Appendix V5-4K

Near-field Plume Mixing Modelling for Discharges to Aimaokatalok Lake

Memorandum

Date: December 16, 2016

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Subject: **Near-field Plume Mixing Modelling for Discharges to Aimaokatalok Lake**

1. INTRODUCTION

This memorandum presents the near-field plume mixing modelling results for the proposed discharge of treated effluent into Aimaokatalok Lake 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 Boston and Madrid deposits within the Hope Bay Project area (Appendix A1) located 153 km from Cambridge Bay on the northern coast of the Nunavut mainland.

The water management strategy at the Boston site will involve discharging treated water from the Boston Water Treatment Plant (WTP) into Aimaokatalok Lake. Mine and site contact water will be collected from the Tailings Management Area, waste rock pile, ore storage pad, and other mine surface infrastructure pads and directed to contact water ponds (CWP). Water from these event ponds will be combined with purge water from the Boston process plant and will be treated and discharged with treated sewage water into the lake. Water quality predictions related to the treated discharge have been generated for Aimaokatalok Lake as part of the site-wide water and load balance (SRK 2016), although the predictions were based on complete mixing in the southwestern section of the lake. The goal of this modelling exercise was to delineate the near-field mixing zone where the initial effluent dilution occurs so water quality can be predicted on a finer scale.

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

- evaluate the near-field mixing zone characteristics in Aimaokatalok Lake related to Phase 2 operations based on a variety of discharge scenarios and receiving environment conditions (ice covered/open water);
- predict the dispersion of the plumes in Aimaokatalok Lake and the dilutions achieved under multiple discharge scenarios; and
- support the water and sediment quality assessments in TMAC's draft Environmental Impact Statement (EIS; TMAC (2016)) submitted to the Nunavut Impact Review Board (NIRB) in December 2016.

The delineation of near-field effluent mixing in Aimaokatalok Lake (extent and dilutions therein) was conducted using the Cornell Mixing Model (CORMIX) (Doneker and Jirka 2007), 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 discharge into Aimaokatalok Lake.

Document Layout

This memo is structured as follows: Section 2 presents an overview of the Boston mining area as it relates to the Hope Bay Project; Section 3 describes the CORMIX model, the discharge scenarios that were modelled, and the diffuser configuration, effluent characteristics, and ambient conditions required for model inputs, and; Section 4 presents and discusses the results of the modelling exercise.

2. BACKGROUND

2.1 Site Description

The Boston site is located on the southern end of Aimaokatalok Lake approximately 80 km south of Roberts Bay (Appendix A1). Aimaokatalok is a large (> 10 km length), irregularly shaped lake that flows northwards into Hope Bay by way of the Koignuk River (Appendix A2). The average depth of the lake is 6 m with a maximum depth of 30 m. The lake is typically frozen solid from October to May, with ice thicknesses ranging between 1.5 m and 2.0 m. The ice melts rapidly in June, with initial exposure of the lake perimeter, and open water is generally present from July into September.

During the Phase 2 implementation of the Hope Bay Project, the Boston process plant is assumed to start processing ore at 400 tonnes per day (tpd) in Year 5, increasing up to 1,600 tpd from Year 6 until Year 13, with a return to 400 tpd in Year 14 (SRK 2016). A total of 5.1 Mt of ore and 2.2 Mt of waste rock will be processed from underground development of the Boston Mine over the 11-year mine life. Mining at the Boston site will be completely within permafrost, and no interception of talik groundwater is anticipated. Water from the CWPs and mill bleed from the Boston processing plant with be treated in a two-stage water treatment plant (WTP). This water will then be combined with treated sewage water and discharged to Aimaokatalok Lake. Discharge of WTP effluent is slated to begin in Year 2 when the Boston site CWPs start collecting water, and will continue through to Year 17 when the site enters post-closure. The Boston WTP peak flows are estimated at 1,130 m^3/day and approach 120,000 m^3/yr (SRK 2016).

