APPENDIX 7.VI

Flooded Open Pit Hydrodynamic Model

Table of Contents

FIGURES

7.VI.1 INTRODUCTION

This appendix provides information on the hydrodynamic modelling of the NICO Project Flooded Open Pit that was completed to support post-closure predictions of water quality in the Flooded Open Pit presented in Appendix 7.II.

The objectives of the Flooded Open Pit hydrodynamic modelling were to predict whether or not the Flooded Open Pit will become vertically stratified and the potential for anoxic conditions to develop. The volume of the fully mixed zone and oxygen status were then used as inputs to the geochemical Flooded Open Pit water quality predictions (Appendix 7.II).

Hydrodynamic modelling was completed using CE-QUAL-W2 (W2) (Cole and Wells 2008). The W2 model is a 2-dimensional, laterally averaged, hydrodynamic and water quality model maintained and supported by the U.S. Army Corp. of Engineers Waterways Experiment Station. The model simulates the interaction of physical and chemical processes, including flow, thermal and substance mass loading regimes, meteorological forcing conditions and lake-bottom interactions. The W2 model also includes a module to simulate ice-cover. The formation of an ice cover prevents re-aeration, provides complete wind sheltering and results in reduced thermal inputs via solar radiation. The model has been extensively used to simulate the behaviour of natural and constructed lakes, including mine pit lakes (Cole and Wells 2008; Castendyk and Eary 2009).

7.VI.2 MODEL SETUP AND INPUTS

The W2 model includes default parameters for momentum and heat transfer and recommended settings for model application to a lake or reservoir environment. These default and recommended settings were generally applied to the NICO Project Flooded Open Pit model, with the exception of ice variables. The most notable change in the model setup was to ice cover albedo (i.e., the proportion of incident sunlight reflected by the ice cover). The default albedo value of 0.25 was replaced with a value of 0.8, as the default albedo value is not representative of a northern ice cover.

Model inputs include:

- meteorological data (i.e., air temperature, dew point, wind speed and direction, and solar radiation);
- Flooded Open Pit bathymetry;
- input rates for each inflow source to the Open Pit; and
- water quality characteristics for each inflow source.

7.VI.2.1 Meteorology

Hourly meteorological data were obtained for the Meteorological Service of Canada long-term climate monitoring station in Yellowknife. Air temperature, dew point, wind speed, and direction data were available for the period of record (i.e., 1953 through 2010). Solar radiation data were not available from the Yellowknife station, so they were estimated on an hourly basis based on the latitude and longitude of the NICO Project.

7.VI.2.2 Bathymetry

A contour map of the Open Pit at the end of operations was used to define bathymetry inputs for the W2 model. The Open Pit was represented in the W2 model as a series of 6 segments with individually defined lengths and orientations that approximate the Flooded Open Pit shape and water surface area. Each segment was composed of multiple layers that are defined with independent widths, which facilitate definition of changes in the Open Pit cross-sectional area with depth. The vertical layer depths ranged from 1 metre (m) near the surface to 2 m near the bottom. The depth-storage characteristics of the modelling grid aligned with volumes calculated from the Open Pit contours. The final W2 model grid volume was within 5 percent (%) of the Open Pit volume at each of the mid-depth bench transitions, and was within 0.1% of the Open Pit volume at the spill elevation of 260 m.

7.VI.2.3 Inflow Rates and Physico-Chemical Characteristics

Inflow rates to the Open Pit were the same as those used in the geochemical Flooded Open Pit water quality predictions, and total dissolved solids (TDS) concentrations were calculated from the corresponding site water chemistry inputs and predictions (Appendix 7.II). Temperatures were assigned to surface inflows during the open water season based on surface water temperatures observed during baseline monitoring (Annex C). Rainfall temperatures were interpolated on a daily basis from monthly average air temperature values from the long-term climate monitoring station in Yellowknife. The temperature of groundwater inflow was identified as an area of uncertainty. As a conservative measure, groundwater inflows were assigned a constant temperature of 4 degrees Celsius (°C) so that any stabilizing effects of groundwater inflow density would be overpredicted. Influx of warmer or colder, less dense groundwater at the bottom of the Flooded Open Pit may result in more vertical mixing than predicted by this model.

Dissolved oxygen (DO) content of precipitation and surface water flows were assumed equal to the saturation concentration at the assigned water temperature, and groundwater was assumed to be anoxic (i.e., DO of 0.1 milligrams per litre). Biochemical oxygen demand concentrations were approximated based on observed measurements from nearby surface waters, and an additional oxygen demand was included to represent chemical oxygen demand of oxidizable metals in pit wall runoff.

7.VI.3 RESULTS

The hydrodynamic model was run for the Flooded Open Pit to determine:

- the frequency of lake stratification and turnover;
- the depth(s) of stratification, if present; and
- the presence of DO in the epilimnion and hypolimnion.

