Appendix V5-4E

Far-field Hydrodynamic Mixing Modeling for Discharges to Aimaokatalok Lake

TMAC RESOURCES

Memorandum

Date: December 14, 2017

To: Oliver Curran and John Roberts, TMAC Resources Ltd.

From: ERM Consultants Canada Ltd.

Subject: **Hydrodynamic Mixing Modelling and Water Quality Predictions for Discharges to Aimaokatalok Lake**

1. INTRODUCTION

This memorandum presents the hydrodynamic mixing modeling results and water quality predictions for the proposed discharge of treated effluent into Aimaokatalok Lake from the Madrid-Boston Project (the Project). TMAC Resources Ltd. (TMAC) is in the process of permitting the Project, with the intent of mining gold from the Boston and Madrid deposits within the broader Hope Bay Project area (Figure 1-1) located 153 km from Cambridge Bay on the northern coast of the Nunavut mainland. The Boston deposit is in the southernmost section of the 80-km long Hope Bay Greenstone Belt, with mining activities occurring along the southeastern end of Aimaokatalok Lake.

The water management strategy at the Boston site will involve combining three treated effluent streams and discharging the water into Aimaokatalok Lake through a single pipeline-diffuser system (ERM 2016; SRK 2017). The three treated effluent streams will originate from the Boston Process Plant Water Treatment Plant (WTP; treated mill bleed), the Boston Contact WTP (treated site contact water from the waste rock pile, ore storage pad, crown pillar recovery trenches, and other mine surfaces), and the Boston Sewage Treatment Plant (STP). Near-field mixing modeling related to this discharge was conducted previously as part of TMAC's *Phase 2 Draft Environmental Impact Statement* (DEIS; TMAC 2016). This modeling predicted that dilutions of 40:1 to 1,100:1 would be achieved within 3 m of the diffuser under multiple scenarios (e.g., under ice, open water), and all aquatic life water quality criteria would be met within this distance (ERM 2016; TMAC 2016). As part of the information requests and technical meetings that followed the DEIS submission, intervenors commented on uncertainties involving the pooling of effluent in bathymetric depressions and the possible retention of water quality constituents within the lake. This hydrodynamic modeling and water quality prediction exercise has been conducted to address these requests.

The specific objectives of the hydrodynamic modeling and predictive water quality exercises were to:

- present a hydrodynamic model that validates model-generated temperature profiles against *in situ* measurements at multiple sites in Aimaokatalok Lake (Commitment INAC-TRC01);

- assess potential effluent pooling in bathymetric depressions in Aimaokatalok Lake (Commitment INAC-TRC02);
- predict the dispersion of the effluent plume and dilutions achieved in Aimaokatalok Lake during the ice-covered and open-water season;
- predict concentrations of key water quality parameters during the period of discharge to ensure Aimaokatalok Lake water is protective of aquatic life; and
- support the water and sediment quality assessments in TMAC's *Madrid-Boston Final Environmental Impact Statement* (FEIS; TMAC 2017) submitted to the Nunavut Impact Review Board (NIRB) in December 2017.

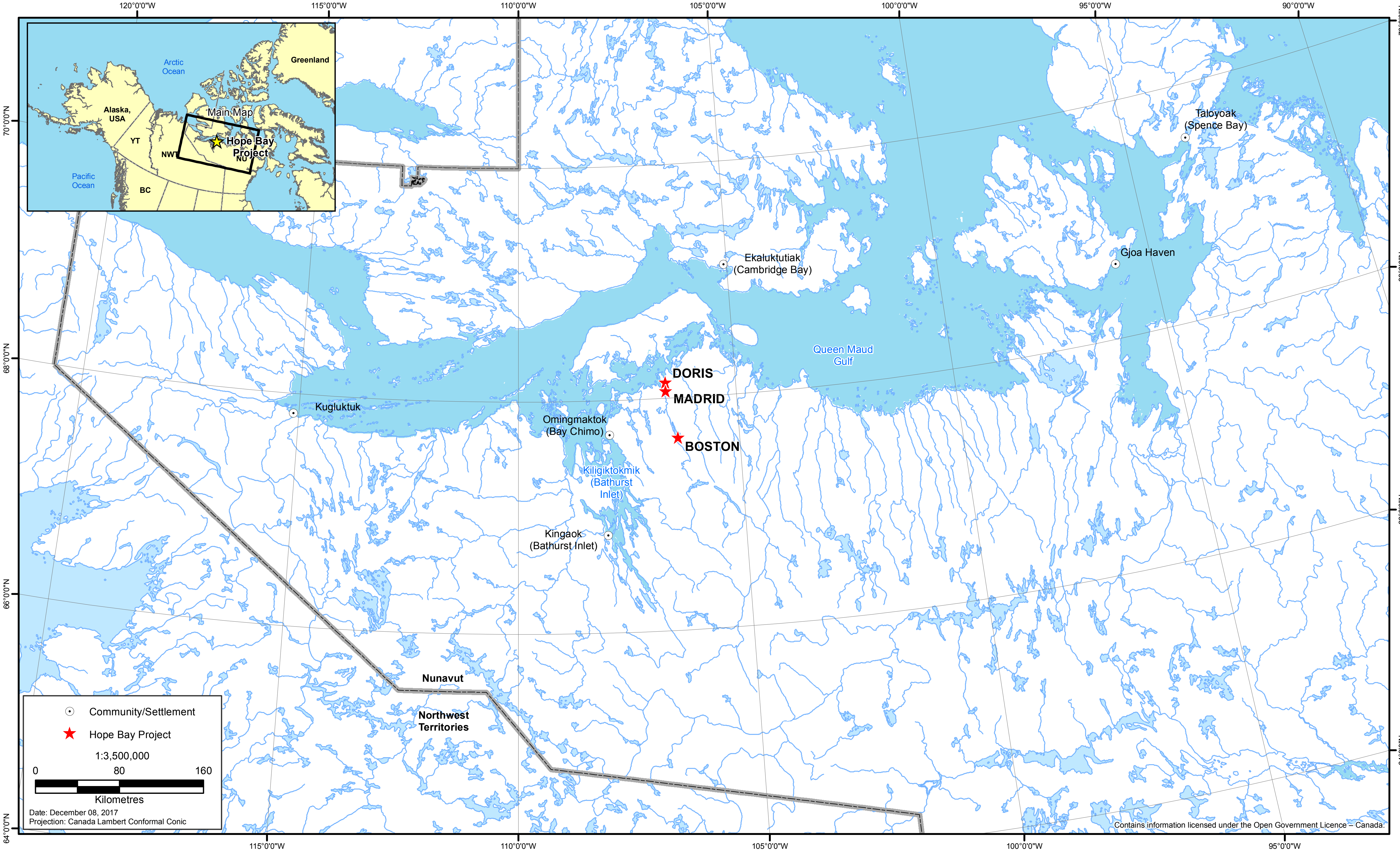
While there are other Project effects that will contribute to the water quality of Aimaokatalok Lake, this modeling and predictive water quality exercise focuses on the combined Boston WTP/STP discharge (Boston combined discharge herein) to the lake during Boston-Madrid operations. The non-discharge sources have been incorporated into the overall modeling exercise using predicted water quality and flow data from the *Hope Bay – Water and Load Balance* (SRK 2017) that was submitted with the Madrid-Boston FEIS. Calculations have shown that the Boston combined discharge source requires the greatest dilution to be safe for aquatic life. More specifically, chromium requires the greatest dilution to meet Canadian Council of Ministers of the Environment (CCME) water quality guidelines for the protection of aquatic life and was therefore included in the water quality predictions. Total phosphorus was also predicted since STP waters will be conveyed to Aimaokatalok Lake and total phosphorus is a nutrient that could increase primary production in the lake.

The mixing of the Boston combined discharge in Aimaokatalok Lake (extent and dilutions therein) was conducted using the Generalized Environmental Modeling System for Surfacewaters (GEMSS®), a three-dimensional freshwater and marine model that can simulate unsteady discretized flows while accounting for density variations, bathymetry, and external forcings such as riverine inputs and wind. Other built-in features of the model include flooding and drying of coastal land, sediment bed resistance, turbulence modeling, sources/sinks of external waters, winter ice growth, and heat exchange with the atmosphere.

Document Layout

This memo is structured as follows: Section 2 presents an overview of the Boston mining area and the discharge pipeline-diffuser system; Section 3 describes the necessary dilution required for the effluent to meet all CCME water quality objectives in Aimaokatalok Lake, and provides rationale for selecting chromium for water quality predictions; Section 4 presents the background and methodology used for the construction of the hydrodynamic numerical model; and Section 5 presents and discusses the results of the modeling and predictive exercises.

Figure 1-1
Hope Bay Project Location



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 (Figure 1-1). Aimaokatalok Lake is large (> 20 km length), irregularly shaped, and flows northwards into Hope Bay by way of the Koignuk River (Figure 2-1). The average depth of the lake is 6 m, with a maximum depth of 30 m in the central basin, and a lake volume near 140,000,000 m^3. 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.

Mining the Boston deposit is expected to occur in Year 4 of the Project, with ore being processed through the Boston Process Plant in Year 5. A maximum total of 5.1 Mt of ore and 2.2 Mt of waste rock will be processed from the underground development over the 12-year Project life, with a maximum throughput of 2,400 tpd from Year 7 to Year 10. Mining at the Boston site will be completely within permafrost, and no interception of talik groundwater is anticipated. Mill bleed from the Boston Process Plant will be treated in a three-stage WTP to remove metals and nitrogen, while site contact water collected in event contact water ponds (CWP) will be treated in a two-stage WTP to remove metals. These treated waters will then be combined with the treated sewage water and discharged to Aimaokatalok Lake. The Boston combined discharge is slated to begin in Year 2 when the Boston site CWPs start collecting water, and will continue through to Year 13 before the site enters post-closure. Average flows from the Boston combined discharge are estimated at 500 m^3/d, peak flows during freshets at 1,600 m^3/day, and average annual flows approaching 210,000 m^3/yr (SRK 2017). The average annual flow represents less than 0.15% of the lake volume.

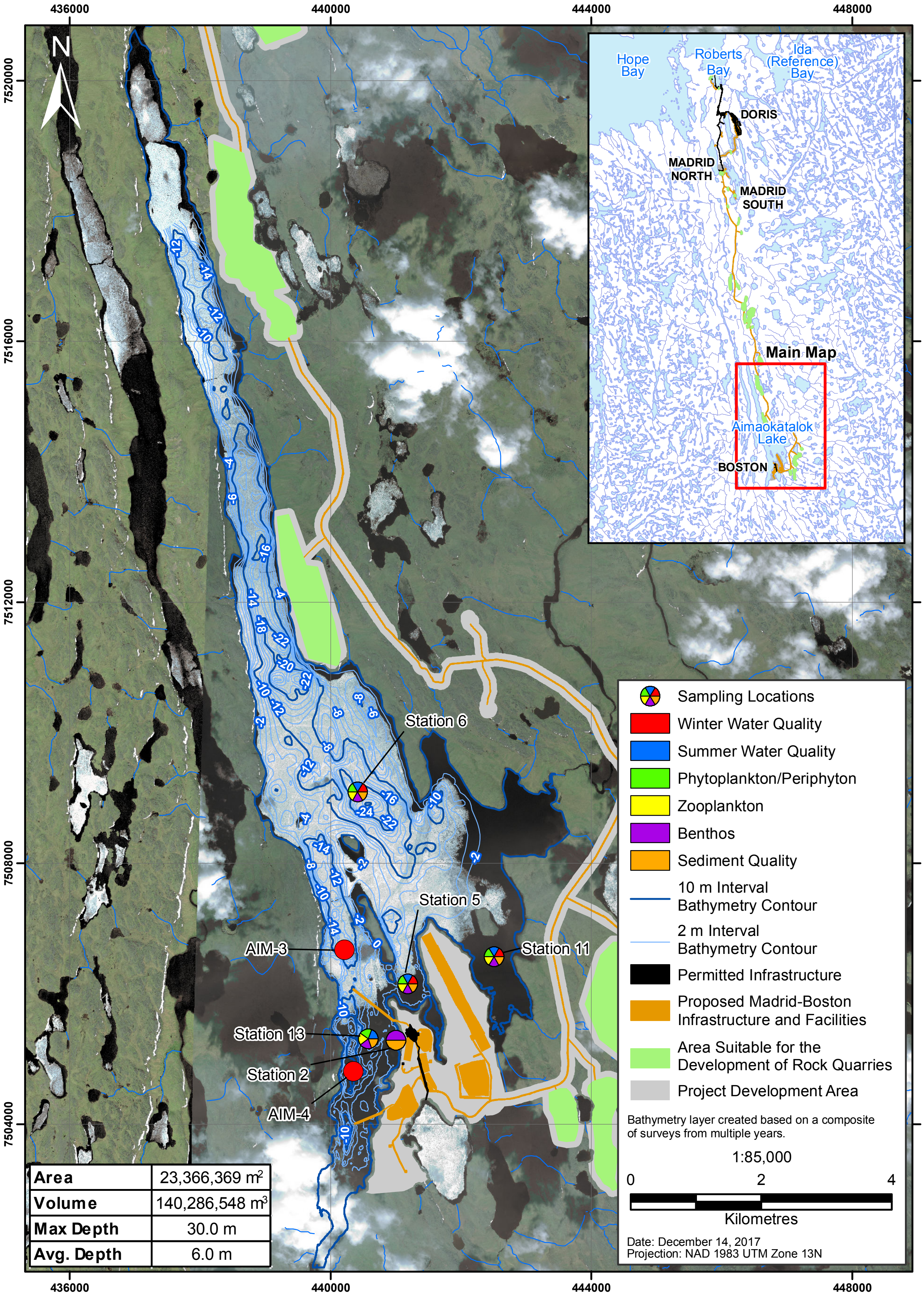
2.2 Discharge System

The treated water will be discharged to Aimaokatalok Lake through a submarine pipeline-diffuser outfall system. The pipeline is projected to run approximately 850 m from the shoreline into the southwestern basin of the lake, discharging into an area of deeper bathymetry (10 m; Figure 2-1). 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 currently proposed for Aimaokatalok Lake is conceptual, and details regarding its configuration and mixing are provided in ERM (2016). The presented modeling work 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.

