Appendix V5-8C

2016 Roberts Bay Hydrodynamic Modelling Report: Numerical Simulation of Effluent and Chromium Predictions

Memorandum

Date: March 11, 2016

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From: Philippe Benoit and Mike Henry, ERM

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Subject: **2016 Roberts Bay Hydrodynamic Modelling Report: Numerical Simulation of Effluent and Chromium Predictions**

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1. INTRODUCTION

TMAC Resources Ltd. (TMAC) plans to increase their production of ore at the Doris North Project, which will extend the life of the Doris Mine from two years to six years and will result in the interception of saline talik water during underground workings. A change in water management strategy will now move the discharge of mine (connate) and groundwater from the freshwater environment to the marine environment to account for the interception of saline water. Figure 1-1 provides a general location map for the Doris North Project.

To account for the changes in Project design, TMAC submitted an application to the Nunavut Impact and Review Board (NIRB) and the Nunavut Water Board (NWB) in June 2015 to amend their current Doris Mine Project Certificate (Project Certificate No. 003) and Type A Water Licence (No. 2AM-DOH1323), part of which involved the assessment of discharging effluent to the marine environment. The following technical review comments were made by intervenors during the application review:

- INAC 7 and INAC 9: Requested additional hydrodynamic modelling to address plume behaviour and mixing zones under variable effluent flow rates, composition, and environmental conditions.

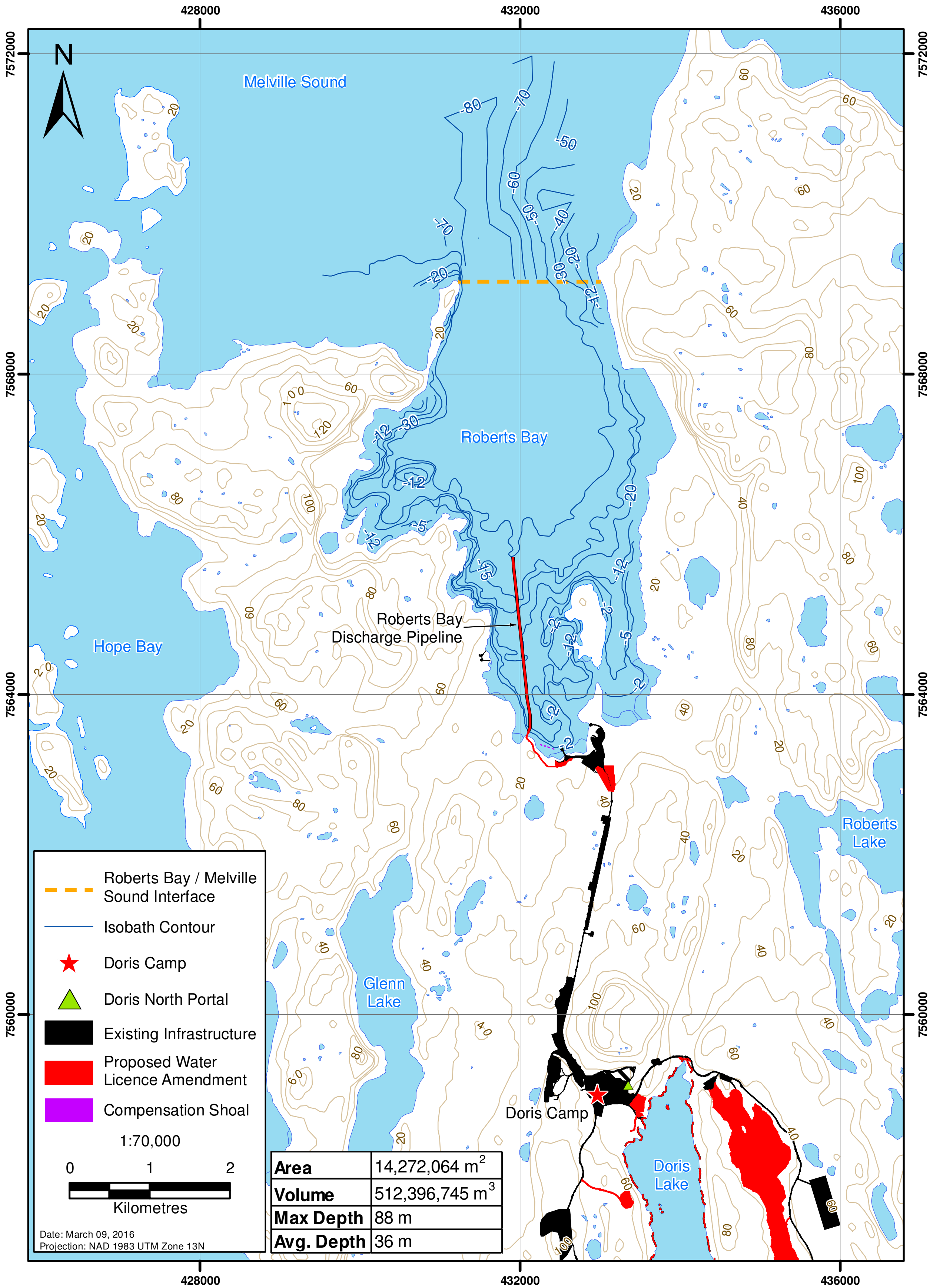
Following discussions with INAC during the technical session on January 27, 2016, TMAC agreed to:

- conduct far-field, three-dimensional dispersion modelling in Roberts Bay for the most sensitive water quality parameter (chromium) for one year of operations (Commitment #8).

The purpose of this report is to present the three-dimensional hydrodynamic modelling and chromium predictions in Roberts Bay due to Doris Mine discharge. The near-field mixing modelling of Doris Mine effluent in Roberts Bay is available in a complimentary report (ERM 2016).

Chromium concentrations were predicted over one year of operations at the spatial scale of all of Roberts Bay and part of adjacent Melville Sound (all depths and locations). The discharge of saline groundwater during the under-ice season (October to May) and TIA and groundwater combined discharge during the open-water season (June to September) were included in the modelling.

Figure 1-1
Location of Doris North Project and Roberts Bay Discharge Pipeline



Area	14,272,064 m^2
Volume	512,396,745 m^3
Max Depth	88 m
Avg. Depth	36 m

Results are presented for chromium concentrations at selected depths with time for three point source stations in Roberts Bay, as well as for the complete water column above the diffuser location. In addition, monthly average chromium concentrations and minimum dilution ratios were plotted as surface heat diagrams throughout Roberts Bay for the open-water and under-ice seasons.

Sections 2 and 3 of this report present the background and methodology used for the construction of the hydrodynamic numerical model, Section 4 presents the simulation results and discussion, and Section 5 presents an overall summary of the results.

2. ROBERTS BAY NUMERICAL MODEL

In order to develop a hydrodynamic model for Roberts Bay, an Advection Dispersion Module (DHI 2009) was coupled to the MIKE3 Flow model (DHI 2012a, 2012b) to predict the fate of total chromium concentration within Roberts Bay during one calendar year of the proposed Doris Mine TIA and saline groundwater discharge. The details of the MIKE3 Flow Model are presented in this section. Details of the DHI Advection Dispersion Module and effluent discharge parameters are included in Section 3.

2.1 Model General Description

Roberts Bay was modelled using the DHI MIKE3 Flow Model. MIKE3 is a three-dimensional baroclinic fluid model that can simulate unsteady discretized flows while accounting for density variations, bathymetry, and external forcings such as riverine inputs and wind. Other built-in features of the model include flooding and drying of coastal land, sediment bed resistance, turbulence modelling, sources/sinks of external waters, and heat exchange with the atmosphere.

The MIKE3 model is based on the numerical solution of the three-dimensional Reynolds-averaged Navier-Stokes fluid equations (Gill 1982; Kundu 1990), including the effects of turbulence (using the Boussinesq approximation), variable density, and the conservation equations for salinity and temperature. The MIKE3 Flow Model can solve the fluid equations using two different algorithmic modules: the hydrodynamic module (DHI 2012a), which incorporates water compressibility and the full vertical momentum equation, and the hydrostatic module (DHI 2012b) that assumes water incompressibility and invokes hydrostatic assumptions (i.e., vertical velocities are presumed negligible compared to horizontal currents; Gill 1982; Kundu 1990).

The spatial discretization of the primitive equations is performed using a cell-centered finite volume method (e.g., see Patankar 1980). The spatial domain is discretized by subdivision of the fluid continuum into non-overlapping elements or cells. A structured or unstructured grid can be used in the horizontal plane while a structured mesh is used in the vertical.

The model solves the pertinent time-dependent hydrodynamic and thermodynamic equations over the discretized regional grid. It therefore produces computed values of variables, such as temperature or current, in each grid cell throughout the model domain for each time step. The model's physical system is driven by environmental inputs comprised of time-series of winds, air temperatures, and freshwater discharges. Other inputs, such as incoming solar radiation, are derived from the latitude of the domain.

The utility of a sophisticated modelling tool like MIKE3 is after the initial model setup, it is possible to evaluate different scenarios such as different wind or discharge magnitudes.

2.2 Model Development for Roberts Bay

The model used was modified from a previous version created by Rescan (2012a), which was developed using baseline data collected from Roberts Bay in 2011 (Rescan 2012b). This section provides a summary of the baseline measurements that were used to calibrate the numerical model, and describes the assumptions for the numerical model.

2.2.1 Site Description

Roberts Bay is a small inlet within Melville Sound located on the northern shore of mainland Nunavut at 68º 12' N, 106º 38' W. Marine data has been collected around the Doris North Project area since the mid-1990s, with the most detailed baseline oceanographic information being collected from 2009 to 2011 (Rescan 2010, 2011c, 2011a, 2012b).

Roberts Bay is a broad estuary, with a maximum north-south length of 5 km and east-west width of 4 km (surface area: 14.3 km^2). The total volume of Roberts Bay is approximately 5.1×10^8 m^3 with a mean depth of 36 m and maximum depth of 88 m at its mouth. The southernmost section of the inlet is shallow (< 20 m), and deepens to between 40 m and 90 m towards Melville Sound. Water exchange in Roberts Bay has free access to Melville Sound as there is no sill present in the inlet. Freshwater enters the bay from a number of tributaries, although primarily from Little Roberts Outflow and less so from Glenn Outflow.

2.2.2 Ice-covered Conditions (October to April)

During the ice-covered season, a 1 to 2 m ice layer forms that shelters Roberts Bay waters from atmospheric winds. Over time, the under-ice convection generated from the ice growth leads to the formation of a two-layer thermohaline structure with weak stratification in the water column, and a colder, fresher layer of 10 to 30 m thickness atop a more saline, warmer layer extending to the bottom.

Under-ice currents, as measured by an Acoustic Doppler Current Profiler (ADCP; see Rescan 2012b), are generally very weak, with mean horizontal current velocities between 1 and 2 cm/s. Deep currents, which are driven either by density gradients formed through ice formation/brine release or advection of waters from Melville Sound, have generally stronger velocities. Tidal ebb and flow currents are almost negligible across the bay.

2.2.3 Open-water Conditions (June to September)

In early summer, the increased sunlight and warming atmospheric temperatures eventually cause the ice cover to melt in late June/early July, flooding the surface of Roberts Bay with a large volume of fresh, warm water. After the ice cover breakup, winds forcing on Roberts Bay waters contribute to a significant increase in current velocity and variability, particularly near the surface.

The addition of freshwater from ice melting, combined with the mixing due to wind generated currents and warmer temperatures, progressively leads to the formation of an alternate two-layered thermohaline structure with a warmer, fresher wind-mixed layer atop a colder more saline bottom layer. Stratification is much stronger during the summer months, with the surface mixed layer being consistently more shallow (10 m) than that found in the winter months (10 m to 35 m).

The current variability changes dramatically during the summer, with a ten-fold increase in water exchange rate estimated at the mouth of Roberts Bay where current measurements have been obtained. Mean horizontal current velocities in the deep layer range from 1 to 5 cm/s, but with maximum of around 30 cm/s during periods of large flow. Similarly, horizontal currents in the upper water column range between 1 and 6 cm/s, with maximum values exceeding 30 cm/s being recorded above 10 m depth.

A map of the different sampling stations for Roberts Bay between 2009 and 2011 is shown in Figure 2.2-1.

2.3 Model Usage

The first objective for this work (i.e., see Section 1) was to simulate the year-long physical conditions in Roberts Bay. The following assumptions were used in the 3D hydrodynamic model:

- MIKE3 has no built-in ice formation module; as such, the ice-cover period was modelled by shutting down wind stresses in the surface waters and limiting the atmospheric heat exchange. This gave a first-order approximation of the water column conditions, but generally resulted in lower modelled under-ice currents compared to measured currents. The latter was expected as there is no built-in mechanism to properly generate under-ice density currents. This resulted in more conservative winter conditions for the effluent discharge due to slower water currents;
- the hydrostatic MIKE3 module was used given the much larger horizontal distances and grid dimensions;
- only three measured data inputs were used within the model: winds, freshwater discharges, and atmospheric temperatures. All other climactic and oceanographic variables were taken as either constants or were modelled using physical models; and
- only the first year of effluent discharge was modelled, hereby identified as Year 1 in this report. The modelled monthly discharge otherwise follows the chronology as detailed by the *Doris North Project – Water and Load Balance Report* (SRK 2015a). The TIA and groundwater discharge will begin when saline talik water is first encountered (May, Year 1) and ending one year later (April, Year 1). The baseline conditions were simulated using the 2011 observed field measurements as reported in the *Doris North Gold Mine Project: 2011 Roberts Bay Physical Oceanography Baseline Report* (Rescan 2012b; also see Section 2.2).

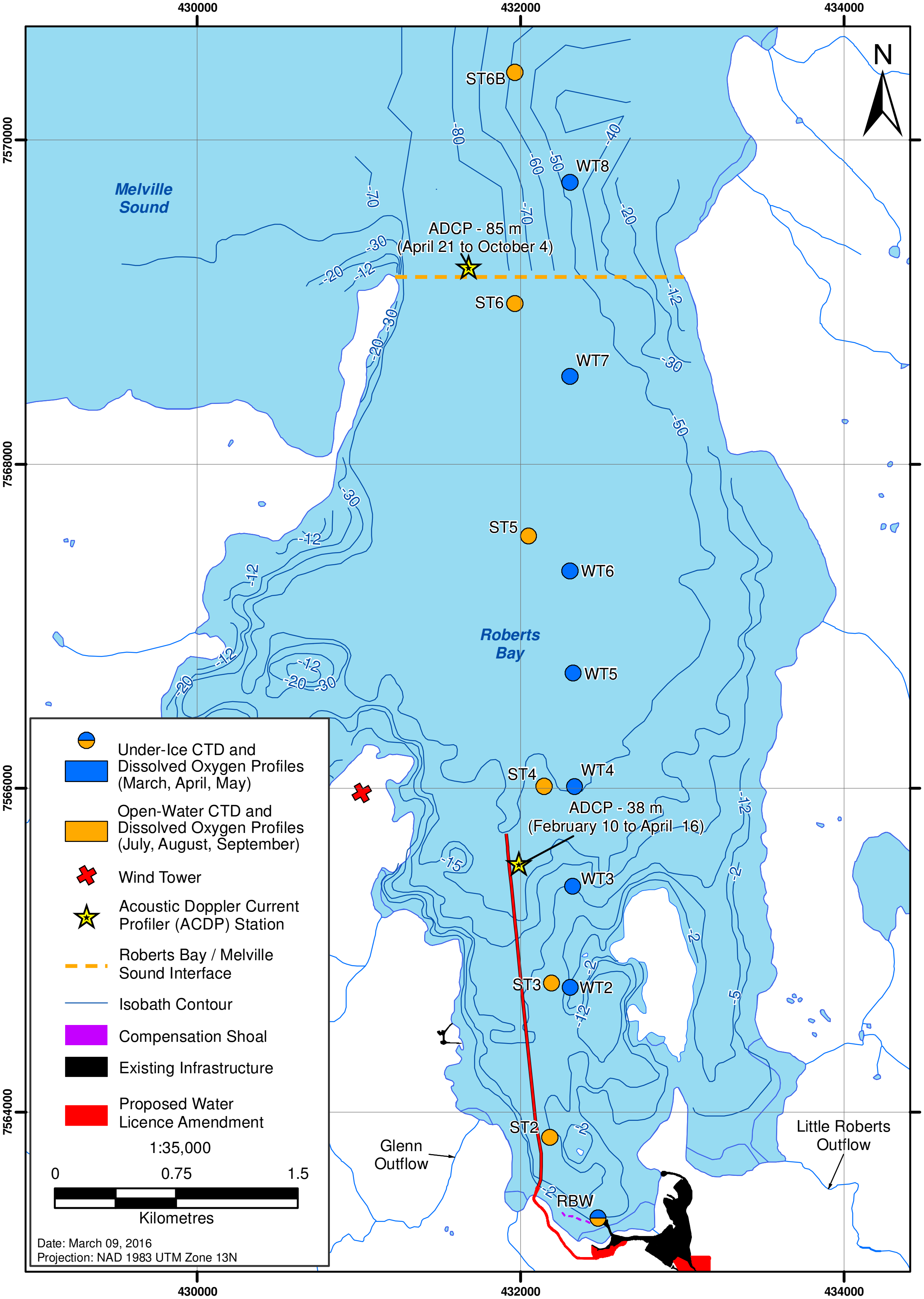
The dispersion of the TIA and groundwater discharge to Roberts Bay could then be calculated from the modelled currents at each timestep. This process is detailed in Section 3.

