterly winds and freshwater inputs resulted in a positive-type two-layered estuarine circulation for roughly 70% of the measurement period, where the top layer flowed seaward and the deeper waters flowed into Roberts Bay from Melville Sound. A schematic interpretation of this type of circulation in Roberts Bay can be found in Figure 7.2-10. For the other 30% of the time, the general estuarine circulation was shown to reverse itself as illustrated in Figure 7.2-11, where strong and generally northerly winds pushed the surface layer southward into Roberts Bay, resulting in a return, outward, northerly flow at depth into Melville Sound.

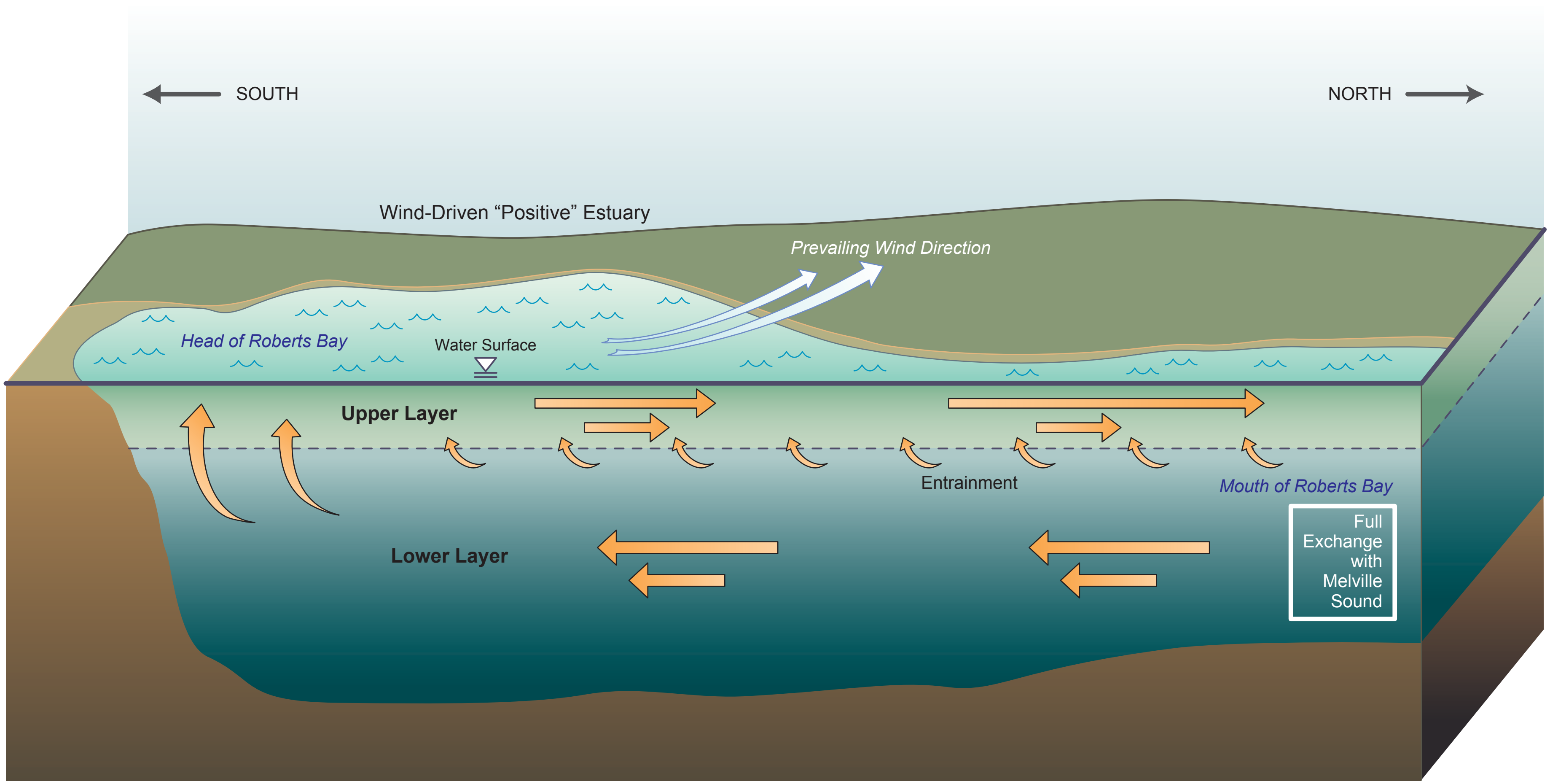
Site-specific wind data and current measurements were used to model the summer circulation of Roberts Bay water, with the results detailed in Rescan (2012b). Figures 7.2-12 and 7.2-13 show examples from the resulting numerically simulated current fields of July and August 2011. The numerical simulation showed that all of the deeper waters (i.e., 30 m and deeper) of Roberts Bay were exchanged with those of Melville Sound over a period of 10 days to nearly a month under various circulation scenarios. Greater rates of flushing were generally obtained in the top 10 to 20 m of the water column, since surface currents were much stronger than their lower depth counterparts due to the wind forcing proximity. A summary of the modeled flushing rates is shown in Table 7.2-4. These results indicate that Roberts Bay would be effectively flushed multiple times with Melville Sound waters during the four-month, open-water season.

