Dominion Diamond Ekati Corporation

EKATI DIAMOND MINE
Modelling Predictions of Water Quality for Pit Lakes

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DOMINION DIAMOND

November 18, 2013

Ms. Violet Camsell-Blondin
Chair
Wek'èezhìi Land and Water Board
#1, 4905-48th Street
Yellowknife, NT, CA X1A 2P6

Dear Ms Camsell-Blondin

Dominion Diamond Ekati Corporation (DDEC) is pleased to provide the Wek'èezhìi Land and Water Board with the Ekati Diamond Mine Modelling Predictions of Water Quality for Pit Lakes report. This report is part of the Ekati Interim Closure and Reclamation Plan Research Plan 1.4. Specifically it completes Tasks 1-4 of the research plan, to undertake preliminary modeling predictions for water quality in the surface layer of full pit lakes, and the potential for meromixis to occur in any of the pit lakes within Ekati's current life of mine plan (Pigeon, Beartooth, Panda, Koala North and Koala, Fox and Misery open pits, as well as the connecting underground mines Panda and Koala).

Surface water within the pit lakes will eventually be allowed to spill naturally to the receiving environment; hence, predicted surface water concentrations in the pit lakes are compared to Water Quality Benchmarks relevant to the receiving waters at Ekati as an initial screening tool.
The report is based on current data and a modelling approach that focuses on assessing key sensitivities controlling water quality and the formation of physical and chemical stratification within the pit lakes. The model results are intended to be indicative and to provide an initial assessment of the potential for any water quality issues of concern related to the pit lakes.

DDEC trusts that you will find the report clear and informative. Please contact Helen Butler, Senior Advisor – Reclamation and Closure at helen.butler@ekati.ddcorp.ca or 867-669-6104 and the undersigned at eric.denholm@ekati.ddcorp.ca or 867-669-6116.

Sincerely,

Dominion Diamond Ekati Corporation

Eric Denholm
Superintendent – Traditional Knowledge and Permitting
Ekati Diamond Mine

EKATI DIAMOND MINE

MODELLING PREDICTIONS OF WATER QUALITY FOR PIT LAKES

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Dominion Diamond Ekati Corporation

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Yellowknife, Northwest Territories

Executive Summary

Executive Summary

The Ekati Interim Closure and Reclamation Plan (ICRP) for the Ekati Diamond Mine (Ekati) in the Northwest Territories was approved by the Wek'èezhìi Land and Water Board (WLWB) in November 2011. For the exhausted open pits, the ICRP outlines a closure process whereby water from nearby lakes will be pumped to the open pits and once filled the pit lakes will become part of the natural hydrological system of the region; they will receive inflows from upstream catchments and precipitation on the lake surface and they will lose water through evaporation and spilling of excess water to downstream lakes or water courses.

This report was prepared as part of reclamation research planning under the ICRP and aims to provide the first detailed water quality predictions for each of the future pit lakes during the infilling process and post-infilling. Specifically, the work was completed under reclamation Research Plan 1.4, Tasks 1-4, which are the tasks to complete the pit lakes water quality modelling. The report presents modelling predictions of water quality in the surface layer of the future full pit lakes and identifies whether there is the potential for meromixis to occur in any of the pit lakes within the Ekati site. Surface water within the pit lakes will be allowed to spill naturally to the receiving environment; hence, predicted surface water concentrations in the pit lakes are compared to Water Quality Benchmarks relevant to the receiving waters at the Ekati site.

Meromixis can often occur in pit lakes due to their morphology (narrow and deep) and the presence of sources of saline or higher density water (e.g., groundwater, pit wall runoff). Pit lakes which experience meromixis do not undergo full mixing between upper and lower layers of the water column and as a result denser, poorer quality water can be retained at depth within the lakes. Meromixis may or may not be desirable for any specific pit lake. However, an assessment of the potential for meromixis is important to understand and predict the evolution of pit lake water quality over the long term.

This report provides predicted water quality for reasonably estimated Base Case scenarios, plus a sensitivity analysis on key variables. The intent is that the modelling results are used to understand the likely water trends in the various pit lakes, to identify areas of greater or lesser water quality risk, and to indicate the general level of water quality risk under conservative assumptions.

Key general conclusions for the study are:

- Pumping of fresh water to fill pit lakes improves the quality of water in the pit lakes. Higher infilling rates will produce cleaner pit lake water.
- Pit lakes with larger upstream watersheds are likely to have better quality water in the surface layer of the pit lakes than pits with smaller upstream watersheds.
- For pit lakes with more reactive wall rock (e.g., Misery and Pigeon) or those with groundwater inflows (e.g., Panda, Koala/Koala North and Fox) the time between the end of operations within the pit and the time of pumped infilling can impact final water quality in the pit lake. The shorter the time before the onset of pumping the better the quality of water within the pit lake.
- Only those pit lakes with groundwater inputs have the potential for the formation of meromixis, with the likelihood of meromixis related to the rate of groundwater inflow, the rate of change of groundwater inflows as pit lake levels rise and the speed at which the pit lakes are filled. It is noted that groundwater flows to full pit lakes are assumed to be zero in the long term (i.e., once the pit lake is full). However, if there is a net flux of groundwater to the pit

lakes (or out of the pit lakes) over the long term this would impact the depth and stability of meromixis in the lakes.

- Pit wall runoff is the main source of long-term loadings to full pit lakes, as there will be areas of exposed pit walls above the pit lake surface of all pit lakes.

A summary of model predictions for each pit lakes is provided in Table 1. Overall, the quality of water in the surface layer of the pit lakes is considered likely to be below Water Quality Benchmarks, unless certain conditions arise for selected pit lakes.

Water quality in Sable and Fox pit lakes is expected to be below Water Quality Benchmarks for all conditions.

Water quality in Beartooth pit is expected to be below Water Quality Benchmarks as long as a significant proportion of the mine water (underground water and FPK supernatant) is pumped out of the pit lake prior to final infilling with a fresh water cover.

Water quality in Panda and Koala/Koala North has the potential for exceedances of chloride, nitrate and sulphate due to inflows from groundwater. However, these results are based on conservative estimates of groundwater inflow rates at the end of operations at Ekati. Observed groundwater flow rates in the existing underground workings are lower than the values used in the model Base Case and if groundwater flow rates continue to be low in the future, modelling predicts no exceedances of Water Quality Benchmarks. Even if underground flows are higher at closure than at present there are management options to control surface layer water quality, such as the placement of a fresh water cover at the surface of these pit lakes. With a fresh water cover modelling predicts concentrations in the surface layer to be below Water Quality Benchmarks.

The largest concerns related to exceedances of Water Quality Benchmarks occur in Misery and Pigeon pit lakes where high loadings from exposed meta-sediments in the pit walls have the potential to increase concentrations in the surface water layer above Water Quality Benchmarks. However, there is evidence that current pit wall runoff predictions for meta-sediment may be high and with additional research there is some confidence that future predictions may show that water quality in the surface layers of these pit lakes will also be below Water Quality Benchmarks.

The model is data driven in that many parameters and inputs are based on analysis of observed data at the Ekati mine. Many of the assumptions of the model are conservative; however, the long-term nature of the predictions (hundreds of years) creates inherent uncertainty in the predictions (e.g., climate change). As with all modelling there remain uncertainties in simulating the behaviour of managed and natural systems, particularly over a span of hundreds of years. Nonetheless, this study has used available monitoring data to make reasonable predictions of water quality in the future pit lakes at the Ekati site based on the closure concepts developed in the ICRP.

Table 1. Summary of Modelling Results for Future Pit Lakes

Pit	Meromixis	Water Quality in Surface Layer of Full Pit Lake[a] Base Case	Comment
Sable	Low likelihood for meromixis	All key water quality variables likely < WQBs.	-
Pigeon	Low likelihood for meromixis	Potential for exceedances of selected metals due to loadings from pit wall runoff.	Key loading is from pit wall runoff from meta-sediment. Uncertainties over pit wall runoff chemistry and rock type exposed in pit wall of full pit lake. However, annual outflow volume from pit lake is very low, tending to zero in summer months, due to small (0.03 to 0.1 km^2) watershed draining to pit lake. As a result likely negligible loads to downstream water body even if surface water quality exceeds WQBs.
Beartooth	Low likelihood for meromixis	Potential for exceedances for nitrate, chloride and sulphate in first 10 years post-infilling, with concentrations < WQBs by Year 10.	Beartooth pit lake will be filled with FPK up to 30 m from the full level of the pit lake. It will then be capped by a layer of water. Water quality in the surface layer will depend on how much mine water remains above FPK at the time of capping with fresh water.
Misery	Low likelihood for meromixis	Potential for exceedances of selected metals due to loadings from pit wall runoff.	Key loading is from pit wall runoff. Uncertainties over pit wall runoff chemistry and rock type exposed in pit wall of full pit lake. However, annual outflow volume from pit lake is very low, tending to zero in summer months, due to small (0.02 km^2) watershed draining to pit lake. As a result likely negligible loads to downstream water bodies even if surface water quality exceeds WQBs.
Fox	Moderate likelihood for meromixis	All key water quality variables likely < WQBs.	Key uncertainties are groundwater inflow rates and how these vary over time and WRSA runoff rates and chemistry. WRSAs surrounding Fox pit will drain to pit lake at closure.
Panda	High likelihood for meromixis	Potential for exceedances of chloride, nitrate and sulphate concentrations up to 100 years post-infilling of pit lake.	Key uncertainties are groundwater inflow rates and how they vary over time and WRSA runoff rates and chemistry. Base Case assumes conservative (high) groundwater flow rates for the end of operations at Panda underground. If lower rates, based on current observed data, are used, modelling predicts all water quality variables will be < WQBs. Model assumes around 1.4 km^2 of WRSAs to the west of Panda pit draining to the pit lake.
Koala/Koala North	High likelihood for meromixis	Potential for exceedances of chloride, nitrate and sulphate concentrations up to 100 years post-infilling of pit lake.	Key uncertainty is groundwater inflow rates and how these vary over time. Base Case assumes conservative (high) groundwater flow rates for the end of operations at Koala/Koala North underground. If lower rates, based on current observed data, are used, modelling predicts all water quality variables will be < WQBs.

