APPENDIX IX.7

WATER QUALITY MODELLING

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1.0 INTRODUCTION

A number of modelling tools were used to predict changes in surface water quality resulting from the Snap Lake Diamond Project. The results of the modelling analysis provide a basis for estimating the effects of the discharge on water quality in Snap Lake. The water quality modelling tools included:

- a hydrodynamic and water quality model of Snap Lake that was used to simulate mixing and transport of all water releases in Snap Lake;
- a near-field mixing zone model that was used to simulate the initial mixing characteristics of the combined discharge through the multi-port diffuser; and,
- a fully-mixed lake model that was used to simulate water quality in lakes north of Snap Lake that will receive mine water affected groundwater discharge at post-closure.

This appendix describes the models, their configuration for the Snap Lake Diamond Project and, where appropriate, calibration procedure and results.

2.0 SNAP LAKE WATER QUALITY MODEL

2.1 Model Description

A two-dimensional dynamic model was selected to simulate the hydrodynamics and water quality in Snap Lake. The lake currents are mainly driven by wind in the ice-free period, therefore, to properly simulate the variability in direction and magnitude, it is necessary to employ a dynamic model. Snap Lake is relatively shallow (mean depth of 5 metres [m]) and there is no significant stratification. It is, therefore, appropriate to utilize two-dimensional models that produce depth-averaged results.

Two finite element models, RMA10 and RMA11, were used in this study to simulate the mixing and transport of the combined discharge in Snap Lake. RMA10 is a one, two and three-dimensional hydrodynamic model used to simulate flow circulation and current velocity in Snap Lake. RMA11 is the complementary water quality model for dispersion modelling.

RMA10 and RMA11 are part of the RMA suite of hydrodynamic and water quality models developed by Professor Ian P. King and Resource Management Associates based in Suisun, California, USA. The models were originally developed for the U.S. Army Corps of Engineers and have been used extensively by that agency.

RMA10 was designed to solve one-, two- and three-dimensional, depth-averaged, free surface flow problems in open channels, lakes, and estuaries. The model accounts for wind shear stress, gravitational force, turbulent shear stress, Coriolis force, and lake bottom shear stresses. The partial differential equations are solved numerically using a finite element method that can handle flows in complex geometric conditions. Water surface levels and flow velocities can be output by the model.

RMA11 is a water quality model capable of simulating the dispersion and transport of dissolved substances and suspended sediments. It is also designed for the simulation of complete nutrient cycles including nitrogen, phosphorus, oxygen, and chlorophyll a (for algae).

2.2 Modelling Approach

In this analysis, circulation in Snap Lake was simulated with the hydrodynamic model, RMA10. Current velocities from the RMA10 model simulations were then used as input to RMA11 for dispersion and transport modelling of the combined discharge in Snap Lake.

The simulation model covers the entire area of Snap Lake. A finite element mesh that covers the study area is shown in Figure IX.7-1. This mesh was used for both the hydrodynamic and water quality modelling.

Continuous hydrodynamic and dispersion modelling was conducted for a 40-year period, consisting of 3 years of construction, 22 years of operations, and 15 years of post-closure conditions. The combined discharge was modelled using weekly average inflows and water quality conditions. The inflow and water quality condition data were obtained from the GoldSim model (Appendix IX.1).

Flow velocities in the lake were simulated using the hydrodynamic model for both the ice-cover and ice-free periods. The ice-free period is defined from June 1 to October 1, while the ice-cover season encompasses the remainder of the year. Daily average wind data from 1998-2000 were used in the flow velocity simulations for each ice-free period to represent the average flow circulation and dispersion conditions in Snap Lake. This period was selected because it represents the data available from the Snap Lake meteorological monitoring station. Lake current velocities for the ice-cover season were also simulated without including wind stress on the water surface, which accounts for the effect of ice cover. The results from the hydrodynamic simulations were then used as input to the water quality model for continuous dispersion modelling.

The water quality parameters simulated for the environmental assessment included metals, major ions, nutrients, and chlorophyll *a*. It was assumed that all metals and ions were conservative and did not settle out. The reaction rates and coefficients for the nutrient cycle were calibrated using a three-year baseline simulation. An iterative process was used to obtain appropriate mean values and ranges for chlorophyll *a*, ammonia, nitrate, nitrite, organic nitrogen, phosphate, and organic phosphorus. The calibration procedure and results are summarized below.

2.3 Model Inputs

The hydrodynamic model, RMA10, required the input of daily average wind speed and direction, initial water surface elevation of Snap Lake, and all inflows into the lake, including natural runoff and all project-related flows, including the mine water discharge, runoff and seepage into Snap Lake. The daily average wind speeds from the site meteorological station for 1998-2000 were used. The initial water surface elevation and mean monthly runoff into Snap Lake were derived as part of the Hydrology baseline assessment for the project (Section 9.3 of the environmental assessment [EA]). The

Figure IX.7-1 Snap Lake Water Quality Model Finite Element Mesh

runoff was partitioned between eleven sub-watersheds, weighted by area. The mine site water quality model (GoldSim model; (Appendix III.2 and Appendix IX.1) provided the average annual flows into Snap Lake. The average flow rates of domestic wastewater effluent are specified in Appendix III.4.