Figure 2-1

Bathymetry and Proposed Boston Combined Discharge Location, Aimaokatalok Lake



3. WATER QUALITY PREDICTIONS

Water quality predictions were generated for two water quality parameters, total phosphorus and chromium. Total phosphorus was selected since STP waters will be conveyed to Aimaokatalok Lake and elevated phosphorus inputs could increase primary production in the lake. Chromium was selected because it is predicted to require the greatest dilution (11.6×) to meet CCME water quality guidelines for the protection of aquatic life, and its baseline concentration tended to be closer to the guideline limit thereby reducing its assimilatory capacity. Table 3-1 summarizes the comparison of predicted water quality concentrations in the Boston combined discharge (SRK 2017) with the applicable CCME guideline concentrations as well as presenting corresponding predicted and measured baseline concentrations in Aimaokatalok Lake. It was assumed all water quality would be protective of aquatic life in Aimaokatalok Lake if chromium concentrations were predicted to be less than the conservative concentration for hexavalent chromium (0.001 mg/L).

Table 3-1. Summary of Aimaokatalok Lake Baseline and Predicted Boston Combined Discharge Water Quality Concentrations for CCME Parameters

Parameter	CCME	Baseline – Aimaokatalok Lake		Predicted Boston Effluent Median[a]	Observed 75th: CCME (X:1)	Dilution Required to Meet CCME (X:1)
		Observed 75th	Predicted Median[a]			
Fluoride	0.12	0.031	0.0	**0.12**	0.26	**1.0**
Chloride	120	13.6	8.3	**539**	0.11	**4.5**
Ammonia (as N)	5.7[b]	0.012	0.010	**10**	0.01	**1.7**
Nitrate (as N)	3	0.042	0.010	1	0.01	0.3
Sulphate	128[c]	2.5	3.0	**226**	0.02	**1.8**
Aluminum	0.1	0.057	0.045	**0.22**	0.57	**2.2**
Arsenic	0.005	0.00019	0.00016	**0.012**	0.04	**2.3**
Boron	0.5	0.0072	0.0049	0.14	0.01	0.3
Cadmium	0.00012	0.0000035	0.0000054	0.000080	0.03	0.7
Chromium	0.001	0.00030	0.00025	**0.012**	0.30	**11.6**
Copper	0.002	0.0012	0.00091	0.0016	0.59	0.8
Iron	0.3	0.11	0.097	**1.1**	0.37	**3.7**
Lead	0.001	0.000049	0.000034	**0.0016**	0.05	**1.6**
Mercury	0.000016	0.0000015	0.0000017	**0.00017**	0.09	**10.6**
Molybdenum	0.01	0.000053	0.000045	0.0078	0.01	0.8
Nickel	0.025	0.00052	0.00040	0.0074	0.02	0.3
Selenium	0.001	0.00035	0.00019	**0.0016**	0.35	**1.6**
Silver	0.00025	0.0000050	0.0000019	**0.00062**	0.02	**2.5**
Thallium	0.0008	0.0000036	0.0000043	0.00034	0.00	0.4

(continued)

Table 3-1. Summary of Aimaokatalok Lake Baseline and Predicted Boston Combined Discharge Water Quality Concentrations for CCME Parameters (completed)

Parameter	CCME	Baseline – Aimaokatalok Lake Observed 75th	Baseline – Aimaokatalok Lake Predicted Median[a]	Predicted Boston Effluent Median[a]	Observed 75th: CCME (X:1)	Dilution Required to Meet CCME (X:1)
Uranium	0.01	0.000026	0.000020	0.0014	0.00	0.1
Zinc	0.03	0.0022	0.0020	0.017	0.07	0.6

Notes:
All concentrations are in mg/L.
Bold indicates greater than CCME Water Quality Guideline for the Protection of Aquatic Life.
CCME concentrations represent minimum limits without hardness modifying factors.
Free cyanide and nitrite were not included because of their rapid transformations to other nitrogen constituents in oxygenated waters.
[a] Predicted lake baseline and effluent concentrations from Hope Bay Project - Water and Load Balance (SRK 2017) outputs.
[b] Assumes discharge temperature of 15°C and pH of 7.0.
[c] Minimum British Columbia sulphate guideline for the protection of aquatic life.

The information in Table 3-1 indicates the following:

- Nearly half of the water quality parameters in the Boston combined effluent are not expected to require dilution to meet CCME guidelines in Aimaokatalok Lake;
- Chromium requires the greatest dilution (11.6×) to meet its CCME water quality guideline in the lake, and its observed baseline concentration is about 37% of the conservative hexavalent chromium guideline concentration of 0.001 mg/L;
- Mercury requires the second greatest dilution (10.6×) to meet its CCME guideline limit in the lake, although its observed baseline concentration is more than an order of magnitude less than the guideline limit (9%);
- Observed baseline levels of copper (59%) and aluminum (57%) are closest to their *in situ* CCME guideline limits, but copper within the effluent does not require dilution, and aluminum only requires 2.2× dilution to meet CCME receiving water criteria.

From Table 3-1 it can be surmised that if the Boston combined discharge is diluted by more than 11.6:1 within the Aimaokatalok Lake mixing zone then all water quality will be protective of aquatic life in the lake as it relates to the Boston combined discharge.

4. AIMAOKATALOK LAKE MODEL

The Aimaokatalok Lake model was developed using a three-dimensional, hydrodynamic and water quality model called the Generalized Environmental Modeling System for Surfacewaters (GEMSS®). This model was selected based on its successful use on similar water quality studies for small lakes with introduced effluents, particularly its ability to represent the seasonal onset, extension, and overturn of lake stratification. The model is capable of simulating ice growth, complete with salt exclusion, as well as detailed descriptions of water quality constituents to accurately depict near- and far-field mixing.

4.1 GEMSS® General Description

GEMSS® is an integrated system of three-dimensional hydrodynamic and transport modules embedded in a geographic information and environmental data system. GEMSS® is in the public domain and has been used for hydrodynamic and water quality studies at other northern Canadian mines (e.g., Ekati Diamond Mine, Northwest Territories), and more generally throughout the USA and worldwide. The software was developed in the mid-80s as a hydrodynamic platform for transport and fate modeling of many types of constituents introduced into waterbodies. The hydrodynamic platform (“kernel”) provides three-dimensional flow fields from which the distribution of various constituents can be computed. The constituent transport and fate computations are grouped into modules that include those used for thermal analysis, water quality, sediment transport, particle tracking, oil and chemical spills, entrainment, and toxics.

The theoretical basis of the hydrodynamic kernel of GEMSS® is the three-dimensional Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport (GLLVHT) model which was first presented in Edinger and Buchak (1980) and subsequently in Edinger and Buchak (1985). The GLLVHT computation has been peer reviewed and published (Edinger, Buchak, and McGurk 1994; Edinger and Buchak 1995; Edinger, Wu, and Buchak 1997; Edinger and Kolluru 1999). The kernel is an extension of the well-known longitudinal-vertical transport model written by Buchak and Edinger (1984) that forms the hydrodynamic and transport basis of the Corps of Engineers' water quality model CE-QUAL-W2 (U. S. Army Engineer Waterways Experiment Station, Environmental Laboratory, and Hydraulics Laboratory 1986). Improvements to the transport scheme, construction of the constituent modules, incorporation of supporting software tools, GIS interoperability, visualization tools, graphical user interface (GUI), and post-processors have been developed by Kolluru, Buchak, and Edinger (1998); Edinger and Kolluru (1999); Kolluru, Buchak, and Wu (1999); Kolluru et al. (2003); Kolluru and Fichera (2003) and by Prakash and Kolluru (2006). GEMSS® development continues as additional applications are completed. For inland waterbodies, GEMSS® has been used for assessing mining discharges in subarctic Canadian lakes (DDEC 2017); mine pit lake analysis (Vandenberg et al. 2011; Prakash, Vandenberg, and Buchak 2012); validating temperatures in cooling lakes (Long et al. 2011; Buchak et al. 2012); temperatures and nutrients in the Han River (Kim and Park 2012a, 2012b) and Lake Paldang, Korea (Na and Park 2005, 2006); and temperature and fecal coliforms in northern Norwegian water supply reservoirs (Tryland et al. 2012).

A GEMSS® application typically requires three types of inputs:

- Lake bathymetry;
- Meteorological data; and
- Lake Inflow/Outflow characteristics with associated transport quantities.

The sources of these model inputs are described in detail below.

4.2 Model Inputs

4.2.1 Aimaokatalok Lake Bathymetry and GEMSS® Model Grid

Aimaokatalok Lake has three distinct regions that comingle together (Figure 2-1):

- a long (> 10 km) and comparatively narrow (~ 1 km) western corridor of 4 to 5 m average depth with several deeper canyons (> 10 to 15 m depths) and a deeper mid-lake basin (~25 m depth);
- the central broader portion of the lake that contains the deepest bathymetric features (30 m depth); and
- a large eastern basin with generally much shallower bathymetries (average of 2 to 3 m depth).

The lake has also several small islands that are located in the southern portion of the middle basin.

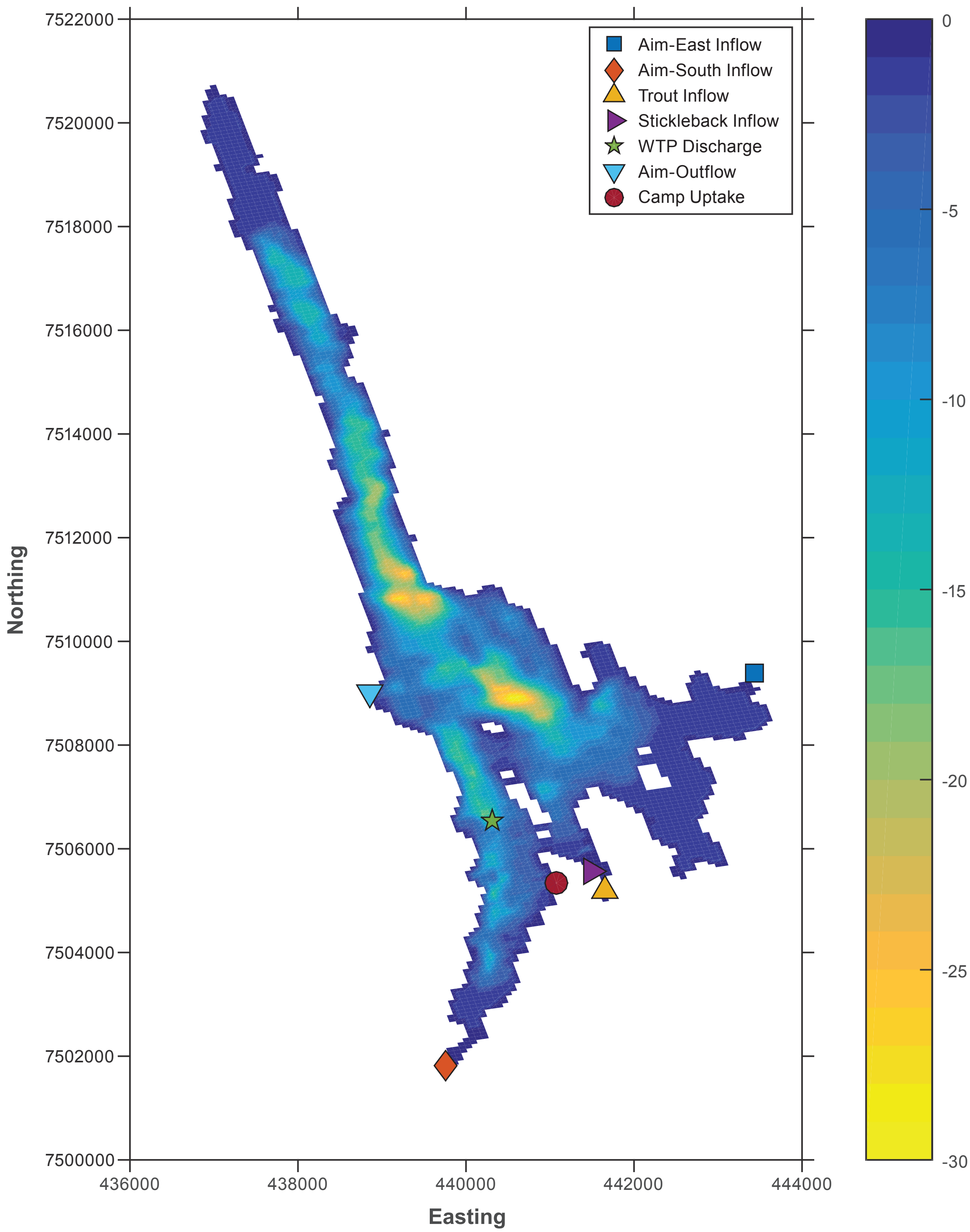
The best available bathymetric information (Figure 2-1) was used in the development of GEMSS® 3-D model grid for Aimaokatalok Lake (Figure 4-1). The model grid consists of 1,233 active surface cells with horizontal grid cell dimensions of 100 m × 100 m. The water column is sub-divided into 30 vertical layers with a resolution of 1 m, which capture the deepest portions of the western and central regions of the lake. This resulted in a total of 4,936 active surface water cells during the open-water season and an average of 15,593 total active water cells during year-long simulations. Lake volumes and water levels significantly vary between seasons (up to 3+ m; Rescan (2011b)), and the model allows variations of up to 5 m to accommodate large freshet flows and ice covers.