The model predicted that the Flooded Open Pit would mix vertically at least once per year to a depth of approximately 150 m. Figure 7.VI.3-1 depicts the time-depth profile for temperature in the Flooded Open Pit, beginning about 5 years before initial discharge, at the deepest segment of the Flooded Open Pit. Temperatures in the contour plots are divided into a number of intervals, and values in each interval are represented with an identical color. Inverse thermal stratification is predicted to occur in winter and persist until air temperature warms in the spring. This continues until temperatures in the lake are isothermal in early summer. Thereafter, the surface water temperature continues to increase and stratification re-appears until the lake reaches maximum stability in August. Then, as air temperature drops in the autumn, the lake surface cools and the cooler water mixes downward. The isothermal conditions lead to a fall turnover, and then the cycle repeats itself annually.

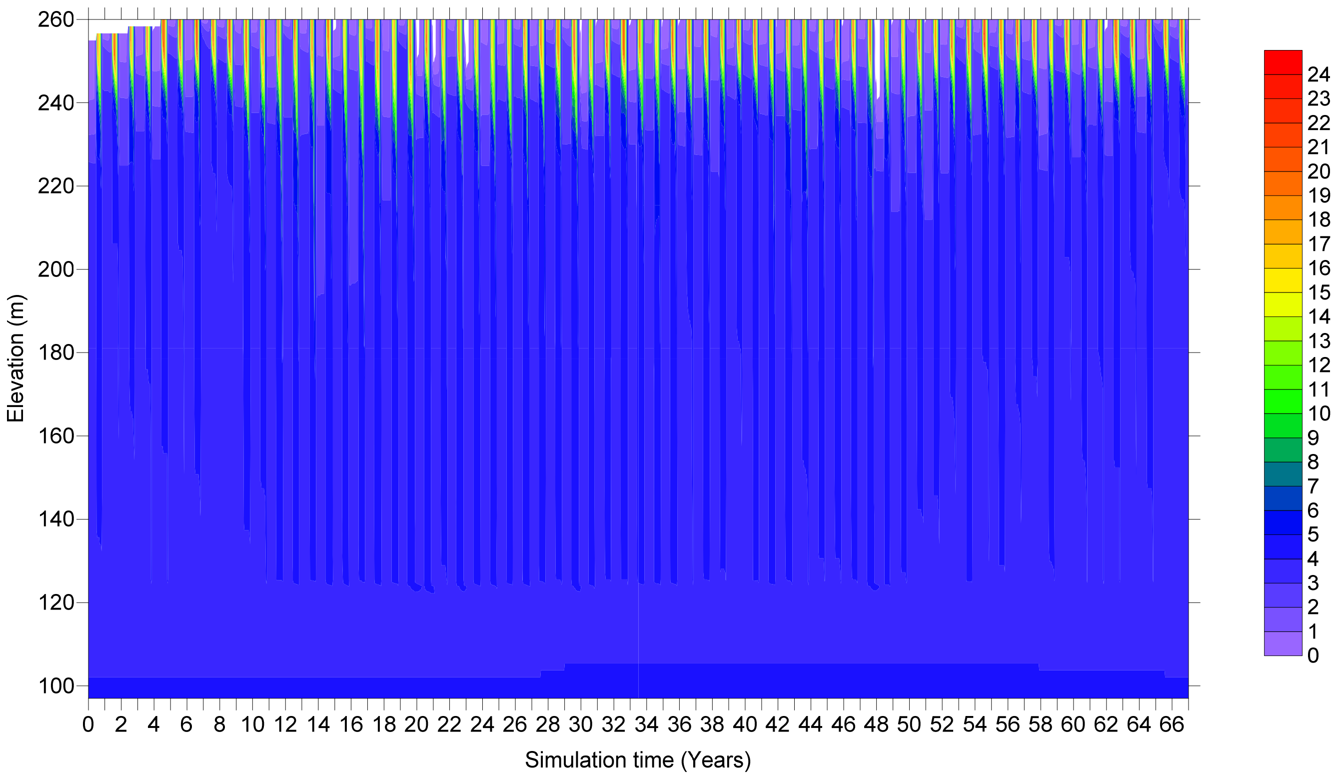

Figure 7.VI.3-1: Time-Depth Profiles of Temperature (ºC) in the Flooded Open Pit

Permanent vertical stratification, or meromixis, is not predicted to develop in the Flooded Open Pit, except possibly in the lowest 35 m. Figures 7.VI.3-2 and 7.VI.3-3 depict the time-depth profile of TDS and DO concentrations at the deepest segment of the Flooded Open Pit. Concentrations in the contour plots are divided into a number of intervals, and values in each interval are represented with an identical color. Figure 7.VI.3-2 indicates that the TDS would stratify seasonally along with temperature, as indicated by the annual cycles of gradients with depth. Limited TDS stratification is mainly predicted to occur near the bottom of the Flooded Open Pit, with a relatively homogenous profile occurring annually in the majority of the water column. A gradual depletion of TDS from the deepest layers is predicted, resulting from diffusion across the chemocline.