2.4 Specific Model Details

This section provides additional information on the parameters used to construct the Roberts Bay numerical model.

Figure 2.2-1

Roberts Bay Physical Oceanographic Sampling Stations, Doris North Project, 2009-2011



2.4.1 *Bathymetry*

Depths within the model domain were digitized with bathymetric data from field surveys (Rescan 2011b). Figure 2.4-1 shows the model region and bathymetric data used for the simulations, as well as the Roberts Bay – Melville Sound boundary. Three stations are identified on Figure 2.4-1: Station 1 (431910 E; 7565719 N) is the location of the proposed discharge diffuser, which is set at 40 m depth; Station 2 (800 m directly north of Station 1) and Station 3 (2,700 m directly north of Station 1) were chosen as point sources to estimate chromium concentrations at mid-field and far-field locations over time across the bay.

For the Roberts Bay far-field simulation, a three-dimensional rectilinear grid was used, covering the complete bay area and part of the surrounding Melville Sound. The grid cells were selected at 100 m length in the horizontal dimensions, which compares favorably with the 95 m diffuser length (SRK 2015b). Fourteen parallel vertical layers were used to represent the water column, with the first thirteen being 4 m deep while at the lowest layer depth was permitted to vary. This arrangement was the best configuration found that reproduced reasonably well the bay stratification while maximizing computational efficiency. Open boundaries were located at the northern and western limits of the Melville sound area, through which waters were allowed to flow in the model area using zero-gradient boundary conditions.

2.4.2 *Winds*

The wind data from 2011 were available from a wind sensor established on the southern shore of the bay, as shown in Figure 2.2-1. Winds measured at this site were applied across the entire model domain. Further details on the winds can be found in (Rescan 2011d).

2.4.3 *Freshwater Influx*

Two freshwater discharge points were implemented in the model: the Little Roberts and Glenn Outflows situated in the southern part of Roberts Bay. The Doris and Roberts Outflow 2011 datasets (see Rescan 2012b), were combined to form the Little Roberts Outflow time-series in the model. No data was available for the Glenn Outflow in 2011; however, based on data acquired in previous sampling years (e.g., see Rescan 2011b), the flow rates for Glenn Outflow were set at 50% of the Doris Creek flow.

2.4.4 *Other Meteorological Inputs*

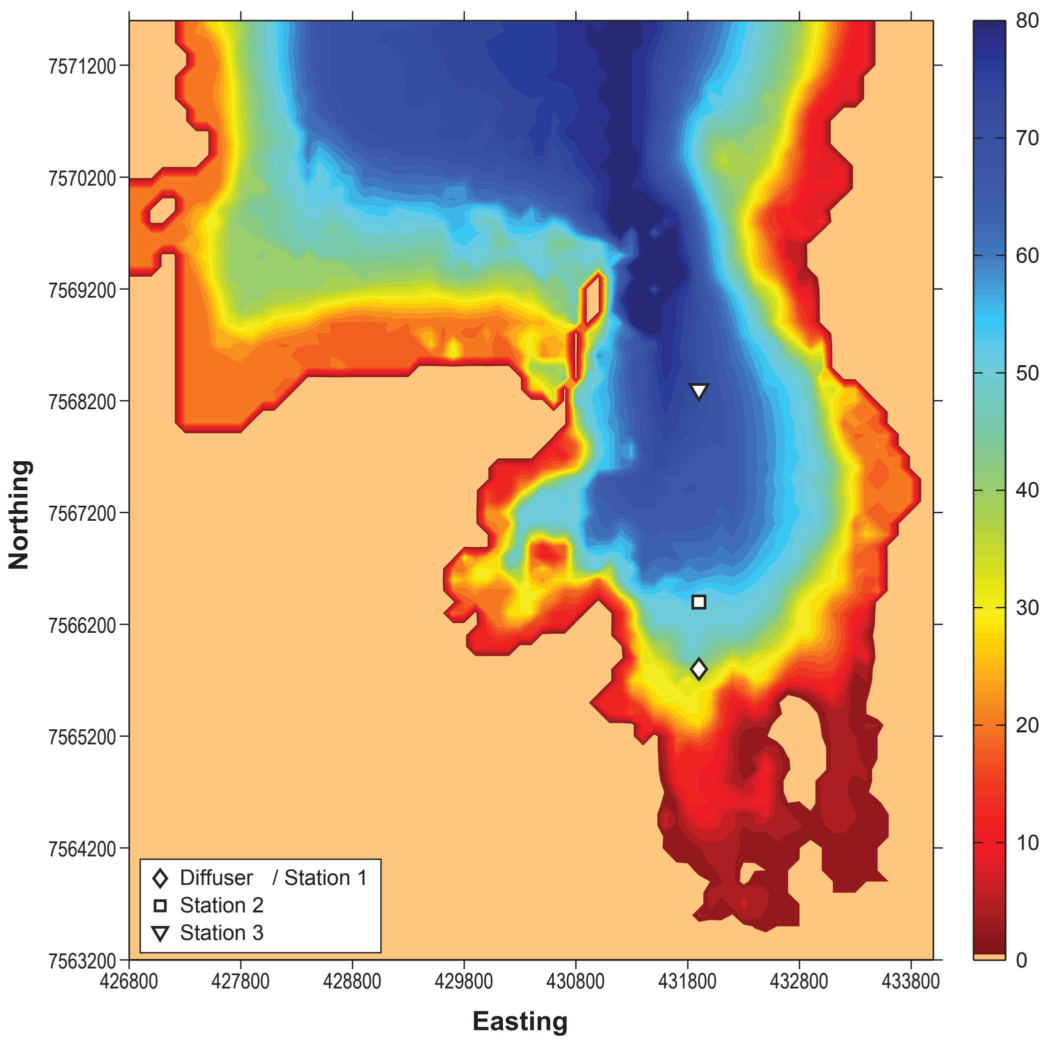
The relative air humidity, air temperature, and precipitation were allowed to vary daily in accordance with the *Hope Bay Belt Project: 2011 Meteorology Baseline Report* (Rescan 2011d).

2.4.5 *Stratification*

Background salinity was assumed to be initially constant at 26 ppt for the top 10 m and 27 ppt for the remainder of the water column, which was then allowed to stabilize itself according to meteorological inputs and freshwater flows. Similarly, the initial background temperature was set at 0ºC. Both temperature and salinity were set to vary spatially and temporally.

Figure 2.4-1

Roberts Bay and Melville Sound Bathymetry Used in the Numerical Model



2.4.6 *Tides*

Tidal heights and currents were previously found to be very weak within Roberts Bay when compared to wind-driven currents during the open-water season (see Rescan 2012b), and almost non-existent during the under-ice period, so tides were not included for this model.

2.4.7 *Model Time: Calibration and Simulation Periods*

The model was set to run at a 5 s time step for 365 days between May 1 and April 30 for Year 1. The first month of modelling was run with under-ice conditions, however, wind speed was allowed to increase from 0 to a minimum value of 0.5 m/s for the transition between under-ice and open-water conditions. This allowed the stratification to adjust itself to a stable state which replicated reasonably well the conditions measured in Roberts Bay for 2011 (see Section 2.5.1 below).

2.4.8 *Turbulence Closure Scheme*

In many numerical simulations, the small-scale turbulence cannot be resolved with the chosen spatial resolution, thus it needs to be approximated through other methods. The turbulence in MIKE3 is parameterized using an eddy viscosity concept (i.e., the Boussinesq approximation), which is described separately for the vertical and the horizontal transport. The Smagorinsky formulation (Smagorinsky 1963) was used in the simulations for this work, which involves the eddy viscosity being linked to a filter size (i.e., the grid spacing) and the velocity gradients of the resolved flow field.

2.4.9 *Other Model Parameters*

Table 2.4-1 summarizes the inputs and model parameters used in the hydrodynamic model.

Table 2.4-1. Important Model Input Parameters

Parameter Name	Values	Comment
Horizontal Grid Size	100 m	
Vertical Grid Size	4 m	Bottom layer varies
Number of Layers	14	
Time Step	5 s	
Simulation Duration	365 days	
Bed Roughness Length	0.05 m	
Smagorinsky vertical coefficient	0.176	
Horizontal Eddy Viscosity Limits	0.01 to 33.3 m^2/s	Smagorinsky formulation
Vertical Eddy Viscosity Limits	0.0001 to 0.003 m^2/s	Smagorinsky formulation
Wind Friction	0.0016 to 0.0026	Drag coefficient
Initial Background Salinity	26/27 ppt	
Initial Background Temperature	0°C	

2.5 2011 Baseline Simulation

2.5.1 Thermohaline Structure

The comparison of temperature and salinity profiles between measured data and model results for Roberts Bay stations (see Figure 2.4-1) are shown in Figures 2.5-1, 2.5-2, and 2.5-3 for the open-water measurements of July, August, and September 2011. Station profiles were reproduced fairly well in the model, the notable exception was station ST2, which was shallow and more difficult to reproduce given the coarse numerical grid. The values modelled at shallow depths (i.e., less than 20 m depth) had generally the greatest departures from the measured data, with differences in temperatures of greater than 3ºC for stations ST5 and ST6, and between 1-2 ppt for salinity. The deeper water column was more accurately reproduced, with differences generally less than 1ºC in temperatures and less than 1 ppt in salinity. Overall, the stratification and layering of the water column was reasonably reproduced, particularly in view of the assumptions by the model. The difference in mixed layer depth between the model and data was at most ~5 m. More details on the comparison between modelled and measured results can be found in Rescan (2012b).

The comparison between modelled and measured data for the under-ice measurements of May 2011 are shown as an example in Figure 2.5-4. The model results compare favorably with the thermohaline data regarding of the overall shape of the temperature and salinity profiles and the deep (20+ m) pycnocline. The model results in Figure 2.5-1 over-predict shallow (i.e., top ~20 m) temperatures by 0.3 to 2ºC and under-predicts shallow salinity by 0.5 to 1 ppt. This discrepancy is due to the assumptions taken in the modelling for the under-ice season; the absence of a true ice growing module prevents the formation of a realistic marine stably stratified winter water column. Given the generally good prediction for the deeper waters, the modelled winter water column was surmised as sufficient for tracking the deep effluent discharge in Roberts Bay.

2.5.2 Currents and Circulation

Model current velocities were plotted versus ADCP observations at four different depths for the 85 m station (see Figure 2.2-1 for the 85m ADCP Station location) in the northern (Figure 2.5-5) and eastern (Figure 2.5-6) directions. The model's effectiveness at simulating the measured currents varied during the entire simulation length. This was to be expected given the multiple assumptions taken in the model formulation, and that the measured wind from only one location was applied over the complete model domain; in reality, wind and wave strength/direction can vary at the sub-metre scale. Despite some dissimilarities, there are several periods within the run where measured and modelled data correlated extremely well, such as between September 8 and September 10 in Figure 2.5-5 or the eastern currents at 4 m depth in Figure 2.5-6. Furthermore, the magnitudes of the model currents are on the same scale (i.e., averages < 5 cm/s) as the ADCP measurements, suggesting that the model output currents reasonably approximate the observed dataset. More details on the comparison between modelled and measured results can be found in Rescan (2012b).

Figure 2.5-1

Temperature and Salinity Comparison between Measured and Modelled Data in Roberts Bay, Doris North Project, July 2011

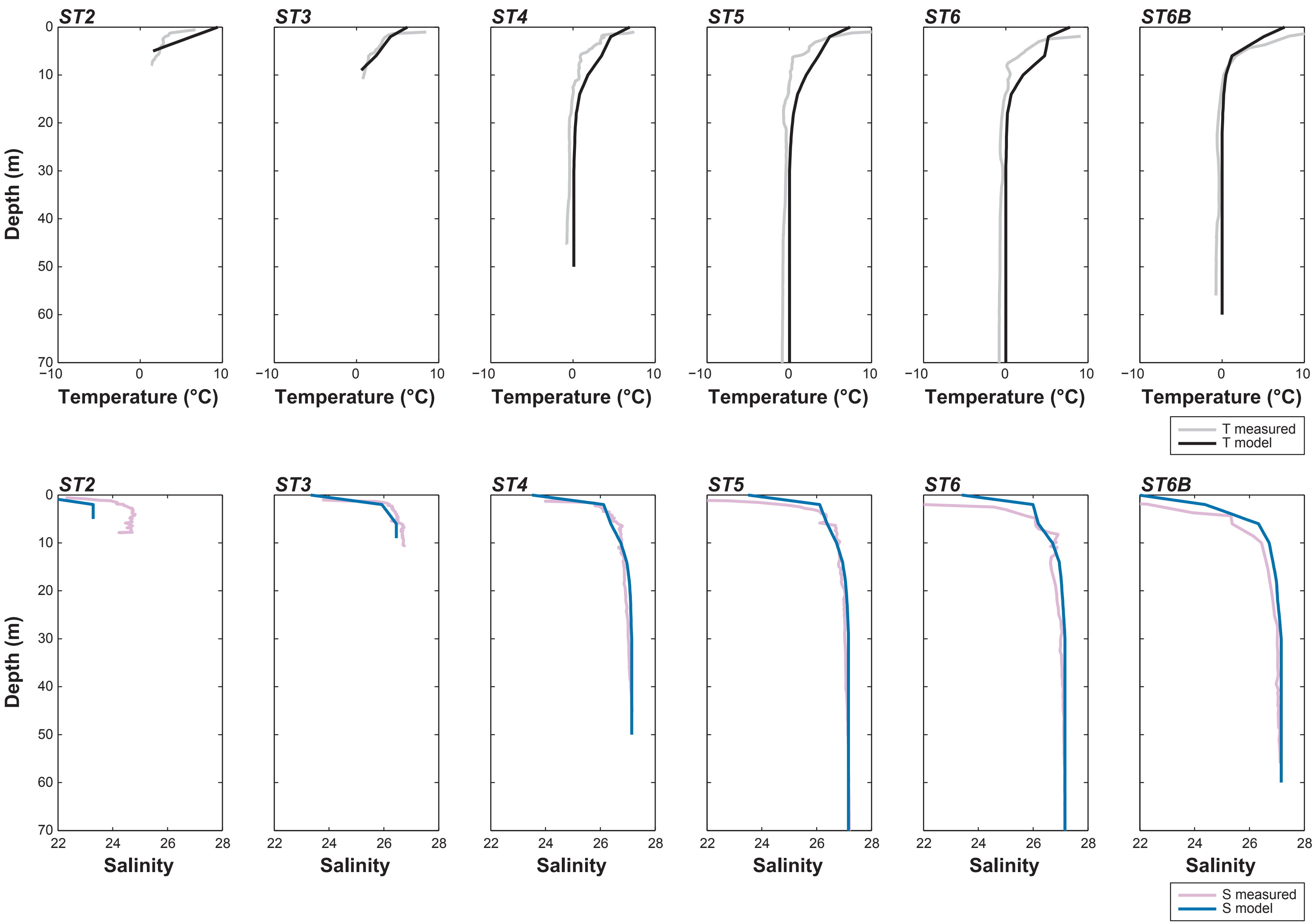


Figure 2.5-2

Temperature and Salinity Comparison between Measured and Modelled Data in Roberts Bay, Doris North Project, August 2011