4.2.2 Meteorological Data

GEMSS® requires the following information to accurately represent temperatures and currents: wind speed and direction; air and dew temperature; atmospheric pressure; relative humidity; and solar radiation. Data from the surrounding area are available since 2006 and have been recorded continuously near the Boston Camp location since 2009. The methodology for these baseline data are described in detail in Rescan (2011c). Winds measured at this site on the southern shore of Aimaokatalok Lake were applied across the entire model domain. During the model calibration/baseline simulation, only the meteorological data available during 2010 were used. For the complete 12-year simulation across the construction, operation, and closure Project phases, each simulation year was randomly assigned to a measured wind year recorded between 2010 and 2014, with each of the measured years being used at least once. Preliminary tests done using a 10-year average of the winds yielded unrealistic wind vectors and lake currents, thus randomizing the wind years resulted in more natural variability of the climate. Extensive testing also yielded the most realistic modeled ice cover growth and decay for the data available between 2010 and 2014.

Figure 4-1

Bathymetry and Inflow/Outflow Locations, Aimaokatalok Lake Model



4.2.3 *Lake Inflow and Outflow Characteristics*

The freshwater inflow and outflow quantities for initiating the GEMSS® 3-D modeling of Aimaokatalok Lake were obtained from the GoldSim Pro™ (version 11.1.5) model inputs used by SRK (2017). Monthly discharge flows and water quality characteristics were used to define time varying inputs for the following stream/catchments (see Figure 4-1): Aimaokatalok Inflow East, Aimaokatalok Inflow South, Stickleback Outflow, Trout Outflow, Camp Uptake and Aimaokatalok Outflow (to Koignuk River). Additionally, the disturbed and undisturbed watershed runoff flows were simulated using distributed flows along the camp location shore (disturbed) and the remainder of the lake's shore (undisturbed). The time varying inflows to the GEMSS® model exactly reproduced the data provided by SRK (2017) to facilitate water quality comparisons between both studies. Ice cover growth and decay was incorporated in the GEMSS® model using a simplified ice growth model as detailed in Brady, Graves, and Geyer (1969). As a conservative assumption, water was removed from the lake while constituents were left behind in the water during ice formation. This "cryo-increase" in winter concentrations is consistently seen in the Project lakes (Rescan 2010, 2011a), and is in part due to the rejection of solutes during ice formation (biogeochemical processes also play a role). The evaporation rates during the simulation were also adjusted to be compatible with the increased evaporation as detailed by SRK (2017).

4.2.4 *Boston Effluent Description*

The main effluent inputs included the discharge rate, density (salinity and temperature), and parameter concentrations so that resulting dilutions and far-field concentrations could be calculated. All discharge rates and water quality concentrations were taken from the site-wide water and load balance for the Hope Bay Project (SRK 2017).

Discharge Rates

The mine water and sewage effluent streams were modeled as maximum, continuous discharges at the designed monthly pump rates used in SRK (2017). These are predicted to range from 250 to 450 m^3/d during the under-ice season, up to approximately 1,600 m^3/d during freshet, and from 500 to 700 m^3/d during the open-water season.

Density

The effluent sources will potentially have different thermohaline characteristics thereby affecting the density and buoyancy of the discharge. The discharge will generally have elevated levels of total dissolved solids (TDS) from which conductivity can be estimated using the simple formula TDS = Conductivity × 0.65 (Carlson 2005). Salinity and ultimately density can then be estimated using standard densimetric algorithms (UNESCO 1983). This method led to more conservative densities than simply estimating salinity from dissolved chloride.

Effluent temperature also contributes 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 modeled at 2°C over maximum expected temperatures in surface collection ponds in June, while during the summer period the effluent was assumed to be 2°C over the maximum daily inflow stream temperatures.

4.3 2010 Baseline Simulation

The first step for the modeling was to simulate the open-water 2010 conditions in Aimaokatalok Lake using the observed meteorological and hydrological measurements collected in 2010 (Rescan 2011b, 2011a, 2011c). Actual measured baseline data, whenever available, were used within the model, and included: winds, freshwater discharges, atmospheric temperatures, and relative humidity. All other variables were taken as constants or were modeled using physical models, and fine-tuned until agreement between modeled and measured temperature profiles was found. The model was run for 18 months to undergo a complete ice cycle.

The comparison of predicted water column temperatures for five available baseline stations (Stations 2, 5, 6, 11 and 13; see Figure 2.2-1) is depicted in Figure 4-2 for the August 2010 sampling period (Rescan 2011a). The modeled values tracked the baseline conditions, with modeled temperatures on average within approximately 0.2 to 0.5°C of measured profiles. A small difference in stratification was seen for the Station 6 deep site at approximately 20 m depth, where the modeled temperatures were roughly 1°C above the observed profile; however, bottom water temperatures were nearly identical which is a good indication that the model accurately transfer heat and momentum from the surface down to the lake bottom.

Modelled water column temperatures were also compared to recent measurements at station AIM-3 (i.e., approximately 14 m depth close to the proposed outfall location) in August 2017, shown in Figure 4-3. The calibration period used 2010 input data and no 2017 meteorological data was available, however August summer conditions in the area are generally consistent between years. The August 18, 2017 temperature profile is shown next to average profiles from the model results for August 16, 17 and 18 of the calibration year. Although the measured profile shape differs slightly from model results, the range of modeled temperatures is generally within 0.5°C of the August 2017 data. Overall Figures 4-2 and 4-3 indicate that the model can accurately predict temperature profile in the salient bathymetric features of Aimaokatalok Lake.

4.4 Simulation Time and Initial Conditions

The model was first set to run at a 120 s time step for 365 days between June 1 and December 31, 2019. This range was defined as the calibration period, where the calculated model adjusted itself with respect to the inflow/outflow model inputs. The initial constituent parameter values for all model grid cells are shown in Table 4-1. For the full Project simulation run, the model was run from 2020 to 2032 at a 120 s time step, encompassing the full duration of the Boston combined discharge.

Table 4-1. Initial Constituent Parameter Values in Aimaokatalok Lake Model

Constituent	Value
Temperature (°C)	0.50000
Salinity (ppt)	0.02150
Total Phosphorus (mg/L)	0.01150
Total Chromium (mg/L)	0.00025

Note:
Total phosphorus and chromium concentrations are median observed baseline values from data collected between 2007 and 2017.

Figure 4-2

Measured vs. Modelled Profile Temperatures, Aimaokatalok Lake, August 2010

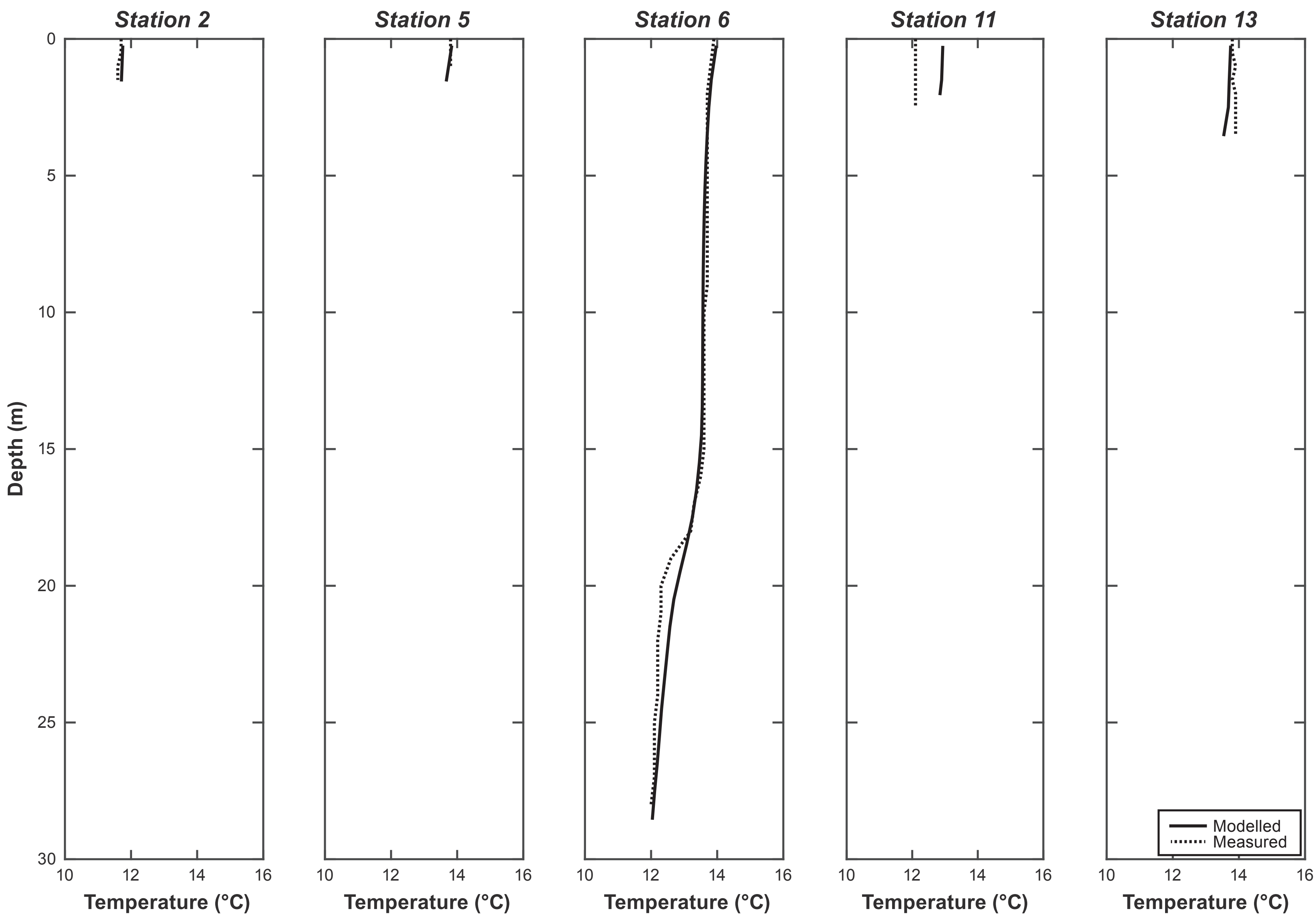
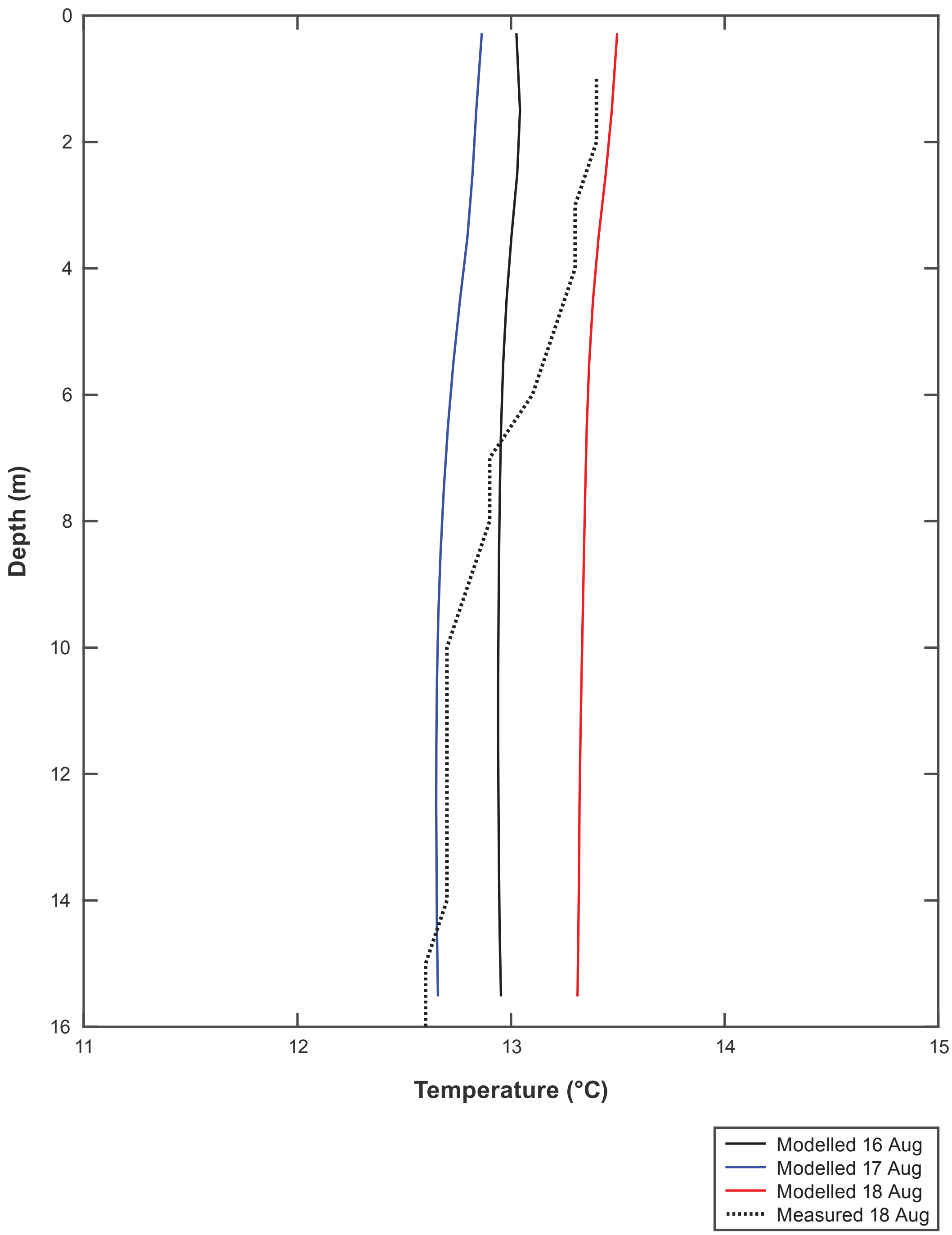