[a] *Excluding cadmium, which is exceeded in all pit lakes. However, cadmium benchmark is known to be low.*
Notes: WQB = Water Quality Benchmark; WRSA = Waste Rock Storage Area; FPK = Fine Processed Kimberlite

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Glossary and Abbreviations

Glossary and Abbreviations

Terminology used in this document is defined where it is first used. The following list will assist readers who may choose to review only portions of the document.

AEMP	Aquatic Effects Monitoring Program
ANFO	Ammonium Nitrate Fuel/Oil
ARD	Acid Rock Drainage
BOD	Biological Oxygen Demand
CCME	Canadian Council of Ministers of the Environment
CTD	Conductivity-Temperature-Depth
DDEC	Dominion Diamond Ekati Corporation
DHI	Danish Hydraulic Institute
EFPK	Extra Fine Processed Kimberlite
EQC	Effluent Quality Criteria
FPK	Fine Processed Kimberlite
GIS	Geographic Information System
ICRP	Interim Closure and Reclamation Plan
LLCF	Long Lake Containment Facility
masl	metres above mean sea level
TDS	Total Dissolved Solids
TMD	Temperature of Maximum Density
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids
UG	Underground
WLWB	Wek’èezhìi Land and Water Board
WQB	Water Quality Benchmark
WRSA	Waste Rock Storage Area

1. Introduction

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1. Introduction

The Ekati Interim Closure and Reclamation Plan (ICRP) for the Ekati Diamond Mine (Ekati) in the Northwest Territories was approved by the Wek’èezhìi Land and Water Board (WLWB) in November 2011. For the exhausted open pits, the ICRP outlines a reclamation process whereby water from nearby lakes will be pumped to the open pits and connected underground (UG) mines. Once filled the pit lakes will become part of the natural hydrological system of the region (BHP Billiton 2011a); they will receive inflows from upstream catchments and precipitation on the lake surface and they will lose water through evaporation and spilling of excess water to a downstream lake or water course.

There are many practical considerations that argue for the pump flooding of open pits and underground mines at mine closure (e.g., to reduce long-term risk related to wildlife accessing a deep open pit); however, a key reason is to submerge mine workings and pit walls to reduce effects of metal leaching on the water quality of the future pit lakes. The ICRP aims to augment natural infilling of the pit lakes with pumped inflows submerging the pit walls as quickly as possible. In concept the plan is to produce good quality water within the pit lakes so that excess water can be discharged to the natural downstream environment without treatment or significant adverse effect to the downstream ecosystem. Water in the full pit lakes that is of acceptable quality can overflow naturally into downstream water courses, resulting in a sustainable and low maintenance closure scenario, where the pit lakes can be left as part of the natural ecosystem in perpetuity.

This report provides the first predictions of water quality within the proposed pit lakes at the Ekati mine site. The report is based on current data and a modelling approach that focusses on assessing key sensitivities controlling water quality and the formation of physical and chemical stratification within the pit lakes. The model results are intended to be indicative and to provide an initial assessment of the potential for any water quality issues of concern related to the pit lakes. The model results are also used to identify key sensitivities and data gaps. Model inputs and results will be improved over time.

A feature of some pit lakes is that chemical and physical stratification (meromixis) can develop within the water body. This can have the benefit of isolating any poorer quality water at depth within the pit lake, with the closed Island Copper Mine being a classic example of a meromictic lake (Poling et al. 2003). In general meromixis can be beneficial if there is a need to contain poor quality water within an isolated layer of a pit lake. However, there are risks involved with meromictic pit lakes. If the layering is able to break down over time, poorer quality water can be brought to the surface. The potential for meromixis is therefore an important physical attribute that requires to be understood for any future pit lake.

Due to the climate at Ekati, there is also the potential for physical stratification in the upper layers of the pit lakes. During freshet, snow and ice melt can form a surface layer of fresh water within natural lakes. The same process would be expected within pit lakes. If the overflow from a lake of pit lake is within the surface layer only (e.g., there is a shallow overspill stream allowing flow out of the lake or pit lake), water flowing from the pit lake may be relatively fresh and not representative of the quality of water at depth in the pit lake. Given the seasonality of steam flows at Ekati (i.e., almost 50% of flow can occur in first few weeks of freshet and 100% of flow typically occurs in the open water season), much of the water flowing from a pit lake to the receiving environment could be associated with melt water and be of good quality.

This report was prepared as a reclamation research plan under the ICRP and aims to provide the first water quality predictions for each of the future pit lakes during the infilling process and post-infilling.

Specifically, the work was completed under reclamation Research Plan 1.4, Tasks 1-4, which are the tasks to complete the pit lakes water quality modelling. The report presents modelling predictions of water quality in the surface layer of the future full pit lakes and identifies whether there is the potential for meromixis to occur in any of the pit lakes within the Ekati site. Fish passage will be allowed into the pit lakes when and if the water quality of the pit lake meets water quality criteria. Water from the pit lakes will also flow to the downstream watershed. Hence, predicted surface water concentrations in the pit lakes are compared to Water Quality Benchmarks relevant to the receiving waters. The potential for meromixis to occur and its long-term stability are important factors to know in advance of closure so that management plans can be developed accordingly to either encourage or hinder the development of meromixis. It is also important to understand physical and chemical stratification that can occur seasonally in the surface layers of pit lakes.

2. Overview of Modelling Work

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2. Overview of Modelling Work

This chapter provides an overview of the modelling approach taken, an outline of the pits considered in the modelling assessment, a summary of the pit lake infilling strategies, mine operations that affect closure of the open pits (e.g., Fine Processed Kimberlite (FPK) backfill into Beartooth), and a review of Water Quality Benchmarks considered for the receiving environment.

2.1 OVERVIEW OF MODELLING APPROACH

The modelling approach was developed to provide two key model outputs:

1. Predictions of the likelihood of the formation of meromixis within the full pit lakes and an assessment of the long-term stability of meromixis. The identification of the conditions under which meromixis might form and an assessment of which pit lakes may develop meromixis are important considerations for developing closure water management strategies at the mine site.
2. Predictions of water quality in the surface layer of full pit lakes. Once the pit lakes are full surface water will be allowed to flow to the receiving environment and an assessment needs to be made of the quality of the outflowing water. This assessment is made using Water Quality Benchmarks developed for the receiving environment at the Ekati site.

A schematic of the modelling approach taken to provide the above model outputs is provided in Figure 2.1-1.

At the heart of the modelling approach is a multi-layer model that predicts variations in water quality with depth in the pit lake and which can predict the potential for the formation of meromixis within pit lakes. The model was developed by University of British Columbia based on research into physical and chemical stratification within pit lakes. The model can predict the formation of stratification in the surface layers of the pit lakes, resulting from snow and ice melt, and it can model stratification at depth within a pit lake, in response to temperature and density differences at depth.

At present, this multi-layer model is not able to simulate the pit lake infilling process (i.e., it cannot model significant changes in water depth over time) and it is not able to simulate the evolution of multiple solutes within the pit lake (i.e., it can model salinity and indicative conservative tracers that can be used to develop dilution rates that can be applied to other water quality variables). Hence, to support the multi-layer model two additional models were developed:

1. A load balance model was developed of each pit lake to simulate the evolution of bulk chemistry within each pit lake as it fills. These models provide the initial conditions (i.e., predicted chemistry within the pit lake once full) for the multi-layer models. The models are also used to undertake scenario runs that assess model sensitivity to key input parameters.
2. A mixing model was developed of each pit lake to simulate the water quality in the surface layer within each pit lake. These models are based on dilution rates calculated by the multi-layer model. The multi-layer model is not able to predict the evolution of multiple water quality variables and the mixing models fill this gap and allow model predictions to be made that can be compared to Water Quality Benchmarks to the aquatic receiving environment at the Ekati site.

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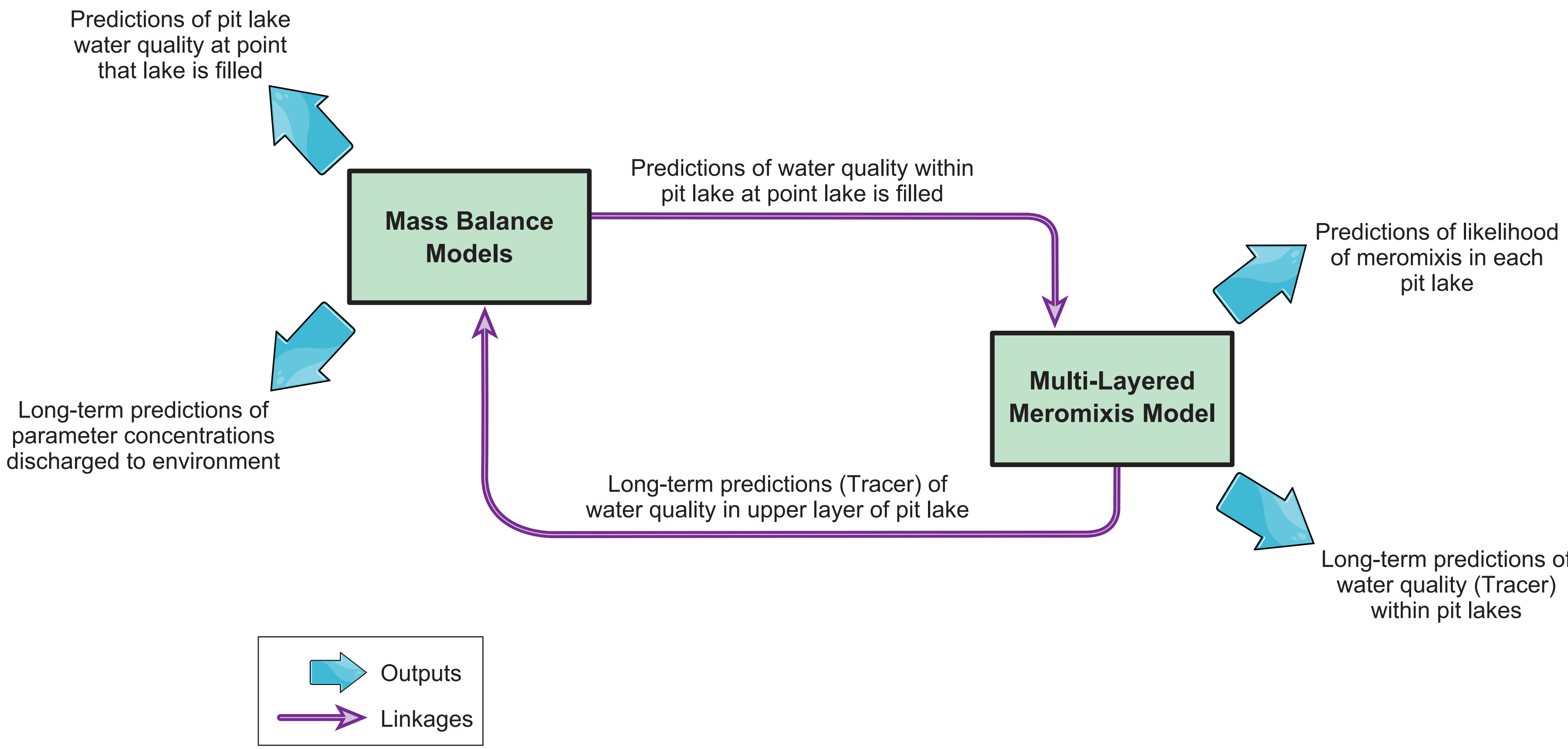

