Appendix V5-8A

Near-field Plume Mixing Modelling for Phase 2 Discharges to Roberts Bay

Memorandum

Date: December 13, 2016

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From: Mike Henry, ERM

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Subject: **Near-field Plume Mixing Modelling for Phase 2 Discharges to Roberts Bay**

1. INTRODUCTION

This memorandum presents the near-field plume mixing modelling results for the proposed discharge of mine effluent into Roberts Bay from Phase 2 of the Hope Bay Project. TMAC Resources Ltd. (TMAC) is in the process of permitting Phase 2, with the intent of mining gold from the Madrid and Boston deposits within the Hope Bay Project area (Appendix A1) located 153 km from Cambridge Bay on the northern coast of the Nunavut mainland. Mining the Madrid deposit will result in the interception of saline talik water during underground workings. The water management strategy will be to discharge the connate, saline groundwater with mine water from the Tailings Impoundment Area (TIA) to the marine environment of Roberts Bay via the Roberts Bay Discharge System.

The objectives of the near-field mixing modelling were to:

- evaluate the near-field mixing zone characteristics in Roberts Bay related to Phase 2 based on a variety of discharge scenarios (groundwater and TIA effluent) and receiving environment conditions (ice covered/open water);
- predict the depths in the Roberts Bay where discharge plumes will be trapped (i.e., 'initial dilution zone') and the dilutions achieved under multiple discharge scenarios; and
- support the marine assessments in TMAC's Draft Environmental Impact Statement (DEIS; TMAC 2016) submitted to the Nunavut Impact Review Board (NIRB) in December 2016.

The delineation of near-field effluent mixing in Roberts Bay (extent and dilutions therein) was conducted using VISUAL PLUMES software (Frick et al. 2003), a plume mixing model accepted by Environment Canada (2003) that is capable of simulating effluent plume dispersion in stratified ambient flows from multi-port diffusers as proposed for the Phase 2 Project. The present work is an extension of previous near-field mixing and far-field hydrodynamic modelling conducted for the Doris Mine as part of the Hope Bay Project (ERM 2016a; 2016b).

Document Layout

This memo is structured as follows: Section 2 presents an overview of the Roberts Bay Discharge System as it applies to the Hope Bay Project and outlines Phase 2's operational timelines regarding the marine discharge; Section 3 describes the VISUAL PLUMES model, the discharge scenarios that were modelled, and the diffuser configuration, effluent characteristics, and ambient conditions required for model inputs; Section 4 presents and discusses the results of the modelling exercise, and Section 5 summarizes the conclusions of the memorandum.

2. BACKGROUND

2.1 Project Description and the Roberts Bay Discharge System

The early stages of Phase 2 of the Hope Bay Project will overlap with the TMAC's currently permitted Doris Project (NIRB Project Certificate No. 003), with approximately two years of construction and operations coinciding with Doris operations. The Doris Project mines the northernmost deposit (Doris) in the Hope Bay Project area, and underground workings beneath Doris Lake were predicted to encounter saline, talik water similar to that at the central Madrid deposit (SRK 2015a). The Doris Project Certificate was amended in 2016, in part, to manage this saline groundwater, with the key design change being the conveyance of the groundwater and TIA water to Roberts Bay via the Roberts Bay Discharge System. This will ensure the saline effluent is more effectively diluted within the marine environment and will be more protective of aquatic life than discharging the effluent into freshwater. Phase 2 will use the infrastructure at the permitted Doris Mine to manage the saline groundwater, mill the ore, and store the tailings from mining the Madrid deposit.

The Roberts Bay Discharge System is a submarine pipeline-diffuser outfall and its design has been described in detail elsewhere (SRK 2015b; ERM 2016a). Briefly, it will consist of a 5.6 km insulated pipeline that runs from the Mill Building near Doris Camp to the Roberts Bay Laydown Area at the Roberts Bay shoreline. The pipe will enter the marine environment through a Marine Outfall Berm and will travel 2.2 km northward where it will terminate with a multi-port diffuser at the 40-m isobath (Appendices A2 and A3). Groundwater and TIA water will be combined in a mixing box in the Mill Building and fed into the pipeline for disposal into Roberts Bay.