Figure 4-3

Measured vs. Modelled Profile Temperatures, Aimaokatalok Lake Station AIM-3, August 2017



5. SIMULATION RESULTS AND DISCUSSION

The Boston combined discharge plume behaviour was numerically simulated in Aimaokatalok Lake based on nominal yearly operating conditions that could occur during the winter (ice covered), freshet, and summer (well mixed, open water) seasons. Total phosphorus and chromium concentrations were predicted over the temporal scale of the Boston combined discharge and the spatial scale of all of Aimaokatalok Lake (all depths and locations).

5.1 Seasonal Cycle, Dilution, and Pooling

The model accurately captures the ice growth and decay cycles of northern Arctic lakes and watersheds (e.g., Woo 1990), as can be seen in the modeled thicknesses in Figure 5-1. Ice growth generally starts by late October, and ends around April/May, with recorded peak thicknesses at 1.4 to 1.9 m, which is very similar to baseline data measurements in Aimaokatalok Lake (Volume 5, Chapter 3 in TMAC 2017). The rapid onset of ice melting in late May/early June, coupled with large freshet flows, results in surging lake volumes that peak in late June/early July. Water volumes generally diminish during the open-water season as water is lost through the outflow stream and evaporation, with slight increases in volume during the fall months (September/ October) as precipitation and runoff increase. Water volumes then decrease throughout winter primarily due to ice production and lack of freshwater inflows, before surging again in the spring.

The large yearly variations in volume contributed to the efficient mixing and flushing of the lake waters during the open-water seasons. Examples of contour dilution plots for surface and bottom waters during May and August 2023 are shown in Figures 5-2 and 5-3. Given the greater density in the effluent, the simulated Boston combined discharge resulted in the negatively buoyant plume spreading along the bottom lake canyon next to the discharge location during the ice-covered months (Figure 5-2). Bottom water dilutions in May 2023 clearly show the under-ice plume signature as it extends over 2 km northwards towards the outflow. Minimum average dilutions are close to 40:1 near the discharge point, similar to past results of near-field dilution mixing for the lake (ERM 2016). Mid-plume dilutions generally range from 100 to 250:1, with the edge dilution values closer to 400:1. The under-ice plume waters are eventually diluted by more 1,000:1 at the lake outflow.

At the onset of the open-water season, the lake waters are rapidly flushed with the melting ice waters/surface runoff and stratification erodes within the water column, as observed in the modeled average August 2023 dilutions in Figure 5-3. Dilution factors in surface and bottom waters are well above 1,000:1 for most regions, and reach 1,000,000:1 at the major inflow locations (i.e., Aimaokatalok East, South and the Trout/Stickleback channel). Only in the direct vicinity of the discharge outfall is the plume signature still apparent, with average recorded minimum dilutions of 250:1. This signal is only present for a few hundred metres beyond the discharge location before mixing with the ambient waters. The plume is not visible in the surface water dilutions.

The winter accumulation and subsequent open-water season flushing is also observed in time-varying water column density profile plots, as shown in Figure 5-4 for the following locations: 250 m from the outfall discharge point; deep Station 6 in the north central basin; and AIM-4 station in the southern portion of the lake.