Figure 2.1-1

Flow Diagram Showing Relationships between Modelling Studies

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Figure 2.1-1

2.2 KEY MODELLING ASSUMPTIONS

The following key assumptions inherent to the model approach are discussed in this section:

- assumption of non-reactive water quality variables (except nutrients);
- assumption of full mixing of pit lakes during filling process; and
- assumption of equivalence of dissolved and total metals in natural waters at the Ekati site.

2.2.1 Assumption of Non-reactive Water Quality Variables

The model assumes that most water quality variables are conservative and do not decay or react over time. The exceptions to this assumption are nutrients (ammonia, nitrate, nitrite and phosphate) that are modelled using a first order decay function to account for losses as these variables are cycled by organisms (i.e., taken up by living plankton and released by decaying plankton) in natural water bodies or volatilized at the lake surface (ammonia). The decay rates for these nutrients were calibrated for the LLCF Load Balance Model (Rescan 2012) and the calibrated values are used in this study, Table 2.2-1.

Table 2.2-1. Calibrated Decay Rates for Non-conservative Water Quality Variables

Variable	Calibrated Half-life for Variable[a]
Phosphate	11.1 months
Nitrate	No decay
Nitrite	8.3 months
Ammonia	4.2 months

[a] *First Order decay equation: Concentration at Time t = Initial Concentration × $(0.5)^{t/half\text{-}life}$*

The assumption that most water quality variables are conservative is reasonable for water bodies where the pH is close to neutral and concentrations are relatively low. Reactions among variables are anticipated to be of lesser importance than the uncertainties associated with estimating inflows and outflows from the system. Attempting to model chemical reactions among metals and other related species would require complex geochemical modelling that typically can only be run effectively for quite narrowly defined conditions and ranges of concentrations of water quality variables. Given expected conditions in the Ekati pit lakes, this level of complexity is not required at this stage of research.

2.2.2 Assumption of Full Mixing during Pit Infilling

There is uncertainty as to whether stratification or layering can occur within a pit lake as it fills. The Base Case assumption used within the pit infilling models is that the pit lakes will be fully mixed as they fill, based on calculations that suggest the energy of the water falling into each pit lake will be sufficient to prevent stratification from persisting during filling. The pumped inflow, released at the top of the pit, will cascade down the benches in a series of waterfalls. The water will have high kinetic energy. In contrast, stratification developing within the infilling pit lake will depend on small density and temperature differences, making the energy needed to mix the pit relatively small.

The kinetic energy of water falling onto the pit lake surface will depend on the height that the water falls and the water flow rate. The height of each bench within the pit walls will control the height that water would be able to fall unimpeded. At the Ekati mine, a typical bench height would be around 15 m.

The total kinetic energy input of water falling per unit surface area of a pit lake is given by:

$$E_F = \frac{\rho gHV}{A} = \frac{(10^3)(9.8)(15.0)(1.0\times10^6)}{3\times10^5} = 495{,}000 \text{ J/m}^2$$

where V = 1.0 × 10^6 m^3 is the estimated volume of water pumped to a pit lake during one month, and A = 3 × 10^5 m^2 is the average surface area of the Ekati pit lakes.

Only a very small proportion of this energy (~1%) will actually contribute to mixing of the lake. How much, will depend on the details of the inflow and the geometry of the pit. However, this energy is more than an order of magnitude larger than salinity stability of pit lakes calculated at the point that the lakes are full (at most ~200 J/m^2 for Panda or Koala/Koala North, calculated using results from Chapter 6 of this report).

The work done by the inflowing water will not only work against the salinity stability, but against any temperature stratification that may develop. For a lake with no inflows, the stability of the temperature stratification at the height of summer would be an order of magnitude more than the salinity stability (e.g., 4,000 J/m^2 for 5 m layer of 15ºC in Panda). This is around 1% of the energy of the inflowing water which suggests that that some temperature stratification may occur during summer. However, the effect of the pumped inflow will work directly against the salinity stratification just after ice-off and during fall cooling, when temperature stratification is weak.

Based on these calculations permanent stratification is considered unlikely during filling. However, there are discharge options (e.g., submerged outfall) that could be adopted to limit mixing during infilling. In such cases some degree of stratification could form during the infilling process. It is difficult to predict the degree of internal stratification that could form during such a dynamic infilling process. To account for the potential for stratification to form during infilling, model runs were undertaken assuming linear stratification through the pit lake, i.e., a linear variation in salinity within the pit lake, with highest values at the bottom of the pit lake, lowest values at the surface. These model runs were undertaken for pit lakes with higher salinity values and where stratification might be expected to occur (i.e., Panda, Koala/Koala North and Fox pit lakes).

2.2.3 Assumption of Equivalence of Dissolved and Total Metals in Natural Waters at the Ekati Site

The information that forms the basis of the Ekati Water Quality Benchmarks for metals is based on total metals. However, the modelling documented in this report does not simulate the transport or deposition of suspended sediment. Hence, all modelled water quality variables are in the dissolved state. When comparing model predictions for metals with Water Quality Benchmarks it is assumed that dissolved metals concentrations are equivalent to total metals. This is considered a reasonable assumption for this study as suspended solids within the pit lakes would be expected to sink to the bottom of the lake and water close to the surface of a pit lake will have very low concentrations of suspended solids, as is typical of Arctic lakes.

Many of the water quality samples from the Ekati field monitoring programs during operations are analyzed for total metals only (e.g., streams and lakes), while the pit lakes models require dissolved metals concentrations as inputs. When developing model inputs suspended solids concentrations for water quality samples were reviewed and if the values were elevated (e.g., for some samples from pit sumps) total metals concentrations in these samples were not considered for model inputs. However, for many samples at the site (e.g., nearly all Aquatic Effects Monitoring Program (AEMP) stream and lake samples) total suspended solids (TSS) concentrations are low and the assumption that totals metals concentrations are equivalent to dissolved metals is valid. It is noted that for some mine water inputs (e.g., sump water), total and dissolved metals samples are available. Where both total and dissolved metals are available, model inputs are based on dissolved metals data.

2.3 MODELLED PIT LAKES AND CLOSURE TIMINGS USED FOR MODELLING

Pit lakes models are developed for each of the following pits:

- Sable open pit;
- Pigeon open pit, considering Pigeon open pit layouts (V17 from EBA 2010);
- Beartooth open pit infilled with processed kimberlite solids, mine water and fresh water;
- Misery open pit;
- Fox open pit;
- Koala and Koala North underground and open pit, which will together form a single pit lake; and
- Panda underground and open pit.

The model has been developed based on the schedule for pit closure presented in the ICRP (see Figure 2.3-1 in BHP Billiton 2011a).

The closure schedule indicates that for Sable, Pigeon, Fox and Misery pits filling of the pit lakes will commence soon after the end of mining operations. In these cases water accumulating at the bottom of the pit between the end of operations and the onset of pit infilling will be a negligible component of the water balance of the pit. In the pit infilling calculations presented in Chapter 7 this water will not be considered. It is noted that if the pit lakes were not filled soon after the end of operations, with part of the pit lake able to fill with surface runoff over pit walls, this would impact on the final water quality in the pit lakes. However, for Sable, Pigeon, Fox and Misery pit lakes the volume of water entering the pit lakes from surface runoff is small, so that uncertainties with the timing of the onset of pumping for these pit lakes are unlikely to be a dominant control on final pit lake water quality.

Beartooth pit receives mine water, and fine processed kimberlite (FPK) during operations. Based on the current plan (BHP Billiton 2011b), it is assumed that a water cover will be placed over FPK solids soon after the pit is full of FPK solids (i.e., to within 30 m of the pit spill level).

In contrast to the other pit lakes, infilling of Panda and Koala/Koala North is planned to commence some 13 years after the end of mining operations. Hence, during the period of time between the end of operations and the start of active infilling of the pits it is expected that water entering the pits and underground workings (natural runoff and groundwater inflows) will be allowed to accumulate in the underground workings. Within this assessment the Base Case model run assumes that there is a delay of 13 years between the end of operations at Ekati and the onset of pumping of water to these pit lakes. During this period it is assumed that open pits and underground workings are allowed to fill naturally with water. Because the time period between the end of operation and pumped infilling could be changed, sensitivity runs were undertaken for a case with pumped infilling starting immediately at the end of operations of Ekati.