The design objective of the Roberts Bay Discharge System is to preserve the marine water quality within Roberts Bay, thereby protecting marine life and the ecological function of the inlet. The diffuser design and placement is intended to rapidly entrain the effluent with the ambient waters of Roberts Bay and 'trap' the buoyant plume in the deep waters where past studies have shown that it will exchange freely with Melville Sound (Rescan 2012a; 2012b). This will limit the effluent that will reach the more productive surface layer, and because the plume is expected to be buoyant, keep the plume from interacting with the sediments. Near-field mixing and far-field hydrodynamic simulations have shown that various modelled discharge plumes will be trapped within the deep waters of Roberts Bay, will not interact with the sediments, and will meet all receiving water quality objectives within 1 m of the diffuser (ERM 2016a; 2016b). The modelling presented in this memo is an extension of the near-field mixing modelling conducted for the Doris Project (ERM 2016a), but is updated with discharge characteristics applicable to the Phase 2 Project.

2.2 Phase 2 Timelines

Mining the Madrid deposit will occur in two phases: Madrid North under the northern section of Patch Lake will be mined from Year 1 to Year 14 of Phase 2 operations and Madrid South under southern Patch Lake will be mined from Year 11 to Year 13. Saline inflows to the Madrid North underground mine are expected in Year 2 of operations (SRK 2016a). Inflows will continue for each sub-deposit until mining operations cease. Discharge associated with the Doris Project will overlap with several months of inflow from Madrid North in Year 2 of the Phase 2 Project.

During Phase 2 operations, the TIA decant and saline groundwater will be largely discharged to Roberts Bay in a tri-modal, intermittent fashion. From Year 2 to Year 10, saline groundwater from Madrid will be discharged year-round and the TIA water will be combined with the groundwater and discharged only during the open-water season (June to September) when Roberts Bay flushing is greatest. Thus, only groundwater will be discharged during the ice-covered period (October to May) from Year 2 to Year 10 when inlet currents are negligible. From Year 11 to Year 14, the TIA water and saline groundwater will be mixed and conveyed continuously to Roberts Bay. The final stage of discharge will occur during the Madrid Closure phase (Years 15 to 17) when the TIA will be de-watered directly to Roberts Bay. Discharge during this phase will occur during the open-water season, except the final three months of pumping when the TIA water will be discharged under ice.

3. NEAR-FIELD MIXING MODEL

3.1 General Description

Modelling was conducted using the three-dimensional Updated Merge (UM3) model within VISUAL PLUMES (Frick et al. 2003), as was done for previous near-field simulations in Roberts Bay for the Hope Bay Project (ERM 2016a). VISUAL PLUMES is used primarily for near-field region mixing simulations; that is, the region of the receiving water where the initial jet characteristic of momentum flux, buoyancy flux, and outfall geometry influence the jet trajectory and mixing of an effluent discharge. UM3 is a Lagrangian plume model that simulates the overall average behaviour of the plume along a plume trajectory, and quantifies the rate at which mass is integrated into a plume in the presence of a current (i.e., forced entrainment).

The model was run as steady state; that is, all inputs were deemed constant over time.

3.2 Discharge Scenarios

The discharge to Roberts Bay will involve three discharge streams (groundwater, combined groundwater and TIA water, and TIA water) of varying densities that will be pumped from the mixing box at a constant rate during the under-ice, moderately stratified season (October to May) and the ice-free, strongly stratified season (June to September). Six discharge scenarios were modelled to represent the most important nominal operating conditions that will be encountered during Phase 2 operations, including three during each of the under-ice and open-water seasons.

During the under-ice season, saline groundwater will be discharged to Roberts Bay for nine years (Years 2 to 10) followed by four years of combined groundwater and TIA discharge (Years 11 to 14).

Groundwater densities (as determined by salinity) are predicted to be variable for Madrid mine inflows (SRK 2016a), therefore, the highest and lowest density discharges were modelled for the groundwater only discharge as this represents the lowest and highest degree of mixing that could be encountered under ice during Years 2 to 10. Because the range of effluent densities decrease when TIA water is combined with the saline groundwater, only the median density of combined groundwater and TIA water discharge was modelled under ice.

The highest and lowest discharge densities were also modelled for the combined groundwater and TIA water that will be discharged into open water for the duration of Madrid operations. The median density scenario was also modelled for the short-term, fresher discharge of TIA water to Roberts Bay during the Closure phase of Madrid.