As shown in Figure 7.VI.3-3, the Flooded Open Pit is anticipated to have vertical gradients of DO, with lower concentrations near the lake bed throughout all of the years. Due to the replenishment during the vertical mixing, the Flooded Open Pit is predicted to be well oxygenated in most of the waterbody at all times.

The modelling results indicate that approximately 900 000 cubic metres of water located in the bottom 35 m of the Flooded Open Pit will remain isolated from the remaining volume, which equates to approximately 3% of the total volume of 28 million cubic metres. Most of this volume was predicted to remain well oxygenated.

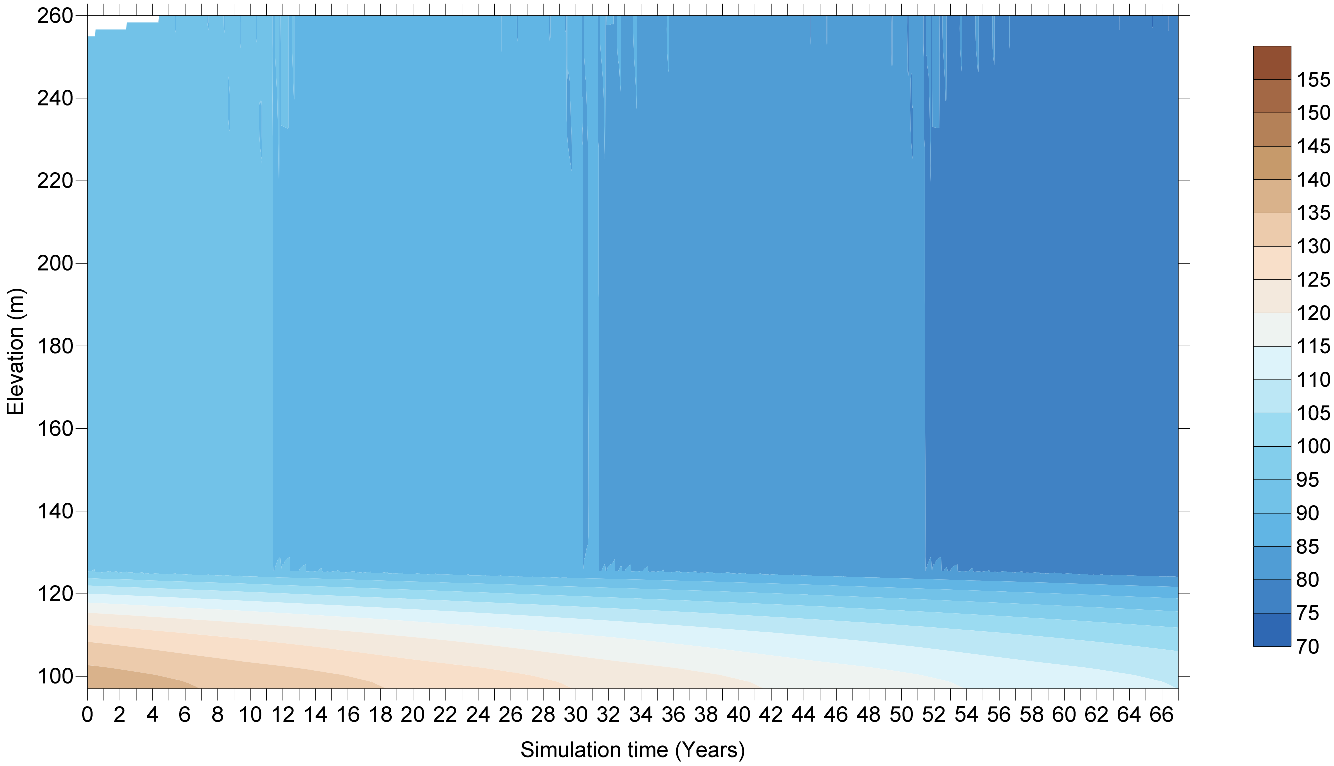

Figure 7.VI.3-2: Time-Depth Profiles of Total Dissolved Solids (mg/L) in the Flooded Open Pit