2.2 Discharge System

Treated water will be discharged to Aimaokatalok Lake through a submarine pipeline-diffuser system. The pipeline is projected to run approximately 1 km from the shoreline into the southwestern basin of the lake, discharging in an area of deeper bathymetry (10 m; Figure A2). The effluent output is surmised to propagate in the long northward channel of the lake, where ample waters would be available to dilute the effluent plume, before entering the Koignuk River approximately 3 km from the discharge system.

The diffuser configuration presented in this modelling exercise is conceptual as detailed engineering and the optimization of the diffuser design will be done prior to the submission of TMAC's final EIS to the NIRB. The presented configuration was designed with the intent of rapidly entraining the effluent with the ambient waters of the lake to preserve the water quality and the ecological function of the system.

3. NEAR-FIELD MIXING MODEL

3.1 General Description

Near-field mixing and dilution near effluent outfalls are primarily influenced by the buoyancy and momentum of the discharge, while the transport and extent of the resulting effluent plume are mainly determined by the ambient currents and water column stratification of the receiving water body. The near-field region contains a recirculation zone where the combined effects of discharge buoyancy, momentum, and ambient currents generate the turbulence responsible for the strong initial mixing within the water column. It is the region of the receiving water where outfall design conditions are most likely to have an effect on water quality.

Existing numerical hydrodynamic models often use turbulence closure schemes with empirical coefficients that have restricted ranges of applicability for varying discharge rates and ambient conditions. Semi-empirical formulas, which are based on the simplified fluid governing equations for conservation of mass and momentum combined with physical laboratory and field modelling data, are generally more reliable than numerical turbulence models in predicting effluent plume dispersions given applicable ranges of discharge conditions. The CORMIX model (Doneker and Jirka 2007) was used for the near-field mixing and dilution analysis, and considers all available physically-based and semi-empirical turbulence formulas to select the appropriate scheme for the discharge scenario considered.

The CORMIX model is an industry standard for the conceptual design and analysis of effluent diffusers within freshwater environments, and has been used in multiple settings (ERM 2015b, 2015a, 2015c). The model generally assumes uniform steady-state ambient conditions and effluent discharges, although it can be applied successfully to tidally recirculating systems. CORMIX has specific sub-systems for analyzing discharges from simple pipe (CORMIX1) or multi-port (CORMIX2) diffusers and thus predict the corresponding effluent plume geometry and dilution characteristics. The predictions of the model are based on the determination of the proper model inputs for any given receiving water body and effluent flow.

3.2 Discharge Scenarios

The mixing of the Boston WTP discharge with ambient Aimaokatalok Lake waters was modelled during the following three periods when lake conditions are expected to vary most:

- the under-ice, moderately stratified season (October to May);
- the short freshet season (June); and
- the ice-free, well-mixed season (July to September).

The under-ice season was modelled because ice inhibits wind-driven currents and therefore the potential dispersion of effluent within the lake (Table 1). Two under-ice scenarios were modelled to account for variations in under-ice currents. Freshet was modelled because discharge from the Boston WTP is predicted to be greatest during this period (SRK 2016). The freshet season was modelled under-ice because the lake does not fully thaw until the beginning of July. Slight increases to under-water currents were applied to the model during this period because of the presence of liquid water around the perimeter of the lake during ice off. Open-water was modelled because of the full exposure of the lake surface to winds. This would be the season when lake currents, and therefore plume mixing, would be expected to be greatest.

Table 1. Modelled Scenarios with Effluent Quantities and Thermohaline Characteristics

Scenarios	1: Under-ice (low currents)	2: Under-ice (high currents)	3: Freshet *(under-ice)	4: Open-water (well-mixed)
Discharge Rate (m^3/d)	350	350	1,130	375
Effluent Temperature (˚C)	2.0	2.0	10	15
Effluent Chloride Concentration (mg/L)	1,750	1,750	1,070	1,582
Effluent Density (kg/m^3)	1002.5	1002.5	1001.3	1001.4
Water Depth (m)	8.5 (under 1.5 m ice cover)	8.5 (under 1.5 m ice cover)	8.5 (under 1.5 m ice cover)	10
Ambient Water Temperature (˚C)	1.5	1.5	1.9	13.7
Ambient Chloride Concentration (mg/L)	14.4	14.4	7.8	7.8
Ambient Current Velocity (m/s)	0.001	0.01	0.015	0.03
Ambient Water Density (kg/m^3)	999.988	999.988	999.997	999.159
Surface Wind Speed (m/s)	0	0	0	5