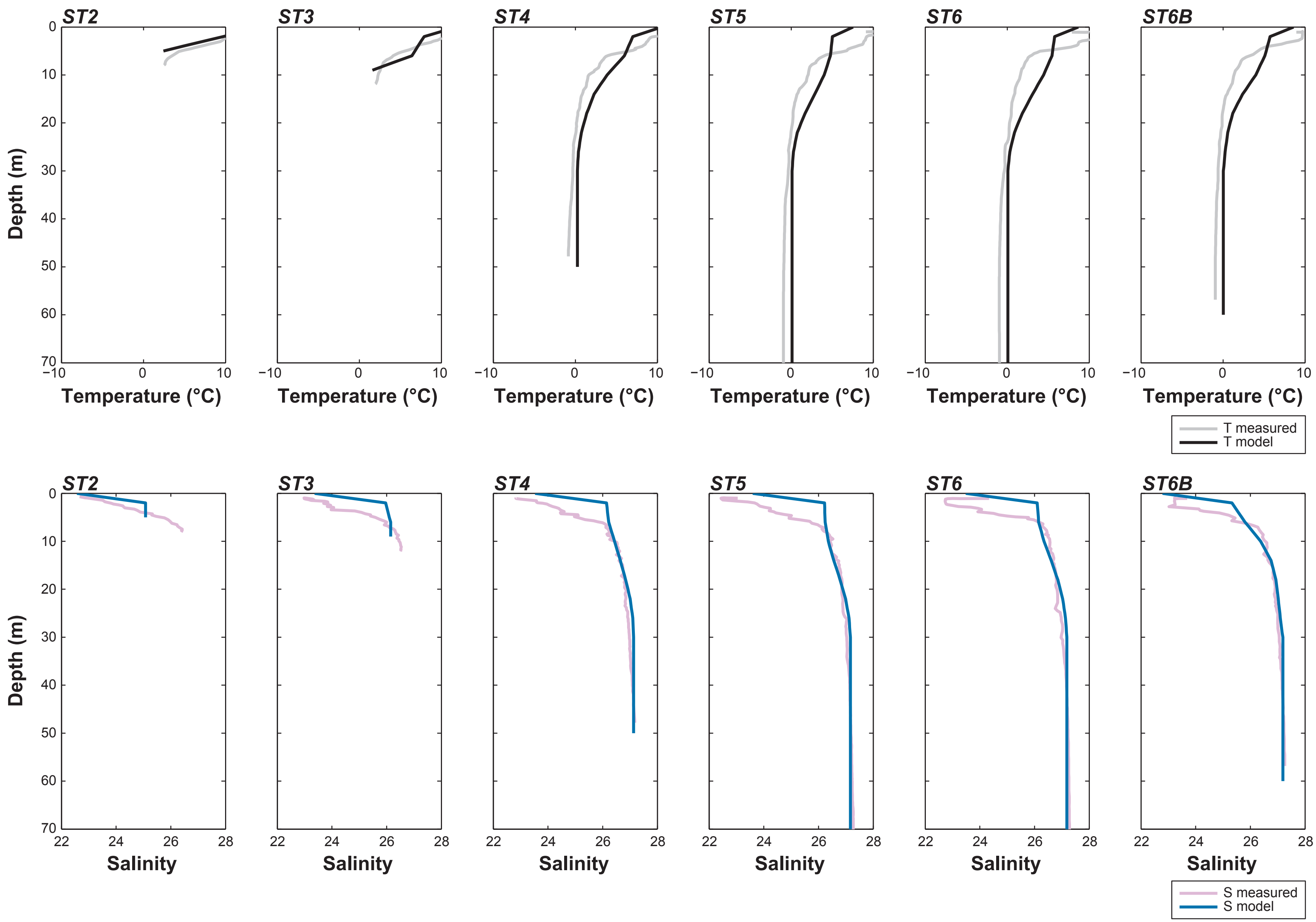


Figure 2.5-3

Temperature and Salinity Comparison between Measured and Modelled Data in Roberts Bay, Doris North Project, September 2011

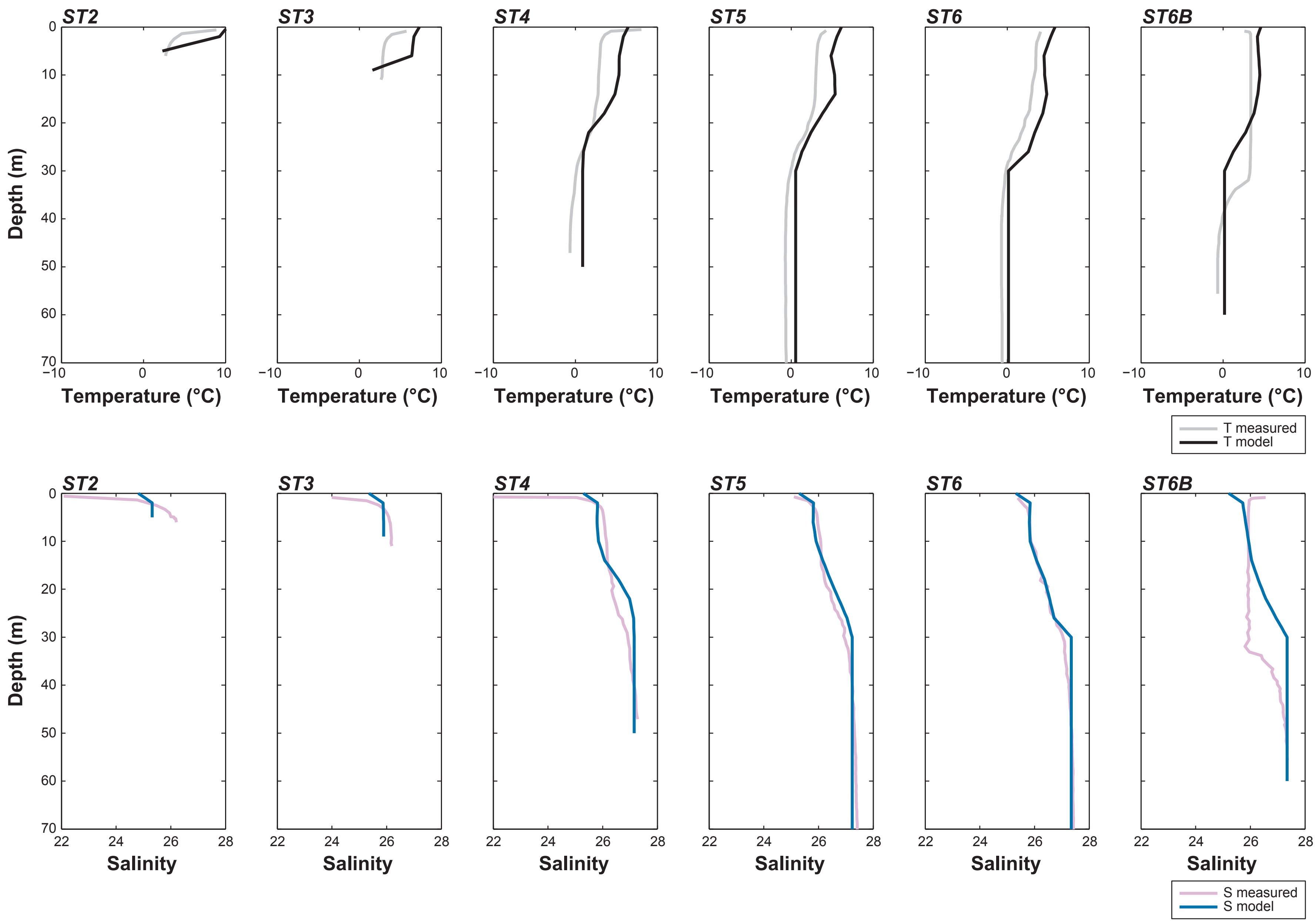


Figure 2.5-4

Temperature and Salinity Comparison between Measured and Modelled Data in Roberts Bay, Doris North Project, May 2011

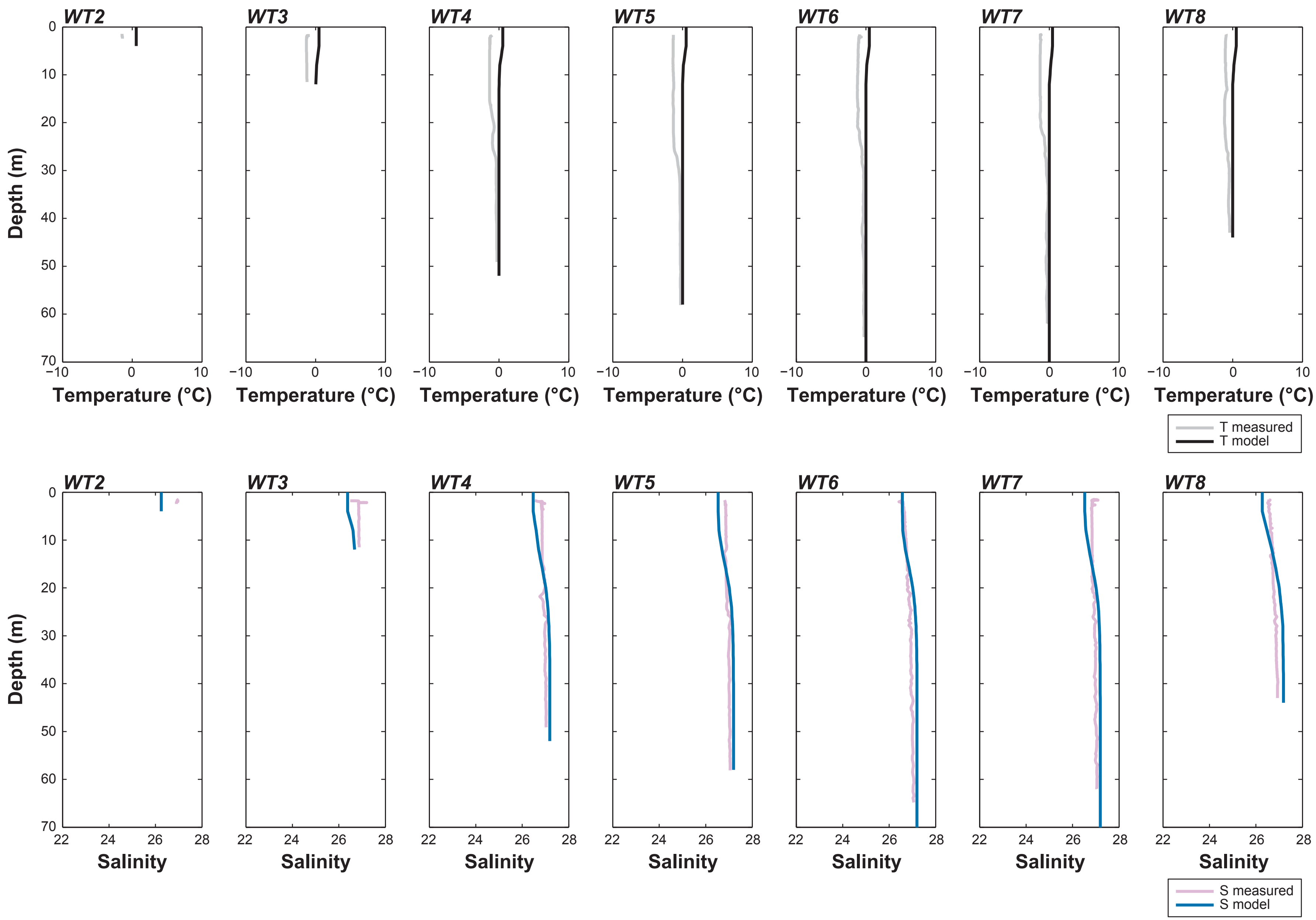


Figure 2.5-5

Comparison of Northern Current Velocities between Measured and Modelled Data, 85 m Site, July to September 2011