2.4 OUTLINE OF PIT LAKE INFILLING STRATEGIES

The general closure concept, as outlined in previous sections, is that each open pit will be infilled with water and connected to downstream water bodies.

Sable, Pigeon and Misery pit lakes will be filled by pumping natural water from source lakes, natural runoff from watersheds surrounding the pits, from precipitation on pit walls and precipitation on the pit lake. There will be evaporation from the pit lake. However, no mine water or processed kimberlite will be discharged to these pit lakes, there are no groundwater inflows and each lake is isolated from all others during the infilling process.

Panda, Koala/Koala North and Fox pit lakes will also be filled by pumping natural water from source lakes, natural runoff from watersheds surrounding the pits, from precipitation on pit walls and precipitation on the pit lake. However, these pit lakes will also receive inflows from groundwater through the bottom of the open pit and into underground workings (at Panda and Koala/Koala North only). There will be evaporation from the pit lake. However, no mine water or processed kimberlite will be discharged to these pit lakes.

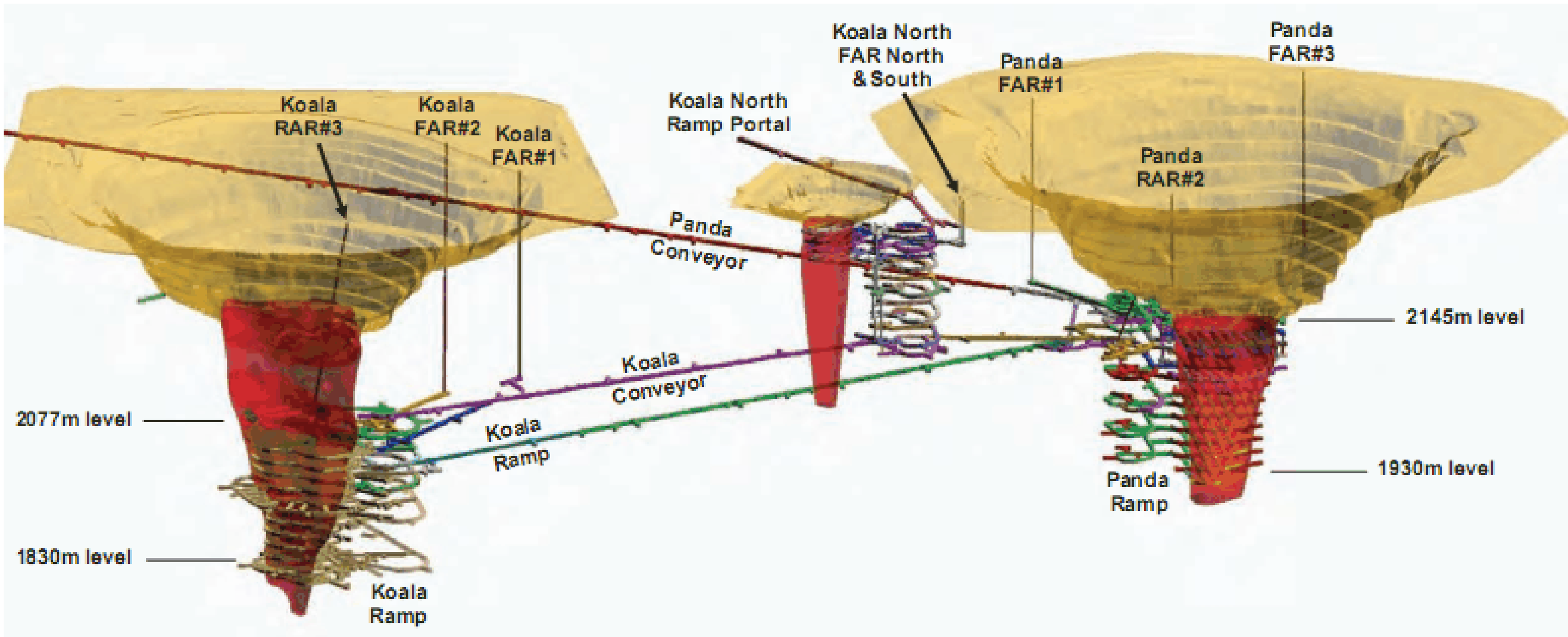
Fox pit lake is isolated from all other pit lakes during the infilling process.

Panda and Koala/Koala North pits are linked at depth through tunnels created to allow access to underground operations (Figure 2.4-1). The underground workings are linked by two tunnel systems; Koala Conveyor and Koala/Panda Ramp. A third tunnel, the Panda Conveyor, does not pass through the footprint of Koala/Koala North pits. The tunnels join the Panda underground at the 2,145 m level, near the top of the underground workings. The tunnels pass near the bottom of the Koala North underground workings and enter the Koala underground near the mid-depth of the workings, at the 2,077 m level.

The filling plan for Panda and Koala/Koala North pit lakes will have hydraulic connections between the pit lakes (EBA 2013). The tunnels linking the pits at depth are large (able to pass trucks) and would be able to pass the proposed pit infilling rates at low velocities. As a result, during infilling water levels in each pit lake would be expected to be similar, which would tend to promote a scenario whereby more dense saline water is retained at depth within underground workings or the bottom of the open pit, with less dense freshwater sitting above it. Maintaining the hydraulic connection between pits means that the maximum pit lake water elevation is determined by the pit with the lowest ground surface elevation. This specifically impacts Panda Pit (located upstream for Koala pit lake) where the final pit lake elevation will be 453.4 metres above mean sea level (masl), as compared to the pre-development lake elevation of 461 masl.

Koala North pit spill elevation is located below the final Koala pit lake elevation and therefore the flooding plan and this report treats the Koala/Koala North as a single pit lake with inflow received from Panda pit lake and outflow towards Kodiak Lake. The current operational plan for Beartooth pit is to fill the pit to within 30 m from the top of the planned pit lake with FPK solids. The remaining 30 m of the pit will have a water cover that will be a mixture of mine water (mixture of underground water and FPK supernatant water) and pumped fresh water. The spill level is estimated to be 457 masl with an operational freeboard of 2 m, bringing the maximum operating level to 455 masl (BHP Billiton 2011b).

Mining at Beartooth pit ceased in 2009 and the pit is currently being used as a store for mine water comprising water pumped from Panda, Koala/Koala North underground workings and fine processed kimberlite slurry. A limited volume of underground water was discharged into the pit in 2009 (18,280 m^3), with underground water discharged from December 2009 onwards. In 2010 approximately 420,000 m^3 of mine water was discharged into the pit and in 2011 the volume was around 540,000 m^3. A secondary stream of FPK discharges to Beartooth pit, commencing in 2012, to reduce the required storage of FPK in the LLCF, which has been the main storage area for FPK and mine water at the Ekati mine (BHP Billiton 2011b). Once water in Beartooth pit approaches 30 m from spill level, the plan is to decant excess water to the Process Plant for use as reclaim water.



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Profile Schematics of Panda and Koala/Koala North Pits and Underground Workings Showing Hydraulic Connections

Figure 2.4-1

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Once FPK solids reach a level 30 m below the full level of the pit (i.e., 427 masl), excess water above this target level will be pumped from the pit and either discharged to LLCF directly or used for reclaim water. FPK solids will be allowed to fill up to 30 m below the spill level. Prior to the end of mining operations the plan is to decant excess mine water in Beartooth pit lying above the FPK solids and to fill the space between the top of the FPK solids and the spill level of the pit with fresh water.

2.5 WATER QUALITY BENCHMARKS

Through a review of water quality guidelines in North America and of literature in the Ecotox database (http://cfpub.epa.gov/ecotox/) a set of Water Quality Benchmarks were developed as a screening tool for identifying the relevance of modelled water quality trends (Rescan 2012). Although these benchmarks were developed specifically for the renewal process for the site's W2009L2-0001 Water Licence, they are considered appropriate for application to receiving environments at the Ekati site during operations and closure.

The benchmarks are not meant to replace regulatory instruments that are in place for the site as part of on-going monitoring activities; rather, they were identified as benchmarks that are both ecologically relevant and scientifically defensible, and provide a reasonable estimate of a concentration above which risk of adverse effects may become elevated. As a result, the Water Quality Benchmarks are compared to model predictions in the surface layer of the pit lakes within this study.

The Water Quality Benchmarks are shown in Table 2.5-1.