The water quality model, RMA11, employed the resultant velocities from the hydrodynamic model to simulate the movement of the various water quality parameters. Meteorological data, including dry and wet bulb temperatures, wind speed, barometric pressure, and cloud cover were required as model input. The mean values of water quality constituents from the baseline study were used as background values for Snap Lake and as the natural inflow concentrations. Average annual mine water discharge, seepage and runoff concentrations were obtained from the GoldSim model (Appendix IX.1). The maximum average water quality of the domestic wastewater treatment plant effluent is noted in Table 9.4-17 of the EA.

2.4 Model Outputs

The results from the hydrodynamic and water quality models provide concentration contour plots of Snap Lake at various points in time throughout the 40-year simulation. A time-series of concentrations at specific locations in Snap Lake can also be derived from the modelling results.

2.5 Calibration

The hydrodynamic and water quality models have numerous parameters, many of which can be estimated, because they have a small range of valid values, or because they are not sensitive. Other model parameters require calibration due to larger ranges of variation and the sensitivity of model results. The parameters requiring calibration were modelled iteratively to match observed values (*e.g.*, baseline nutrient calibration) or expected values based on observed values in similar systems (*e.g.*, simulated current velocities).

The hydrodynamic parameters requiring calibration include Manning's "n" for bottom roughness and evaporation loss constants. The Manning's "n" was estimated based on previous lake modelling experience and published values (Chow 1959). A value of 0.03 was used in the model; however, due to the relatively low velocities in the lake, a plus or minus 20 percent (±20%) variation in values would not produce significantly different results. The evaporation loss coefficients were estimated based on the average ice-free period (from June to October) and a maximum summer lake temperature of approximately 15°C. The model was run iteratively to obtain these lake temperature conditions, producing values of 0.00001 metre per hour per unit pressure (m/hr/mbar) and 0.00001 m/hr/mbar per metre per second (m/s) wind speed for the evaporation constants.

The water quality model required calibration for transport and nutrient cycling. Metals were simulated conservatively and no calibration was required. Dispersion coefficients were calculated by the model using simulated current velocities. Minimum default values were set to 0.05 square metres per second (m^2/s) and 0.01 m^2/s for the x- and y-direction dispersion coefficients, respectively based on advice from the model developer (Ian King, personal communication 2001). These values also fall within published ranges (Bowie *et al*. 1985).

RMA11 parameters that require calibration for the nutrient cycle include settling, precipitation, growth, decay, and interaction of the modelled constituents. Initial values for these parameters were based on literature values (King 1998; Bowie *et al*. 1985), and were then adjusted until minimum, mean, and maximum simulated baseline concentrations for a three-year period matched the baseline monitoring data for Snap Lake. A comparison of observed and simulated values are shown in Table IX.7-1. The calibrated model parameters for the nutrient cycle are presented in Table IX.7-2.

Table IX.7-1
Baseline Model Calibration Results for Nutrients

		Actual values			Calibrated results		
Parameter	**Units**	**minimum**	**maximum**	**mean**	**minimum**	**maximum**	**mean**
Chlorophyll a	µg/L	0.44	1.15	0.85	0.48	1.11	0.78
Org N	mg/L	0.139	0.863	0.293	0.281	0.304	0.295
NH3	mg/L	<0.005	0.041	0.018	0.004	0.036	0.015
NO2	mg/L	<0.002	<0.002	<0.002	0.00004	0.0002	0.0001
NO3	mg/L	<0.006	0.038	0.02	0.01	0.039	0.023
Org P	mg/L	0.003	0.012	0.007	0.004	0.009	0.007
PO4	mg/L	0.002	0.002	0.002	0.001	0.003	0.002

Notes: µg/L = micrograms per litre; mg/L = milligrams per litre; Org N = organic nitrogen; NH3 = ammonia; NO2 = nitrite; NO3 = nitrate; Org P = organic phosphorus; PO4 = phosphate.