Table 7.2-4. Flushing Rates of Roberts Bay (in days) at the Melville Sound Exchange Location for Different Water Column Sections and Modeling Scenarios (Rescan 2012b)

Model Scenarios	All Depths	10 m Depth to Bottom	20 m to Bottom	30 m to Bottom
2011 Baseline	6.71	8.58	15.00	17.58
2009 Winds	6.92	8.54	18.38	25.13
2007 Winds	8.83	11.54	19.04	26.33
2005 Winds	7.75	10.04	18.75	27.71
Double Outflow	6.95	10.08	16.67	21.08
Quadruple Outflow	6.33	12.38	22.33	28.50
North Winds	6.29	7.05	14.83	23.54
South Winds	5.25	6.63	7.92	9.96
East Winds	6.29	8.42	17.63	24.25
West Winds	6.79	8.71	17.67	25.50

Figure 7.2-10

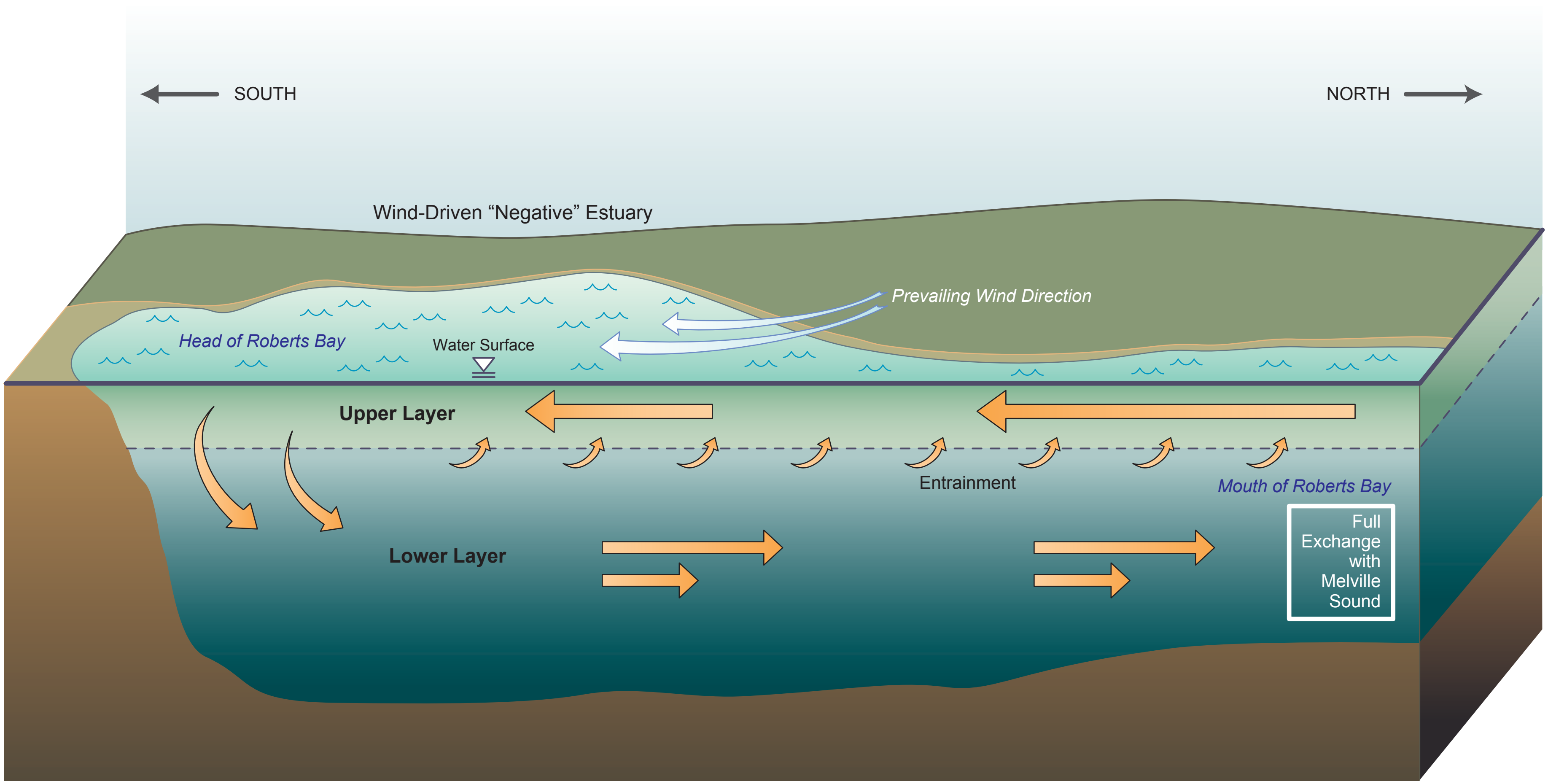
Example of Roberts Bay "Positive" Estuarine Circulation during the 2011 Summer: Vertical Side View



Note: The Prevailing Wind Direction refers to the wind direction that will most easily drive the circulation shown in the figure.

Figure 7.2-11

Example of Roberts Bay "Negative" Estuarine Circulation during the 2011 Summer: Vertical Side View



Note: The Prevailing Wind Direction refers to the wind direction that will most easily drive the circulation shown in the figure.

Figure 7.2-12

Mean Model Current Velocities and Directions at 4 and 36 m Depths, July 1 to July 7, 2011