Table 2.5-1. Summary of Water Quality Benchmark Values Used to Interpret Modelling Results

		W2009L2-0001	
Variable	**Water Quality Benchmark (mg/L)**	**LLCF and KPSF**	**Sable Area**
Chloride	116.6 × ln(hardness) - 204.1, to maximum hardness of 160 mg/L $CaCO_3$		
Sulphate	e (0.9116 × ln (hardness) + 1.712), to maximum hardness of 250 mg/L $CaCO_3$		
Total Dissolved Solids (TDS)	None proposed, but modelled due to importance for meromixis calculations		
Phosphate	Leslie Lake 0.0096 , Moose Lake 0.0077, Nema Lake 0.0091, Slipper Lake 0.01	0.2	
Nitrate-N	e (0.9518[ln(hardness)]-2.032, to maximum hardness of 160 mg/L $CaCO_3$		20
Nitrite-N	0.06		1
Ammonia-N	0.59[a]	2	4
Aluminium	0.1	1.0	1.0
Antimony	0.02		
Arsenic	0.005	0.5	0.05
Barium	1		
Boron	1.5		
Cadmium	10 (0.86[log10(hardness)]-3.2) /1,000		0.0015
Total Chromium			0.02
Chromium (III)	0.0089		

(continued)

Table 2.5-1. Summary of Water Quality Benchmark Values Used to Interpret Modelling Results (completed)

		W2009L2-0001	
Variable	**Water Quality Benchmark (mg/L)**	**LLCF and KPSF**	**Sable Area**
Chromium (VI)	0.001		
Copper	0.2 × e (0.8545[ln(hardness)]-1.465) /1,000, with minimum Benchmark of 0.002	0.1	0.02
Iron	0.3		
Lead	$e^{(1.273[\ln(\text{hardness})]-4.705)}$ /1,000		0.01
Manganese	(4.4 × hardness + 605) /1,000		
Molybdenum	19		
Nickel	$e^{0.76[\ln(\text{hardness})]+1.06}$ / 1,000, to maximum hardness of 350 mg/L $CaCO_3$	0.15	0.05
Potassium	41		
Selenium	0.001		
Strontium	6.242		
Uranium	0.015		
Vanadium	0.03		
Zinc	0.03		0.03

Notes:
W2009L2-0001 also includes Effluent Quality Criteria (EQCs) for TSS, total petroleum hydrocarbons (TPH), biological oxygen demand (BOD) and turbidity. These are not included in the table as they are not modelled.
[a] *Ammonia benchmark is based on total ammonia value equivalent to Canadian Council of Ministers of the Environment (CCME) guideline for unionized ammonia of 0.019 mg/L, at temperature = 15°C and pH = 8, which are upper (conservative) values for the Ekati site.*

The model simulates variations in un-speciated Chromium over time. A chromium speciation analysis was undertaken on three water quality samples from Cell E of the LLCF and three samples from Nero-Nema stream downstream of the LLCF, and reported in Rescan (2012). The results from Cell E of the LLCF are considered as being more representative of waters impacted by mining activities and as a result, modelled chromium concentrations are post-processed and converted into Chromium (III) and Chromium (VI) species in the proportions 23% Chromium (III) and 77% Chromium (VI). The post-processed values for Chromium (III) and Chromium (VI) can then be compared to the chromium benchmarks given in Table 2.5-1.

Many of the Water Quality Benchmarks are dependent on the hardness of water. In the report model predictions are compared to benchmarks calculated for a low hardness of 4 mg/L (or 15 mg/L for chloride due to restrictions with application of benchmark at low hardness values), which is a typical hardness for natural water in the Ekati area. This value was chosen to provide consistent benchmarks throughout the report to allow comparison of results from different pit lakes and as these benchmarks might be considered representative of natural receiving waters at in the Ekati area. Within pit lakes hardness may be higher than this and as a result, within the pits higher Water Quality Benchmarks would be warranted.

3. Physical Details of Pits and Pit Lakes

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3. Physical Details of Pits and Pit Lakes

The location of the open pits at the completion of mining are shown in Figure 3-1 and key physical data for each future pit lake are provided in Tables 3-1 and 3-2. The data is based on information provided in the ICRP. A discussion of the data sources is provided below.

Table 3-1. Key Physical Data for Each Open Pit and Connected Underground Mines

Open Pit	Max Expected Diameter (m)	Max Expected Depth (m)	Max Open Pit Surface Area (m^2)	Expected Final Volume Open Pit to Spill Point (m^3)	Estimated Area of Pit Walls above the Full Pit Lake (m^2)
Sable	600	234	400,000	33,750,000	5,700
Pigeon V17[a]	~500	179	159,000	6,500,000	9,000
Pigeon V20[a]	~500	179	243,000	6,500,000	9,000
Pigeon V26[a]	~500	179	200,000	6,500,000	9,000
Beartooth	420	200	157,000	13,400,000	3,600
Misery	620	275	500,000	26,000,000	12,600
Fox	900	310	575,000	70,300,000	6,900
Koala/Koala North					
Koala Open Pit	700	249	300,000	39,200,000	9,800
Koala Underground	-	630	-	5,300,000	
Koala North Open Pit	270	184[b]	50,000	1,450,000	2,000
Koala North Underground	-	270	-	650000	
Panda					
Open Pit	720	294	345,000	38,900,000	8,000
Underground	-	535	-	1,800,000	

Notes:
[a] *Mining at Pigeon is yet to commence. There are three potential pit layout as outlined in EBA (2010).*
[b] *The main cone of Koala North open pit is only 51 m deep. The remaining 132 m depth results from narrow, deep excavations at the bottom of the pit as shown in Figure 2.4-1*

3.1 PIT VOLUMES, SURFACE AREAS, AND PIT WALL AREAS AT CLOSURE

The pit lake design volumes at closure, shown in Table 3-1, for when pit operations are completed, are based on Geographic Information System (GIS) analysis of available pit survey information. These values are based on data from the current operational mine site layout. The final pit landscape at closure (e.g., including design of littoral zones) has not been finalized and as a result some values may change as closure plans are developed.

For pits that are in operation or have been mined (i.e., Beartooth, Misery, Fox, Panda, Koala/Koala North) there is detailed information on the actual pit geometries, including the relationship between pit volume, surface area and pit wall area with water depth within the infilling pit lake. The final “full” pit lake levels relate to the spill level at which each pit lake will overflow into the neighbouring pit, stream or lake. Spill levels for each pit lake are given in Table 3-2 and are based on EBA (2013).

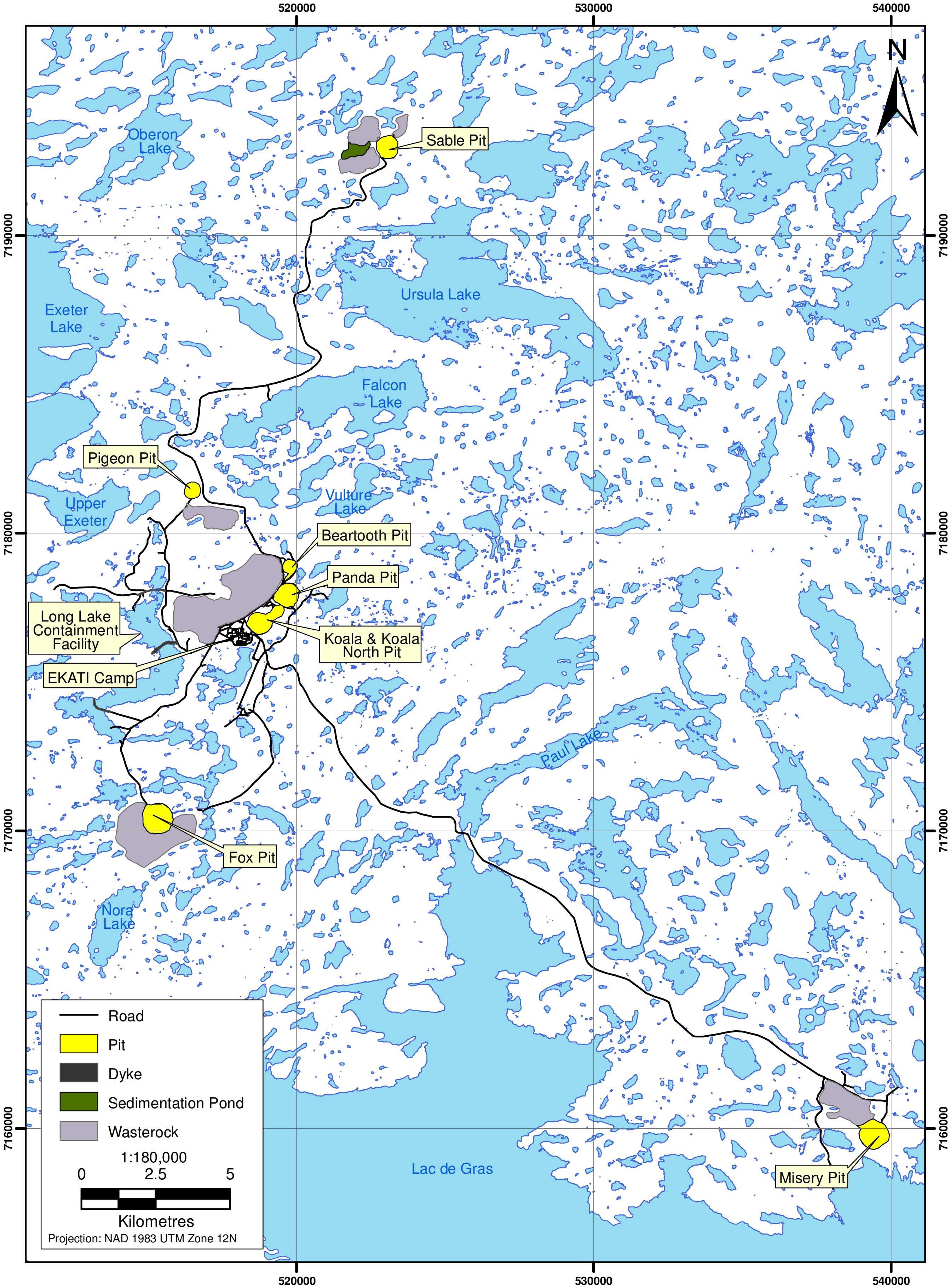

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Figure 3-1

Ekati Mine Layout at Completion

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Table 3-2. Hydrological Connections for Pit Lakes

Pit Lakes	Inflowing Watershed Area (km^2)		Inflowing Pit	Outflows to	Full Pit Lake Spill Elevation (masl)
	During Pit Infilling	Final post-closure			
Sable	0.6	0.6	None	Two Rock	505.0
Pigeon V17[a]	0.11[b]	0.11[b]	None	Fay lake	457.9
Beartooth	0.21[c]	1.87[c]	Bearclaw Lake	Upper Panda Lake	463.0
Misery	0.02[d]	0.02[d]	None	Lac de Gras	443.
Fox	2.28[e]	2.28[e]	None	1-Hump	450.7
Koala/Koala North					
Open Pit	0.62[f]	2.24[f,g]	Panda Pit	Kodiak Lake	453.4
Underground	-	-	-	-	-
Panda					
Open Pit	1.6[h]	1.6[h]	None	Koala/Koala North	453.4
Underground	-	-	-	-	-