Table IX.7-2
Model Calibration Parameters for Nutrients

Parameters[1]	Value	Units[2]	Source[3]
Algae			
conversion factor *u*g chl *a* to mg algae	15		U.S. EPA
fraction af algal biomass that is N	0.085		U.S. EPA
fraction of algal biomass that is Org P	0.012		U.S. EPA
O_2 production rate per unit of algal photosynthesis	1.6	mgO/mgA	model
O_2 uptake rate per unit of algae respired	2	mgO/mgA	model
algal growth rate temperature factor	1.03		**calibrated**
algal respiration rate temperature factor	1.03		**calibrated**
algal settling rate temperature factor	1.03		**calibrated**
preference for NH_3	0.9		model
light half-saturation coefficient	0.0168	$kJ/m^2/s$	U.S. EPA
N half-saturation coefficient	0.2	mg/L	U.S. EPA
phosphate half-saturation coefficient	0.02	mg/L	U.S. EPA
non-algal portion of light extinction coefficient	0.38	$metre^{-1}$	model
linear algal self-shading coefficient	0.0088		model
non-linear algal self-shading coefficient	0.054		model
maximum algae growth rate	1.87	day^{-1}	**calibrated**
algal respiration rate	0.08	day^{-1}	**calibrated**
algal settling rate	0.08	day^{-1}	**calibrated**
Nitrogen			
O_2 uptake rate per unit of NH_3 oxidation	3.5	mgO/mgN	model
O_2 uptake rate per unit of NO_2 oxidation	1.2	mgO/mgN	model
Temperature coefficient for Org N decay	1.12		**calibrated**
Temperature coefficient for Org N settling	1.12		**calibrated**
Temperature coefficient for NH_3 decay	1.11		**calibrated**
Temperature coefficient for NH_3 benthic sources	1.11		**calibrated**
Temperature coefficient for NO_2 decay	1.11		**calibrated**
First order nitrification inhibition	0.6	$(mg/L)^{-1}$	model
Org N			
Org N to NH_3 conversion rate	0.0025	day^{-1}	**calibrated**
Org-N settling rate	0	day^{-1}	**calibrated**
NH_3			
NH_3 to NO_2 conversion rate	0.03	day^{-1}	**calibrated**
Benthos source rate for NH3-N	0.7	day^{-1}	**calibrated**
NO_2			
NO_2 to NO_3 conversion rate	3	day^{-1}	**calibrated**

Table IX.7-2
Model Calibration Parameters for Nutrients (Continued)

Parameters	Value	Units	Source[a]
Phosphorus			
Temperature coefficient for Org P decay	1.06		**calibrated**
Temperature coefficient for Org P settling	1.06		**calibrated**
Temperature coefficient for PO_4 benthic sources	1.06		**calibrated**
Org P			
Org P decay rate	0.0072	day^{-1}	**calibrated**
Org P settling rate	0	day^{-1}	**calibrated**
PO_4			
Benthos source rate for PO4 P	0.48	day^{-1}	**calibrated**
PO_4 decay rate	0.012	day^{-1}	**calibrated**
Reaeration			
Use Churchill formula			
DO-BOD			
Temperature coefficient for BOD decay	1.04		**calibrated**
Temperature coefficient for BOD settling	1.04		**calibrated**
Temperature coefficient for DO benthic demand	1.04		**calibrated**
temperature coefficient for DO reaeration rate	1.04		**calibrated**
BOD			
decay rate for BOD	0.3	day^{-1}	**calibrated**
BOD settling rate	0	m/day	**calibrated**
DO			
oxygen demand rate for sediment	200	$mg/m^2/day$	**calibrated**

Notes: µg = micrograms; mg = milligrams; mg/mg = milligrams of parameter per milligrams of parameter; $kj/m^2/s$ = kilojoules per square metre per second; m/day = metres per day; $mg/m^2/day$ = milligrams per square metre per day; mg/L = milligrams; Org N = organic nitrogen; NH_3 = ammonia; NO_2 = nitrite; NO_3 = nitrate; Org P = organic phosphorus; PO_4 = phosphate N = nitrogen; O_2 = oxygen; DO = dissolved oxygen; BOD = biochemical oxygen demand.

3 United States Environmental Protection Agency (U.S. EPA) 1995. Model refers to "Documentation - RMA-11 -- A Three-Dimensional Finite Element Model for Water Quality in Estuaries and Streams, Version 2.6", King, I.P., 1998.

3.0 NEAR-FIELD MIXING MODEL

3.1 General

Near-field mixing and dilution near the proposed outfall are influenced by the buoyancy and momentum of the discharge, while the transport and shape of the resulting plume are determined mainly by the ambient currents within the lake. The effects of discharge buoyancy and momentum and ambient currents create turbulence, which is responsible for mixing within the lake. The major challenge in modelling near-field mixing and dilution in surface waterbodies involves representing turbulence near the discharge point and downstream of the outfall in the mixing model. Existing numerical turbulence models often have empirical coefficients that are not universal and have restricted ranges of applicability for different combinations of discharge and ambient conditions. Semi-empirical formulas with applicable ranges, based on simplified governing equations for conservation of mass and momentum and on physical laboratory and field modelling data, are generally more reliable than numerical turbulence models. The Cornell Mixing Model (CORMIX) (Jirka *et al*. 1996), which was used for near-field mixing and dilution analysis, considers all available physically-based and semi-empirical turbulence formulas and selects the appropriate formula for the discharge and ambient conditions.