The modelled discharge scenarios and their effluent characteristics are outlined in Table 3-1.

Table 3-1. Modelled Scenarios with Effluent Quantities and Thermohaline Characteristics

Case	Source of Water	Season	Effluent Pump Rate (m^3/d)	Effluent Salinity (ppt)	Effluent Temperature (°C)
Winter Cases					
1a	Groundwater only (high salinity)	Under ice (8 months)	3,000	25.3	2.0
1b	Groundwater only (low salinity)	Under ice (8 months)	3,000	15.5	2.0
1c	Groundwater + TIA	Under ice (8 months)	8,000	5.0	2.0
Summer Cases					
2a	Groundwater + TIA (high salinity)	Open water (4 months)	8,000	15.5	7.8
2b	Groundwater + TIA (low salinity)	Open water (4 months)	8,000	2.0	7.8
2c	TIA discharge only (de-watering)	Open water (4 months)	5,000	0.2	10.0

3.3 Model Inputs

VISUAL PLUMES requires three types of data inputs:

- the dimensions, depth, and configuration of the discharge structure (i.e., diffuser);
- the properties of the effluent; and
- the properties and characteristics of the receiving environment, in this case, Roberts Bay.

3.3.1 Diffuser Configuration

The model inputs for the diffuser configuration were based on previous designs (SRK 2015b). Specifically, the diffuser will be a 95-m long structure anchored at 40 m depth and raised approximately 0.6 m above the seafloor. The diffuser will have 20 ports of 30 mm diameter staggered on either side of the pipe spaced at 5 m intervals and discharging horizontally.

3.3.2 Effluent Description

The main effluent inputs included the discharge rate and density (salinity and temperature) as these affect the momentum of the discharge and the buoyancy of the resulting discharge plume. The inputs are summarized in Table 1.

3.3.2.1 Discharge Rates

The groundwater, TIA, and combined groundwater and TIA effluent streams were modelled conservatively as continuous discharges at the designed pump rates shown in Table 1. Groundwater will be pumped at a maximum rate of 3,000 m^3/d (35 L/s), TIA water at 5,000 m^3/d (58 L/s), and groundwater and TIA combined discharge at 8,000 m^3/d (93 L/s). In reality, the pumping will be intermittent as discharge will only occur when there is sufficient water volume to support pumping for a least six continuous hours.

3.3.2.2 Density

The effluent sources will have different thermohaline characteristics that will affect the density of the discharge and consequently alter the mixing potential of the effluent with the receiving water of Roberts Bay. Discharged water density was calculated from the model inputs of effluent temperature and salinity, with the latter being estimated from modelled chloride levels for groundwater inflows (SRK 2016a) and TIA water (SRK 2016b) following the conversion of salinity (ppt) = 0.0018 × [chloride] (mg/L) (Vernier 2016).

Groundwater predictions for Phase 2 indicated that inflows will always be saline (SRK 2016a). The highest (25.3 ppt; 14,030 mg chloride/L) and lowest salinities (15.5 ppt; 8,600 mg chloride/L) expected to be discharged under ice were used as inputs for groundwater (Table 1). There is a brief seven-month period in late Year 2 and early Year 3 of Phase 2 where small inflows ($< 125\ m^3/d$) of higher salinity groundwater are predicted from mining Madrid North (> 28.8 ppt; 16,000 mg chloride/L). This high salinity scenario was not modelled because all groundwater that have salinities above 27 ppt (15,000 mg chloride/L) will be conveyed to the TIA (SRK 2016b). This is to ensure that the effluent discharged into Roberts Bay is less dense than the receiving water and will rise in the water column thereby avoiding the sediments.

The TIA water will be fresher with predicted chloride levels usually below 190 mg/L (salinity: 0.3 ppt; SRK 2016b). During closure, the TIA will be de-watered over a three-year period during the open-water season and will be the only water discharged into Roberts Bay during this time. For modelling purposes, a salinity of 0.3 ppt was used for the de-watering scenario (Table 3-1). During operations, the TIA water will also be combined with the saline groundwater and released into Roberts Bay during the open-water (Years 2 to 14) and under-ice seasons (Years 11 to 14). The highest (15.5 ppt; 8,600 mg chloride/L) and lowest (2.0 ppt; 1,130 mg chloride/L) estimated salinities were used as inputs for the open-water discharge of combined TIA and groundwater. The median salinity (5.0 ppt; 2,750 mg chloride/L) was used for the under-ice, groundwater-TIA discharge because of the lower range of salinities for this scenario.