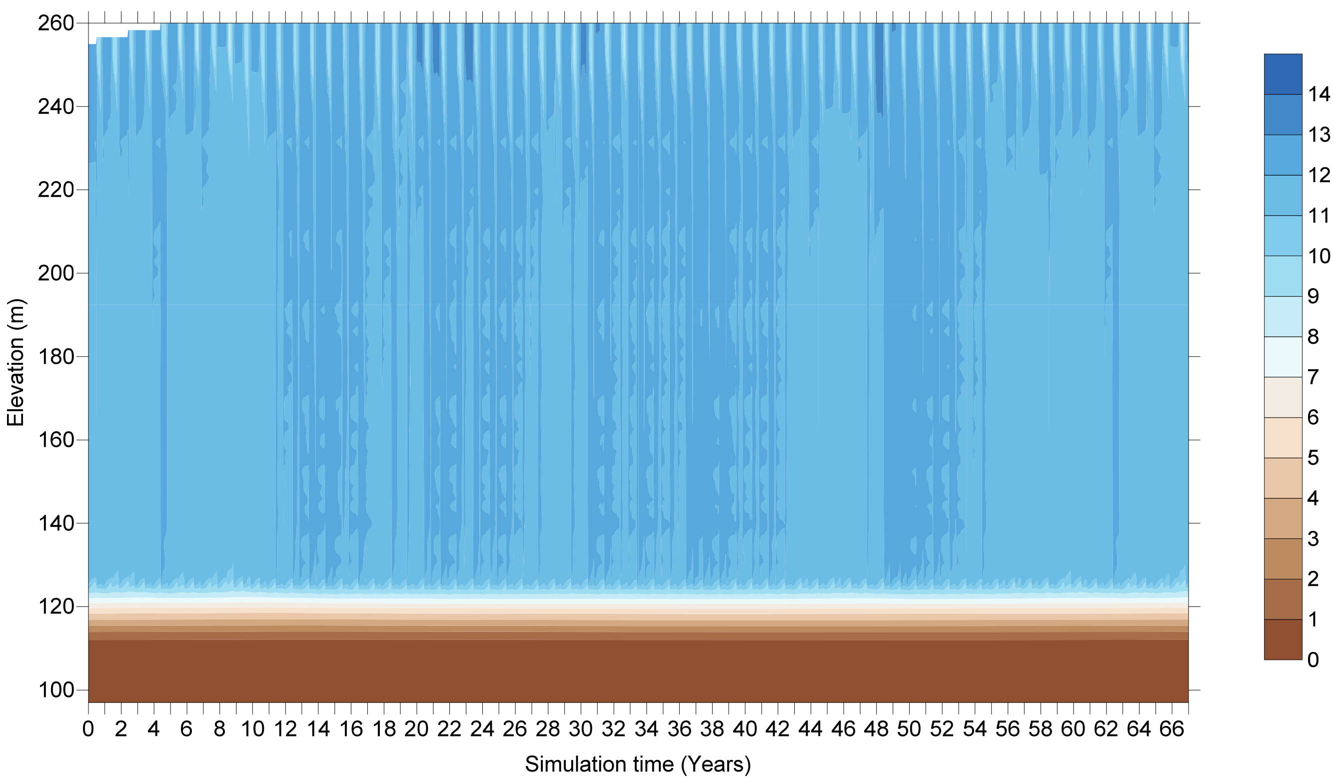

Figure 7.VI.3-3: Time-Depth Profiles of Dissolved Oxygen (mg/L) in the Flooded Open Pit

The small size of the monolimnion appears to be attributable to the relatively small differences in TDS content of the predicted post-closure Flooded Open Pit water sources, associated weak or absent pycnocline at depth, and high evaporation rates (which tends to result in evapoconcentration in the warmer surface layers in summer relative to the cooler waters below, followed by density-driven turnover in fall). Vertical mixing is further promoted by the long fetch of the Flooded Open Pit, which is generally aligned with the orientation of dominant winds (i.e., northwest to southeast).

7.VI.4 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to examine the potential influence of wind sheltering on the modelling results. In addition to the modelling described above, completed with a 20% reduction in wind speed inputs to match evaporation rates in the water balance, modelling runs were completed with further wind reductions (i.e., reduced by much as 90% of the original input wind speeds). The results of the sensitivity analysis support the conclusions of the analysis, as wind speed reductions of up to 50% produced profiles consistent with those presented above. At a wind speed reduction of 70%, which is unlikely to occur, a larger monolimnion was evident but still accounted for less than 10% of the Flooded Open Pit volume.

7.VI.5 REFERENCES

Castendyk, D.N., and L.E., Eary. 2009. Mine pit lakes: characteristics, predictive modeling, and sustainability: Society for Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado, 61-76 p.

Cole, T.M. and S.A. Wells. 2008. CE-QUAL-W2: A Two-dimensional, laterally averaged, hydrodynamic and water quality model, Version 3.5. Prepared for U.S. Army Corps of Engineers, Washington, DC 20314-1000. 239 p.