Figure 5-1

Average Ice Thicknesses and Total Lake Water Volumes, Aimaokatalok Lake Model

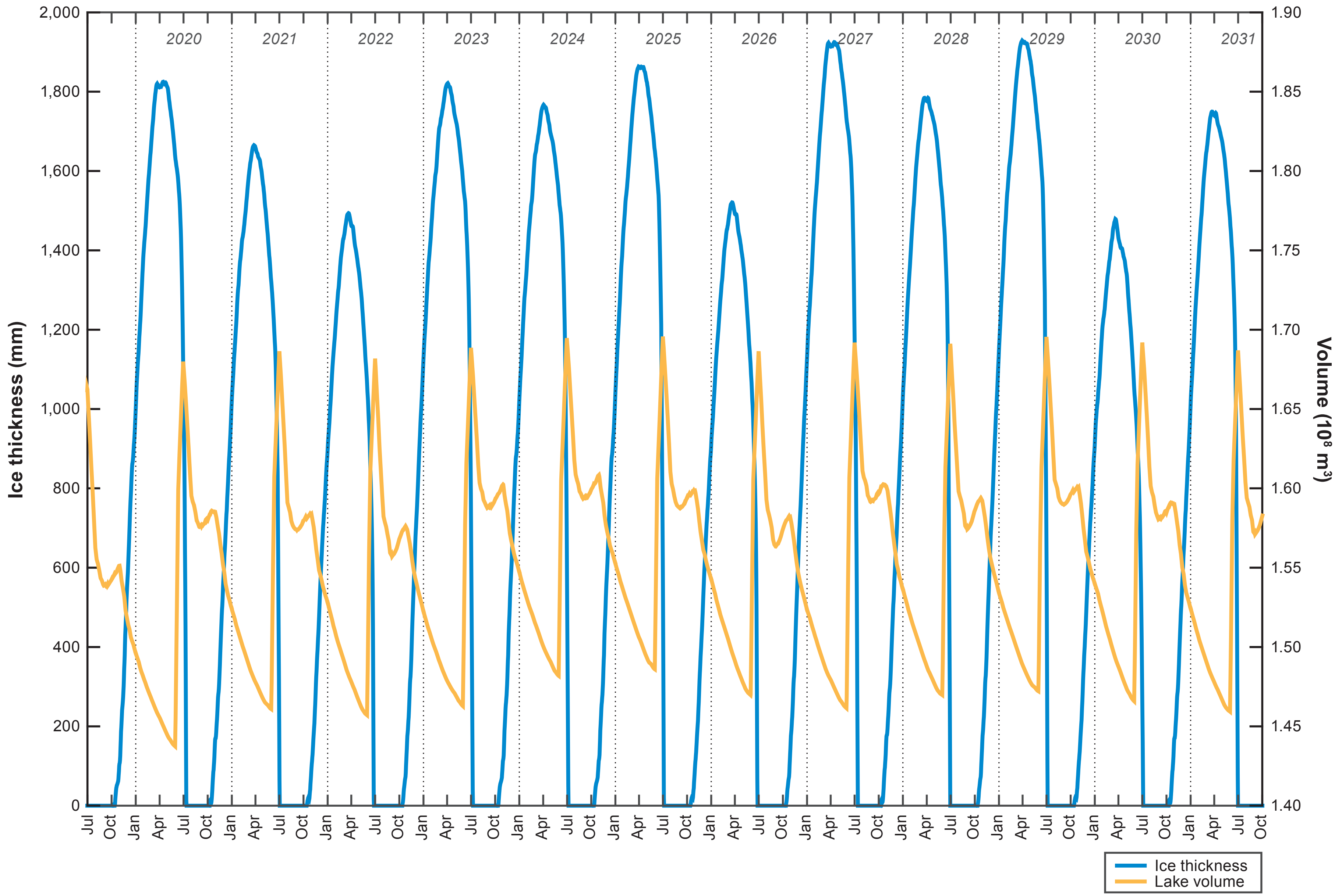


Figure 5-2

Average Surface and Bottom Water Dilutions, May 2023, Aimaokatalok Lake Model

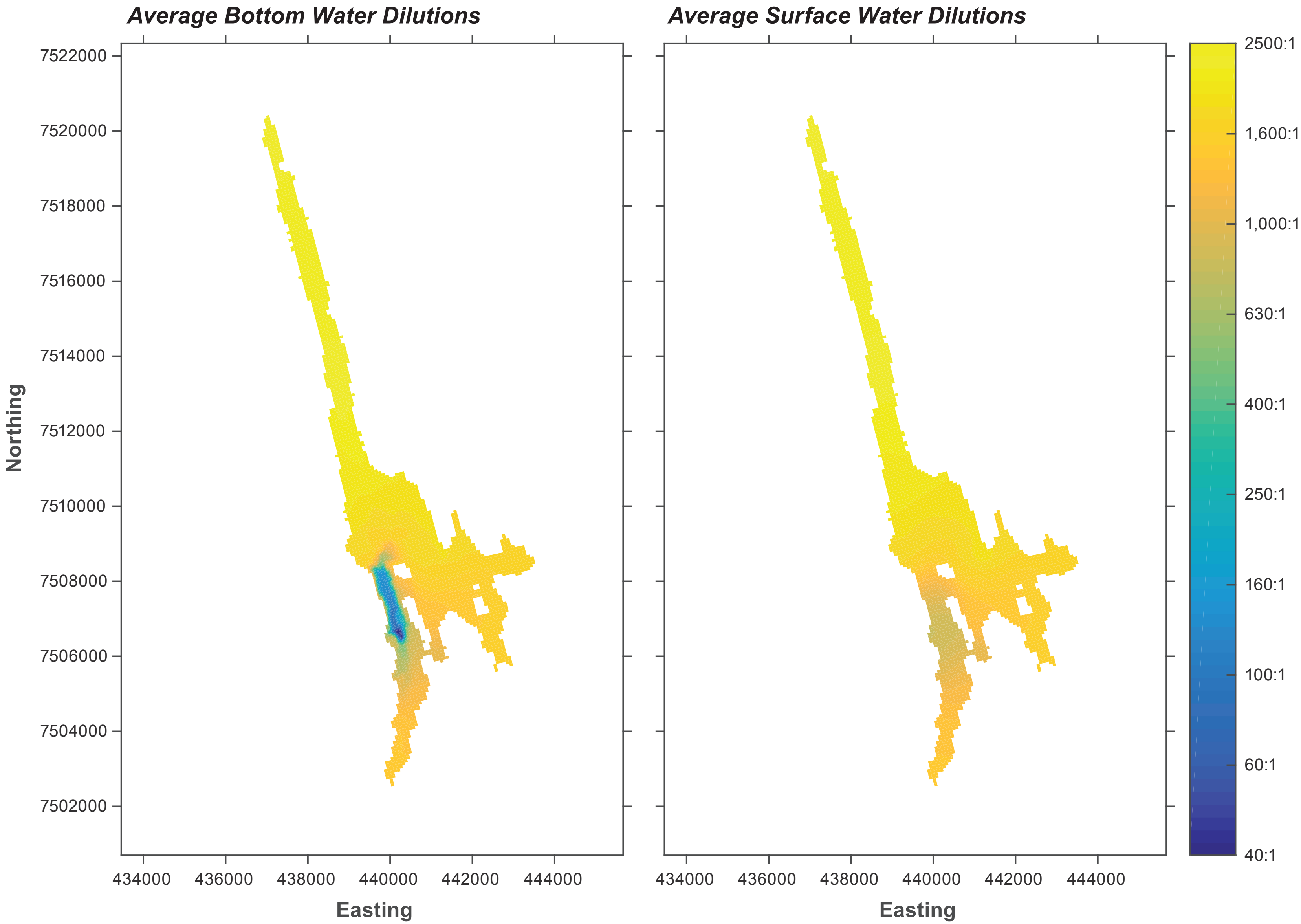


Figure 5-3

Average Surface and Bottom Water Dilutions, August 2023, Aimaokatalok Lake Model

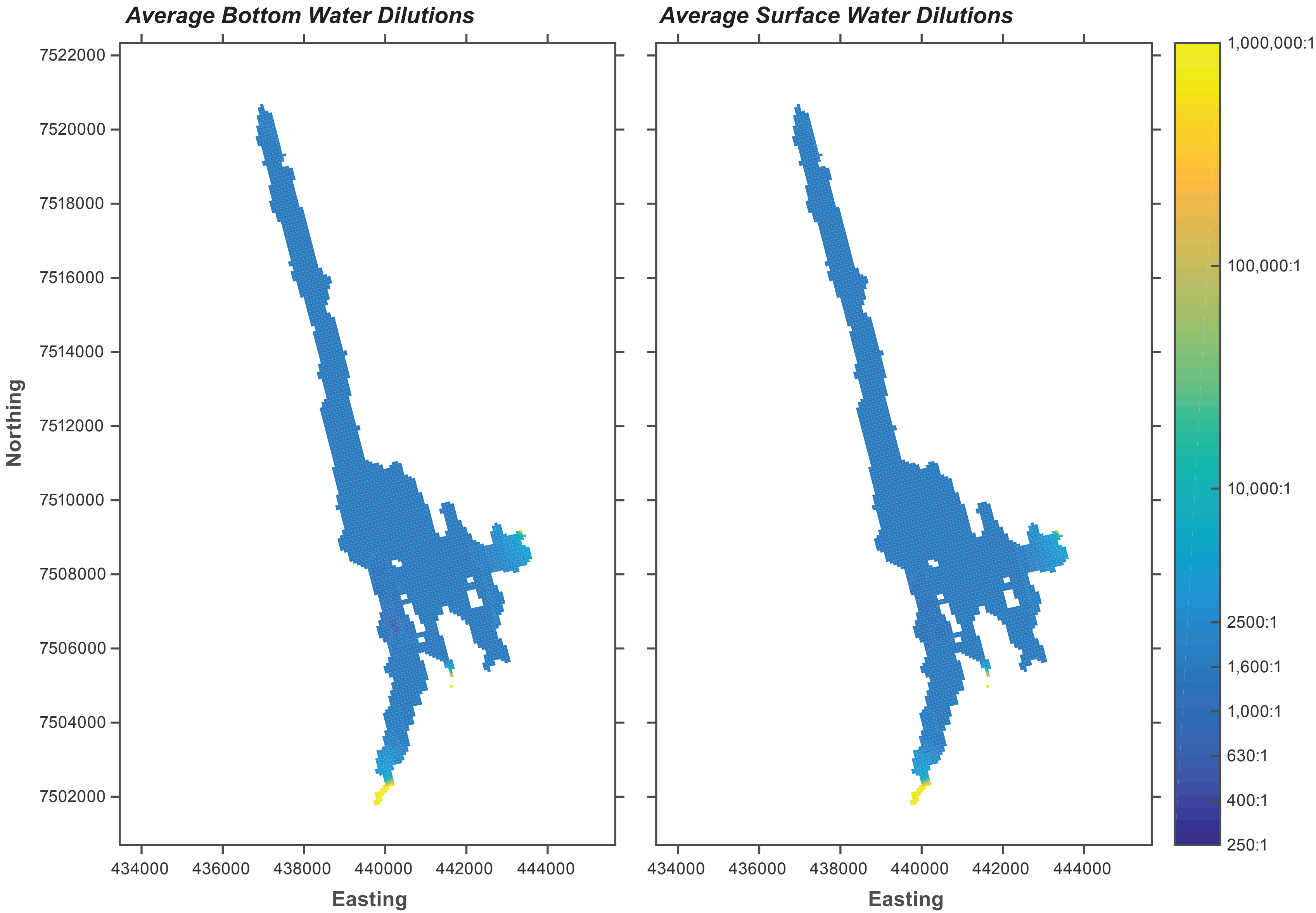
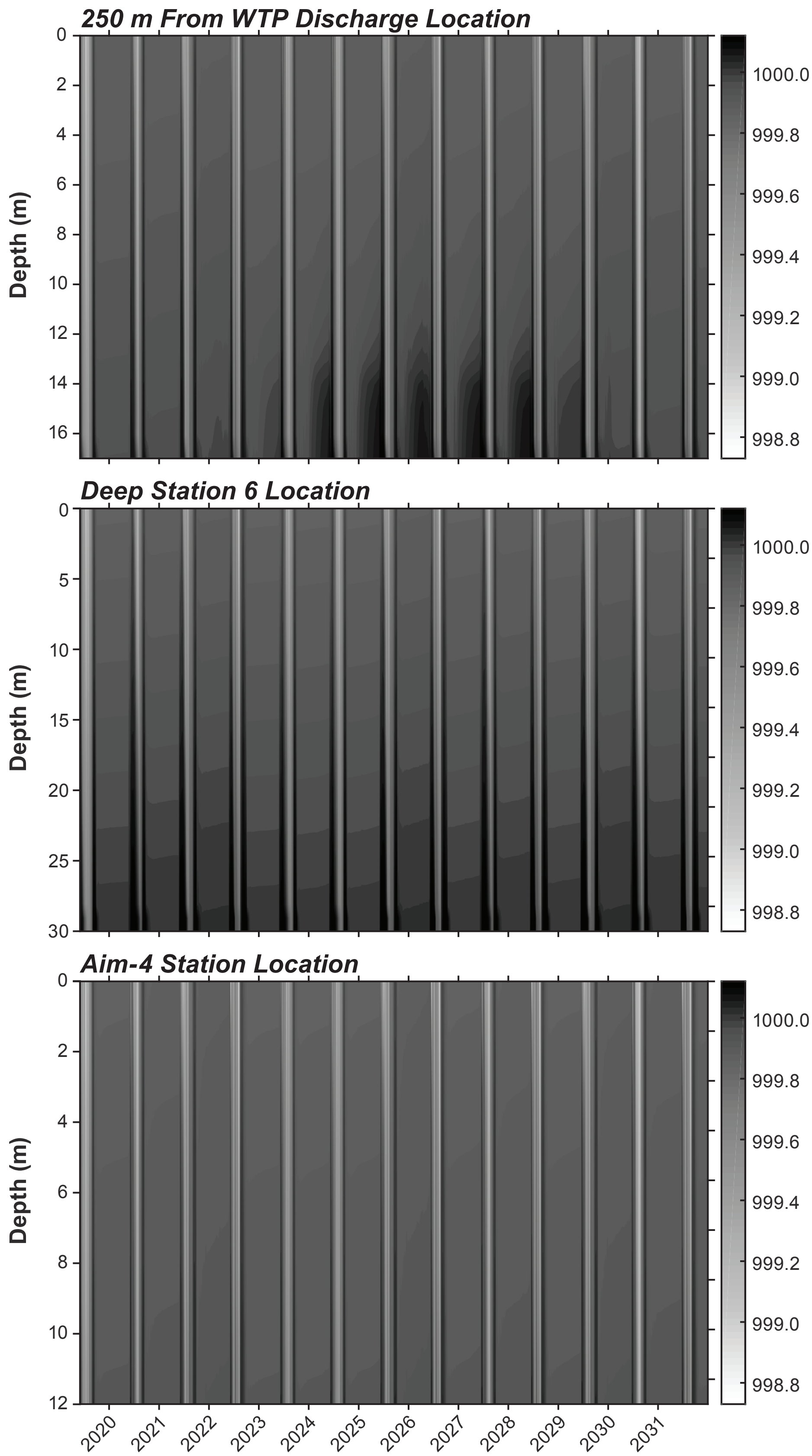


Figure 5-4

Modelled Water Column Density vs. Time at Select Stations, Aimaokatalok Lake Model



Denser plume material is observed 250 m from the discharge point at depths below 10 m for the main effluent discharge years (2023 to 2029); however, the accumulated material completely flushes during the open-water season (as noted by the vertical contours). Conversely, no density signatures are apparent in the other two deep stations, indicating that the plume material remains localized within the discharge trench during winter and is mixed thoroughly during the open-water season.

5.2 Total Phosphorus

Figure 5-5 presents the predicted total phosphorus concentrations with time in Aimaokatalok Lake at 4 main locations:

- 250 m north of the Boston outfall location (at surface, 5, 10, and 15 m depth);
- near the Aimaokatalok Outflow to Koignuk River (at surface);
- Station 6 in the deepest portion of the lake (at surface, 5, 10, 15, 20, and 25 m depth); and
- AIM-4 station in the southern portion of the lake (at surface, 5, and 10 m depth);

All four of these areas are located either within the long western basin of the lake or nearby within the deep central basin. As can be seen, there is very little difference in predicted phosphorus concentrations among the three areas not located within the main effluent discharge trench (i.e., outflow, Station 6, and station AIM-4) as predicted phosphorus concentrations remain nearly uniform with depth during the modeled period. Both the outflow and Station 6 concentrations (0.010 to 0.012 mg/L) remain slightly mesotrophic (0.010 to 0.020 mg/L) for the complete modeled period, while AIM-4 concentrations were oligotrophic during the open-water season due to its proximity to the Aimaokatalok south freshwater inflow.

The only elevated concentrations are below 10 m at 250 m from the outfall location, particularly during the ice-covered period. Peak concentrations are predicted to be above 0.02 mg/L during the winter months due to a combination of limited bottom water flushing and cryoconcentration effects. These higher concentrations rapidly decrease in late June once freshet currents and ice melting thoroughly mix the water column and dilute the accumulated winter effluent. Peaks in the near-field bottom water winter concentration are no longer present past January 2030 as the lake returns to baseline conditions when discharge ends.

Figures 5-6 to 5-8 present modeled lake-wide phosphorus concentration averages for surface and bottom waters during May and August. Three specific years are represented: 2023, 2028, and 2031 representing roughly the beginning, middle, and end of the Boston combined discharge. The results are presented in terms of trophic levels: ultra-oligotrophic (<0.004 mg/L), oligotrophic (0.004 to 0.01 mg/L), mesotrophic (0.01 to 0.02 mg/L), meso-eutrophic (0.02 to 0.035 mg/L), and eutrophic (>0.035 mg/L). Results show that the vast majority of the lake area maintains total phosphorus concentrations in the lower mesotrophic range across the three observable years of modeling, with oligotrophic waters present at the eastern and southern freshwater inflows during August. Meso-eutrophic waters were only recorded in the bottom waters nearest the effluent discharge point during the effluent discharge years; only mesotrophic or lower levels of total phosphorus are present in 2031.