Effluent temperature also contributes to the overall density of the effluent, although far less so in the saline discharges. A temperature of 2°C was used for all under-ice discharge scenarios (groundwater only and combined groundwater and TIA water) as this will be the minimum temperature required to ensure the effluent will not freeze in the discharge system. The TIA-only discharge during the open-water season was modelled at 10°C based on average baseline measurements in the TIA (Rescan 2012c). The temperature for the combined groundwater and TIA effluent during the open-water discharge was estimated at 7.8°C based on the 10°C summer TIA temperature and the 4°C groundwater temperature and their 5:3 mixing ratio in the marine mixing box.

3.3.3 *Ambient Conditions*

The existing ambient conditions of Roberts Bay relevant to this modelling exercise have been summarized in the DEIS (TMAC 2016; Volume 5, Chapter 7). The main inputs required in the model included physical water column structure (depth, salinity, and temperature) and currents. Discharge scenarios were modelled for both the open-water and under-ice periods (Table 3-1) to account for the seasonal differences in the aforementioned physical inputs.

The physical structure and circulation of Roberts Bay is determined by the presence or absence of ice. When ice covered, Roberts Bay is weakly stratified, with colder (-1.5°C), less saline water (25 to 27 ppt) overlying warmer (-0.2°C), more saline water (27 to 28 ppt), with a surface mixed layer depth ranging between 10 m to 35 m. Deep-water currents in Roberts Bay are usually less than 1 cm/s (Rescan 2012a). In open water, the bay is strongly stratified due to ice melt and riverine inputs, with a warmer (10°C), less saline (15 to 20 ppt) layer overlying a colder (-1°C), more saline (27 to 28 ppt) bottom layer, with a very stable pycnocline near 10 m. During this time, Roberts Bay circulation is dominated by winds (as opposed to riverine or tidal inputs), with the bay capable of being flushed several times with Melville Sound water over the open-water season (Rescan 2012a). Deep-water currents range between 1 cm/s to 25 cm/s, and are usually between 3 cm/s and 5 cm/s (Rescan 2012a).

For modelling purposes, data from representative thermohaline profiles were used as inputs from under-ice and open-water discharge scenarios (Table 3-2). The winter profile was taken on April 30, 2009, near the proposed diffuser location and the summer profile was collected on August 14, 2009 (Rescan 2010). Ocean currents were conservatively set at 0 cm/s for under ice and 5 cm/s for open water. Tides were not considered as their contribution to the overall current structure in Roberts Bay is minimal (Rescan 2012a; 2012b).

Table 3-2. Baseline Thermohaline Profile Data Used in Modelling Scenarios

Under Ice (April 30, 2009)			Open Water (August 14, 2009)		
Depth (m)	Salinity (ppt)	Temp (°C)	Depth (m)	Salinity (ppt)	Temp (°C)
0.00	26.80	-1.51	0.00	14.92	10.51
4.03	26.80	-1.52	0.74	15.41	9.73
6.04	26.80	-1.51	1.15	15.68	9.30
7.94	26.80	-1.51	1.32	15.83	9.23

Under Ice (April 30, 2009)			Open Water (August 14, 2009)		
Depth (m)	Salinity (ppt)	Temp (°C)	Depth (m)	Salinity (ppt)	Temp (°C)
9.27	26.78	-1.48	2.21	16.40	9.15
10.00	26.74	-1.42	3.38	16.64	9.05
11.21	26.56	-1.08	4.96	17.71	8.41
12.71	27.11	-0.95	6.90	18.88	7.75
14.25	27.05	-0.93	9.26	22.29	5.63
16.70	27.21	-0.90	10.80	24.48	2.78
19.91	27.27	-0.92	12.77	25.40	1.79
21.81	27.35	-0.92	14.32	25.99	1.14
23.98	27.40	-0.94	15.74	26.32	0.78
26.08	27.44	-0.95	18.30	26.47	0.44
27.98	27.48	-0.98	20.20	26.68	0.08
31.74	27.54	-0.99	22.14	26.83	-0.13
34.09	27.57	-1.01	23.92	26.91	-0.25
36.20	27.60	-1.04	27.77	27.12	-0.43
38.17	27.60	-1.03	32.70	27.25	-0.56
40.47	27.62	-1.04	37.03	27.36	-0.64
-	-	-	40.70	27.39	-0.67

4. SIMULATION RESULTS AND DISCUSSION

Near-field discharge plume behaviour was numerically simulated based on nominal operating conditions (groundwater only, TIA only, and combined TIA and groundwater discharge) that could occur during the winter (ice covered) and summer (open water) seasons. A total of six discharge scenarios were simulated: three during the under-ice season (Cases 1a-1c in Table 4-1) and three in open water (Cases 2a-2c).