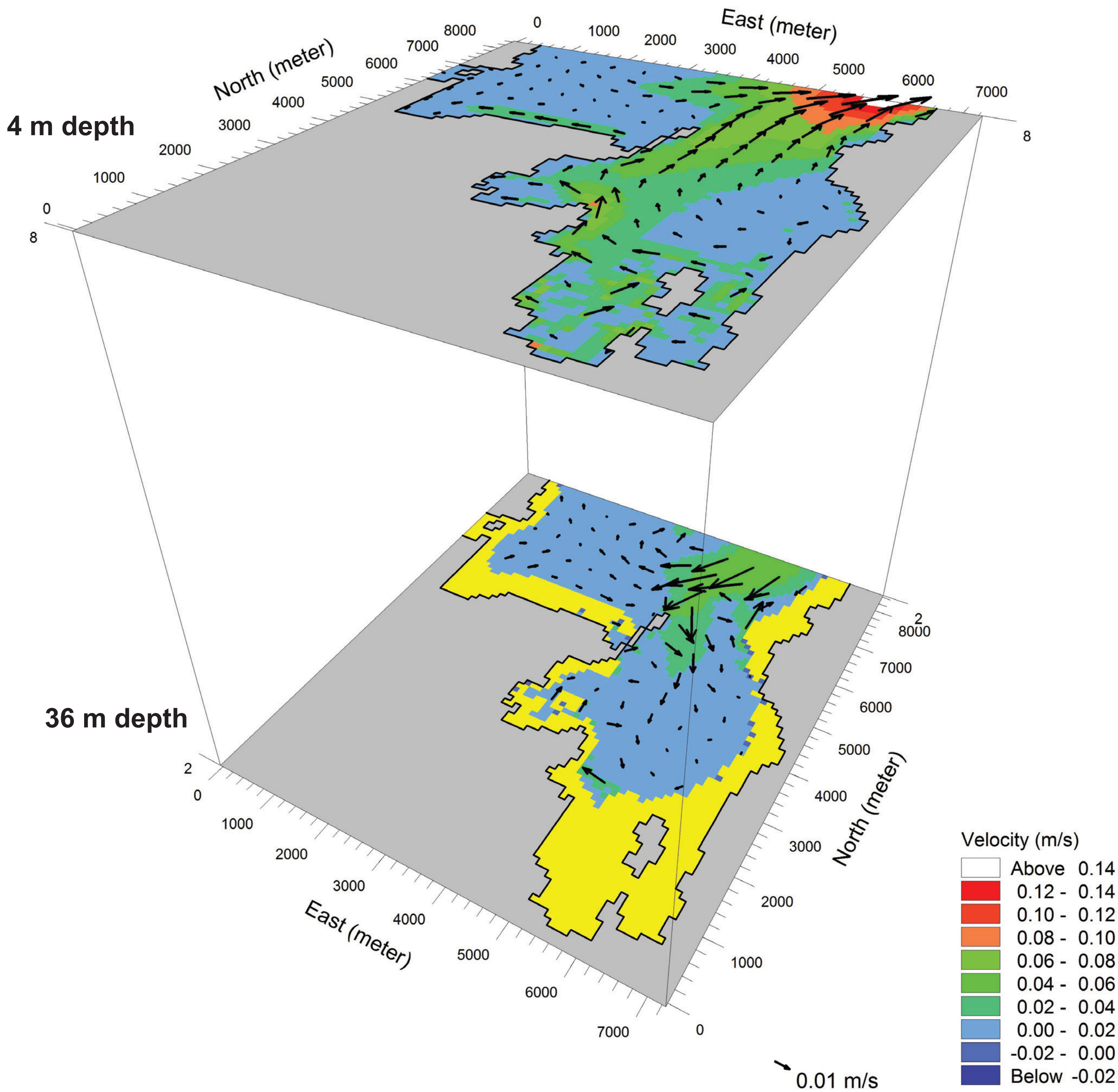
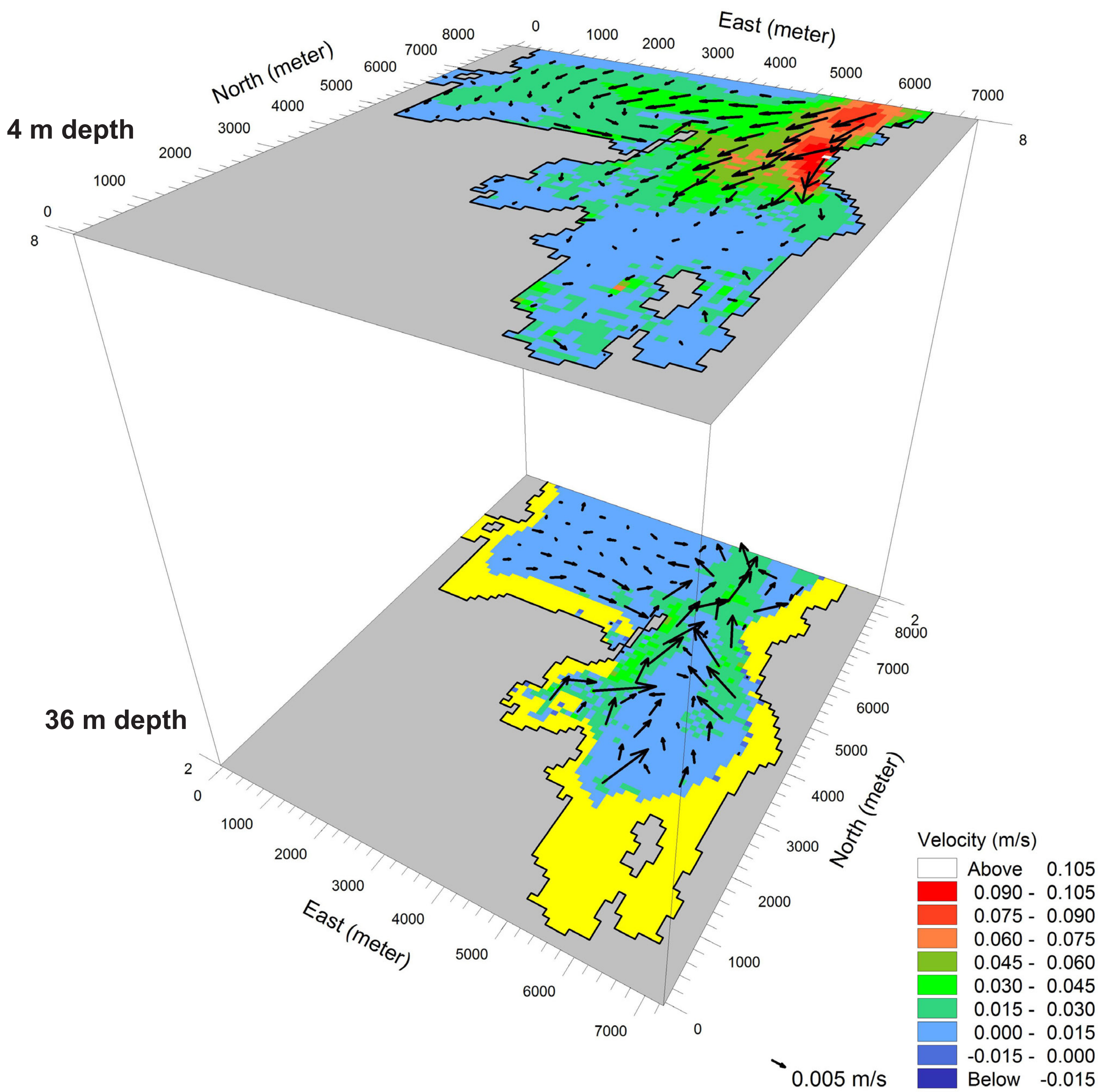


Figure 7.2-13

Mean Model Current Velocities and Directions at 4 and 36 m Depths, August 5 to August 8, 2011



7.3 VALUED COMPONENTS

7.3.1 Potential Valued Components and Scoping

Marine physical processes were included in the scoping and refining process with all other potential VECs (see Volume 2, Chapter 4). Based on TMAC-led public consultation, the NTKP report (Banci and Spicker 2016), and regulatory considerations, marine physical processes were classified as Subjects of Note.

7.3.2 Ecosystem Components Excluded in the Assessment

Marine physical processes are considered Subjects of Note for the EIS. All information requested in the EIS Guidelines (NIRB 2012) related to marine physical processes are included in this EIS. Marine physical processes are not further assessed because Madrid-Boston activities have limited potential for altering the physical structure and mixing processes in Roberts Bay. Physical measurements and three-dimensional hydrodynamic modeling have shown that the vertical structure and circulation of Roberts Bay are driven by winds (Rescan 2012c, 2012b) and Madrid-Boston Project activities will not alter wind conditions.

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