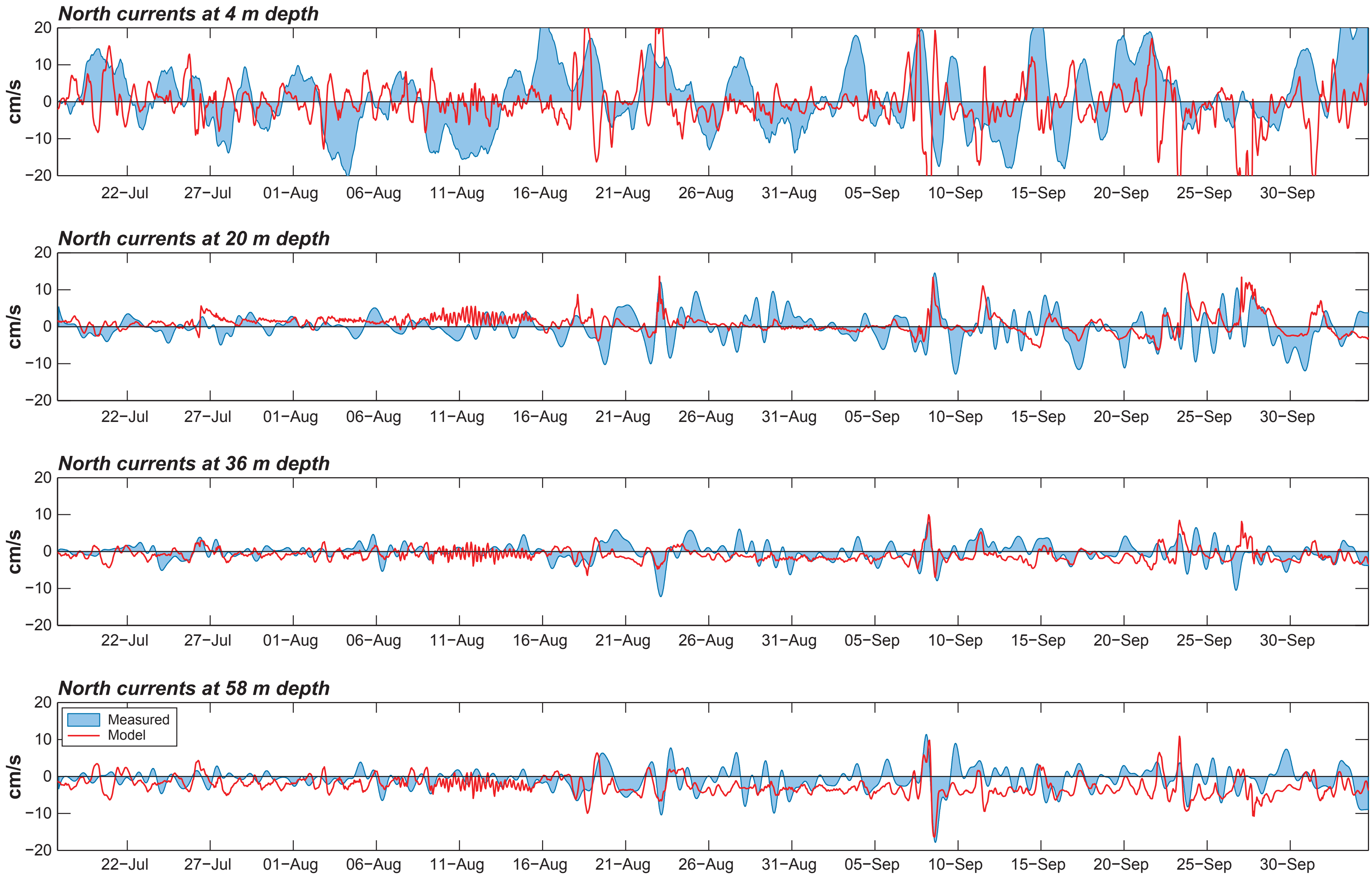
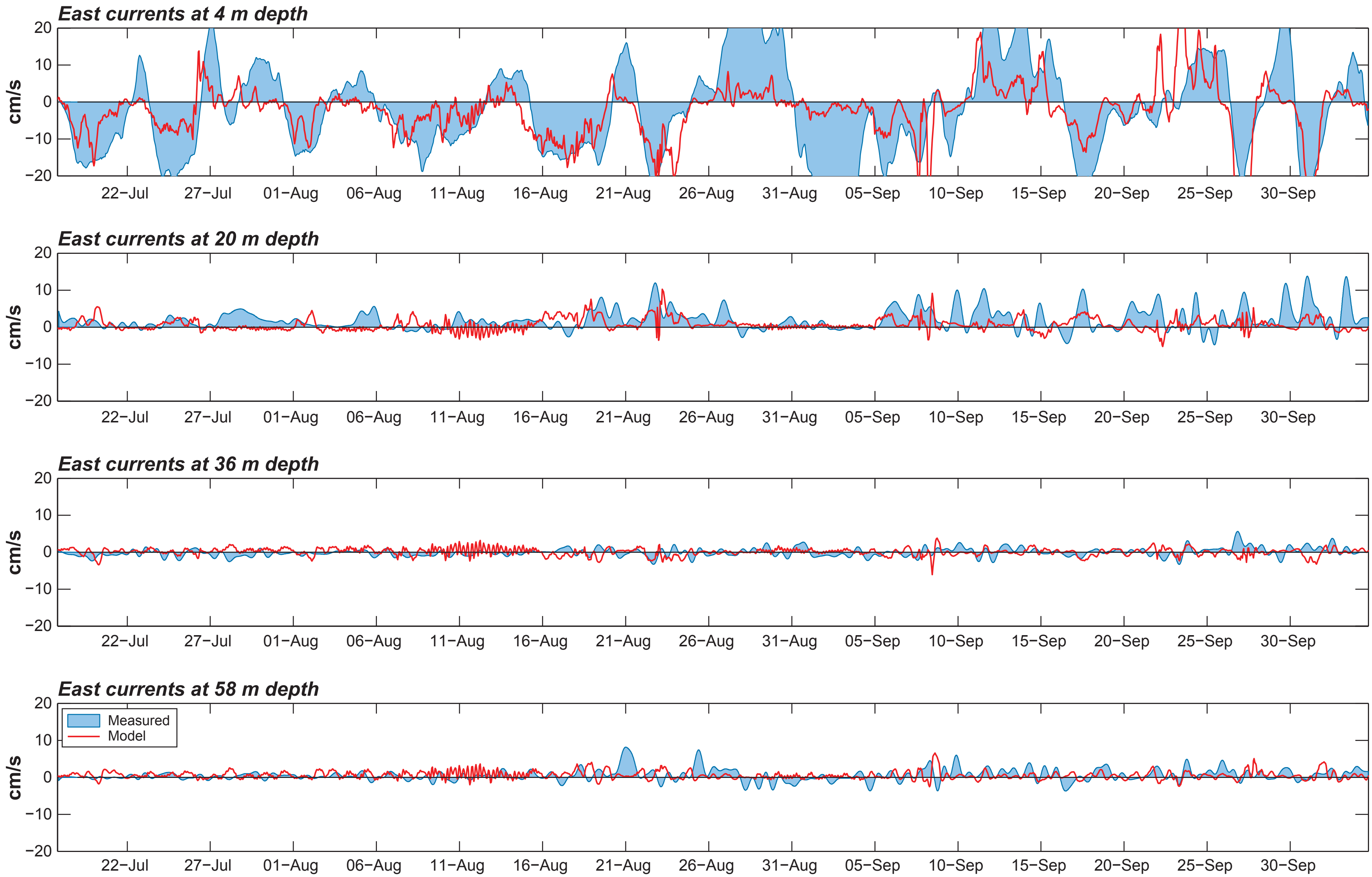


Figure 2.5-6

Comparison of Eastern Current Velocities between Measured and Modelled Data, 85 m Site, July to September 2011



3. ROBERTS BAY ADVECTION DISPERSION MODEL

3.1 Model Description

The DHI Advection Dispersion module (DHI 2009) was coupled to the MIKE3 Flow model output (see Section 2) to predict the concentrations of total chromium in Roberts Bay. The model is a Lagrangian model of advection/diffusion (see Kundu 1990) that runs decoupled from the fluid dynamics simulated by the MIKE3 model. Although the TIA and groundwater effluents introduce several parameters in Roberts Bay, only chromium was modelled as it required the greatest dilution within the effluent to meet marine CCME water quality guidelines in Roberts Bay (ERM 2016), thus preserving water quality and ensuring protection for all marine and estuarine life in the bay.

The baseline value for chromium in Roberts Bay for the modelling run was set at 0.0005 mg/L. This was the median baseline concentrate from all deep-water baseline data collected in Roberts Bay. Greater percentile data (e.g., 75^{th}) were not used because they were all below analytical detection, with the detection limit levels (0.05 mg/L) being greater than the TIA and groundwater discharge chromium concentrations. This would artificially dilute chromium concentrations in Roberts Bay under each of the TIA and groundwater discharge scenarios. Only deep-water concentrations (samples taken below the pycnocline) were used for the baseline chromium input as the effluent will be discharged into and is expected to be trapped within this layer.

For the purposes of the Roberts Bay chromium predictions, the model considered chromium as a passive tracer in the bay. This ensured that the predicted chromium concentrations were conservative in nature because burial and sequestration were not considered. Results were compared against baseline concentrations and the most conservative CCME marine guideline for chromium (hexavalent form at 0.0015 mg/L;CCME 2015).

3.2 Roberts Bay Inflow and Associated Effluent Concentrations

Effluent data, including discharge volumes and predicted TIA and groundwater chromium concentrations, were obtained from the load and balance model found in the SRK *Doris North Project – Water and Load Balance Report* (SRK 2015a). The timeseries of chloride concentrations was taken from SRK's groundwater modeling report (SRK 2015c). The discharge volumes and associated chromium concentrations for the one modelled year of inflow into Roberts Bay are shown in Table 3.2-1. Discharge volumes were modelled conservatively at their maximum rates; during under-ice months (October to May), only groundwater will be discharged and was set to the maximum rate of 3,000 m^3/day; during the open-water months (June to September), both TIA and groundwater will be discharged at a maximum combined discharge flow of 7,000 m^3/day. The greatest chromium concentrations were predicted in the combined TIA and groundwater effluent (0.002 mg/L) during Year 1 of open-water discharge, which was four-fold greater than the Roberts Bay median baseline concentration (0.0005 mg/L). The groundwater effluent to be discharged under-ice had predicted concentrations that were less than twice the baseline concentration input. Salinity was calculated from the predicted inflow chloride concentrations, while temperatures were set at 2°C.

Table 3.2-1. Roberts Bay Diffuser Discharge Parameters for Year 1

Month	Discharge (m^3/day)	Chloride (mg/L)	Chromium (mg/L)	Temperature (°C)	Salinity
May	3,000	14,780	0.00086	2	26.70
June	7,000	4,854	0.0018	2	8.77
July	7,000	4,351	0.0019	2	7.86
August	7,000	3,844	0.0020	2	6.94
September	7,000	3,042	0.0020	2	5.50
October	3,000	8,823	0.00086	2	15.94
November	3,000	6,947	0.00086	2	12.55
December	3,000	6,308	0.00086	2	11.40
January	3,000	6,123	0.00086	2	11.06
February	3,000	6,003	0.00086	2	10.85
March	3,000	6,034	0.00086	2	10.90
April	3,000	5,994	0.00086	2	10.83

For the purpose of the far-field modelling, effluent mixing was assumed to be instantaneous within the discharge grid point.

4. SIMULATION RESULTS AND DISCUSSION

Chromium concentrations were predicted over the spatial scale of all of Roberts Bay and nearby Melville Sound (all depths and locations) as shown in Figure 2.4-1. Groundwater only discharge during the under-ice season (October to May) and TIA and groundwater combined discharge during the open-water (June to September) were included in the modelling.

This section presents the modelling results in two main formats. First, results are presented as concentration graphs with time for the three station locations from Figure 2.4-1, as well as for the water column above the diffuser location. Results are then presented as monthly chromium concentrations throughout the model area at three specific depths:

- 4 m depth: surface waters which are subjected to the largest wind stresses, currents, and freshwater/precipitation inflow;
- 32 m depth: approximate trapping depth of the plume material from the diffuser; and
- 40 m depth: depth of the diffuser discharge.

These results are presented as two-dimensional "heat" diagrams covering the open-water and under-ice periods. All four open-water months (i.e., June to September) are represented in the heat plots, while every other under-ice month (i.e., October, December, February, and April) is shown.

4.1 Predicted Chromium Concentrations at Roberts Bay Stations

The percent increase of chromium concentrations above baseline values at the diffuser are shown in Figure 4.1-1 between May and April of Year 1. The initial discharge occurring late in the under-ice season (May) was limited to a few metres above the diffuser, and concentrations were usually below 2% over baseline. Limited plume material was entrained in the water column above 30 m, which resulted in a less than 0.2% increase above baseline values. This corroborates near-field modelling results (ERM 2016) and is due to the density of the discharge effluent being greater in May compared to other months, given the greater effluent salinity (26 ppt in May versus less than 10 ppt for the summer months; see Table 3.2-1 for details).

In June, full open-water conditions are present with an increased discharge volume component as both TIA and groundwater will be discharged to Roberts Bay. The bottom stratification breaks down due to the wind-driven currents as more material gets entrained in the water column. Nearly all material remains below 15 m depth, with increases above 2% confined to depths below 30 m (Figure 4.1-1). Towards the end of the open-water season in September, the chromium concentrations increased in the bottom waters up to a maximum of 6% above baseline values at the diffuser, but slightly decreased in the surface waters. The main trapping depth for the plume material ranged between 30 and 32 m depth.

From October onwards, under-ice conditions apply, with limited ocean currents, and only groundwater being discharged. At this transition from summer to winter, most of the plume material gets flushed out of the bay and chromium concentrations increased by less than 0.4% over baseline. From October to January, shifting water masses in the cooling water column resulted in increased mixing and chromium dispersion in the bottom waters. This movement decreased in December, and for the remainder of Year 1, the stratification stabilized and the water column achieved a steady state with chromium dispersing throughout the bottom waters (see Section 4.2 below for further comment).

During the full model run, chromium concentrations remained near baseline levels and were far below the CCME guidelines for all seasons.

Figure 4.1-2 presents the predicted chromium concentrations with time at the three stations depicted in Figure 2.4-1 for three different water column depths. At the shallowest depth (4 m), the concentrations were barely perceptible from baseline levels (0.0005 mg/L) at each station, indicating little chromium (or any other water quality constituent) was entrained into the Roberts Bay surface layer during any discharge scenario.

Slightly greater chromium concentrations were predicted in the deeper waters (32 m and 40 m) where the discharge plume was trapped. The greatest concentrations were predicted at the diffuser station (Station 1) during the open-water season when the TIA and groundwater combined effluent was discharged; however, these concentrations were only about 1 to 2% greater than baseline concentrations. Under-ice concentrations remained fairly stable for the complete model run at all observed depths, and were always less than 0.5% over baseline. Overall, increases in chromium concentrations were usually less than 2% over baseline across the bay, with a maximum of 6% occurring in September during a period of limited deep currents.

Figure 4.1-1

Chromium Percent Concentration Increase over Baseline Values at Diffuser Location

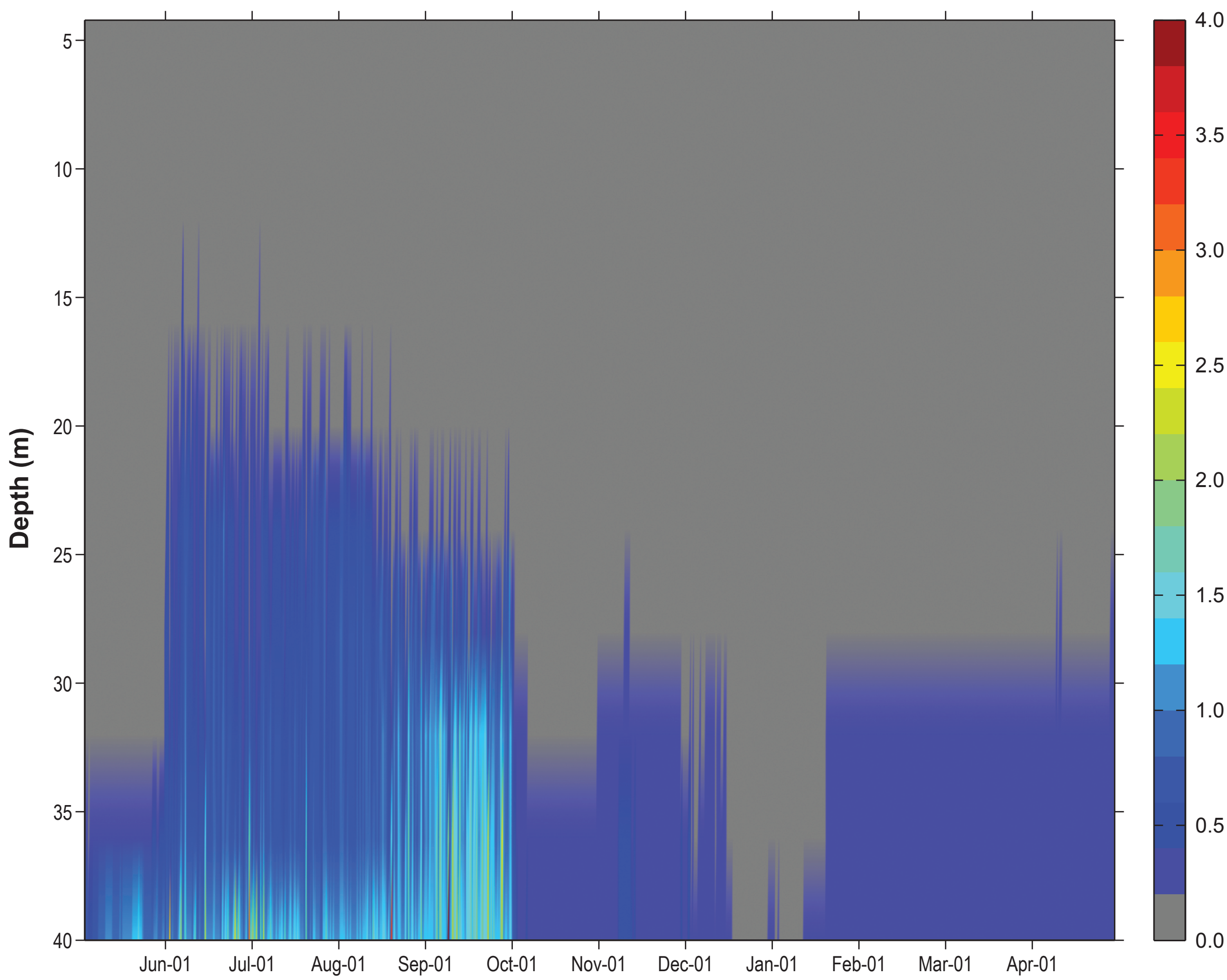
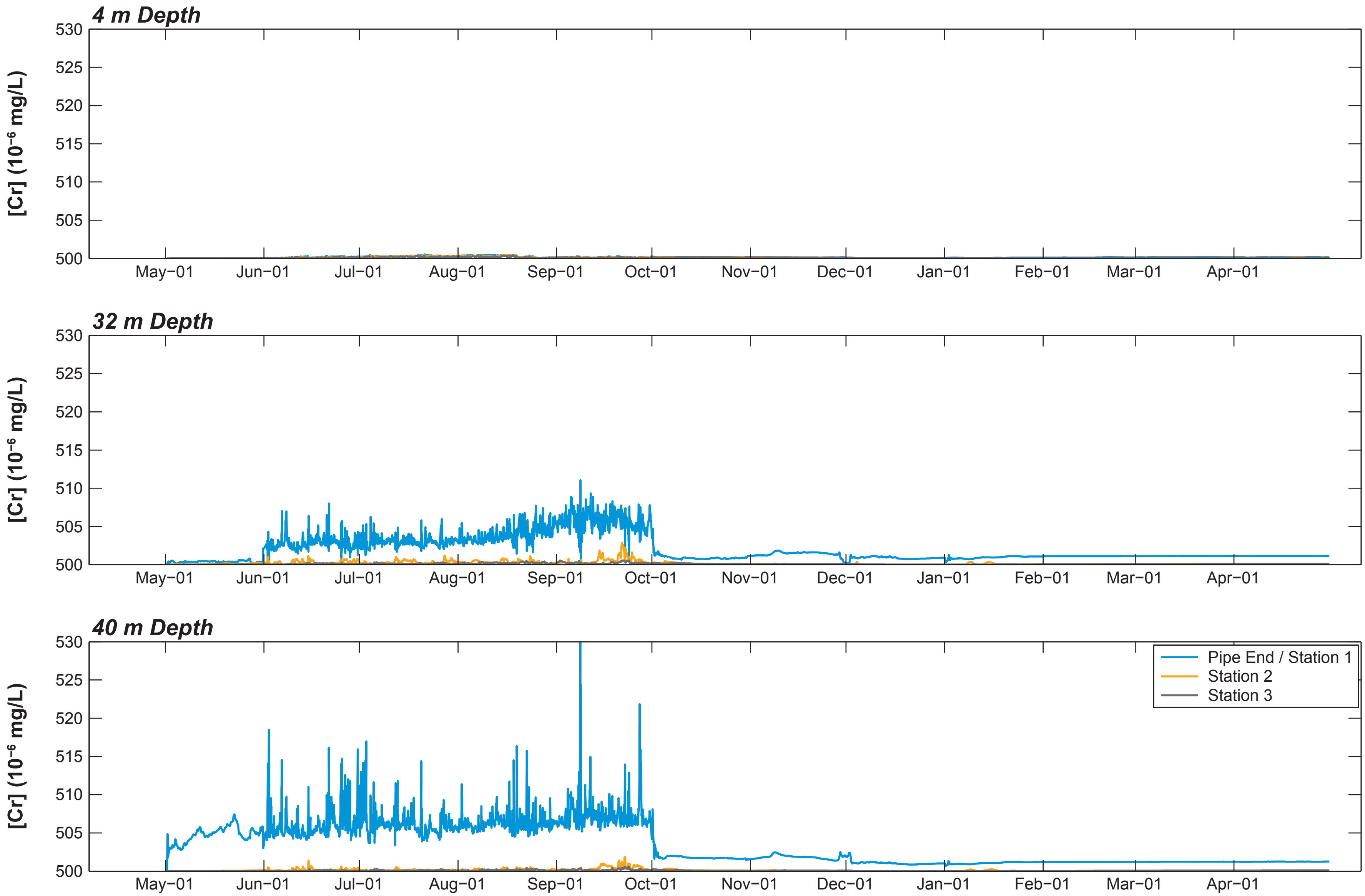