The simulations showed that the discharge plume will be buoyant under all discharge scenarios, with the plume being trapped 28.3 m to 35.7 m below the surface of Roberts Bay, or roughly 11.7 m to 4.3 m above the diffuser, with horizontal boundaries ranging from 5.8 m to 14.8 m (Table 4-1). Large dilutions of 160:1 to 542:1 were attained within the vertical (trapping depth) and horizontal plume boundaries for each modelled scenario. A conceptual diagram showing the behaviour of a buoyant plume in Roberts Bay is presented in Appendix A3.

Overall, trapping depths were deeper and dilutions and horizontal spreading greater during the open-water season than under ice (Table 4-1). This is due to the stronger currents laterally spreading the plume as it rises through the water column, as well as the higher exit velocities from the diffuser ports (i.e., greater discharge rate) leading to greater entrainment when the TIA water is combined with groundwater.

Table 4-1. Summary of Modelled Plume Mixing Zone Results for Under-ice and Open-water Discharge Scenarios

	Source of Water	Effluent Flow Rate (m^3/d)	Effluent Salinity (ppt)	Trapping Depth (m)	Horizontal Distance from Diffuser Port at Trapping Depth (m)	Minimum Average (Centreline) Dilution at Trapping Depth (X:1)
Under-ice Cases						
1a	Groundwater only (high salinity)	3,000	25.3	34.7	8.7	160 (118)
1b	Groundwater only (low salinity)	3,000	15.5	30.7	5.8	245 (194)
1c	GW + TIA	8,000	5.0	28.3	10.2	303 (248)
Open-water Cases						
2a	GW+ TIA (high salinity)	8,000	15.5	35.7	14.8	369 (270)
2b	GW+ TIA (low salinity)	8,000	2.0	33.8	13.0	437 (342)
2c	TIA only (de-watering)	5,000	0.3	33.9	10.7	542 (426)

Increased buoyancy (i.e., lower salinity) also contributed to larger dilutions for each of the under-ice and open-water seasons (Cases 1c and 2c), although less so during the open-water season. This can be seen with the estimated 50% increase in dilution with a 50-fold decrease in effluent salinity during the open-water season compared to the 100% increase in dilution with only a 5-fold salinity decrease under ice (Table 4-1). This indicates that ocean currents diluted the simulated Phase 2 discharges to a greater degree than variations in effluent density. In the absence of currents and horizontal spreading, the shallowest trapping depth (28.3 m), or greatest rise above the diffuser (11.7 m), occurred when larger volumes of buoyant combined TIA and groundwater (Case 1c) were discharged under ice.

The greatest dilution (542:1) was predicted when only fresh, warm TIA water was discharged to Roberts Bay during the open-water season and the lowest dilution (160:1) when the most saline and coldest groundwater was discharged under ice. These differences reflect the traits that ultimately control mixing in the near-field environment: the density differential between the warmer and fresher TIA discharge and ambient Roberts Bay water was greater than it was for the cold, saline groundwater discharge (greater buoyancy), the TIA water was discharged at a greater rate than the groundwater (greater momentum flux), and the increased currents during the open-water season promoted greater spreading of the discharge plume. These traits explain the enhanced entrainment and mixing of the TIA-only discharge into the surrounding Roberts Bay waters, and the greater dilutions observed during the open-water season overall.

5. CONCLUSIONS

The results of the modelling exercise revealed that large dilutions (greater than 160:1) will be attained within the near-field plume boundaries in Roberts Bay under all Phase 2 discharge scenarios. The discharge plumes are predicted to be buoyant and are expected to be trapped below the surface layer of Roberts Bay and not interact with the seafloor. This corroborates the findings from previous near-field plume modelling in Roberts Bay (ERM 2016a). Further, the far-field hydrodynamic modelling conducted for the Doris Project (ERM 2016b) indicates the near-field plumes would be diluted by several more orders of magnitude as they move through Roberts Bay into Melville Sound.