The important discharge and ambient parameters for the four modelled scenarios are displayed in Table 1. Dissolved chloride concentrations were used as the conservative tracing parameter for all model runs as chloride has the greatest influence on the density differential between the effluent and the ambient waters. Detailed explanations of the parameters and their inputs are provided in Section 3.3 below.

3.3 Model Inputs

Data inputs to the CORMIX model are grouped into four main categories: effluent description, ambient conditions, diffuser characteristics, and mixing zone. The effluent description includes the flow rate, density, and parameter concentration of the discharge. Ambient conditions include stratification information and water density, water current, depth and width of the receiving water, wind speed, and bottom water roughness coefficient. The required diffuser configuration includes the geometrical characteristics of the effluent jet at the point of discharge and the location/orientation of the discharge port(s) within the water. The mixing zone data consists of a definition of the spatial region where mixing and plume characteristics are required and optional information on ambient water quality standards and regulatory mixing zone delineations.

3.3.1 *Effluent Description*

The main effluent inputs included the discharge rate, density (salinity and temperature), and parameter concentration so that resulting mixing zone concentrations could be calculated. Estimates for WTP discharge rates and chloride concentrations were taken from the site-wide water and load balance for the Hope Bay Project (SRK 2016).

Discharge Rates

The mine water and sewage effluent streams were modelled as maximum, continuous discharges at the designed pump rates shown in Table 1. These are predicted to be 350 m^3/d during the under-ice season, 1,130 m^3/d during freshet, and 375 m^3/d during the open-water season.

Density

The effluent sources will have different thermohaline characteristics thereby affecting the density of the discharge. The discharge will generally have elevated levels of dissolved chloride, from which salinity can be estimated using the formula salinity (ppt) = 0.0018 × [chloride] (mg/L) (Vernier 2016). Table 2 shows the 50^{th}, 75^{th} and maximum concentrations of chloride and associated salinity for each season considered. Plume mixing was modelled at the 75^{th} chloride percentile for each season (see Table 2), which was deemed conservative given that elevated levels are only anticipated to occur over a few months every season.

Table 2. Predicted Seasonal Discharge Chloride Concentrations and Associated Salinities to Aimaokatalok Lake

Seasons		Under-ice	Freshet	Open-water
50th percentile	Chloride (mg/L)	1,749	778	1,483
	Salinity (ppt)	3.2	1.4	2.7
75th percentile	Chloride (mg/L)	1,750	1,070	1,582
	Salinity (ppt)	3.2	1.9	2.9
Maximum	Chloride (mg/L)	1,875	1,356	1,697
	Salinity (ppt)	3.4	2.4	3.1

Effluent temperature will also contribute to the overall density of the effluent. A temperature of 2°C was used for under-ice discharge scenarios as this will be the minimum temperature required to ensure that the effluent will not freeze in the discharge system. Discharge during the freshet period was modelled at 10°C based expected temperatures in surface collection ponds in June. The temperature during the open-water discharge in mid-summer was estimated at 15°C (SRK Consulting Ltd., personal communication).

3.3.1.1 *Ambient Conditions*

The main inputs required in the model included physical water column structure (depth and temperature) and currents. Discharge scenarios were modelled for both the open-water and under-ice periods (Table 1) to account for the seasonal differences in the aforementioned physical inputs.