Figure 4.1-2

Predicted Chromium Concentrations for Roberts Bay Stations with Time



4.2 Predicted Bay-wide Monthly Chromium Concentrations

This section presents the modelled bay-wide monthly average chromium concentrations for the open-water and under-ice seasons of Year 1 of TIA and groundwater discharge. Also included are the monthly dilution ratios at each selected depth. The dilution ratios were calculated using the monthly discharge volumes and concentrations, as well as the maximum monthly predicted chromium concentrations recorded at each grid point. This resulted in conservative maps of minimum dilution at each grid point.

4.2.1 Open-water Period

Figure 4.2-1 presents the predicted average chromium concentrations at 4 m depth in Roberts Bay for the open-water months, while Figure 4.2-2 shows the calculated dilution ratios. As previously discussed in Section 4.1, very little of the effluent plume material gets entrained into the surface layer, but due to the currents this material quickly spreads out in the bay. This is easily observable in Figure 4.2-2 as the dilutions are large (i.e., mostly between 1,000:1 and 10,000:1) and extend into Melville Sound.

Figure 4.2-3 presents the predicted average chromium concentrations at 32 m depth in Roberts Bay for the open-water months, while Figure 4.2-4 shows the calculated dilution ratios. Results indicate that the discharge plume will be diluted quickly within the trapping layer during the open-water season, with average chromium concentrations increasing by only 0.4% (0.000502 mg/L) over baseline (0.000500 mg/L) in the immediate vicinity of the diffuser and orders of magnitude less than that in the far field (Figure 4.2-3). Because of the changing wind speeds and directions, the plume is dispersed throughout the bottom waters of Roberts Bay before moving into Melville Sound.

The highest concentrations remained within 300 m of the diffuser by September, with maximums of up to 6% above baseline values. The dilution plot shows the smallest dilutions around the diffuser were on the order of 100:1, but quickly increased to 1,000:1 throughout the mid-bay area. The plume material then propagated into Melville Sound, where dilutions exceeded 100,000:1.

Figure 4.2-5 presents the predicted average chromium concentrations at 40 m depth (diffuser depth) in Roberts Bay for the open-water months, while Figure 4.2-6 shows the calculated dilution ratios. The relatively slow currents at depth coupled with the buoyant plume lead to most of the effluent rising in the water column instead of spreading horizontally along the 40 m isobath. Hence, in Figure 4.2-5, increases in average chromium concentrations (< 0.4% above baseline) only occurred at the diffuser location with minimal spreading elsewhere. Only in September was significantly more horizontal spreading recorded in the bottom waters. The lower dilution ratios from Figure 4.2-6 were limited to the discharge grid point and adjacent points, with an average of 206:1 recorded in September. Dilution immediately increased to 1,000:1 in other nearby points.

Overall, chromium concentrations throughout the bay during the open-water season were consistently predicted to be less than 0.4% above baseline and were far below the CCME guideline for the protection of marine and estuarine life (0.0015 mg/L) at all times.

Figure 4.2-1

Predicted Chromium Concentrations for Roberts Bay: Open-Water Period (4 m Depth)

ERM

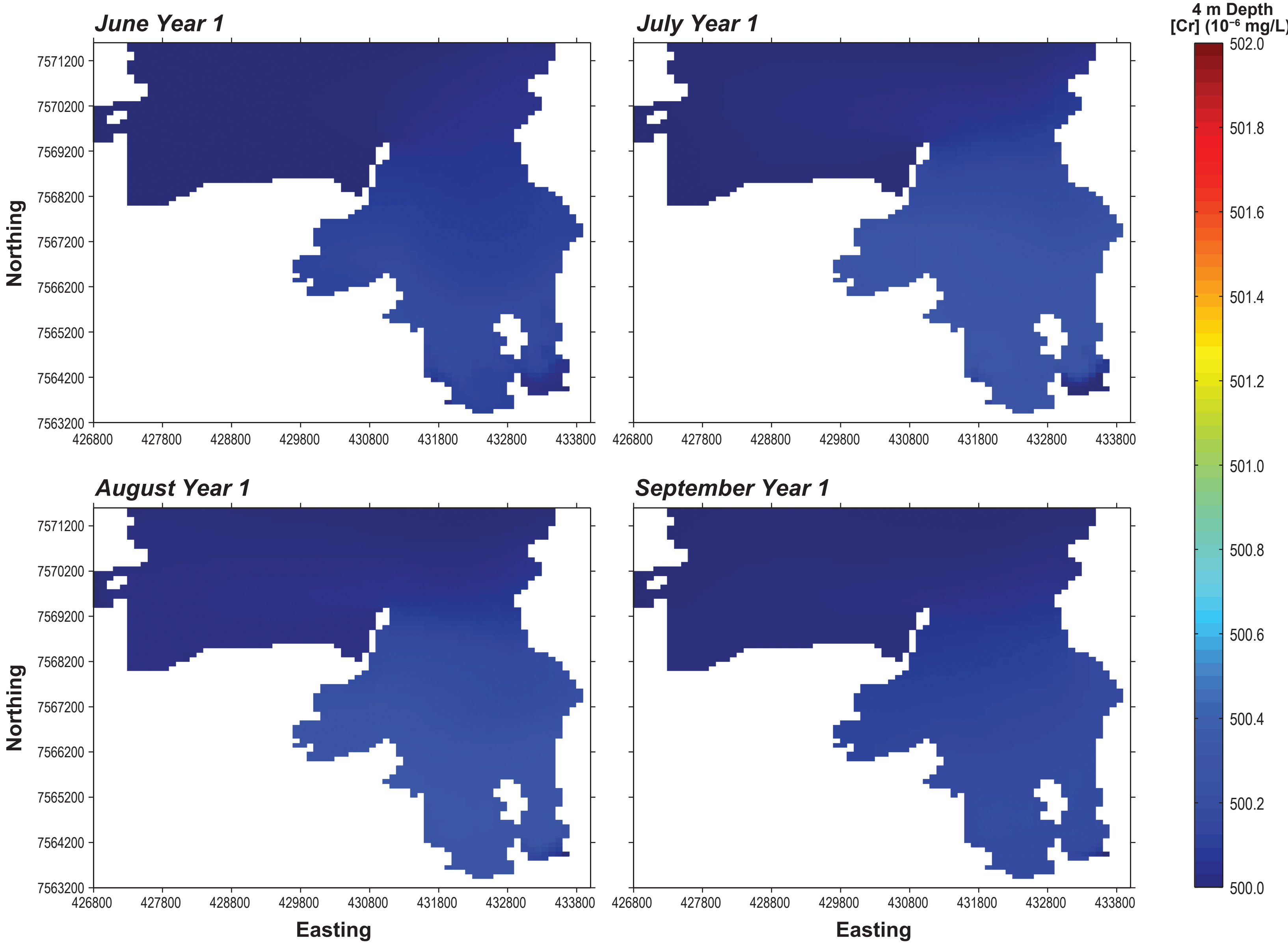


Figure 4.2-2

Minimum Dilution Ratio for Roberts Bay: Open-Water Period (4 m Depth)

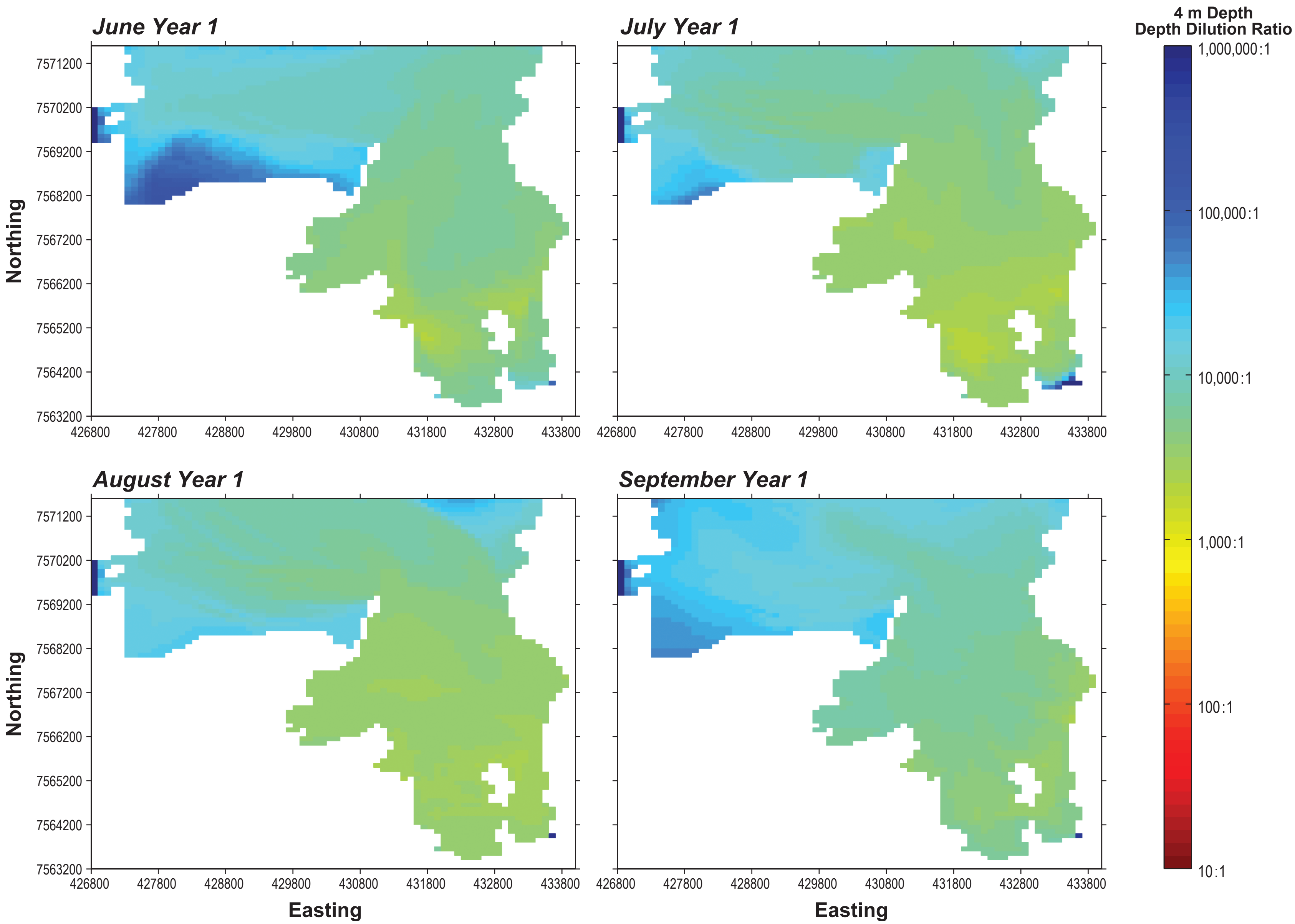


Figure 4.2-3

Predicted Chromium Concentrations for Roberts Bay: Open-Water Period (32 m Depth)