Figure 5-5

Total P Timeseries for Selected Stations, Aimaokatalok Lake Model

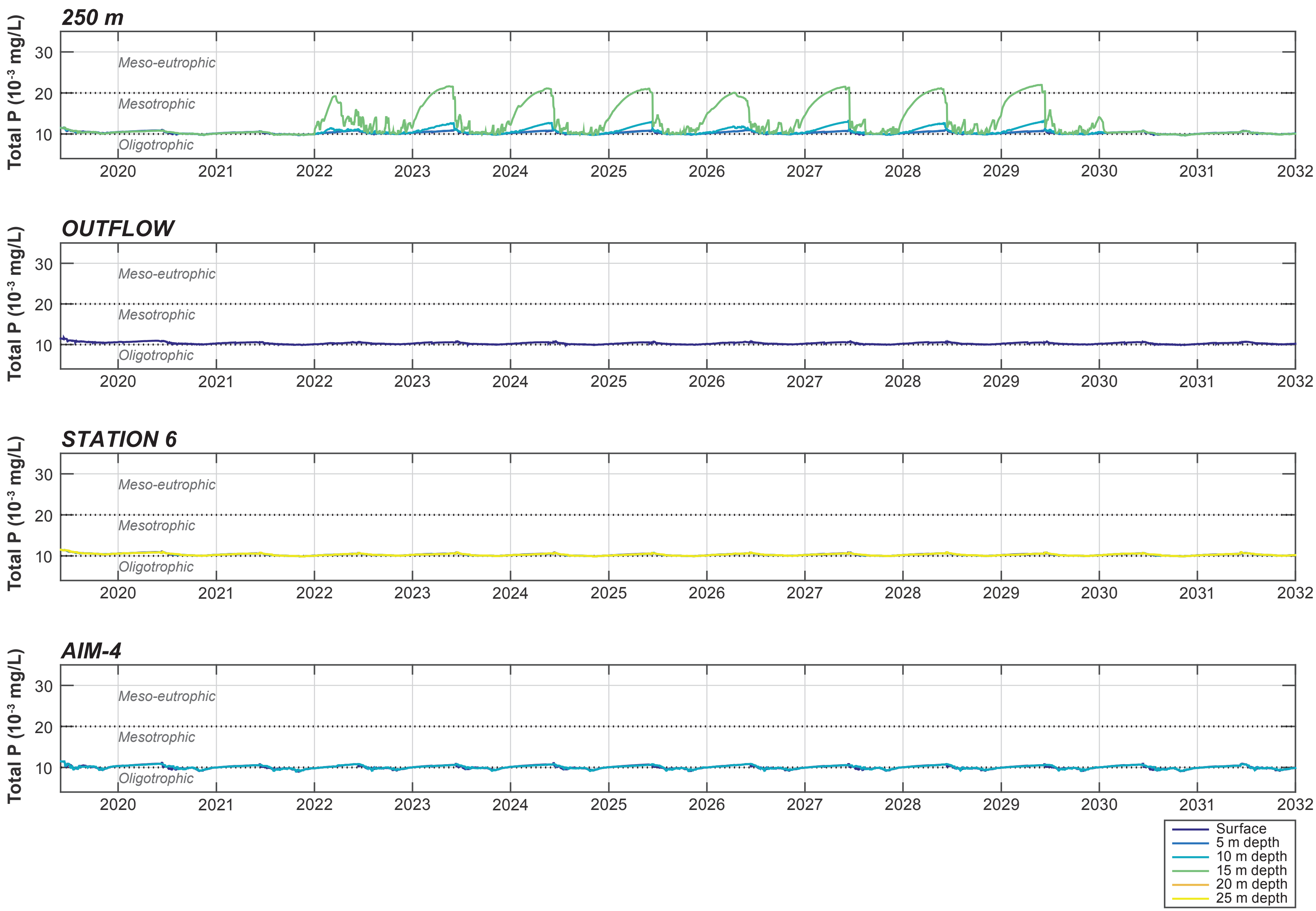


Figure 5-6

Total P Average Predictions for Aimaokatalok Lake: May and August 2023

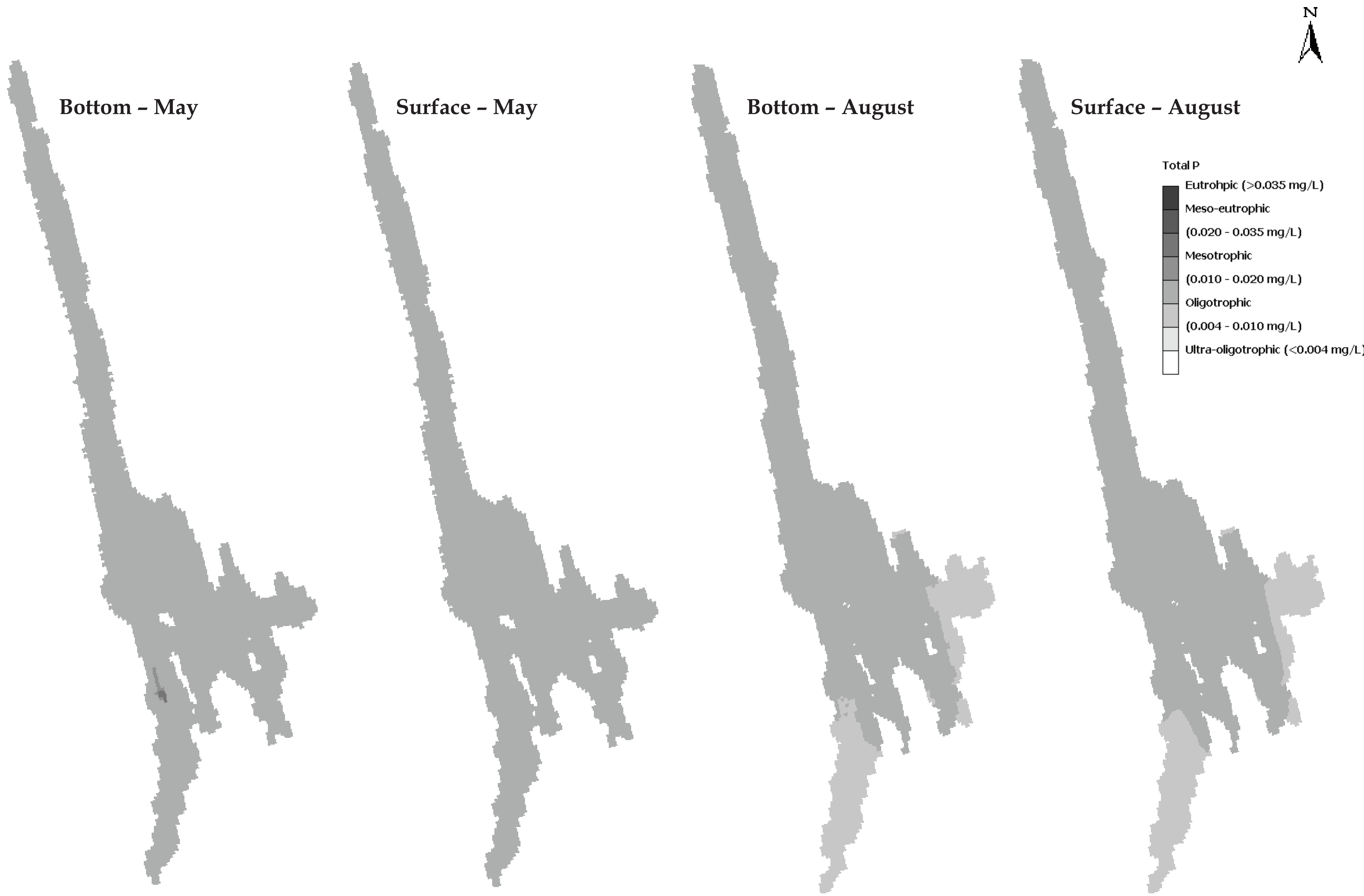


Figure 5-7
Total P Average Predictions for Aimaokatalok Lake: May and August 2028

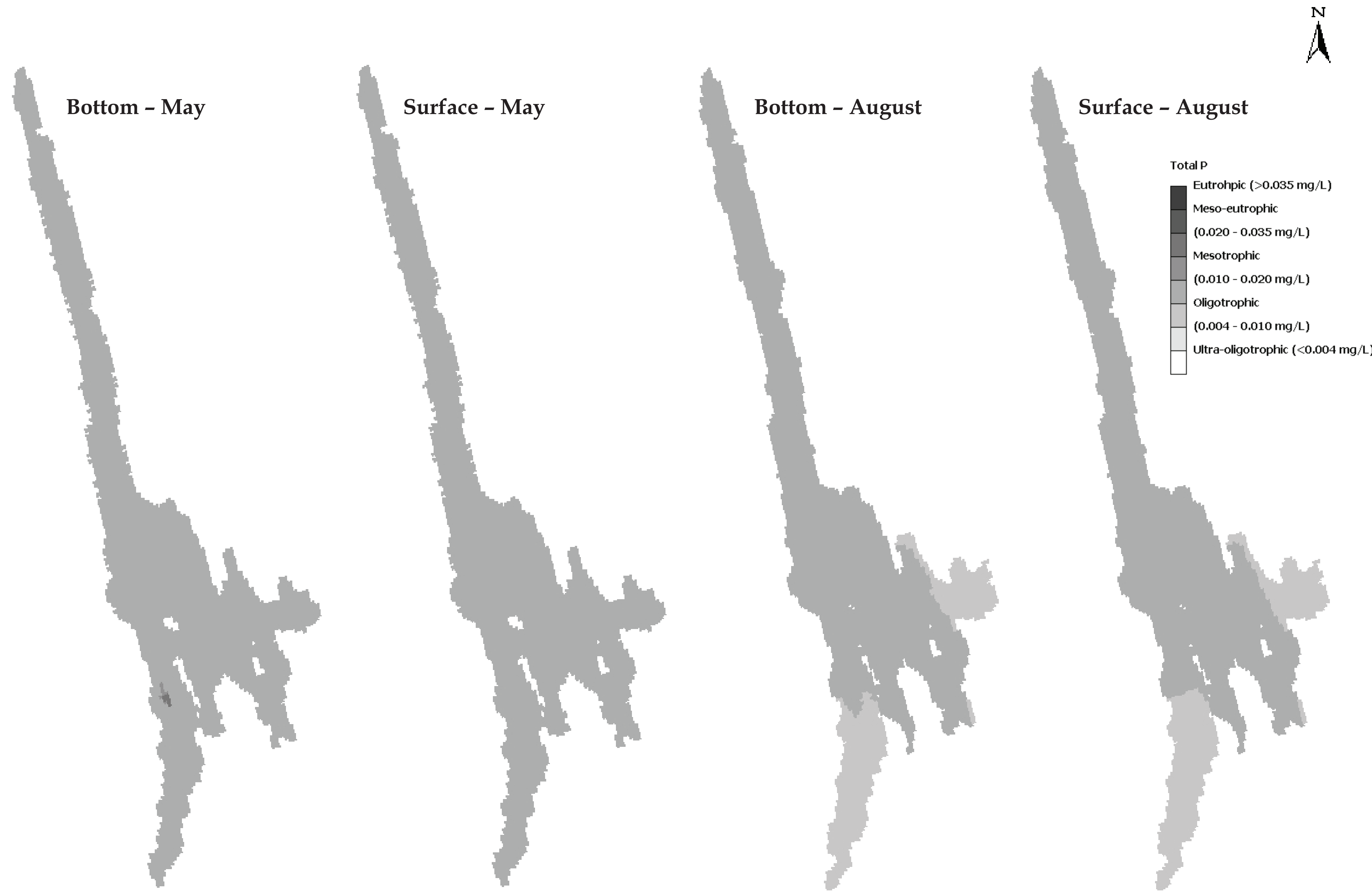
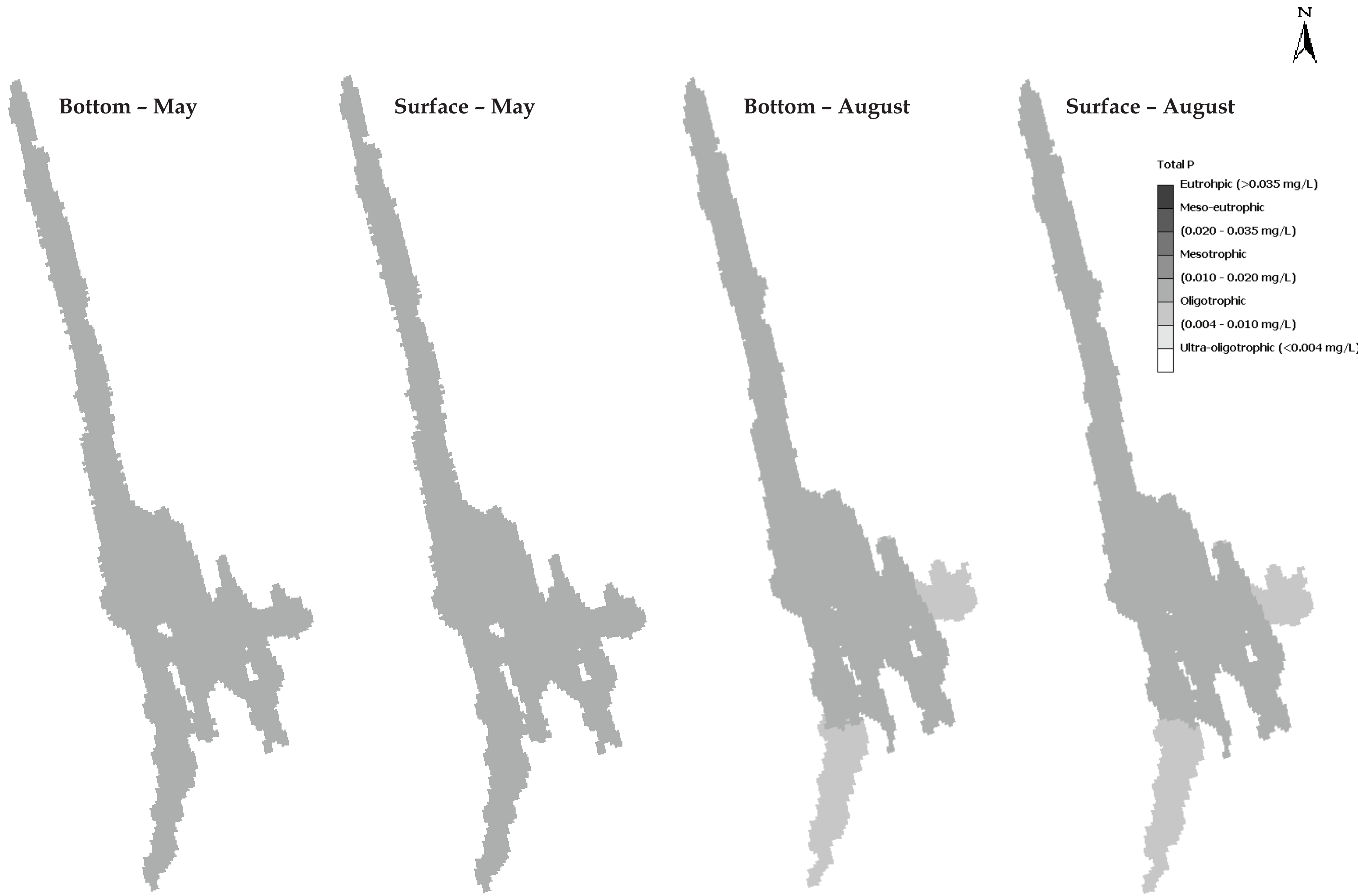


Figure 5-8

Total P Average Predictions for Aimaokatalok Lake: May and August 2031



Nearly all modeled total phosphorus within the lake remains near baseline concentrations in the lower mesotrophic range. Examples of concentration percent above baseline contour plots for surface and bottom waters during May and August 2026 (mid-Project year) are shown in Figures 5-9 and 5-10. Bottom water contour plot in May 2026 (Figure 5-9) clearly shows the under-ice plume signature, with a maximum of near 90% above baseline in the immediate, deep water mixing zone, but quickly tapers to roughly 30% at the plume edge. The vast majority of the lake increases by less than 5% over baseline concentrations in bottom waters. At the winter's surface, the waters directly over the plume have a maximum concentration above baseline slightly above 6.5%, which decreases to approximately 4 to 5% nearly the Aimaokatalok Outflow and less than 3% in the northern arm of the lake. Open-water concentrations above baseline in August 2026 (Figure 5-10) are generally much lower, with the bottom waters showing a maximum of 25% at the discharge location decreasing to lower than 3% at the Aimaokatalok Outflow. August 2026 surface phosphorus concentrations hovered around 3% above baseline over the vast majority of the lake, with values closer to 0% at the freshwater inflow location.