3.2 Model Description

The CORMIX was used to simulate the near-field mixing and dilution behaviour of mine water discharges. The model is one of the most extensively used models for predicting near-field mixing and dilution of both conservative and non-conservative substances in surface waterbodies. The model has specific sub-systems for analyzing submerged multi-port diffuser (CORMIX2). The CORMIX model system assumes steady-state and generally uniform ambient conditions and effluent discharges. The model predicts the jet or plume geometry and the dilution characteristics required for assessment of near-field mixing. The predictions of the model are typically based on determination of an appropriate hydrodynamic flow pattern using an expert system and the solutions of the corresponding simple flow patterns to obtain complete analysis from the discharge point into the far-field.

3.3 Model Input

Input data to the CORMIX model are grouped into four categories: namely, site/case identifier, ambient conditions, discharge characteristics, and mixing zone data. The site/case identifier is the name given to model simulation scenario. The ambient conditions include stratification information and/or water density, water current, water depth and width, wind speed, and lake bottom roughness coefficient. The required discharge data include the geometry of the effluent at the point of discharge, location and orientation of the discharge ports within the surface waterbody, effluent flow rate, density, and concentration. The mixing zone data consist of definition of the spatial region where mixing and plume characteristics are required and optional information on ambient water quality standard, toxic dilution zone and regulatory mixing zone. Due to significantly different ambient and discharge conditions during ice-cover and ice-free periods, different sets of input data scenarios representing these two seasons are often required for analysis.

3.4 Model Output

The output from the CORMIX model is presented by qualitative descriptions, detailed quantitative numerical predictions, and 2-dimensional or 3-dimensional graphical output using the CMXGRAPH and CorVue graphic packages, respectively, to show predicted effluent jets and plumes. Qualitative descriptions provided by the output file include descriptive message addressing the simulated scenario and the logic reasoning employed by the model system. Detailed quantitative predictions of the jet or plume geometry and dilution characteristics are provided in the output file that presents the coordinates of the jet or plume centerline, the bulk or centerline dilution and concentration and the jet or plume width. In addition, information is provided on the different types of simulation modules used and the reasons for using them, the cumulative travel time at the end of each simulation module, and if application the location of plume attachment to the bed and bank and possible model limitations.

3.5 Simulation Analysis

Treated mine water and treated sewage from the Snap Lake Diamond Project will be discharged into Snap Lake as a combined discharge through a multi-port diffuser. The main objective of the near-field mixing and dilution analysis undertaken in this study was to identify a preliminary diffuser configuration that achieved good dilution near the diffuser location. The CORMIX2 subsystem, which is suitable for submerged multi-port diffuser simulations, was used for analysis.

3.5.1 Lake Ambient Information near Proposed Diffuser Location

The proposed location of the diffuser is shown in Figure IX.7-2. This location is estimated to be 125 m from shore with water depth between 12 and 14 m. The diffuser location was selected to ensure a deep-water column required for effective dilution of treated mine water discharges and to minimize the length and cost of an outfall pipe. During the months of October through May, water depths are reduced by approximately 2 m of ice-cover (Section 9.3 of the EA).

Water temperature data near the proposed diffuser location and throughout Snap Lake indicate that vertical temperature variation does not typically exceed 2^{o}C. Based on the measured data at sample location water quality (WQ)1 (see Figure 9.4-2), the ambient vertically averaged water temperature at the proposed diffuser location is estimated to be approximately 1^{o}C to 3^{o}C during the ice-cover season and 14^{o}C during the mid-summer ice-free period.

Baseline total dissolved solids (TDS) concentration data in the lake range from below 10 milligrams per litre (mg/L) to 70 mg/L, with a mean value of about 17 mg/L. The TDS concentrations are predicted to increase to about 400 mg/L due to discharge from the Snap Lake Diamond Project.

There are no lake current measurements within Snap Lake, but hydrodynamic simulation of the lake using the RMA10 model indicates that average current velocities near the proposed outfall may vary between 3 to 5 millimetres per second (mm/s) during the ice-cover period and higher during the ice-free period. The currents are likely to occur in any direction.

3.5.2 Characteristics of Combined Discharge

Water temperature of the combined discharge is estimated to be approximately 6 - 8^{o}C during ice-cover conditions in Snap Lake. Typical TDS concentrations are estimated to be approximately 1,100 mg/L (Appendix III.2 and Appendix IX.1).

Discharge volumes of treated mine water and sewage effluent into Snap Lake were initially predicted to increase from an average annual of about 600 cubic metres per day (m^3/d) in the first year of construction to a maximum annual average of about 19,500 m^3/d after approximately 19 years of full-scale mining. The maximum peak weekly flow was initially estimated at 26,000 m^3/d. Subsequent groundwater flow modelling has refined these predictions (Table 3.6-1 of Section 3 of the EA). However, because the initial predictions of maximum flow do not differ in magnitude from the refined flow, the CORMIX model was run with the initial flow prediction.