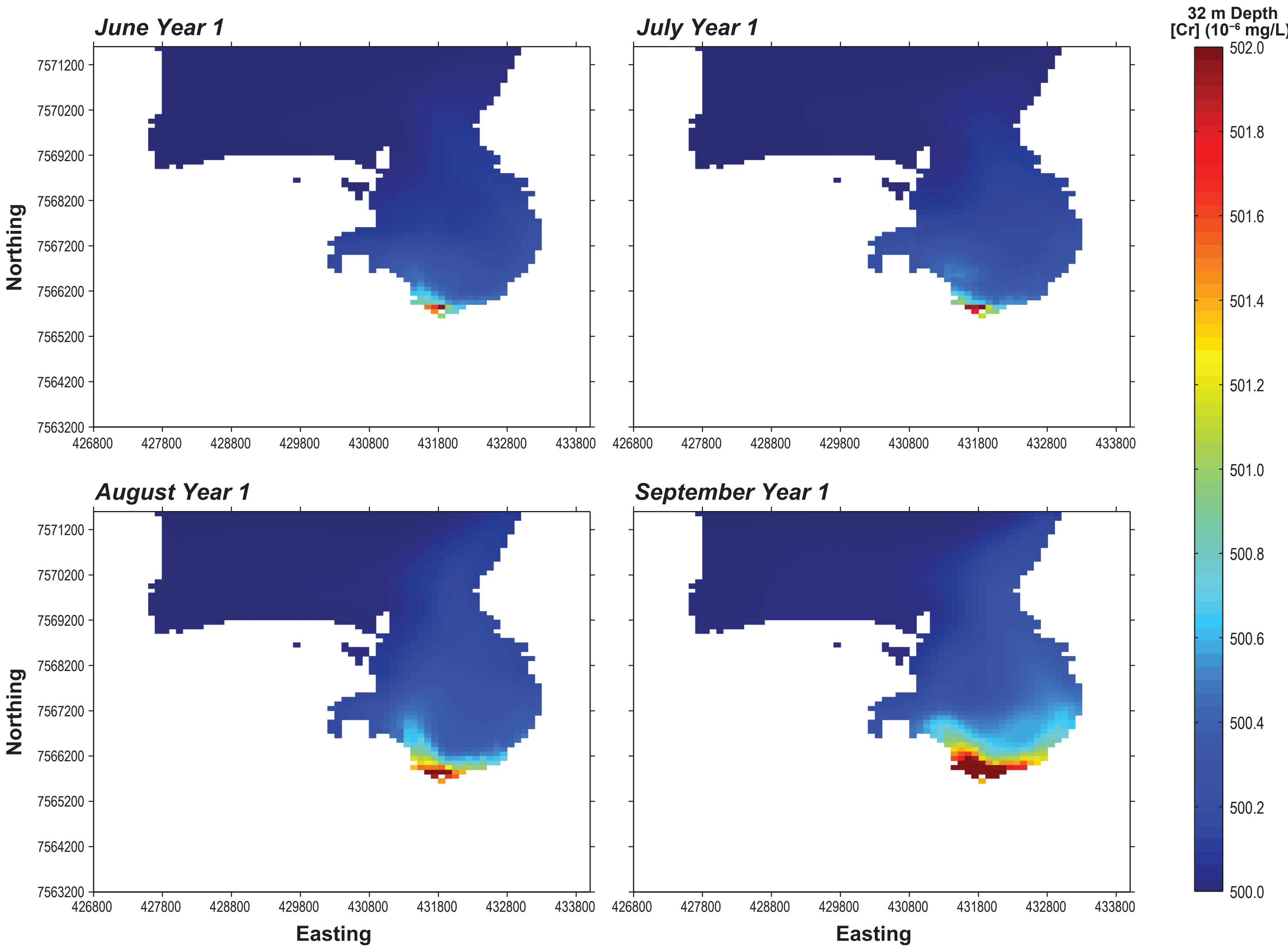


Figure 4.2-4

Minimum Dilution Ratio for Roberts Bay: Open-Water Period (32 m Depth)

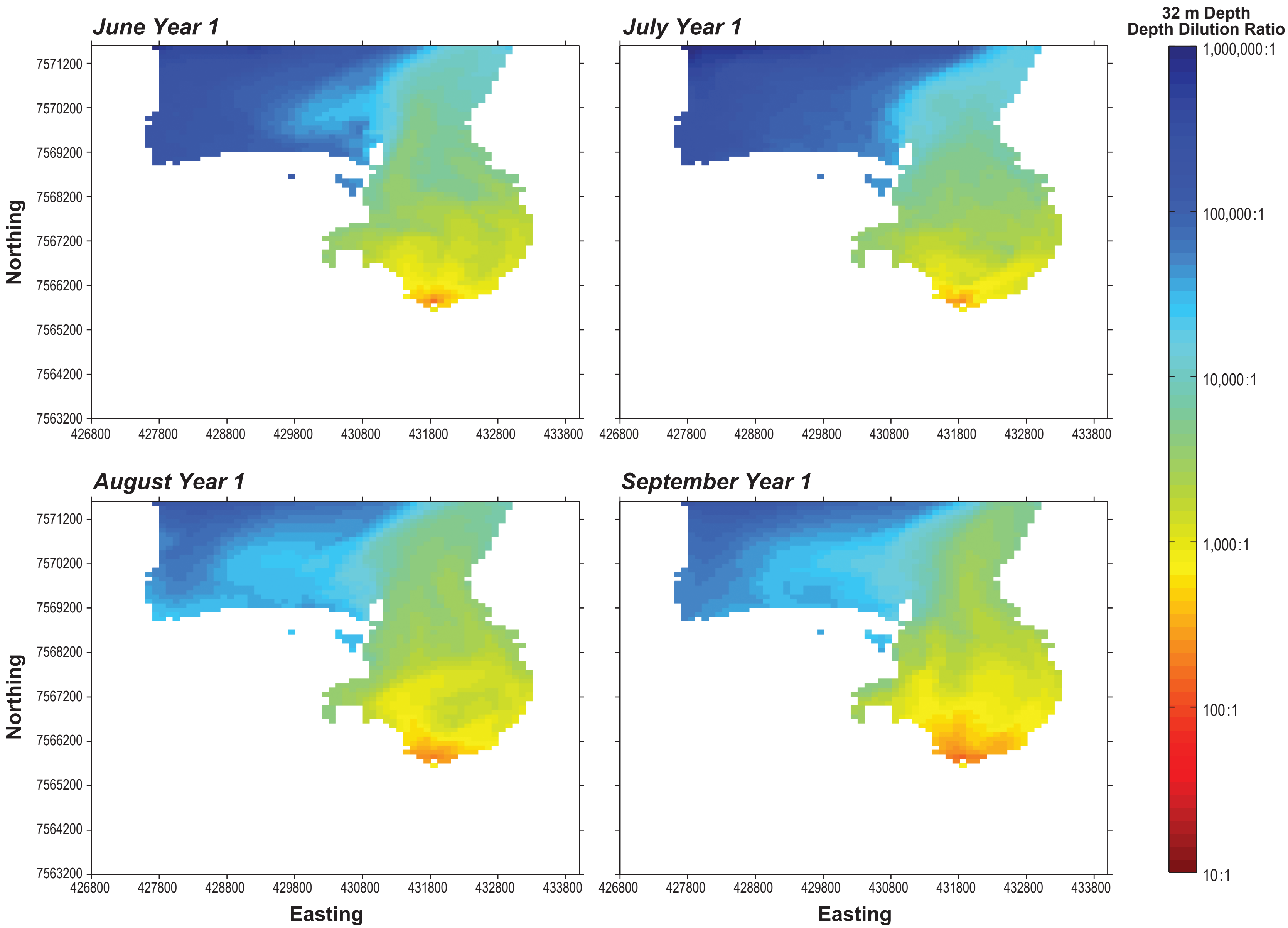


Figure 4.2-5

Predicted Chromium Concentrations for Roberts Bay: Open-Water Period (40 m Depth)

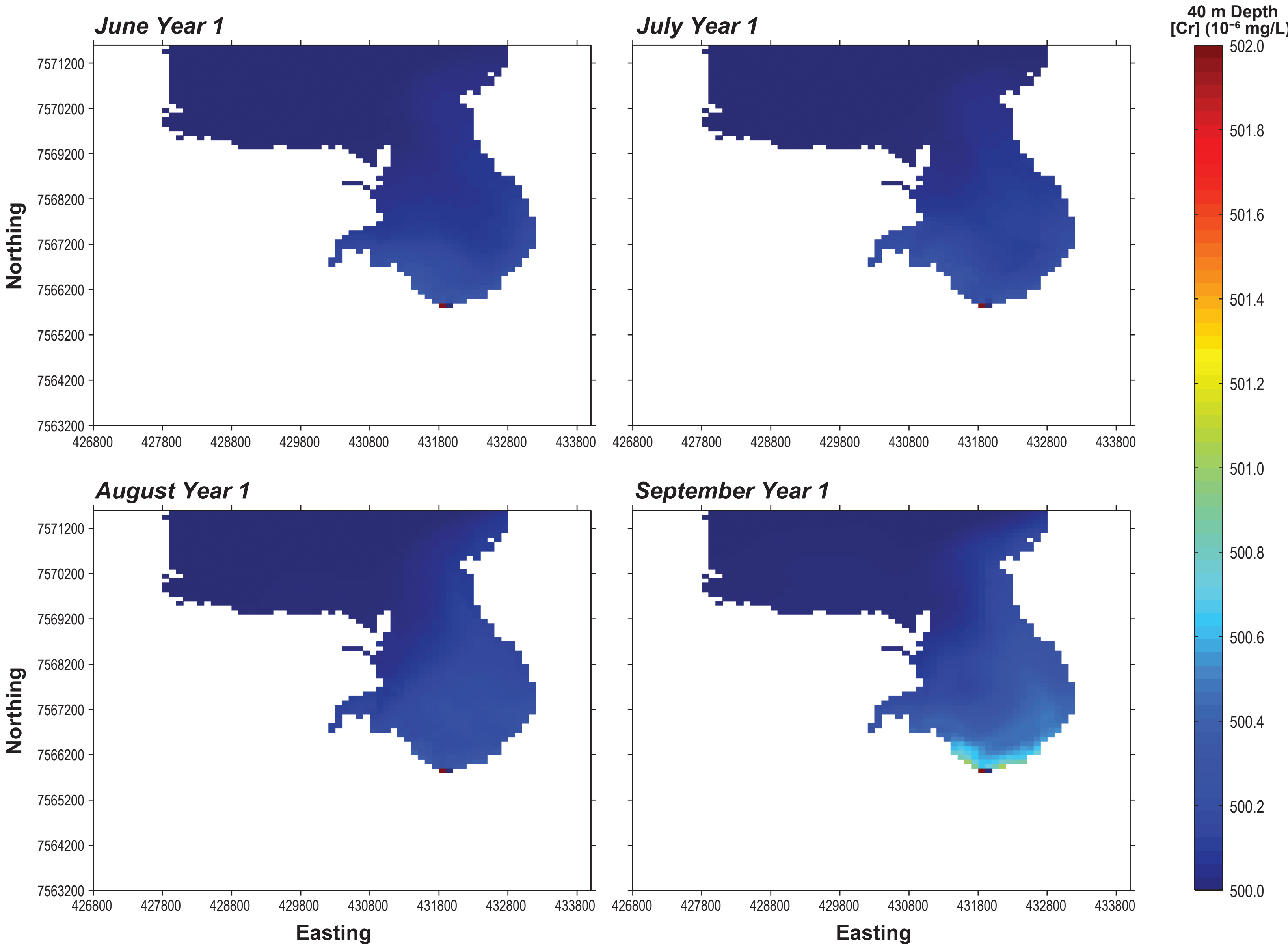
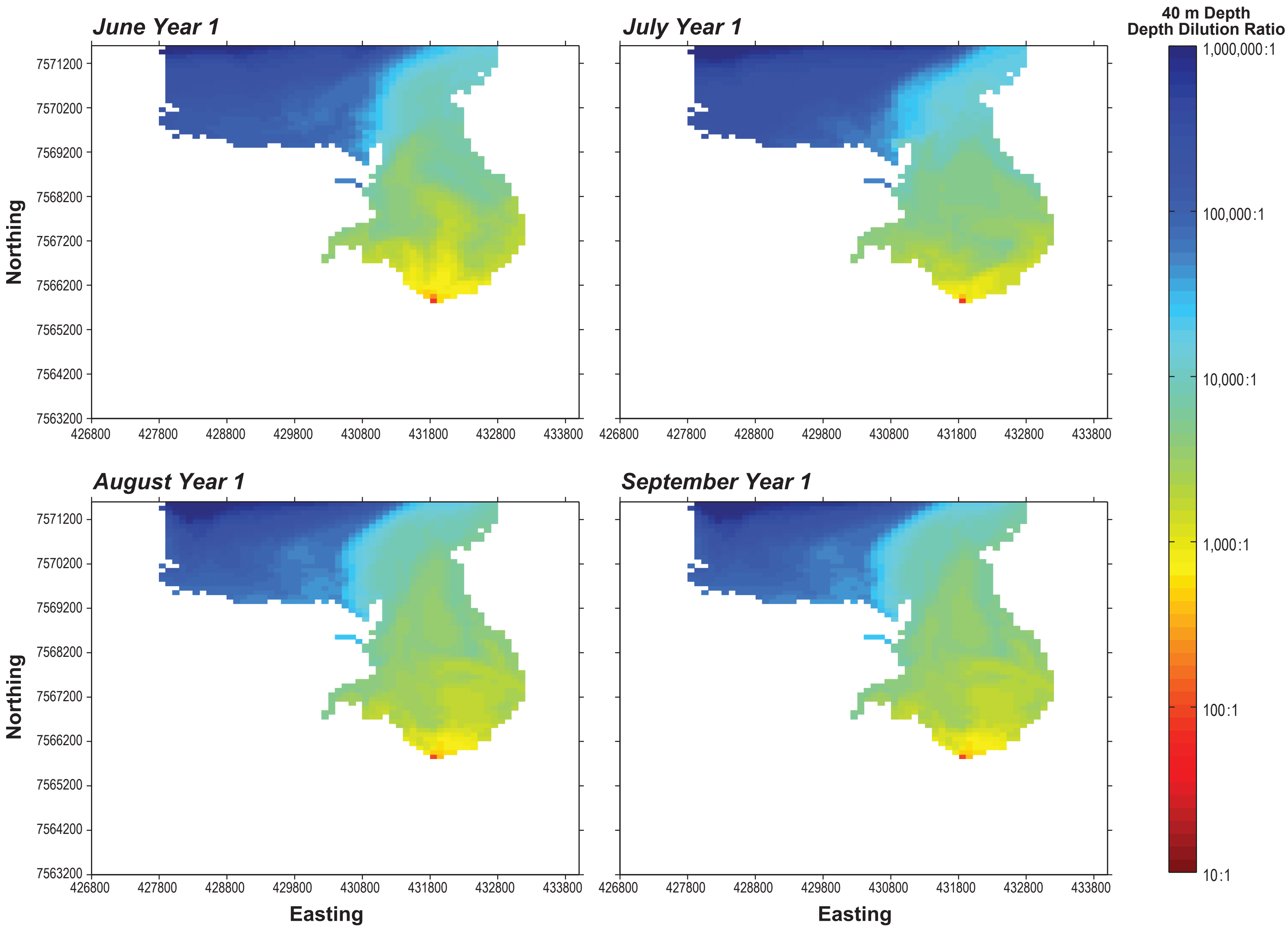


Figure 4.2-6

Minimum Dilution Ratio for Roberts Bay: Open-Water Period (40 m Depth)



4.2.2 *Under-ice Period*

Figure 4.2-7 presents the predicted average chromium concentrations at 4 m depth in Roberts Bay for the selected under-ice months, while Figure 4.2-8 shows the calculated dilution ratios. Concentrations were extremely low and similar to the open-water season, with the dilution plots showing that comparatively less dilution occurs in the bay given the absence of surface currents. Concentrations were slightly higher in October compared to later winter months (by less than 1%) because the excess material from the greater discharge rates and chromium concentrations in September had yet to be fully flushed from the inlet.

Figure 4.2-9 presents the predicted average chromium concentrations at 32 m depth in Roberts Bay for the selected under-ice months, while Figure 4.2-10 shows the calculated dilution ratios. The transition to a stable under-ice system can be observed from October to February in Figure 4.2-9; in October, chromium concentrations are spread out within the bay as the larger discharge in September has yet to be fully flushed and the cooling of the water column leads to enhanced mixing despite the lack of winds. By December, the plume material moved from the diffuser area and spread counter-clockwise around the bay, with a signature of concentrations between 0.15 to 0.3% above baseline values. The latter results from the lack of under-ice current in the current model implementation, such that the circulation of the bay is driven by the plume discharge. The Coriolis force then angles the discharge flow to the right, leading to the counter-clockwise spread of the plume. This circulation pattern is enhanced in the dilution plots of Figure 4.2-10, with the lowest dilutions seen in October again due to the excess chromium present in the water column from the TIA and groundwater combined discharge in September. As winter progressed, concentrations stabilized in the bay with the plume material spreading on the eastern side of the bay up to the Melville Sound boundary. These dilution patterns are different from the 32 m open-water season dilution as depicted in Figure 4.2-4, where the plume material visibly spreads more broadly within Roberts Bay and at the Melville Sound boundary due to the wind-driven currents.