Notes:
[a] *Mining at Pigeon is yet to commence. There are three potential pit designs as outlined in EBA (2010). The modelling work in this assessment is based on design V17.*
[b] *This value is for local watershed only. There is a watershed of approximately 10.3 km^2 lying upstream of Pigeon and approximately 50% of the runoff from this watershed could contribute to infilling. However, it will not contribute once the pit has been filled (EBA 2010).*
[c] *The local catchment is 0.21 km^2 only. However, there is a watershed of approximately 1.66 km^2 lying upstream of Beartooth, but this water is diverted from Bearclaw to Upper Panda. This diversion will continue during the infilling period, but the full upstream catchment should be available once the pit lake is filled.*
[d] *Values for Misery pit lake estimated from topographic data. WRSA in Misery area drains to King Pond and Desperation Pond at closure and not to pit lake.*
[e] *Fox catchment includes 2 km^2 of WRSA that lies to the south and south-west of the pit lake.*
[f] *Includes channel flow from Panda.*
[g] *Note that BHP Billiton (2011a) gives 0.85 and 3.1 km^2 for Koala and Koala North, respectively, while EBA (2006) give a local watershed area of 0.32 km^2 for each. The differing values reflect uncertainty as to where runoff from disturbed areas will flow post-closure.*
[h] *Panda catchment includes around 1.4 km^2 of WRSA lying to the west of the pit lake. It should be noted that the WRSA reporting to Panda pit is not well constrained and this catchment area should be considered as an estimate. No waste rock areas are assumed to drain to Koala/Koala North pit lake.*

Estimates of the pit water volume and surface area at closure for pits that have not yet gone into operation (i.e., Sable and Pigeon) are based on data provided by Dominion Diamonds Ekati Corporation (DDEC). The pit wall area for each of these pits is estimated, based on the mine design. Each pit is conical shaped, with the variation in pit volume, surface area and wall area varying with depth as predicted by standard geometrical equations for a cone. The pit wall angle used in the calculations was approximated based on average bench dimensions of 10 m wide and 20 m high, giving a wall angle of 63^o.

Relationships between pit depth, pit lake area and pit volume were developed based on available data and used within the balance models and multi-layer pit lake models.

The area of exposed pit wall will decrease over time as the pit lakes fill. Once the pit lakes are full to an elevation above the littoral shelf there will be some pit wall that remains exposed if the spill level of the pit lake is lower than the original pre-development ground surface. Once the pit lakes have filled, the exposed pit-wall areas are generally small compared to the natural watershed flowing into most of the pit lakes. For Sable, Beartooth, Fox, Panda and Koala/Koala North the pit walls contribute less than 1% of the total area flowing to the pit. However, for Pigeon (around 30%) and Misery (around 40%) the pit wall area is a significant percentage of the total watershed area flowing to the pit lake.

3.2 WATERSHED AREAS FLOWING TO PIT LAKES

Estimates of watersheds flowing into each pit lake at closure (Table 3-2) are based on available topographic information and an assessment of the future topography around each pit (e.g., location of WRSAs) at closure. Watershed areas were prepared using GIS data provided by Ekati personnel.

3.3 SOURCE LAKES

The current closure plan proposes that the rate of infilling of pit lakes will be accelerated through the pumping of fresh water from selected source lakes. Three lakes were identified in BHP Billiton (2011a) as potential source lakes to provide water for active pit filling. These lakes are Ursula Lake, Upper Exeter Lake and Lac de Gras. These are some of the largest lakes close to the Ekati mine and were identified as candidate source lakes so that pumping would have a limited effect on lake water levels and downstream flows. The aquatic effect on sourcing water from these lakes is the subject of a Reclamation Research plan (BHP Billiton 2011a).

The model assumes that water would be pumped from donor lakes during the open water season (June 1 to October 30), with no pumping under ice.

3.4 UPSTREAM AND DOWNSTREAM PIT LAKES AND/OR LAKES

The Ekati pit lakes will eventually fill and be hydrologically connected to their neighbouring pit lake or a downstream natural lake or water course (natural or man-made). Once filled, the pit lakes are expected to become part of the natural hydrological system of the area, with outflow volumes a result of natural processes such as precipitation, evaporation and run-in.

Some pit lakes will receive runoff from other upstream pit lakes and/or lakes (e.g., Panda from Beartooth, Koala/Koala North from Panda). A number of diversion channels were constructed during operations to divert water, which would have drained toward the operational pits, around the pits to a downstream water body (e.g., Panda Diversion Channel and Pigeon Stream Diversion). These channels will remain in place at closure to maintain fish habitat (BHP Billiton 2011a).

4. Model Set-up

4. Model Set-up

This chapter briefly describes the models used in the study (Section 4.1), describes the inflow volume and water quality data for both the filling and long-term evolution of the pit lakes (Sections 4.2 and 4.3), and summarizes the Base Case and scenarios considered for pit filling and long-term evolution of water quality in the surface layer of the pit lake (Section 4.4). A general conceptual model for the pit lake water balance is shown in Figure 4-1, illustrating the main inflows and outflows for a pit lake during the infilling process. A general conceptual water quality model is shown in Figure 4-2, indicating the main chemical loadings to the pit lakes during infilling. Figures 4-3 and 4-4 show the conceptual water balance and water quality model of a full pit lake.

4.1 MODEL SELECTION

As discussed in Chapter 2, three different models are used to arrive at a prediction of water quality. The first model gives the initial water quality of the filled pit lakes (Section 4.1.1). The second model describes the evolution of each pit lake after it fills (Section 4.1.2). The results from the second model are then used to evaluate the water quality of the long-term outflow from each pit lake (Section 4.1.3).

4.1.1 Load Balance Models for Pit Infilling

A load balance model is used to predict the water quality of the filled pit lakes. This model was developed using the GoldSim modelling suite, Version 10.11. GoldSim is an industry standard modelling package used for mass balance modelling of mine site water balances at many other mine sites worldwide. The model includes all key inputs to each pit lake and permits calculation of water quality within each pit lake. As outlined in Section 2.1 each pit lake was modelled as a fully mixed box during the pit infilling process. The results of the model are described in Section 7.1.

4.1.2 Multi-layer Models

Using the salinity of the filled pit lake from the first model, the second model calculates the evolution of the filled pit lake. There are a number of off-the-shelf mathematical models used to simulate lakes. However, none of these models have been developed or rigorously tested for northern pit lakes. In addition, these models do not simulate all of the key processes that would allow accurate prediction of water quality in pit lakes at the Ekati site. For example:

- DYRESM is a 1-D (vertical) hydrodynamic lake model. However, it does not contain a stable ice cover routine. In addition, questions have arisen about excessive mixing in DYRESM in cases of marginal stability similar to those that are anticipated in the proposed Ekati pit lakes (Nassar et al. 2007).
- CE-QUAL-W2 is a 2-D (vertical) model used to simulate lakes and reservoirs. Although CE-QUAL-W2 can model the formation of ice cover, it does not include salt exclusion, a process important to pit lake dynamics.
- ELCOM a 3-D hydrodynamic lake model simulates ice formation and ice exclusion, but it is computationally demanding and cannot be run in a reasonable time frame for the type of multi-year simulations required for this assessment.
- MIKE3, developed by the Danish Hydraulics Institute (DHI) is a 3D hydrodynamic and water quality model that is used throughout the world. However, this model does not include an ice formation routine suitable for use in this study.