From an ecological perspective, the outcomes of the plume modelling are desirable since the plumes are expected to trapped far below the more biologically productive surface mixed layer (10 m deep), and far above the productive benthic environment. It is surmised that the effluent plumes will be confined to the most unproductive region of Roberts Bay (deep pelagic waters) where they will be substantially diluted and advected into Melville Sound. These results show that discharging Phase 2 effluent into the deep water of Roberts Bay using a diffuser is a strong design that will mitigate potential effects to marine life in the bay. This is confirmed in the marine water quality assessment for the Phase 2 DEIS (TMAC 2016; Volume 5, Chapter 8).

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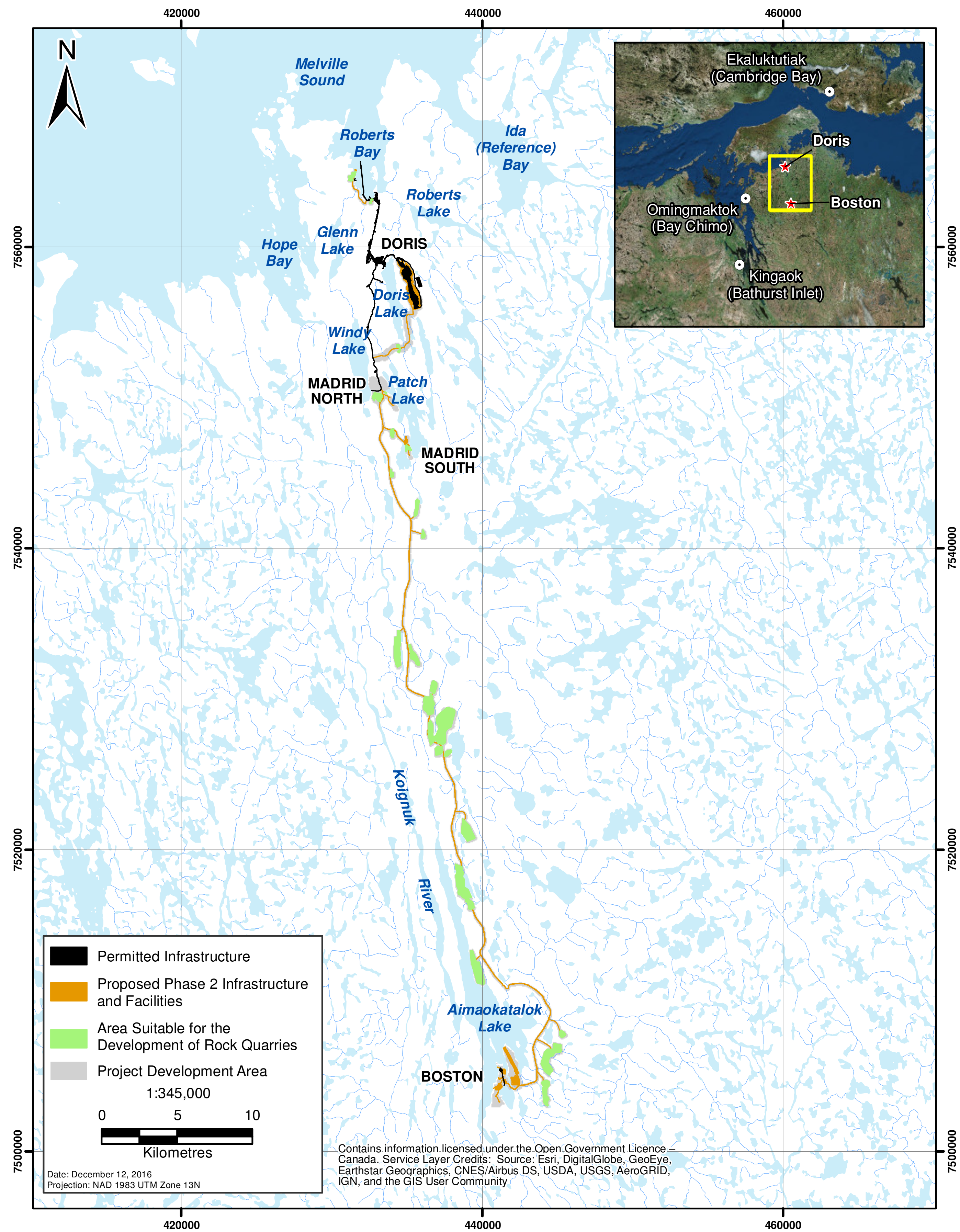
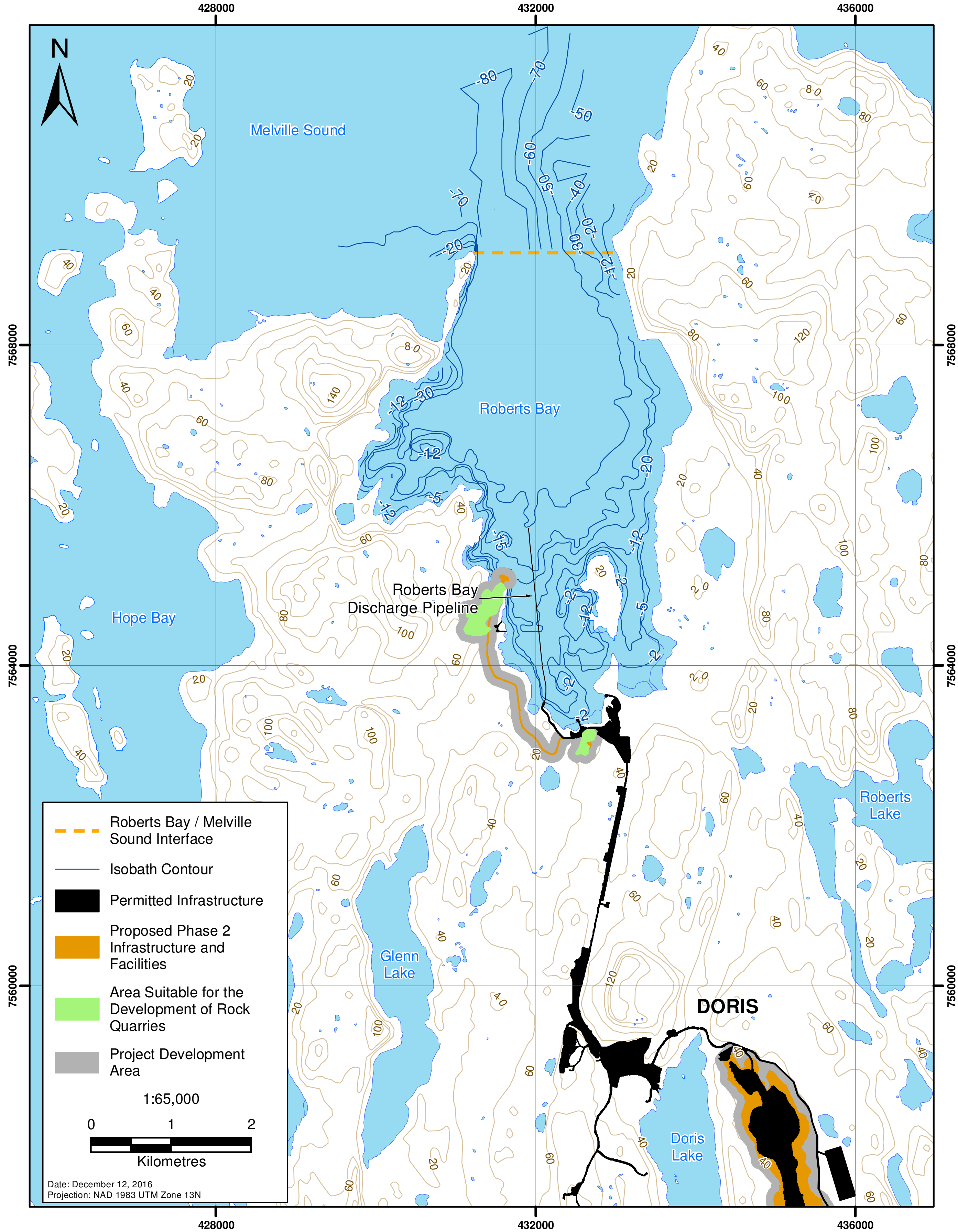
— Appendix A —