Water Column

The physical structure and circulation of Aimaokatalok Lake is determined by the presence or absence of ice. When ice covered, the lake is weakly stratified, with a thin (~1-3 m) thermocline of colder surface waters (~0.5-0.7 °C) overlying the warmer bottom waters (~1.3-1.6°C; Rescan 2011). During the beginning of the freshet period, most of the lake remains under-ice, but temperatures at depth increase slightly (2°C) due to the exposure of the lake perimeter during early ice melt. By summer, the waters are much warmer (10 to 14°C; Rescan 2011) and well mixed.

For modelling purposes, data from representative temperature profiles collected during the under-ice, early freshet, and open-water seasons were used as inputs (Table 3). The winter profile was taken near the proposed diffuser location (April 25, 2010; Rescan 2011), while the freshet (June 3, 2006; Golder 2008) and summer profiles (August 14, 2010; (Rescan 2011) were taken from mid-lake stations.

Table 3. Baseline Temperature Profile Data Used in Modelling Scenarios

Under Ice (April 25, 2010)		Freshet (June 3, 2006)		Open Water (August 14, 2010)	
Depth (m)	Temp (°C)	Depth (m)	Temp (°C)	Depth (m)	Temp (°C)
0	-	0	-	0	13.9
1	-	1	-	1	13.8
2	0.7	2	1.5	2	13.7
3	1.2	3	1.7	3	13.7
4	1.3	4	1.8	4	13.7
5	1.4	5	1.8	5	13.7
6	1.4	6	1.8	6	13.7
7	1.5	7	1.9	7	13.7
8	1.5	8	1.9	8	13.7
9	1.5	9	1.9	9	13.7
10	1.5	10	1.9	10	13.6
11	1.5	11	1.9	11	13.6
12	1.6	12	1.9	12	13.6

Water Currents

Deep-water currents in Aimaokatalok Lake were more difficult to estimate given that in-situ measurements have never been taken in the lake. However, current measurements taken at other Arctic lakes have shown that under-ice currents can range between 0.001 m/s to more than 0.04 m/s (Mudge et al. 2012; Lewis et al. 2016). Because changes in ambient currents for extremely low velocity can play a significant role in the CORMIX plume dispersion, two ambient currents were modelled during the under-ice season: 0.001 m/s and 0.01 m/s.

During the freshet period, most of the lake is still under-ice; however, the exposure of the lake perimeter and the large runoff from snowmelt during the spring thaw can cause deep-water disturbances that significantly increase bottom currents. As such, ambient currents for the CORMIX simulations were set at 0.015 m/s, based on previous Arctic lake data showing at least a 50% increase in bottom currents at the onset of ice melt (Mudge et al. 2012).

For the open-water season, Aimaokatalok Lake circulation is dominated by winds, with average regional wind speed varying between 3 and 7 m/s. The winds are generally strong enough to remove any surface stratification and result in a well-mixed water column. Deep-water currents in large lakes during this period can range between 1 cm/s to 14 cm/s, with an average around 3 cm/s (Mudge et al. 2012). The average value was used for the open-water simulation.

3.3.1.2 Diffuser Configuration

A multi-port diffuser was used for the near-field modelling as it is often a critical design feature to achieve the dilutions required to meet receiving water quality objectives. The model inputs for the diffuser configuration were modified from a previous design for discharging mine effluent into an Arctic lake (Golder 2007). Table 4 shows the characteristics of the modelled diffuser, with the explanation given below. Note that this configuration is conceptual. A future sensitivity analysis will optimize the design to satisfy future Project and engineering requirements.

Table 4. Characteristics of Modelled Multi-Port Diffuser

Diffuser Length	40 m
# of Diffuser Ports	5
Port Diameter	0.0375 m
Port Vertical Angle	45 deg
Height Above Bottom	2.5 m
Port Horizontal Angle	0 deg
Port Alignment Angle	90 deg
Port Relative Orientation	90 deg

The diffuser configuration influences near-field mixing through variations in the number of ports as well as their diameter, height above the sediment surface, spacing along the diffuser, and exit velocity. The port diameter affects the dilution primarily by constricting the outgoing effluent jet; smaller port diameters tend to increase the jet velocity for a given discharge rate (in absence of aperture clogging), which increases the mixing and dilution with the ambient receiving water. A diameter of 0.0375 m was chosen as an acceptable threshold diameter.