Figure IX.7-2 Diffuser Location for Combined Discharge

3.5.3 Input Information Used for Modelling

3.5.3.1 Ambient Information

The ice-cover period was identified as the most critical for diffuser performance in achieving good dilution. Generally, during ice-free conditions, winds generate stronger currents within the lake than those produced during the ice-cover period when wind effects are absent. Strong currents would effectively increase near-field dispersion due to a long curved discharge jet from the ambient currents and high turbulence within the lake. Therefore, a diffuser configuration based on ice-cover conditions is expected to produce better near-field mixing and dilution during the ice-free period when stronger lake currents are present. Thus, diffuser selection and near-field mixing analysis were based on the critical ice-cover conditions.

Ambient information used to characterize the local area surrounding the proposed diffuser location in the CORMIX model under ice-cover conditions are summarized in Table IX.7-3.

Table IX.7-3
Summary of Ambient Lake Information used for Analysis

Parameter	Ice-Cover Period
water depth (m)	11
mean lake currents (mm/s)	3
temperature (^{o}C)	1
TDS (mg/l)	400
water density (kg/m^3)	1000.134
Manning's coefficient	0.015

Notes: m = metre; mm/s = millimetres per second; ^{o}C = degrees Celsius; mg/L = milligrams per litre; kg/m3 = kilograms per cubic metre; TDS = total dissolved solids.

Water depth and lake current velocity were selected based on RMA10 model simulations for the local area surrounding the proposed diffuser location (shown in Figure IX.7-2). The average simulated water depth during the ice-cover period was conservatively reduced by 2 m to account for the thickness of the ice-cover. The minimum simulated lake current during the ice-cover period was used to ensure conservative analysis, because weaker ambient currents would result in lower dilution potential.

Mean water temperature data and expected TDS concentrations in Snap Lake near the proposed diffuser location were used to compute water density. Total suspended solids (TSS) contribution to the density of the lake water was assumed to be negligible due to the low ambient TSS concentration (< 5 mg/L) for current conditions and after discharge from the treatment plant. Generally, mixing simulations within the near-field depend more on the momentum and buoyancy of the discharge and are not sensitive to Manning's resistance coefficient, therefore the Manning's coefficient used for modelling is a typical value for lakes.

3.5.3.2 Treated Mine Water Information

Proposed treated mine water discharge information used for near-field mixing and dilution analysis for the ice-cover period is summarized in Table IX.7-4. Apart from discharge rate and temperature, the remaining data are based on expected combined discharge characteristics prior to discharge into Snap Lake.

Table IX.7-4
Summary of Treated Mine water Characteristics Used for Analysis

Parameter	Ice-cover Period
discharge rate (m^3/day)	26,000
concentration (%)	100
temperature (^oC)	4
TDS (mg/L)	1,100
density (kg/m^3)	1000.645

Notes: m3/day = cubic metres per day; % = percent; ^oC = degrees Celsius; mg/L = milligrams per litre; kg/m3 = kilograms per cubic metre.

The TSS effect on water density was assumed to be negligible due to low TSS concentration relative to TDS concentration in both ambient and discharge waters. The computed density for ambient and treated mine waters, based on water temperature and TDS concentration from Table IX.7-3 and Table IX.7-4, indicated that treated mine water from the Snap Lake site will be negatively buoyant when discharged into Snap Lake.

3.5.4 Temperature of Discharge

The combined discharge during the ice-cover period will consist of a combination of groundwater from the underground mine operations and a relatively smaller volume of treated sewage. The temperature of the combined discharge is estimated to be between 6 and 8^oC, based on monitored temperature of water from ports, seeps and drill holes of the current underground mine workings (Appendix III.2 and Appendix IX.1). The lake ambient temperature is estimated to have a typical vertically averaged value ranging from 1 to 4^oC near the proposed diffuser location, based on baseline monitoring results

(Appendix IX.6). Discharge of warmer treated mine water into Snap Lake could raise the following two environmental concerns during winter:

- A warmer discharge could result in a warmer plume that may attract fish to the initial mixing region. Mixing areas within surface waterbodies are generally not recommended in cases where the effluent could attract aquatic life.

- A warmer discharge could delay freeze-up and result in a thinner ice-cover above the discharge during winter. An earlier ice break-up at and around the diffuser location could pose a risk to wildlife and possibly to humans. Quantitative estimates of the impacts of a warmer discharge on ice-cover in and around the diffuser location would require ice modelling and is considered beyond the scope of this preliminary diffuser analysis. The potential consequences of the likely effects of a warmer discharge on ice-cover should be investigated and addressed during the detailed diffuser design stage.

For the near-field mixing analysis, it was assumed that the temperature of the combined discharge during ice-cover conditions will be reduced to at least 4^{o}C, which would avoid the potential problems associated with a warmer combined discharge.