Figure 4.2-11 presents the predicted average chromium concentrations at 40 m depth in Roberts Bay for the selected under-ice months, while Figure 4.2-12 shows the calculated dilution ratios. The concentrations and patterns are very similar to the results plotted for 32 m depth. The highest concentrations and lowest dilutions were present at the discharge point, with maximum concentrations of 0.5% above baseline values and minimum dilutions of 144:1. While the lack of currents theoretically could have resulted in pooling of the effluent in bottom waters, none was observed in the model results and chromium concentrations were always slightly above baseline values and far below CCME guideline levels.

5. SUMMARY AND CONCLUSIONS

Chromium concentrations were predicted over the temporal scale of the proposed first year of Doris Mine operations and the spatial scale of all of Roberts Bay and part of Melville Sound (all depths and locations). Both open-water (June to September) and under-ice (October to April) seasons were included in the modelling, which incorporated the TIA and groundwater combined discharge and the groundwater only discharge to Roberts Bay.

Figure 4.2-7

Predicted Chromium Concentrations for Roberts Bay: Under-Ice Period (4 m Depth)

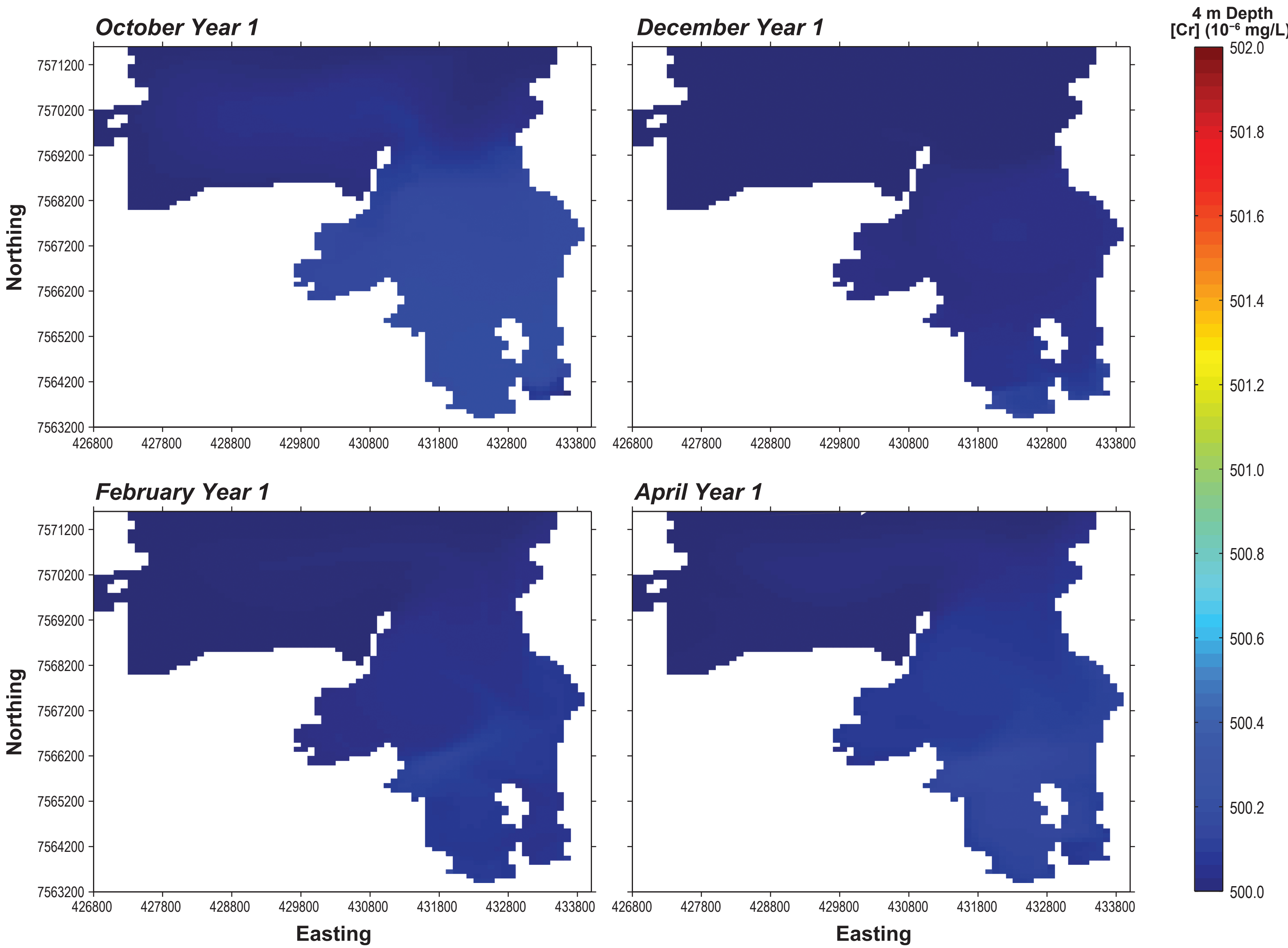


Figure 4.2-8
Minimum Dilution Ratio for Roberts Bay: Under-Ice Period (4 m Depth)

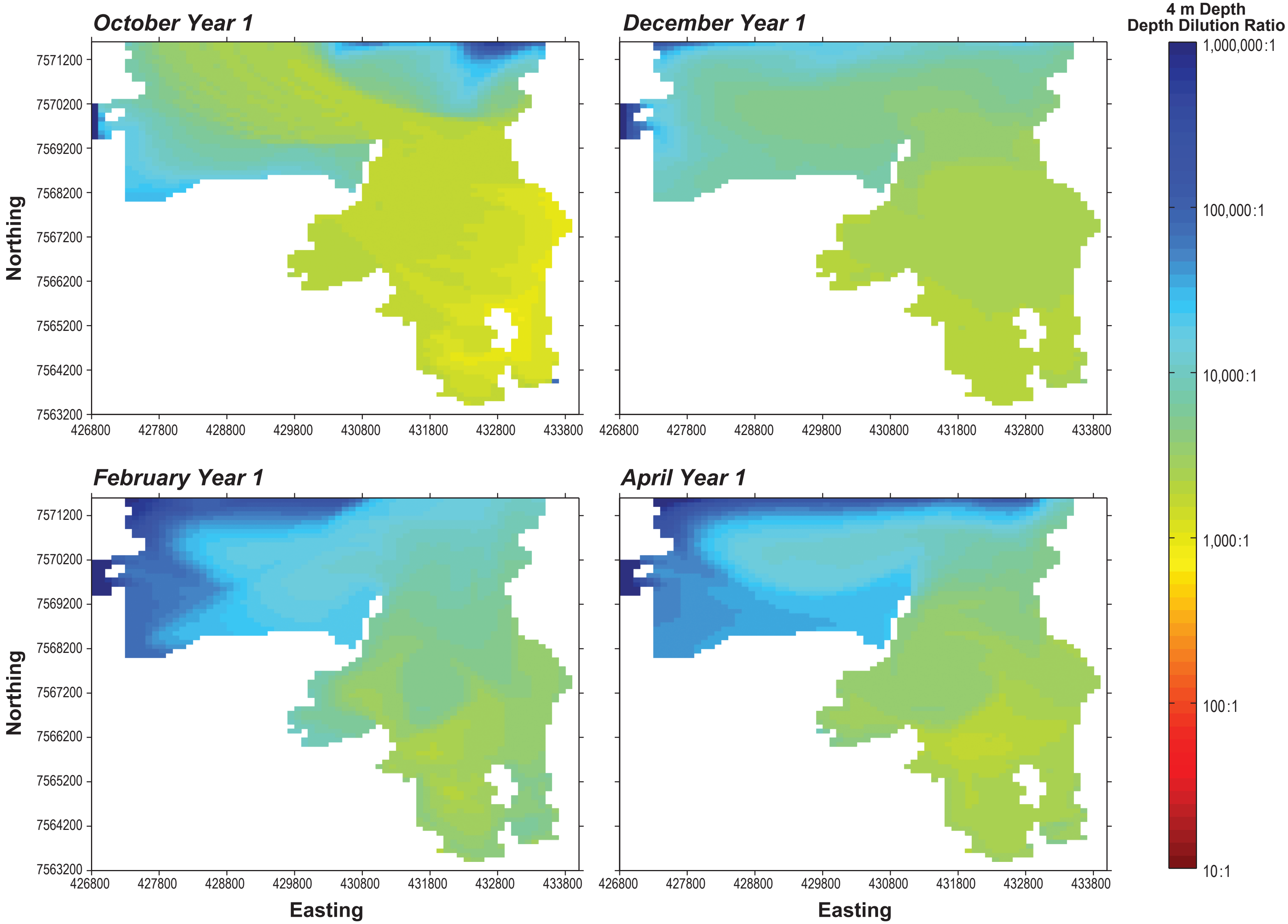


Figure 4.2-9

Predicted Chromium Concentrations for Roberts Bay: Under-Ice Period (32 m Depth)

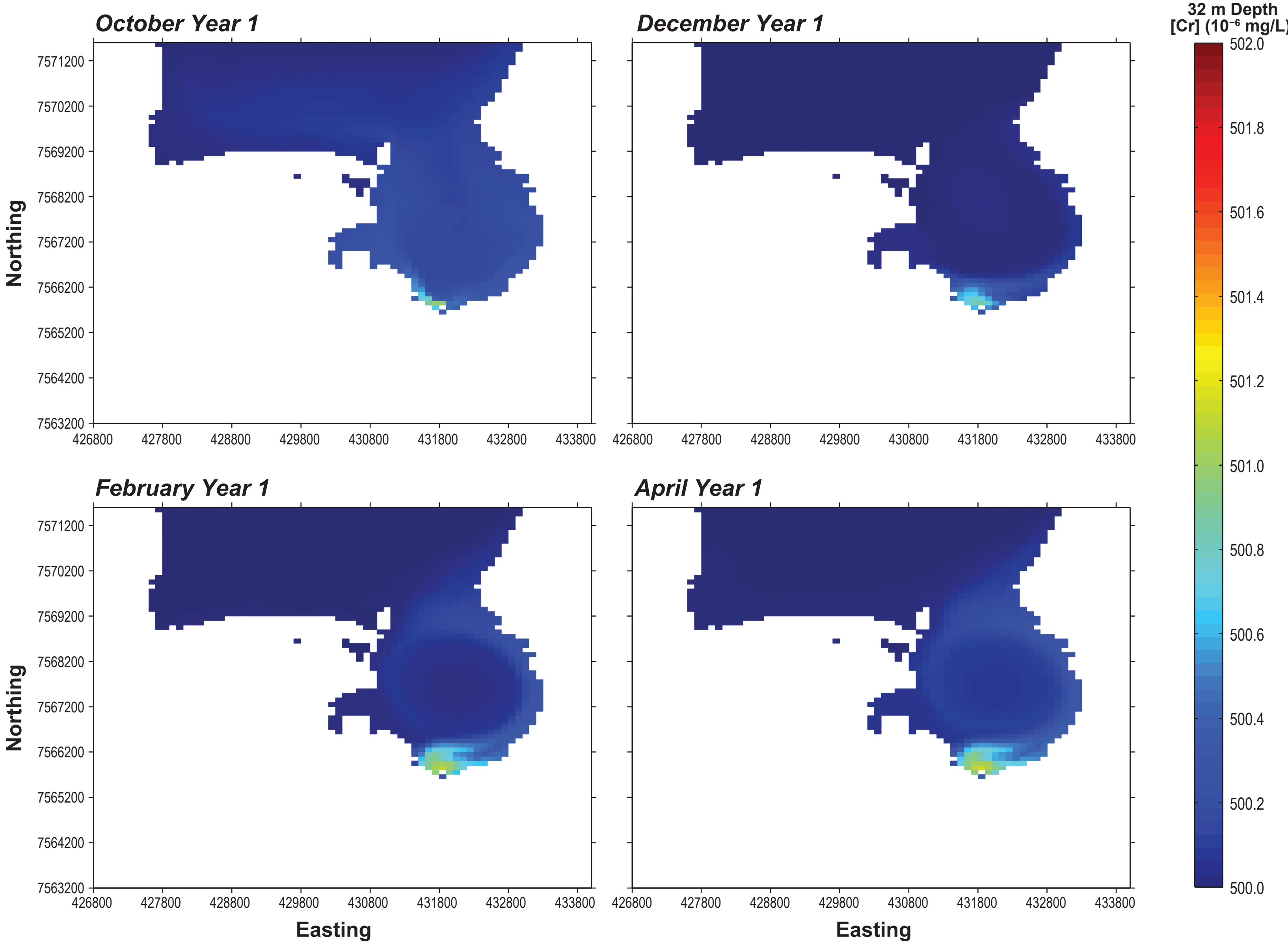


Figure 4.2-10

Minimum Dilution Ratio for Roberts Bay: Under-Ice Period (32 m Depth)

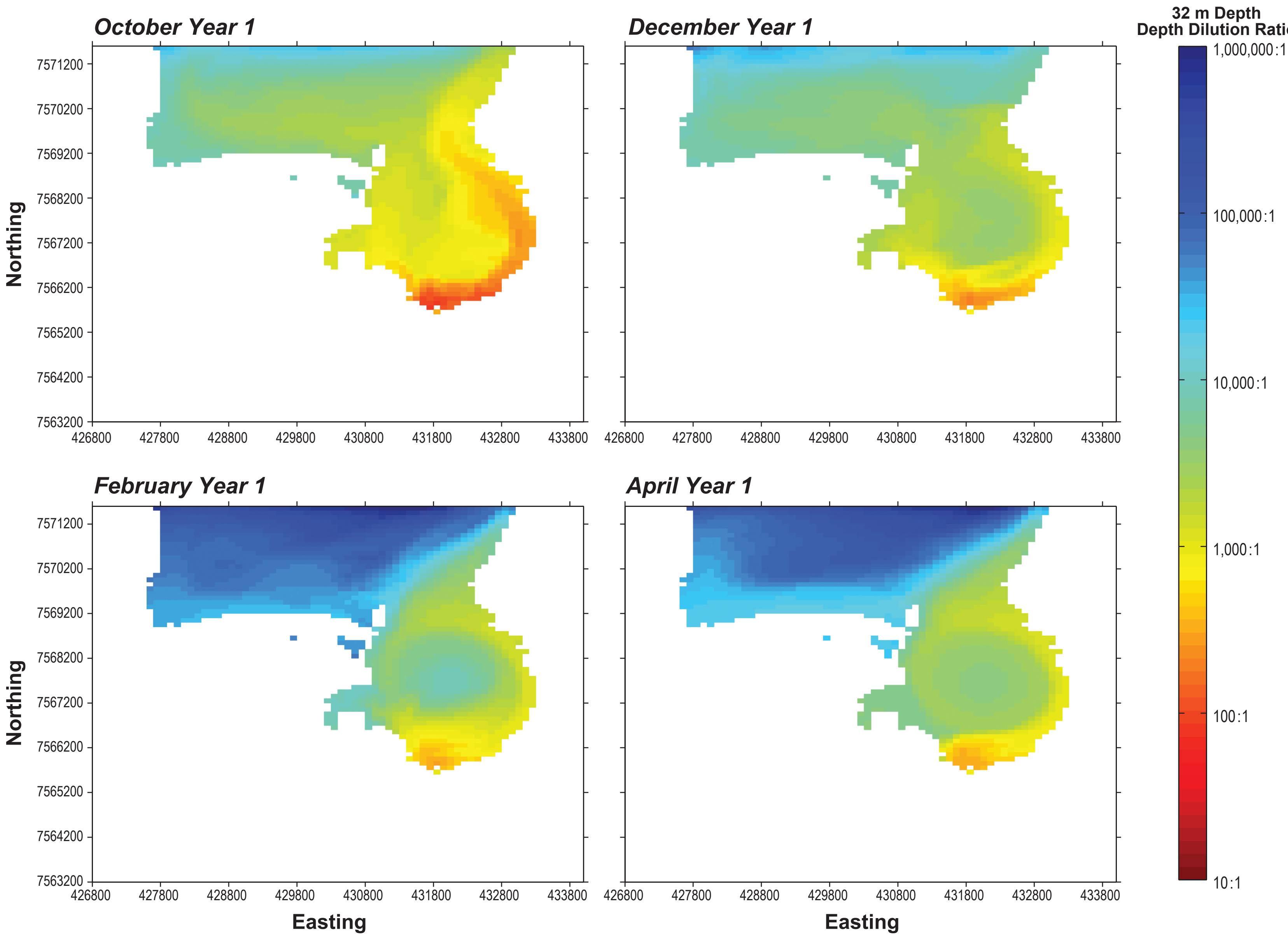


Figure 4.2-11

Predicted Chromium Concentrations for Roberts Bay: Under-Ice Period (40 m Depth)