5.3 Chromium

Figure 5-11 presents the predicted total chromium concentrations with time in Aimaokatalok Lake at the same four locations presented in Section 5.2 for total phosphorus.

Similarly to total phosphorus results, there is very little difference in predicted chromium concentrations among the three areas not located within the main effluent discharge trench (i.e., outflow, Station 6 and station AIM-4), and the predicted chromium concentrations remain nearly uniform with depth during the modeled period. There is a slight increase (approximately 5 to 6%) in outflow chromium concentrations during the effluent discharge years as the excess concentrations are flushed out of the lake, but generally most concentrations remain near the typical baseline values of 0.00025 mg/L and far below the conservative hexavalent chromium CCME guideline of 0.001 mg/L. Again, the only elevated concentrations are below 10 m at 250 m from the outfall location, particularly during the ice-covered period. Peak concentrations are predicted to be above 0.00075 mg/L within the near-field mixing zone during the ice-covered months but remain below the CCME guideline. These concentrations rapidly decrease in late June once freshet currents and ice melting thoroughly mix the water column and dilute the effluent. The bottom water winter chromium concentration peaks are no longer present past January 2030 as the lake returns to baseline conditions when discharge ends.

Figures 5-12 to 5-14 present modeled lake-wide chromium concentrations averages for surface and bottom waters plotted for the same periods as phosphorus in Section 5.2. August results show that the vast majority of the lake area maintains chromium concentrations near baseline concentrations (below 0.00024 mg/L) across the three observable years of modeling, with increased concentrations only present in the near-field mixing area of the Boston combined discharge location. May under-ice concentrations were more variable, with a peak at the outfall location and slightly larger concentrations found in the northern and southern portions of the lake. The latter is due to the cryoconcentration effect disproportionally affecting shallower stagnant water. This demarcation quickly dissipates once currents mix lake waters in the open-water season.

Figure 5-9

Average Surface and Bottom Water % Total P above Baseline, May 2026, Aimaokatalok Lake Model

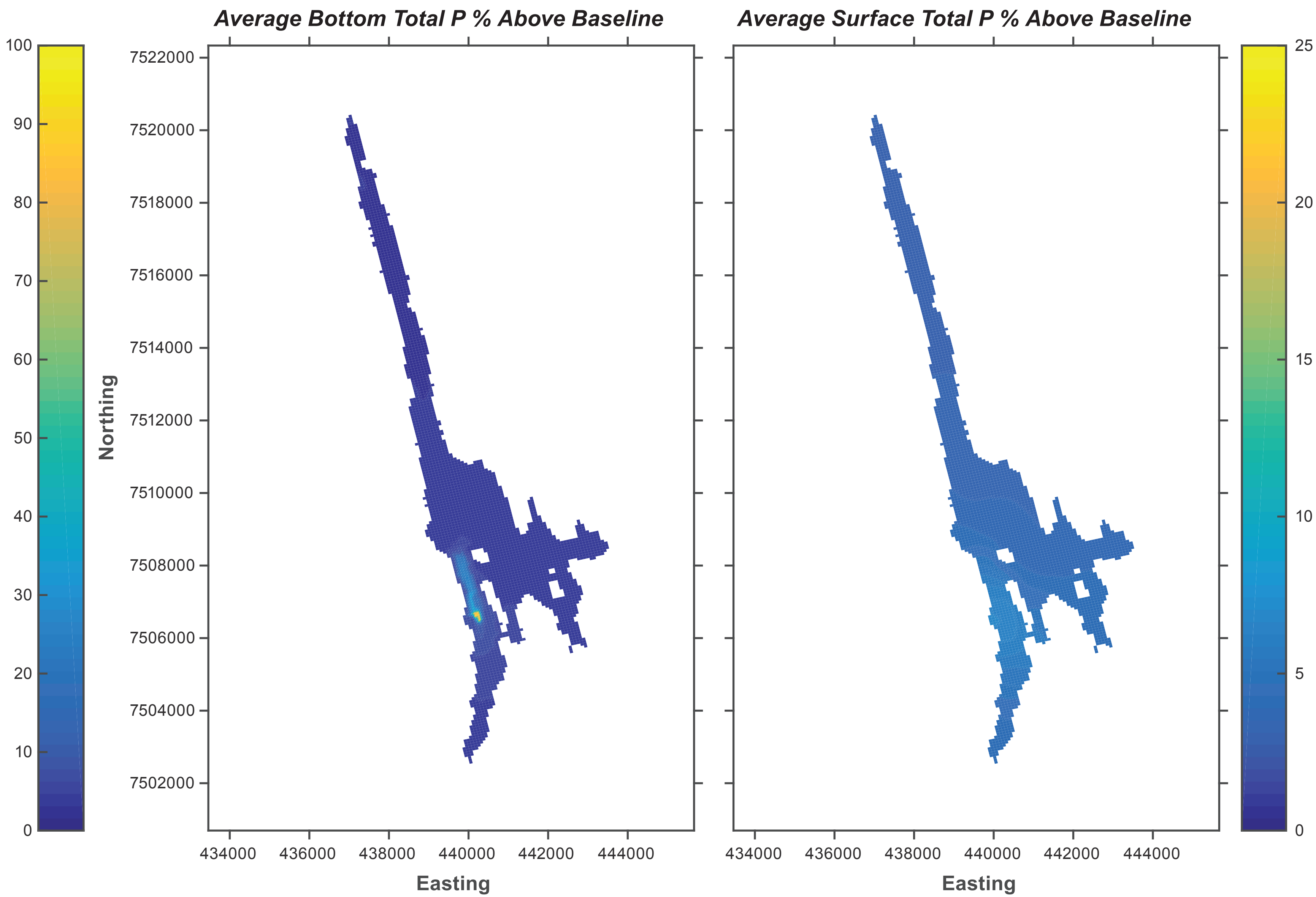


Figure 5-10

Average Surface and Bottom Water % Total P above Baseline, August 2026, Aimaokatalok Lake Model