A number of possible cooling systems have been identified. Further analysis and selection of a final cooling system will occur as part of the ongoing engineering design work for the Snap Lake Diamond Project. Possible winter cooling options for the combined discharge include:

- running the discharge through a cooling pond;
- cooling the water in within a cooling pipe; and,
- running the combined discharge through a heat exchanger.

During the ice-free period, there is a potential for a cooler discharge than the lake ambient temperature. A combined discharge temperature that is cooler than the ambient lake temperature in the summer period would not present the same problem because the resulting plume would not attract fish.

3.5.5 Diffuser Configuration

3.5.5.1 General

The potential dilution that can be achieved by a selected diffuser configuration depends on diffuser port diameter, port exit velocity, port height, and port spacing. For a given port, dilution decreases with increasing port diameter. Therefore, it is desired to use the smallest possible port diameter. A minimum port diameter is necessary to minimize costs and operational difficulties associated with small diameter discharge ports.

The port exit velocity affects the distance travelled by the jet and the momentum and local turbulence, which determine the initial mixing and dilution near the ports. Higher exit velocities produces longer mixing length of the jet and higher local turbulence and, consequently, a better initial mixing. However, an exit velocity much higher than 10 m/s could produce problems such as cavitation, which can lead to foaming and also result in high head (energy) losses in the diffuser pipes.

The height of the diffuser ports above the lake bottom affects the maximum depth of water available for mixing, as well as the potential for entrainment of fine particles at the bed of the lake in the discharge jet. If the port exit is close to the bottom of the lake, the water depth available for mixing is maximized; however, there would be a higher potential for sediment scouring, and for sediment entrainment in the water column.

The spacing of the diffuser ports are constrained by a minimum distance to reduce the potential for overlap of plumes from different ports and a maximum spacing determined by the length of diffuser line and the number of ports. Larger spacing enhances dilution by allowing easier entrainment of fresh ambient water into the plume.

3.5.5.2 Diffuser Selection

Preliminary analysis of several scenarios of port diameter and exit velocity combinations was undertaken using the CORMIX model. The analysis was aimed at selecting a practical diffuser configuration that achieves good dilution. Bulk dilution factors and the initial mixing region predicted by the CORMIX model for several combinations of port diameter and exit velocity are summarized in Table IX.7-5. The ports for each diffuser scenario in Table IX.7-5 are equally spaced along a 60-m diffuser line.

Table IX.7-5
Dilution Factors at 26,000 m^3/day Discharge Rate (Distance [m] of the Boundary of Initial Mixing Region from Centre of Diffuser is Shown in Brackets)

Exit Velocity (m/s)	Diameter of Ports (mm)				
	Variable[1]	175[2]	125	100	75
7.5 – 8.2	16 (138)	- (-)	34 (146)	34 (139)	34 (138)
6.1 – 6.4	16 (118)	- (-)	34 (118)	34 (122)	34 (119)
3.8 – 4.3	16 (90)	34 (88)	34 (85)	34 (83)	34 (86)

Notes: m^3/day = cubic metres per day; m/s = metres per second; mm = millimetres.
1 Diameter of single port (between 225 and 300 mm that results in a discharge rate of 26,000 m^3/day.
2 No CORMIX model simulations produced for exit velocities above 6 m/s since two ports are required. The CORMIX model allows simulations of either single port or multi-ports (≥3).

For the diffuser results shown in Table IX.7-5, hydrodynamic instability and complete mixing over the entire water depth occur in the initial mixing region due to high discharge momentum in a relatively shallow lake. The CORMIX model does not provide dilution factors within the hydrodynamically unstable (turbulent) mixing region, but predicts bulk dilution factors at the boundary of this initial mixing region. The results shown in the column labelled “Variable” represent single port discharge cases. The remaining columns that have simulation results are for multi-port discharges with more than two ports.

Dilution at the end of the initial mixing region generally increases when smaller diameter multiple ports are used instead of a larger diameter single discharge port. A fairly constant bulk dilution factor of about 34 at the boundary of the initial mixing region is predicted when more than two ports are used. Table IX.7-5 also indicates that the spatial extent of the unstable initial mixing region depends on port exit velocity. The spatial extent of the region typically decreases with a decrease in port exit velocity. At the same bulk dilution factor, a smaller initial mixing region suggests that the area surrounding the diffuser is more effectively utilized for dilution.

On the basis of results of the preliminary CORMIX model simulations summarized in Table IX.7-5, a diffuser configuration was selected and will undergo further analysis in the future. The diffuser has one 50 mm diameter port and six 125 mm diameter ports. The 50-mm diameter port would be used for flows less than 1500 m^3/d and the 125-mm ports would be used for higher flows. The configuration of the selected diffuser is summarized in Table IX.7-6 and shown in Figure IX.7-3.