The thickness of the water column available for effluent mixing primarily results from the diffuser port height above the bottom. Ports located closer to the bottom have greater mixing potential when discharging a buoyant effluent, but reduced mixing potential for a negatively buoyant plume. A diffuser port height of 2.5 m was assumed in this report for the calculation of dilution potentials.

The spacing of the diffuser ports is constrained by the minimum distance needed to reduce the plume overlap from different ports. Larger spacing enhances dilution by facilitating greater entrainment of ambient water into the plume. The length of the diffuser must also be larger than the water depth in the CORMIX model. The diffuser length was set as at 40 m anchored at 10 m depth. The ports were spaced at 10 m intervals and discharged at a 45 degree vertical angle to maximize the effluent travel time in the water. Port directions were assumed to be parallel to the ambient currents.

3.3.1.3 Channel Dimensions

The effluent was assumed to be discharged in a 522 m wide channel of roughly 10 km length as approximated by the bathymetric map (Figure A2).

4. SIMULATION RESULTS AND DISCUSSION

The near-field discharge plume behaviour was numerically simulated in Aimaokatalok Lake based on nominal operating conditions that could occur during the winter (ice covered), freshet, and summer (well-mixed open water) seasons. A total of four discharge scenarios were modelled (see Table 1): two in the winter (1-2), one during freshet (3), and one in the summer (4). The near-field centerline dilution results for each scenario is presented in Table 4, and the summary of each plume extent is presented in Table 5.

Given the greater chloride concentrations in the effluent, all simulated discharge scenarios resulted in negatively buoyant plumes.

4.1 Scenario 1: Under-ice (low currents)

The low ambient currents, port exit velocity, and large density difference between the effluent and ambient waters lead to a negatively buoyant plume during this scenario. The port jets did not merge during the simulation, instead the initial jet momentum made the individual plumes rise slowly to a maximum height of 3.4 m above the lake bottom before sinking towards the sediment. Each port plume traveled a maximum distance of 3.1 m horizontally before reaching the sediment, where the CORMIX model run ended. A maximum dilution of 40.4:1 was achieved at the extent of the near-field region (Table 4).

4.2 Scenario 2: Under-ice (high currents)

The higher currents in this scenario facilitated greater under-ice mixing when interacting with the effluent jet momentum at the port discharge. In this scenario, the port plumes rapidly merged, effectively diluting the effluent into neutral buoyancy with the plume starting to mix vertically. The plume was predicted to reach the sediment approximately 14.8 m from the diffuser, with dilutions over 735:1. At the near-field region extent of 20 m, the diffuser plume becomes vertically fully mixed over the entire layer depth (8.5 m) with dilutions up to 855:1. Afterwards the plume continued to spread laterally into the far-field, eventually achieving ambient mixing of 1,716:1 over 1,200 m from the diffuser.

Table 4. Near-field Centerline Dilution Results for Modelled Scenarios, Aimaokatalok Lake

1: Under-ice (low currents)		2: Under-ice (high currents)		3: Freshet *(under-ice)		4: Open-water (well-mixed)	
Distance from port (m)	Hydrodynamic Centerline Dilution	Distance from port (m)	Hydrodynamic Centerline Dilution	Distance from port (m)	Hydrodynamic Centerline Dilution	Distance from port (m)	Hydrodynamic Centerline Dilution
0	1	0	1	0	1	0	1
0.3	2.1	1	192	1	99	1	627
0.5	3.3	2	271	2	140	2	886
0.7	4.4	3	332	3	171	3	1,085
0.9	5.4	4	383	4	197	4	1,253
1.2	6.3	5	428	5	220	5	1,400
1.4	7.4	6	469	6	241	6	1,534
1.7	8.5	7	506	7	260	7	1,657
1.9	9.8	8	541	8	278	8	1,771
2.1	11.3	9	574	9	295	9	1,878
2.2	13.1	10	605	10	311	10	1,980
2.4	15	11	634	11	326	11	2,077
2.5	17.1	12	662	12	340	12	2,169
2.6	19.5	13	689	13	354	13	2,258
2.7	22	14	715	14	367	14	2,343
2.8	24.7	15	740	15	380	15	2,425
2.9	27.5	16	765	16	393	16	2,504
2.9	30.6	17	788	17	405	17	2,581
3	33.7	18	811	18	416	18	2,656
3.1	37	19	833	19	428	19	2,729
3.1	40.4	20	855	20	439	20	2,800