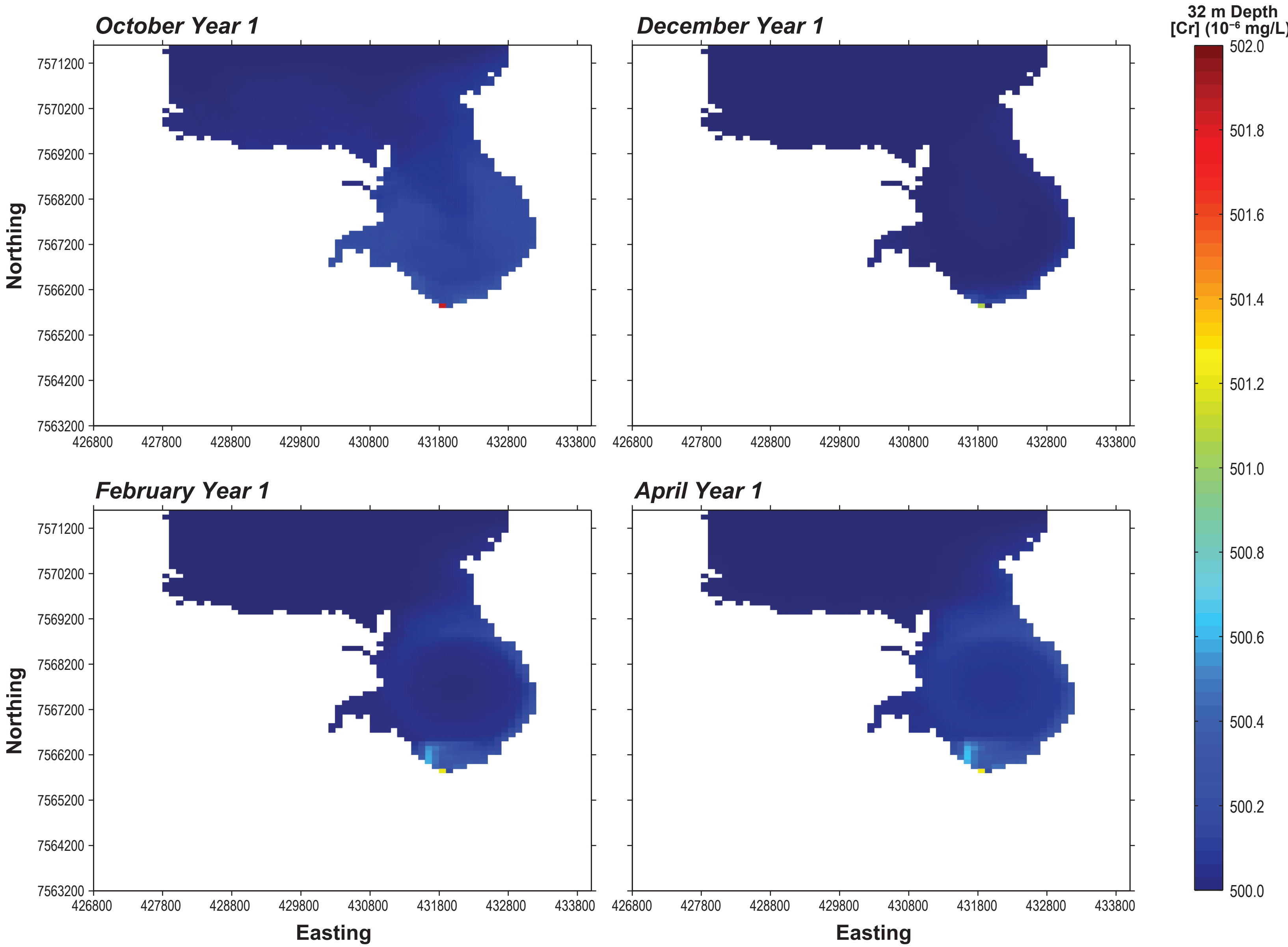
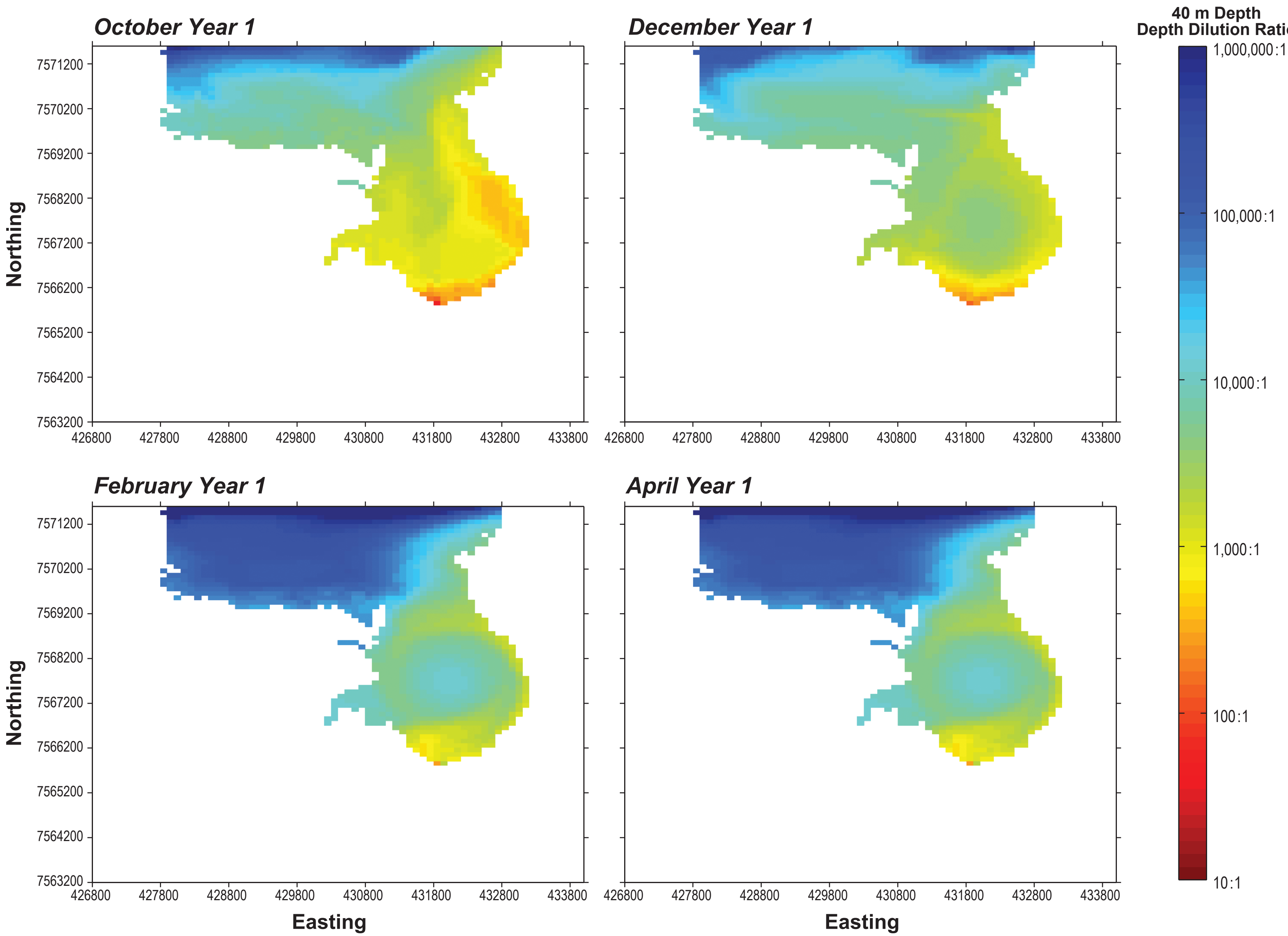


Figure 4.2-12

Minimum Dilution Ratio for Roberts Bay: Under-Ice Period (40 m Depth)



A total of three stations were included for monitoring timeseries of modelled chromium in Roberts Bay. The proposed discharge diffuser was located at 40 m depth in the southern portion of the bay and had varying flows and chromium concentrations due to Project activities. Baseline concentrations of chromium in Roberts Bay and from the other freshwater discharges were assumed constant to cleanly monitor the effluent plume propagation.

Predicted Chromium Concentrations at Roberts Bay Stations

Predicted chromium concentrations remained close to baseline values at all depths of the water column, with the largest increases between 3 to 6% above baseline values occurring within 10 to 20 m of the discharge location depth. At the two station locations in the main basin of the bay, predicted chromium concentrations were barely above baseline (between 0.01% and 0.4% over baseline) and were far below the CCME guideline for the protection of marine aquatic life (0.0015 mg/L) during both the open-water and under-ice seasons.

Predicted Bay-wide Monthly Chromium Concentrations

For the open-water season, far-field dispersion results indicated that predicted chromium concentrations were barely over baseline values (average < 2% above baseline) and remained below the CCME guideline for the protection of marine aquatic life (0.0015 mg/L) in all parts of the bay at all times. Results indicated that very little plume material gets entrained into the surface waters due to the plume being trapped below the pycnocline and the strong stratification present in the bay. The small amounts of chromium that were in the surface waters were rapidly diluted and transported out of the bay due to the large currents. Most of the plume material was trapped below 30 m depth and slowly dissipated across the bay, with average dilutions on the order of 100:1 near the discharge location but quickly increasing to 1,000:1 and 10,000:1 elsewhere in the bay.

For the under-ice season, surface chromium concentrations were barely above baseline and were similar to predicted summer concentrations. In deeper waters, the water column concentrations stabilized by propagating in a counter-clockwise flow pattern resulting from the flow discharge current, with concentrations between 0.15 to 0.30% above baseline values. Dilutions were between 100:1 and 200:1 in the immediate area near the diffuser and increased substantially approaching 10,000:1 in the main basin of the inlet.

The discharge flow volumes and chromium concentrations as presented in this work were not sufficient to substantially alter the background concentrations of chromium within Roberts Bay. The model results showed the plume material was rapidly diluted outside the diffuser discharge location and was ultimately flushed out of the bay. The results confirmed that the plume was buoyant and was largely trapped far below the pycnocline; therefore, it would not interact with the sediments and would interact little with the surface waters. Overall, the projected small increases in chromium concentrations within the discharge plume would be difficult to discern from surrounding ambient waters.

These results support the effects assessment conclusions presented in the original amendment submission, *Revisions to TMAC Resources Inc. Amendment Application No. 1 of Project Certificate*

No. 003 and Water Licence 2AM-DOH1323 (Document P4-1; ERM 2015), and subsequent near-field plume mixing modelling (ERM 2016); that is, tremendous dilutions are expected near the Roberts Bay diffuser and orders of magnitude more dilution will occur as the discharge plume spreads throughout the entire bay. The resulting water quality in Roberts Bay will be barely above baseline levels, far below CCME guideline concentrations, and therefore safe for marine life in the bay.

REFERENCES

CCME. 2015. *Water Quality Guidelines for the Protection of Aquatic Life*. Ministry of Environment, Province of British Columbia. http://st-ts.ccme.ca/ (accessed January 2015).

DHI. 2009. *MIKE3 Flow Model: Advection/Dispersion Module*. http://www.mikebydhi.com/Products/CoastAndSea/MIKE3.aspx (accessed June 2015).

DHI. 2012a. *MIKE 3 Flow Model: Hydrodynamic Module Scientific Documentation*. http://www.mikebydhi.com/Products/CoastAndSea/MIKE3.aspx (accessed June 2013).

DHI. 2012b. *MIKE 3 Flow Model: Hydrostatic Module Scientific Documentation*. http://www.mikebydhi.com/Products/CoastAndSea/MIKE3.aspx (accessed June 2013).

ERM. 2015. Document P4-1: *Identification of Potential Environmental Effects and Proposed Mitigation.* In: Revisions to TMAC Resources Inc. Amendment Aplication No. 1 of Project Certificate No. 003 and Water License 2AM-DOH1323. Prepared by ERM Consultants Canada Ltd. for TMAC Resources Inc.: Vancouver, BC.

ERM. 2016. *Memorandum: Near-field Plume Mixing Modelling and Water Quality Predictions for Discharges to Roberts Bay*. Prepared by ERM Consultants Canada Ltd. for TMAC Resources Inc.: Vancouver, BC.

Gill, A. E. 1982. *Atmosphere-Ocean Dynamics*. Vol. 30 of *International Geophysics Series*. San Diego, CA: Academic Press.

Kundu, P. K. 1990. *Fluid Mechanics*. San Diego, CA: Academic Press.

Patankar, S. V. 1980. *Numerical Heat Transfer and Fluid Flow*. New York, NY: Hemisphere Publishing Corporation.

Rescan. 2010. *Hope Bay Belt Project: 2009 Marine Baseline Report*. Prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd.: Vancouver, British Columbia.

Rescan. 2011a. *Doris North Gold Project: 2011 Aquatics Effects Monitoring Program (AEMP) Marine Expansion Baseline Report*. Prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd.: Vancouver, BC.

Rescan. 2011b. *Hope Bay Belt Project: 2010 Hydrology Baseline Report*. Prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd.: Vancouver, BC.

Rescan. 2011c. *Hope Bay Belt Project: 2010 Marine Baseline Report*. Prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd.: Vancouver, BC.

Rescan. 2011d. *Hope Bay Belt Project: 2011 Meteorology Baseline Report*. Prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd.: Vancouver, BC.

Rescan. 2012a. *Doris North Gold Mine Project: 2011 Numerical Simulation of Roberts Bay Circulation*. Prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd.: Vancouver, BC.

Rescan. 2012b. *Doris North Gold Mine Project: 2011 Roberts Bay Physical Oceanography Baseline Report*. Prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd.: Vancouver, BC.

Smagorinsky, J. 1963. General circulation experiments with the primitive equations: I. the basic experiment. *Mon Wea Rev*, 91: 99-164.

SRK. 2015a. Document P6-10. *Doris North Project – Water and Load Balance Report*. In: Revisions to TMAC Resources Inc. Amendment Application No. 1 of Project Certificate No. 003 and Water Licence 2AM-DOH1323. Prepared by SRK for TMAC Resources Inc.: Vancouver, BC.

SRK. 2015b Document P6-7: Doris North Project: Roberts Bay Discharge System Surface Infrastructure Design Brief. In: *Revisions to TMAC Resources Inc. Amendment Application No. 1 of Project Certificate No. 003 and Water Licence 2AM-DOH1323.* Prepared by SRK for TMAC Resources Inc., May 2015.

SRK. 2015c. Document P6-3: *Hydrogeological Modeling of the Proposed Doris North Project, Hope Bay, Nunavut*. In: Revisions to TMAC Resources Inc. Amendment Application No. 1 of Project Certificate No.003 and Water License 2AM-DOH1323. Prepared by SRK for TMAC Resources Inc.: Vancouver, BC.