Figure IX.7-3 Schematic of Multi-Port Diffuser for the Combined Discharge

For practical considerations, it was necessary to use a diffuser with port diameters larger than 37.5 mm to reduce the risk of clogging within the ports, minimize head losses, and to avoid the use of a large number of ports. A maximum port diameter was selected to optimize the number of ports required to enhance dilution over a range of flow rates.

The multiple ports will include valves or other flow control arrangements to adjust the number of active ports to achieve good mixing and dilution for a range of flow rates. Only one port would be required for discharge less than 4,000 m^3/d. As flows increase the number of ports used would increase to a maximum of six, which will support a discharge rate of 26,000 m^3/d.

The exit velocity used for analyzing the proposed diffuser falls within the range recommended for use in the CORMIX model (4 to 8 m/s). Simulations of mixing at the selected diffuser location, based on velocities that are higher than 4 m/s, did not produce any further improvements in bulk dilutions produced by the CORMIX model (see Table IX.7-5). The relatively shallow water depth available for mixing does not provide any significant improvement in mixing for exit velocities higher than 4 m/s.

The spacing of the ports was based on equal distances between the seven selected ports (one 50-mm and six 125-mm ports). The selected length of diffuser also allows a minimum 30-m mixing distance from any of the ports to the boundary of a 60-m radius from the centre of the diffuser.

The diffuser ports rise 1.0 m vertically above the lake bottom to minimize the risk of scouring and bottom sediment entrainment in the jet plume. The direction of the local ambient lake currents near the diffuser location is variable, especially during the ice-free period. Therefore, if the ports are oriented towards one particular direction away from the vertical plane, the discharge jet may encounter lake currents flowing in the opposite direction and reduce the associated mixing and dilution outside of the near-field zone. Therefore, vertical port orientation was selected to avoid a situation where lake currents and discharge jet from the ports would be in opposite directions.

Table IX.7-6
Summary of Diffuser Configuration

Description	Value Used
port diameter (mm)	50 and 125
port exit velocity (m/s)	4
number of 50 mm diameter ports	1
number of 125 mm diameter ports	6
length of diffuser line (m)	60
port spacing (m)	10
vertical angle of port	90°

Notes: mm = millimetres; m/s = metres per second; m = metres; ° = degrees.

3.5.6 Mixing and Dilution Performance of Diffuser

For the proposed diffuser configuration, description of the flow classification by the CORMIX system indicate that the local effect of the discharge momentum flux is strong in relation to the water depth and in relation to the stabilizing effect of the discharge buoyancy. The vertical jet from the diffuser ports result in near-vertical surface impingement, upstream spreading, vertical mixing, and buoyant restratification in the vicinity of the ports. However, for the weak lake currents during ice-cover conditions, a vertical recirculation zone is produced leading to mixing over the full water depth in the near-field region in which strong initial mixing takes place. For the maximum treated mine water discharge rate, the initial mixing region extends for about 85 m from the centre of the diffuser line.

After the initial mixing near the diffuser ports, buoyant spreading occurs with the plume spreading laterally while being advected by the weak ambient lake currents during the ice-cover period. The flow tends to re-stratify, however, for strong lake currents, especially during the ice-free period, when additional destratification and mixing will be produced. The mixing rate is relatively small just after the initial mixing region, but after some distance from this region background turbulence in the ambient shear flow becomes the dominating mixing mechanism, especially during the ice-free period, and produces rapid passive ambient mixing and dilution over the entire water depth.

CORMIX simulation of dispersion within the mixing area indicated that during ice-cover conditions the minimum average dilution when the jet plume from the diffuser ports encounters the bottom of the ice cover is estimated to be approximately 27:1 at the maximum discharge rate of 26,000 m^3/d. The corresponding bulk dilution factor is estimated to be 34:1. Due to the strong discharge momentum flux relative to the mixing depth, it is estimated that the discharge will mix with the ambient water over the entire depth of the lake in the near-field. Therefore, for the near-field region, only the bulk dilution factor at the boundary of the near-field is produced by the CORMIX model. However, due to approximately complete mixing over the water depth, spatial variability of the dilution factor within the near-field would not be large.

The diffuser dilution performance described above assumes that the discharge rate is equal to the maximum weekly value of 26,000 m^3/d. Also, steady-state assumptions are made for both ambient and discharge conditions. However, it is expected that the discharge rate will vary with time. Table IX.7-7 summarizes the diffuser performance for different discharge rates.

Table IX.7-7
Diffuser Performance at Different Mine water Discharge Rates

Discharge (m^3/day)	Port Diameter (mm)	No. of Ports	Minimum Bulk Dilution Factor During Ice-Cover Period Predicted by CORMIX			
			60 m	125 m	250 m	500 m
600	50	1	200	237	2560	7820
2000	125	1	92	98	122	331
5000	125	2	82	88	110	313
10000	125	3	66	70	89	284
20000	125	5	40	42	47	122
25000	125	6	34	35	39	80

Notes: mm = millimetres; m^3/day = cubic metres per day; m = metres.