Table 5. Summary of Modelled Plume Mixing Zone Results for Under-ice and Open-water Discharge Scenarios

Scenarios	1: Under-ice (low currents)	2: Under-ice (high currents)	3: Freshet *(under-ice)	4: Open-water (well-mixed)
Model Inputs				
Effluent Discharge Rate (m^3/d)	350	350	1,130	375
Effluent Density (kg/m^3)	1,002.5	1,002.5	1,001.3	1001.4
Ambient Water Density (kg/m^3)	999.988	999.988	999.997	999.159
Ambient Current Velocity (m/s)	0.001	0.01	0.015	0.03
Model Outputs				
Distance from Diffuser that Plume hits Bottom (m)	3.1	14.8	14.5	12.3
Dilution at Plume/Sediment Boundary	40.4	624	374	2,200
Near-field Region Extent (m)	3.1	20	20	20
Dilution at Near-field Boundary	40.4	855	439	2,800
Maximum Centerline Plume Height in Near-Field Region (m)	3.4	3.3	3.3	3.5

4.3 Scenario 3: Freshet (under-ice)

The freshet scenario displayed the same characteristics of the high current, under-ice regime; that is, rapid merging of the port jets with the effluent plume being vertically fully mixed at the extent of the near-field region. Dilutions were overall lower due to the greater discharge occurring during the freshet period. The effluent plume reached the sediment approximately 14.5 m from the diffuser, with dilutions around 374:1. A dilution ratio of 439:1 was estimated at the end of the 20-m near-field boundary. Beyond the near-field region, the plume continued to spread laterally into the far-field with dilutions of 942:1 over 1,600 m from the diffuser.

4.4 Scenario 4: Open-water (well-mixed)

The open-water scenario displayed the same characteristics as both Scenarios 2 and 3, and had by far the greatest mixing potential of all modelled cases. The combination of a lower discharge rate and higher ambient currents lead to a dilution of over 627:1 merely 1 m from the diffuser pipe. The effluent plume reached the sediment approximately 12.3 m from the diffuser, with dilutions around 2,200:1. The plume was nearly indistinguishable from the ambient waters at the near-field boundary of 20 m, with a dilution of 2,800:1.

5. CONCLUSIONS

The simulations revealed that the effluent plume will be negatively buoyant under all discharge scenarios, given the density differences between the effluent and the ambient waters. The potential for dilution within Aimaokatalok Lake is highly dependent on the ambient current velocities of the receiving water. During the under-ice simulations with very low currents (0.001 m/s), the diffuser jet plumes did not merge and the effluent reached the sediment bottom at the end of the near-field boundary (3.1 m), with dilution of over 40:1. For the other three scenarios, large dilutions (>400:1) were attained within the near-field plume boundaries due to greater currents. The latter discharge plumes were predicted to become neutrally buoyant close to the diffuser and achieved much greater dilutions (~1,000:1) in the far-field.

The present modelling results were used to support the water and sediment quality assessments in TMAC's Phase 2 draft EIS (TMAC 2016) and will be used to guide future diffuser optimization and engineering design.