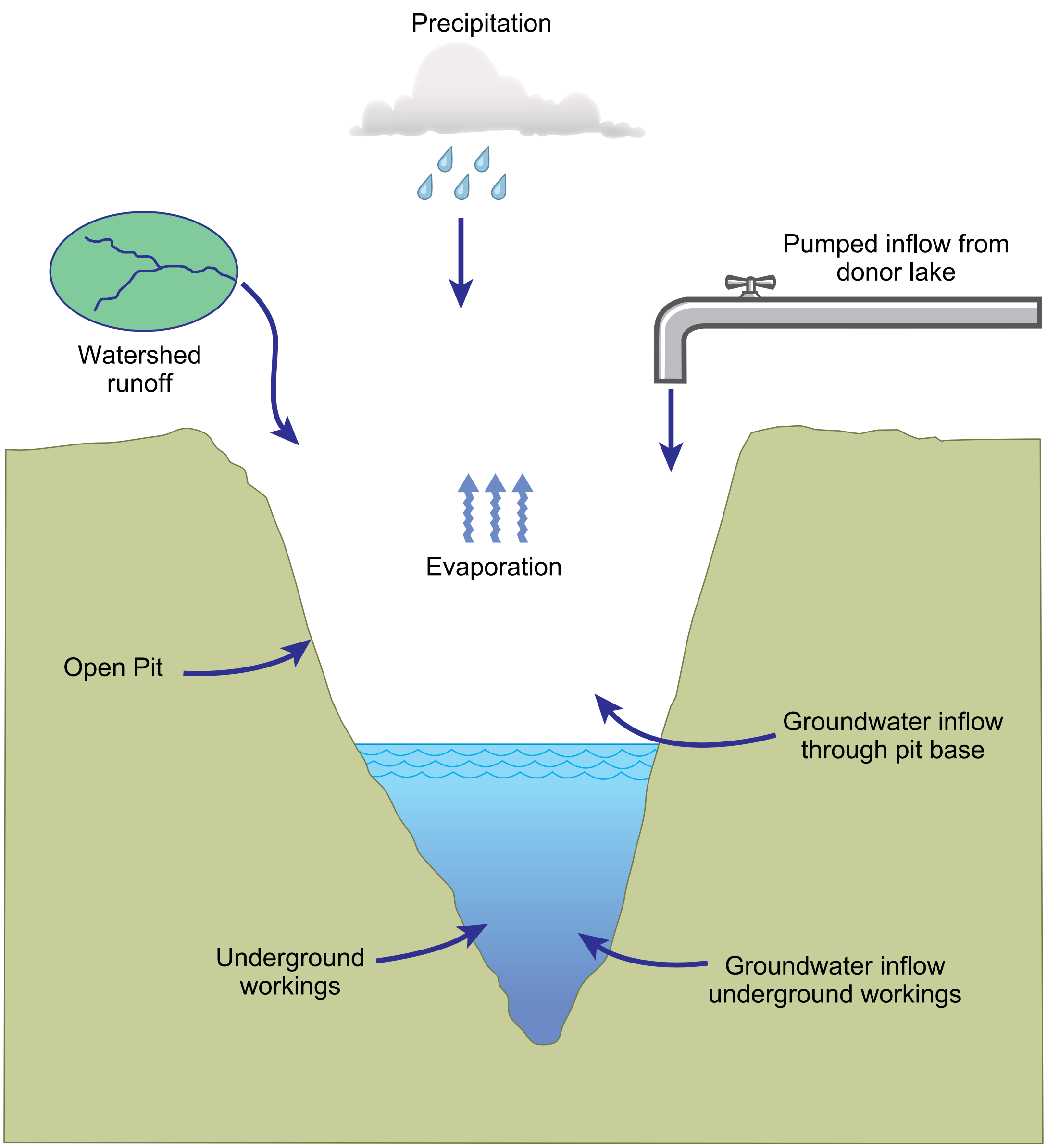

Figure 4-1

General Conceptual Model for Water Balance of Infilling Pit Lakes

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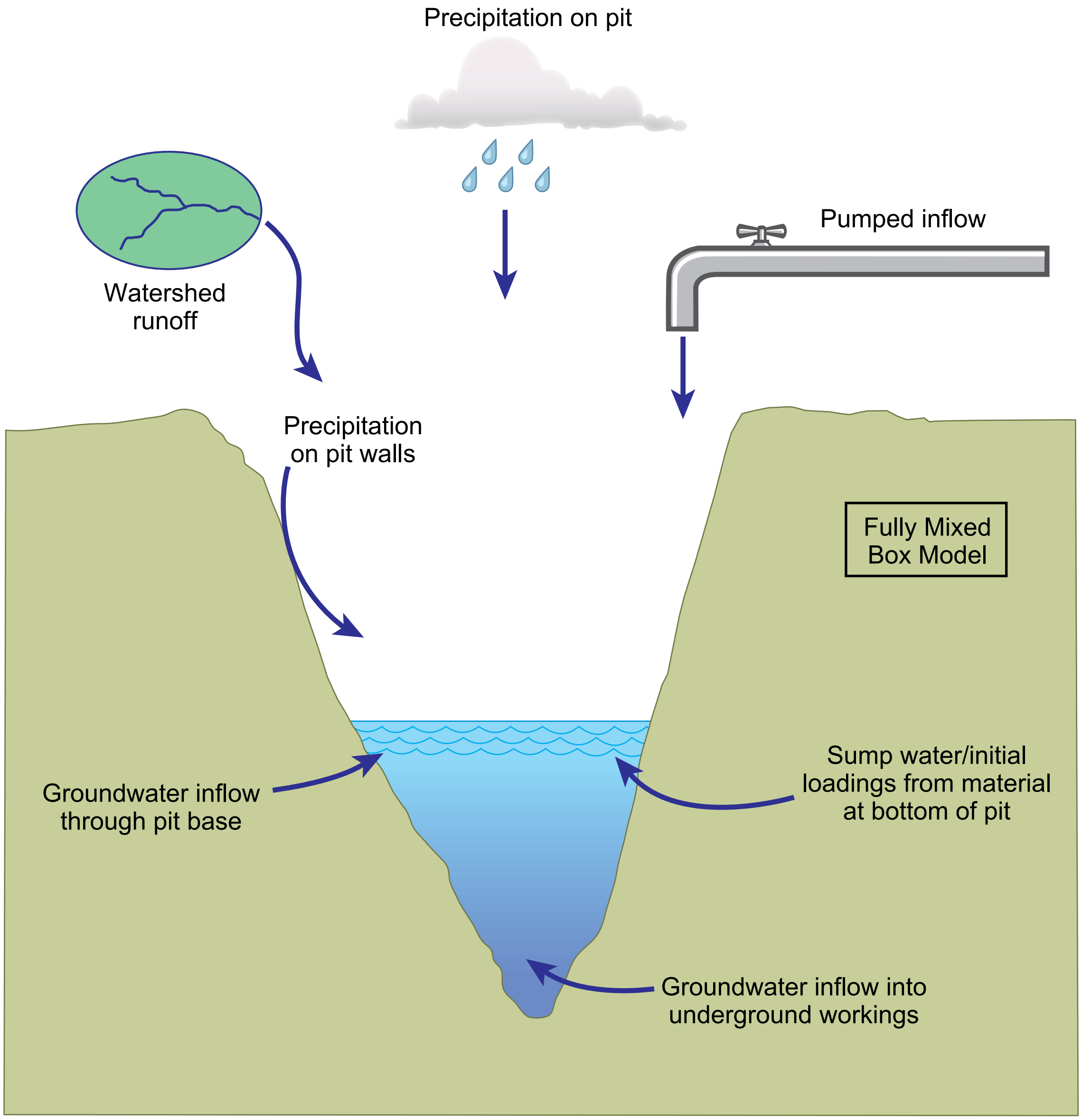