The final near-field dilution properties of the diffuser will depend on the mixing properties in the remainder of the lake (*i.e.*, in the far-field). The CORMIX model provides a bulk dilution factor that indicates the ratio of lake water that will mix with the discharge. The far-field concentrations will therefore influence concentrations within the near-field mixing zone.

3.6 Conclusions

Predicted dilution factors predicted by the CORMIX model are based on assumptions of steady-state conditions of treated mine water discharge and dilution of the discharge from continuous supply of fresh ambient water from other parts of the lake outside the discharge area. The analysis of mixing of the proposed treated mine water discharge into Snap Lake indicates the following:

- the ice-cover period is the most limiting period for diffuser design; and,

- the minimum bulk dilution rate achieved by CORMIX was 34:1, this was used in the environmental assessment to calculate near-field mixing during ice-covered conditions.

These conclusions are based on the following conceptual multi-port diffuser design:

- one 50-mm and six 125-mm ports equally spaced along a 60-m long diffuser line (the 50 mm port would be used to discharge flow rates below 1,500 m^3/d);
- the diffuser ports rise vertically 1.0 m above the lake bottom to maximize mixing in the water column and to minimize the risk of bottom sediment entrainment;
- valves or other flow control devices will be installed between each set of consecutive ports;
- the diffuser is located in a 11-m average depth of water during the ice-cover period at a location shown in Figure IX.7-2; and,
- the 60-m wide diffuser is connected to a 125-m outfall pipe that transports the treated discharge to the diffuser line.

4.0 FULLY MIXED LAKE MODEL

A continuous, fully mixed lake model was used to simulate water quality in lakes north of Snap Lake that receive mine-affected groundwater during post-closure (Section 9.2 of the EA). The model is based on the following mass balance equation:

$$C = C_{in}(1 - \exp(\frac{-t}{t_d})) + C_o(\exp(\frac{-t}{t_d}))$$ Equation 1

where,

C	=	simulated lake concentration [mg/L];
C_{in}	=	flow weighted average inflow concentration [mg/L]
t	=	the model time-step [years];
t_d	=	the retention time of the lake (lake volume/sum of inflows) [years]; and
Co	=	the lake concentration at the previous time-step [mg/L].

With the exception of chromium, all parameters were modelled conservatively (*i.e.*., without any losses due to settling, chemical reaction, precipitation, *etc*.) using Equation 1. The reaction (loss) of hexavalent chromium to trivalent chromium was modelled by adding a first-order exponential loss-term to the mass balance equation. The resulting equation is:

$$C = C_{in}(1 - \exp(\frac{-t}{t_d})) + C_o(\exp(k * t) * \exp(\frac{-t}{t_d}))$$ Equation 2

where,

k	=	first order loss (reaction) rate.

Total chromium was modelled using Equation 1 and hexavalent chromium was modelled using Equation 2. Trivalent chromium was calculated as the difference between total chromium and hexavalent chromium.

Concentrations in the lakes were simulated on a monthly time-step. Each lake was assumed to be completely mixed during the ice-free period. During the ice-cover period, the mine-affected groundwater inflow was isolated from the majority of the lake and was assumed to accumulate in a thin bottom layer in areas receiving mine affected groundwater. The accumulated bottom water was added back into the lake during the

June time-step, when ice-breakup would occur and wind-driven mixing would mix the accumulated mine-affected groundwater throughout the water column.

To simplify the model, the baseline water quality of all inflow to the lake, was assigned the baseline water quality of the lake. This assumption assumes that the baseline water quality of the lakes is stable and does not change over time. Long-term water quality monitoring at the Artillery Lake monitoring station (Appendix IX.6) indicates that this is a valid assumption for lakes in the Lockhart River watershed.

5.0 REFERENCES

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6.0 UNITS AND ACRONYMS

UNITS

°	degrees
°C	degrees Celsius
µg/L	micrograms per litre
$kg/m^2/s$	kilojoules per square metre per second
kg/m^3	kilogram per cubic metre
m	metre
m/day	metres per day
m/hr/mbar	metres per hour per unit pressure
m/s	metres per second
m^2/s	square metre per second
m^3/day	cubic metres per day
mg/L	milligrams per litre
$mg/m^2/day$	milligrams per square metre per day
mg/mg	milligrams of parameter per milligrams of parameter
mm	millimetre
mm/s	millimetres per second

ACRONYMS

EA	environmental assessment
BOD	biological oxygen demand
CORMIX	cornell mixing model
DO	dissolved oxygen

NH_3	ammonia
NO^2	nitrite
NO^3	nitrate
O^2	oxygen
OrgN	organic nitrogen
OrgP	organic phosphorus
PO_4	phosphate
TDS	total dissolved solids
TSS	total suspended solids
U.S. EPA	United States Environmental Protection Agency
WQ	water quality