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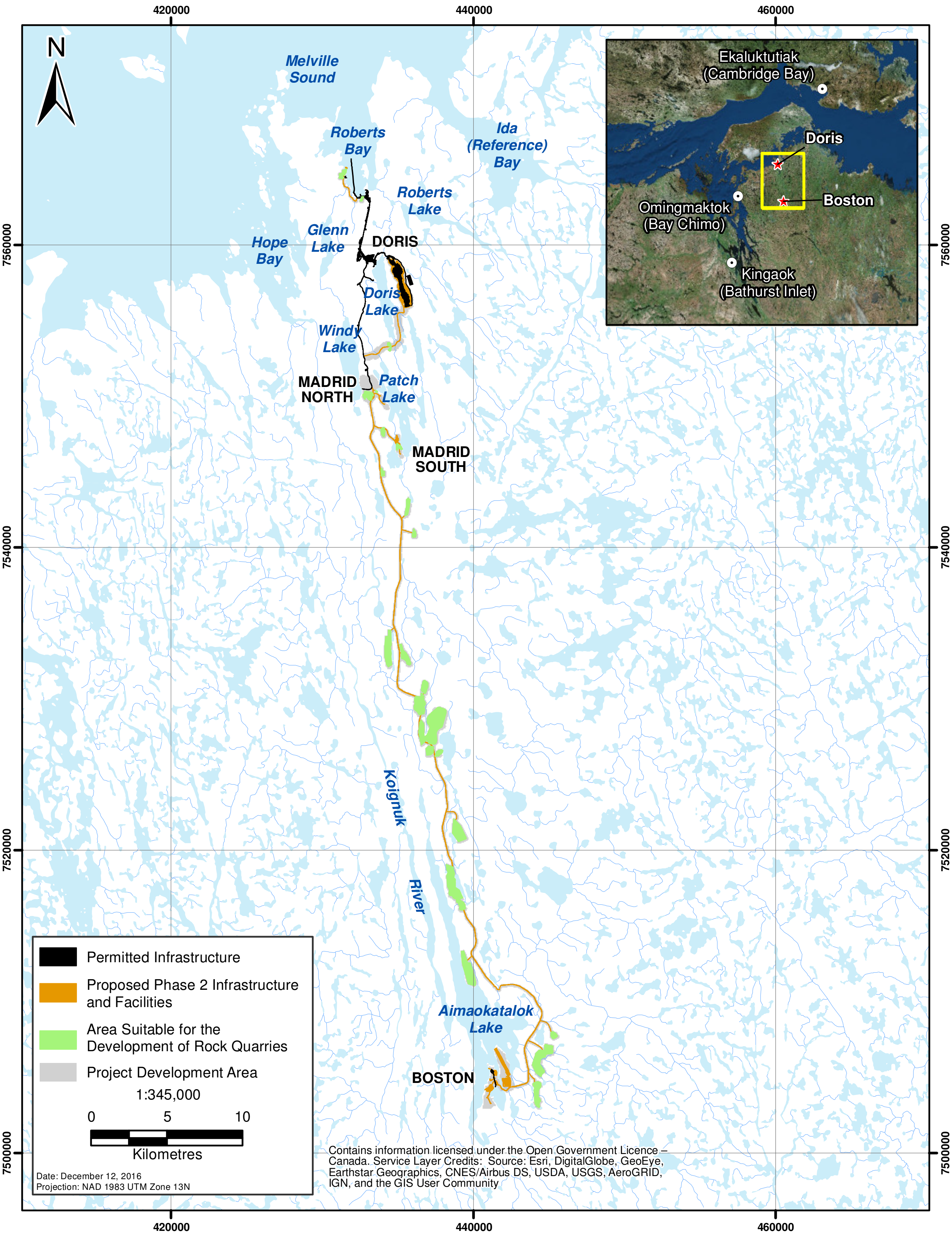
— Appendix A —

Appendix A1. Hope Bay Project Location

Appendix A2. Bathymetry and Proposed Boston WTP Discharge Location, Aimaokatalok Lake

Appendix A1

Hope Bay Project Location and Existing and Proposed Phase 2 Infrastructure



Appendix A2

Bathymetry and Proposed Boston WTP Discharge Location, Aimaokatalok Lake