Appendix A1

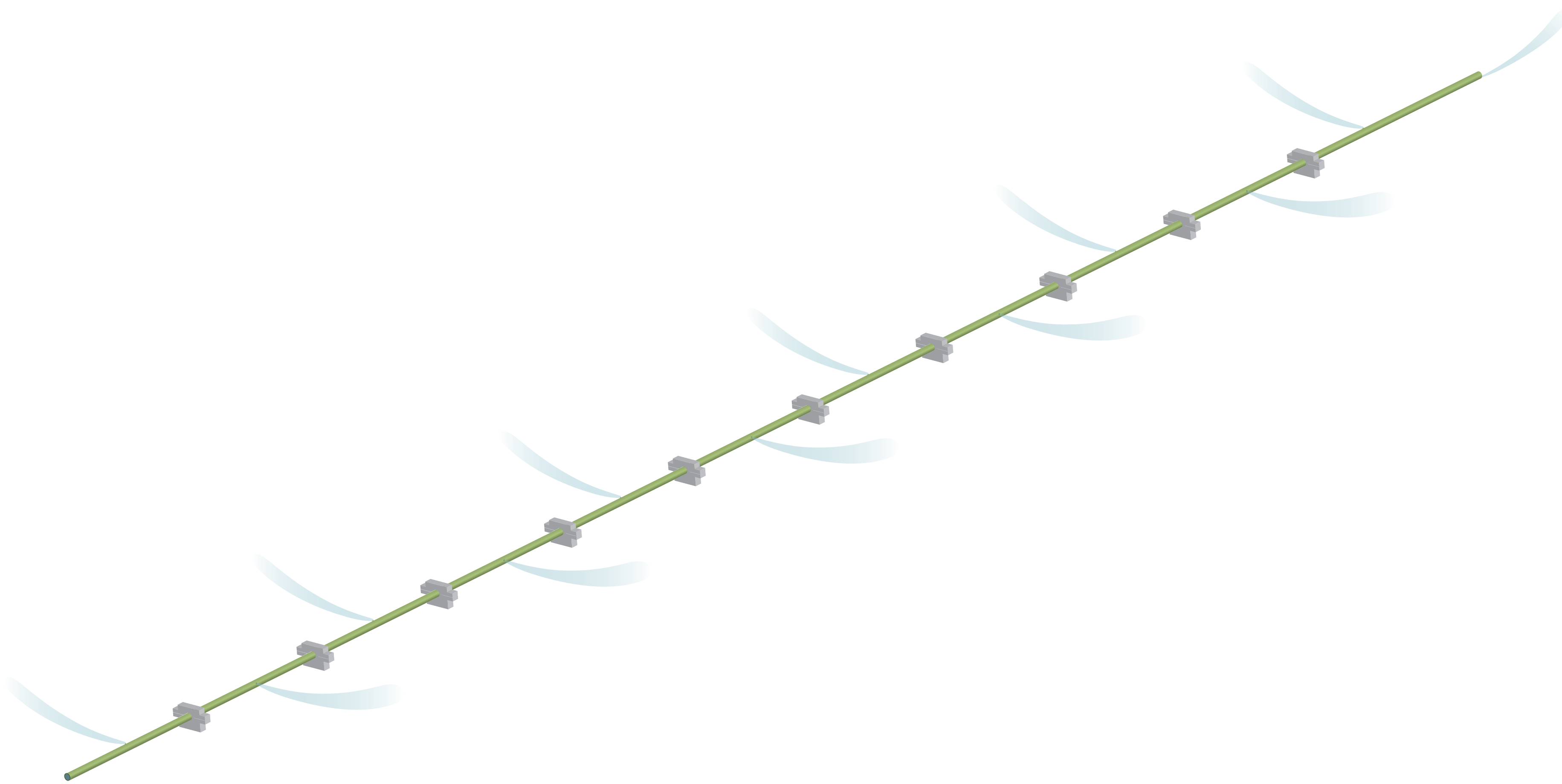
Hope Bay Project Location and Existing and Proposed Phase 2 Infrastructure



Appendix A2
Location of Roberts Bay and Roberts Bay Discharge System



Concept Sketch of One Half of the Diffuser showing the Discharge Plumes



Note: Drawing not to scale.

Appendix A4

Conceptual Sketch of Discharge Plume Behaviour in Roberts Bay