ERM

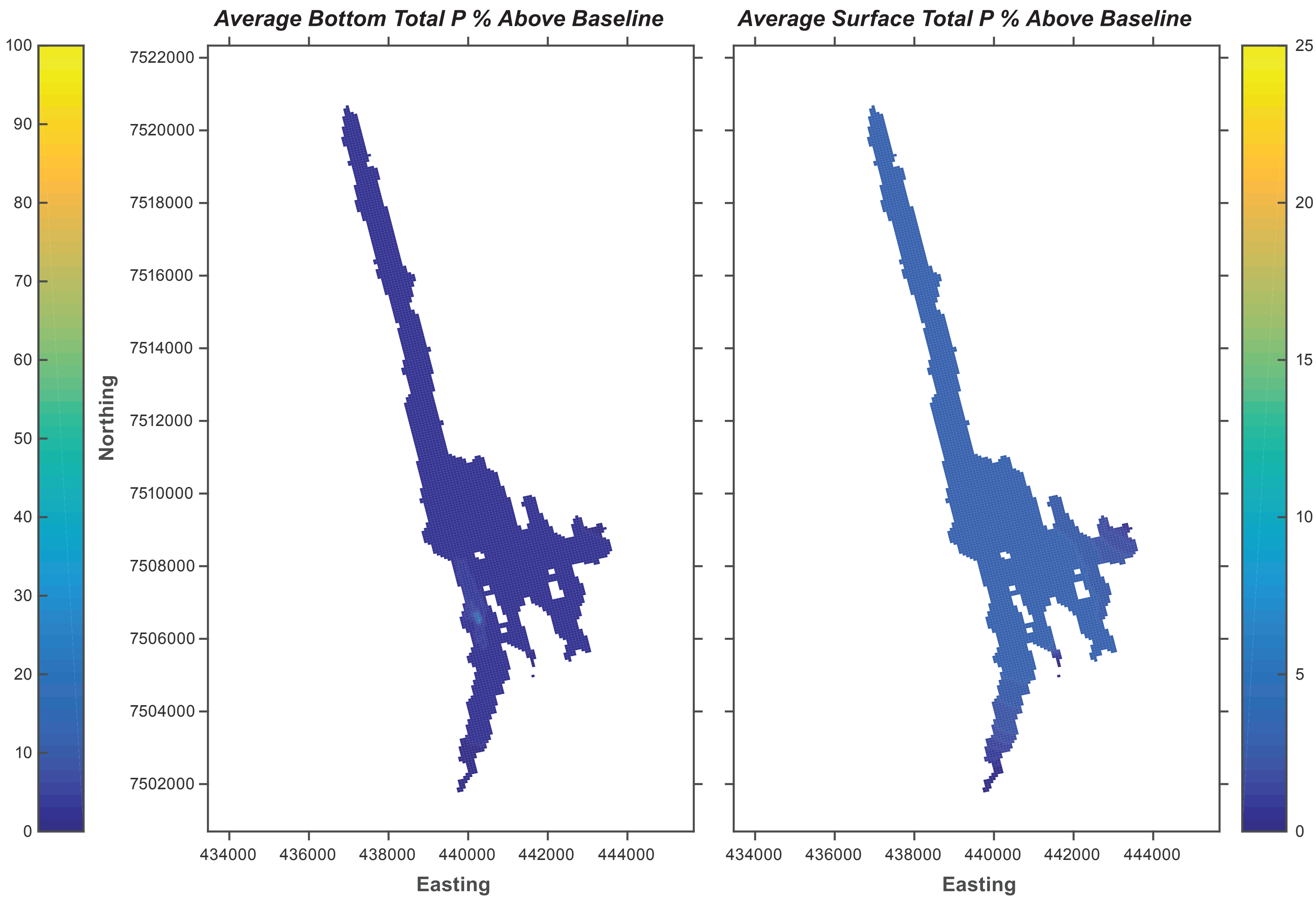


Figure 5-11

Total Cr Timeseries for Selected Stations, Aimaokatalok Lake Model

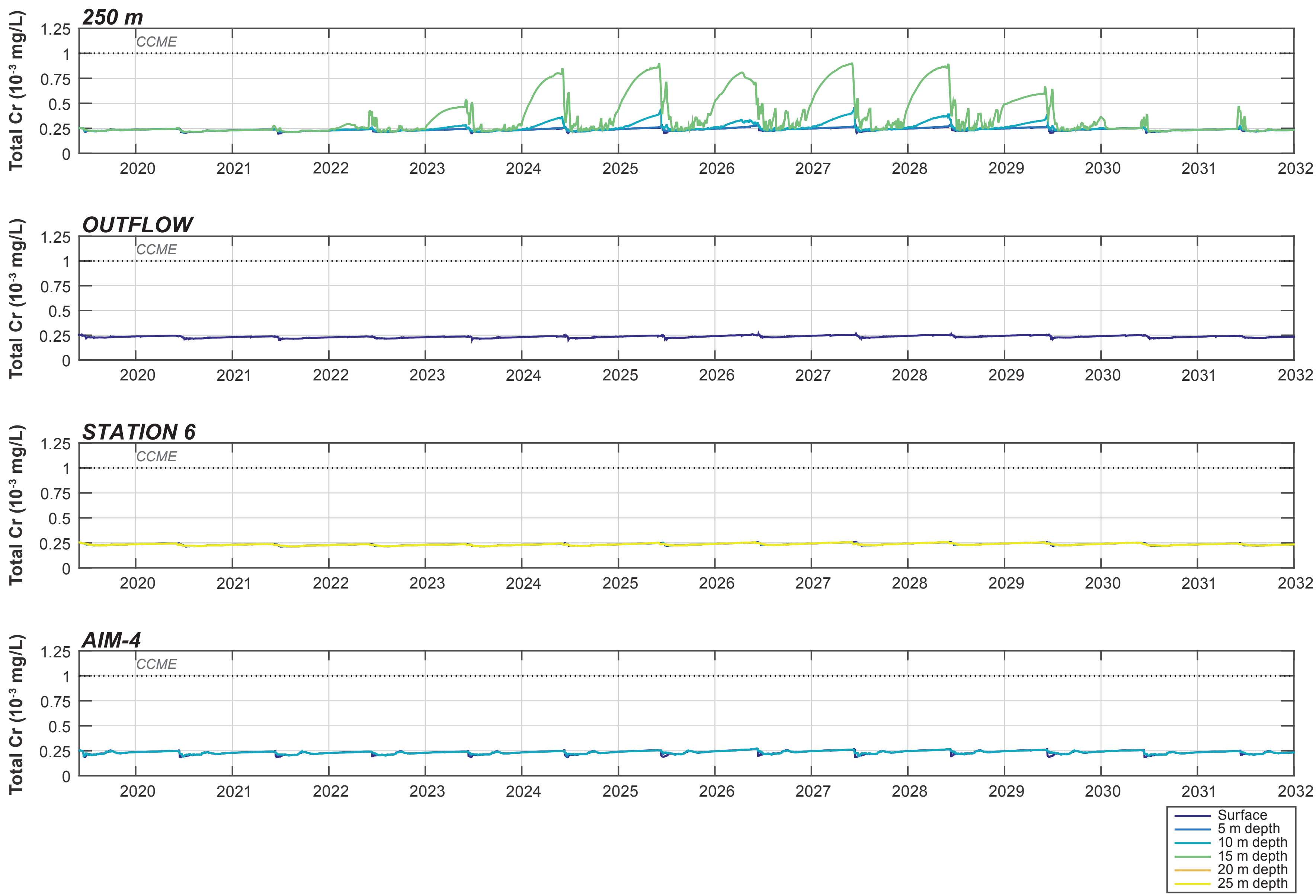


Figure 5-12

Total Cr Average Predictions for Aimaokatalok Lake: May and August 2023

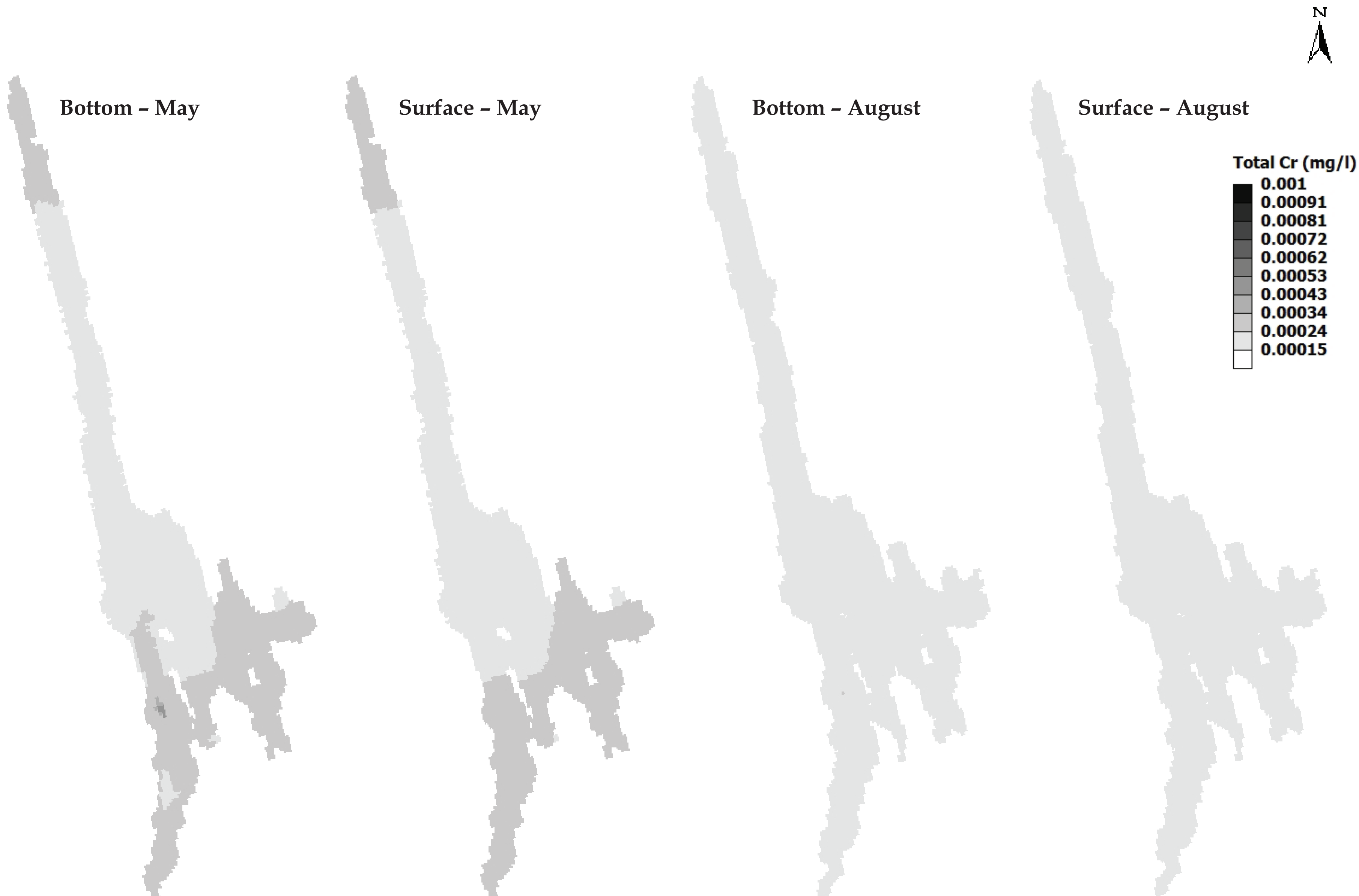


Figure 5-13

Total Cr Average Predictions for Aimaokatalok Lake: May and August 2028

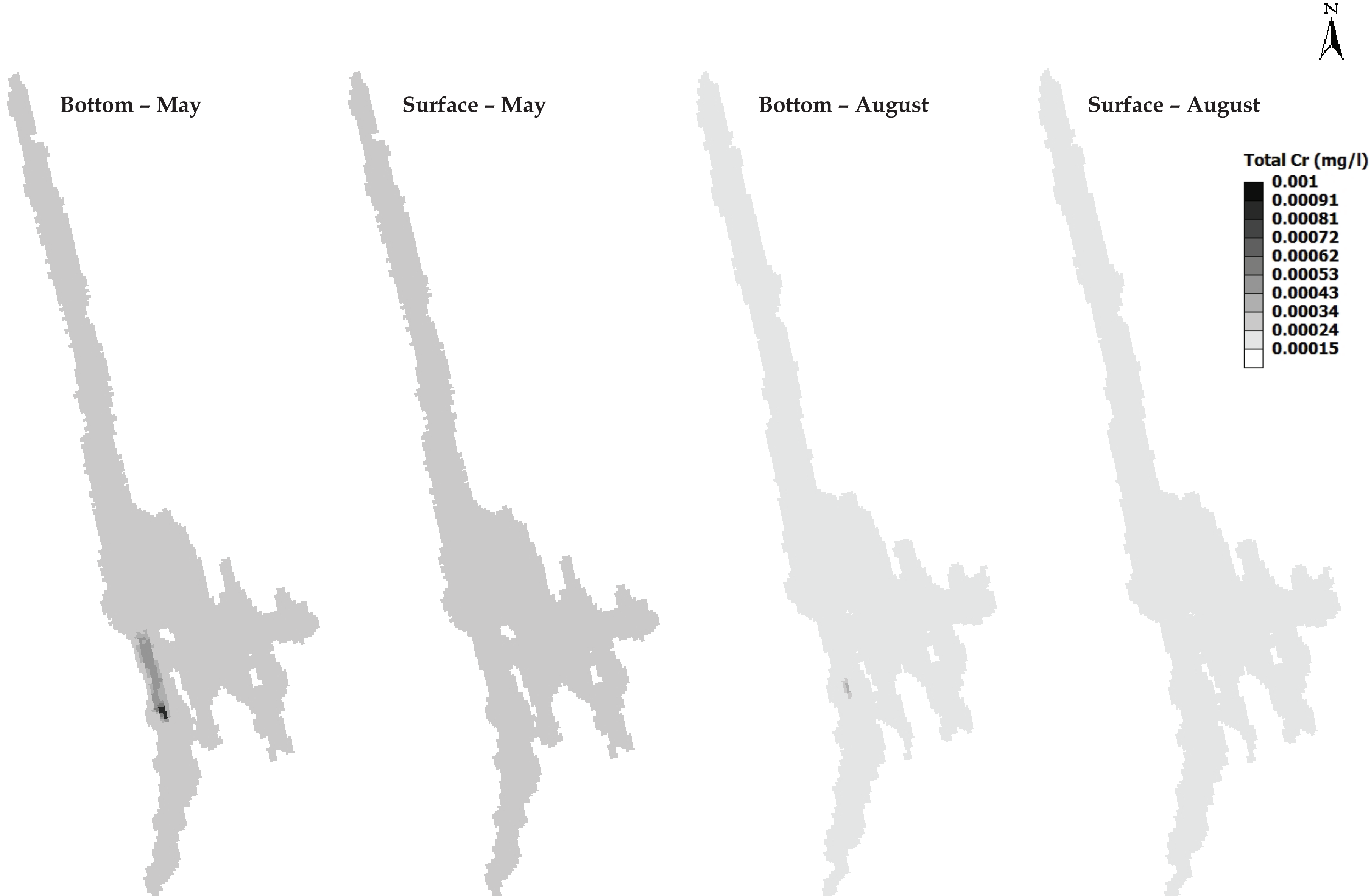


Figure 5-14

Total Cr Average Predictions for Aimaokatalok Lake: May and August 2031

6. CONCLUSIONS

Total phosphorus and chromium concentrations were predicted over the temporal scale of the Boston combined discharge period (June 2020 to December 2031) and the spatial scale of all of Aimaokatalok Lake (all depths and locations). Both open-water (June to October) and under-ice (November to May) seasons were included in the modeling.

Given the greater density in the effluent, the simulated discharge resulted in a negatively buoyant plume that spread along the bottom lake canyon next to the discharge location during the ice-covered months. Bottom water dilutions clearly show the plume signature as it extends over 2 km northwards towards the outflow. Minimum average dilutions during the winter discharge years range from 40:1 near the discharge point, while plume edge dilution values are closer to 400:1. The plume waters are mostly confined to lower depths of the lake during winter, and with the onset of open-water season, lake waters are rapidly flushed with the melting ice waters/surface runoff and stratification erodes within the water column. Dilution factors in surface and bottom waters are well above 1,000:1 for most regions in the open-water season, and the effluent plume is not visible in the surface water dilutions.

Predicted total phosphorus and chromium concentrations versus time were analyzed in Aimaokatalok Lake at four main locations:

- 250 m north of the Boston combined discharge location (at surface, 5, 10, and 15 m depth);
- near the lake outflow to the Koignuk River (at surface);
- Station 6 in the deepest portion of the lake (at surface, 5, 10, 15, 20, and 25 m depth); and
- AIM-4 station in the southern portion of the lake (at surface, 5, and 10 m depth).

There was very little difference in either predicted phosphorus or chromium concentrations among the three areas not located within the main effluent discharge trench (i.e., outflow, Station 6, and station AIM-4). At those locations the predicted constituent concentrations remain nearly uniform with depth during the modeled period. The only elevated concentrations were below 10 m at 250 m from the outfall, particularly when the effluent was confined to the bottoms waters during the ice-covered period.

Nearly all modeled total phosphorus within the lake remains near baseline concentration in the lower mesotrophic range. Modelled concentrations near the Aimaokatalok outflow to Koignuk River generally resulted in 3 to 5% values above baseline levels, indicating that no significant nutrient loading would occur during Project operational years. Peak concentrations in phosphorus were slightly meso-eutrophic (i.e., above 0.02 mg/L) and only present during the winter months near the outfall location due to a combination of stagnant ambient conditions limiting bottom water flushing and cryoconcentration effects. The elevated concentrations only occurred when (winter) and where (bottom waters) primary production within the lake is low or non-existent, and rapidly returned to near-baseline levels in late June once freshet currents and ice melting thoroughly mixed the water column and diluted the discharge. Because total phosphorus concentrations are predicted to remain near baseline concentrations, and within baseline meso-trophic classification throughout the lake, there are not expected to be effects to lake primary productivity from the Boston combined discharge. This is not unexpected since the annual discharge makes up a very small percentage of the lake volume (0.15%), the diffuser achieves very high dilutions in the near field (>1,000:1 during the open-water season; ERM 2016), and the resulting plume is negatively buoyant keeping the highest total phosphorus concentrations in the deep waters where light for photosynthesis is limiting.

Similar to total phosphorus, chromium concentrations within the lake were nearly at baseline concentrations following the Boston combined discharge, and far below CCME guidelines. Elevated concentrations were only predicted at the outfall location during the ice-covered months but remained below the conservative hexavalent chromium CCME guideline of 0.001 mg/L for the modeled period. Since chromium required the greatest dilution from all effluent constituents, it can be extrapolated such that all parameters discharged from the Boston combined discharge will be lower than their respective CCME guideline concentrations, and the water in Aimaokatalok Lake will be safe for aquatic life of all life stages.

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