Figure 4-2

General Conceptual Model for Water Quality of Infilling Pit Lakes

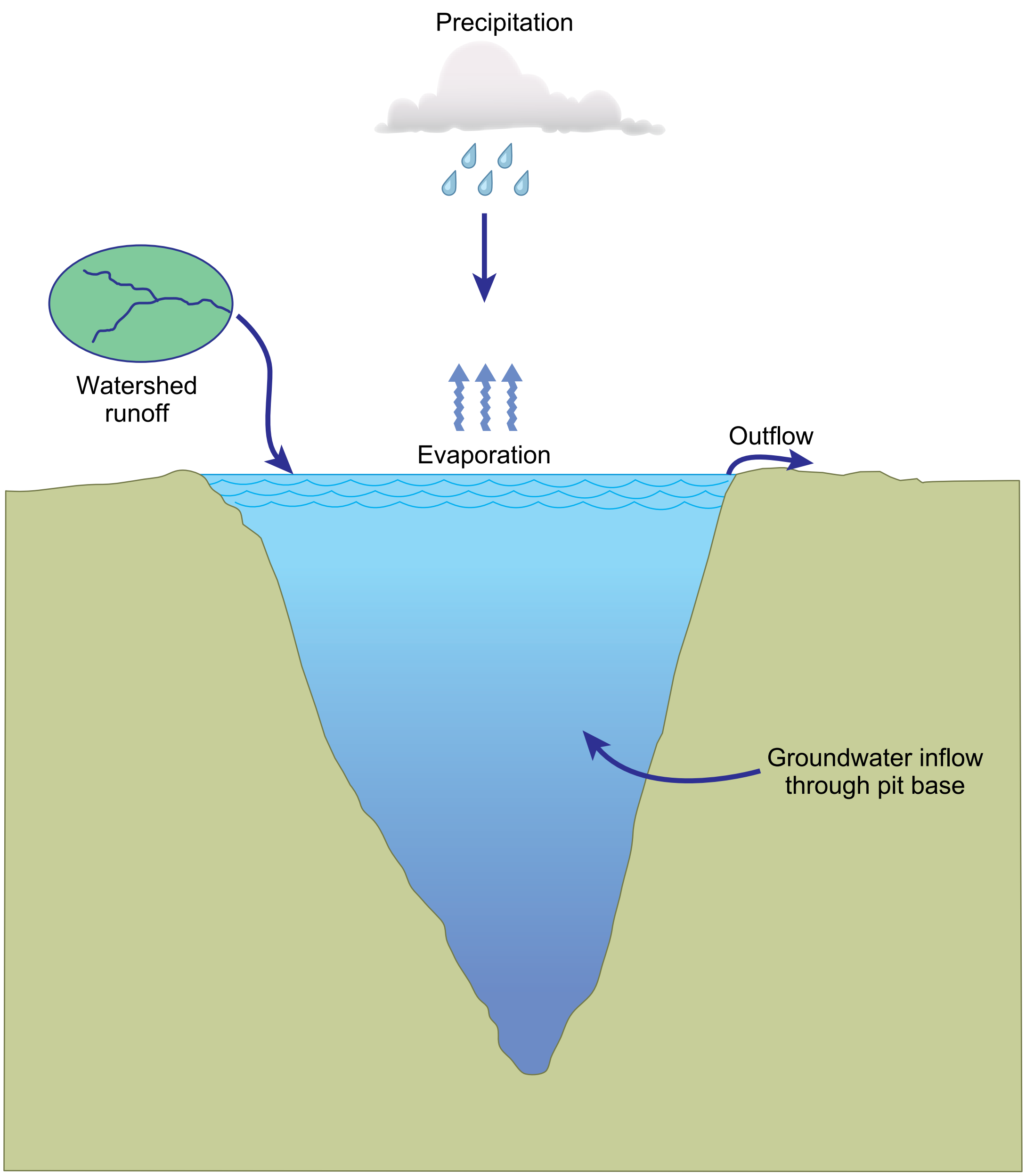

Figure 4-3

General Conceptual Model for Water Balance of Full Pit Lakes

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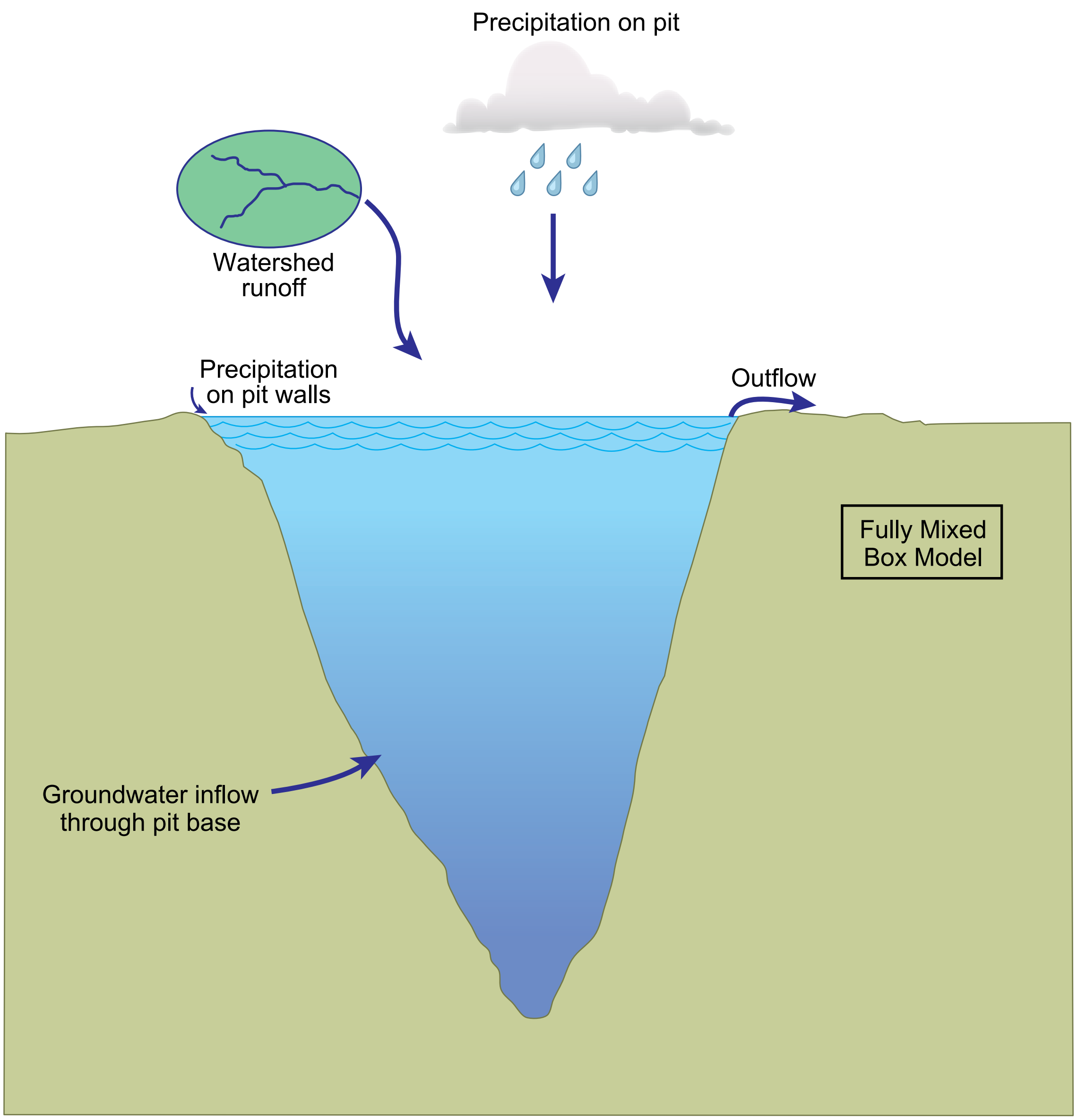

Figure 4-4

General Conceptual Model for Water Quality of Full Pit Lakes

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As a result, this assessment uses a multi-layer compartment model developed by University of British Columbia specifically for the modelling of pit lakes, and which was developed to address many of the current issues with available off-the-shelf lake models (Pieters and Lawrence 2009b). Compartment models do not try to resolve detailed processes such as advection and turbulent mixing within a lake. Rather than focus on all of the detailed physics, compartment models start with the relevant processes and build by calibration to observed data. In this way the models are guided by real observations and they are flexible so they can be run rapidly for a number of different model scenarios.

The multi-layer model uses a vertical stack of compartments (or layers) to track the salinity and tracers in the pit lake. Each compartment represents water over a different depth range, and the number of compartments varies in time to accommodate ice cover and changes in stratification.

The stability model simulates ice cover, salt exclusion, watershed and pit-wall runoff, mixing at ice-off, summer surface-layer deepening, and fall mixing. The model prescribes changes to the salinity stability in fall to predict the depth of mixing. The results of this model are described in Chapter 6.

4.1.3 Dilution Calculations

Once the pit lakes have been filled, they will continue to receive rainfall and watershed runoff and will lose water from the pit lake surface through evaporation. The overall water balance for the pit lakes will be positive in most years and excess water will overflow from the lakes at a spill point and enter the water body (adjacent pit lake, stream or natural lake) lying downstream of each pit lake. Over the long term, the pit lakes will become part of the natural hydrological system in the Ekati area.

Within the layered model the water quality in the surface layer is represented by conservative tracers and the model accounts for the change in concentration of the tracers, considering inputs from natural runoff, groundwater and pit wall runoff. The final model uses the results of the multi-layer model to predict the water quality of the pit lakes.

The predicted tracer concentrations are used to calculate dilution factors, which were then applied to all water quality variables producing long-term predictions of concentrations of all key variables in waters discharged from the pit lakes. This approach was taken as it utilised the ability of the layered model to represent the mixing processes in the surface layer of each pit lake, while allowing predictions to be extended to a full range of water quality variables. The results of this model are described in Section 7.2.

4.2 WATER BALANCE INPUTS

4.2.1 Surface Hydrological Inputs

<u>Available Data</u>

A continuous series of meteorological and hydrological data for the Ekati site are available since 1994 (i.e., precipitation, temperature, evaporation and stream flows). Precipitation and evaporation records are available for the Koala Meteorological Station located near the main Ekati site. Stream flow gauges are operated on eight streams and lake outflow channels across the Ekati site. Data are reported annually as part of the AEMP or form part of original datasets collected during baseline studies prior to the beginning of mining at the site.

There are a limited number of Environment Canada (meteorology) and Water Survey of Canada (stream flow) monitoring stations in northern Canada. Hence, the Ekati dataset is one of the best available for small northern catchments as it provides a reasonably long period of record and flow measurements focussed on small catchments of the type that drain to open pits. Hence, although there is a degree of uncertainty associated with estimation of surface water runoff from watersheds in the Ekati area, the methods used in this assessment are considered as being reasonably robust and based on good quality field data.

Periodically, detailed analyses of the available meteorological and hydrological data are undertaken for the Ekati site with the purpose of developing site specific averages and return period estimates for key meteorological and hydrological variables. The latest update was undertaken using data up to and including 2009 and these values are used in this assessment (see Rescan 2012 for more details). Return period precipitation estimates for the Ekati site are summarised in Table 4.2-1.

Table 4.2-1. Ekati Return Period Precipitation Estimates

Return Period	[a]Annual Precipitation (mm)
1 in 100 dry year	234
1 in 50 dry year	242
1 in 20 dry year	256
1 in 10 dry year	270
Average year	338
1 in 10 wet year	451
1 in 20 wet year	495
1 in 50 wet year	554
1 in 100 wet year	598

[a] *Return period analysis was undertaken based on on-site Koala Meteorological Station data supplemented by Environment Canada Lupin data. For the period 1994 to 2009 data from Koala Meteorological Station was used. For the period 1982 to 1994 Lupin data was used scaled by the average ratio of Koala and Lupin annual precipitation totals for the period of overlapping data (1994 to 2005). This gives a combined dataset of 28 years.*

Estimation of Runoff Rates from Natural Watersheds

Annual flow rates for watersheds within the study area are calculated using the equation:

$$\textit{Total Annual Flow } (m^3/year) =$$
$$\textit{Total Annual Precipitation } (m/year) \times \textit{Runoff Coefficient} \times \textit{Watershed Area } (m^2)$$

This equation is applicable for all types of watershed (e.g., natural, disturbed by mining activities, pit walls) with the value of the runoff coefficient varying for each watershed type, as per Table 4.2-2.

Table 4.2-2. Runoff Coefficients for Different Watersheds/Source Areas

Input	Runoff Coefficient	Comment
Natural catchments	0.5	Value based on average of all observed stream flow data.
Disturbed catchments	0.5	Insufficient data to allow different value for disturbed versus natural watersheds.
Runoff on pit walls	0.85	Tested/calibrated against observed sump flow data (Appendix 1).
WRSA	0.2	Tested/calibrated against observed runoff rates from Misery WRSA (BHP Billiton 2011a).
Precipitation on lake surface	1	Losses from lakes due to evaporation are accounted separately.

The average runoff coefficient for catchments in the Ekati area based on all flow records is 0.5; however, from year to year and gauge to gauge runoff coefficient values can range from 0.17 to 0.87. The available flow records were analysed to assess whether there were relationships between runoff coefficient and precipitation total (e.g., higher runoff coefficients could be associated with wet years and lower values for dry years), watershed area and/or annual snowfall. However, it was not possible to determine any clear relationships using the available data at the Ekati site. The lack of any relationships of this form may be due to a lack of data, but it may also indicate that such simple relationships do not exist due to the complexity in runoff generating processes in northern Canada. As a result, constant runoff coefficients are used within pit lakes models for all years.

The natural watershed areas flowing to each pit lake are summarized in Table 3-2.

The runoff coefficient for runoff from pit walls was calibrated against observed pit sump data in Appendix 1. The calibrated runoff coefficient for pit wall runoff was estimated as 0.85.

The model predicts the change in exposed pit wall area over time as it fills. Pit wall areas are calculated as the difference between the total pit area (Table 3-1) and the pit lake area. Over time the pit wall area will become steadily smaller as the pit lake expands and submerges the pit walls. Once the pit lakes are full there will still be relatively small pit wall areas exposed around the pit lake surface, Table 3-1. These pit wall areas will have a negligible impact on the pit lake water balance, but they may impact water quality within the pit lakes.

Many pits at the Ekati mine either do not have a WRSA lying adjacent to the pit or have a WRSA that does not drain directly to the pit (e.g., Misery WRSA lies adjacent to Misery pit but runoff from the WRSA drains to Desperation Pond and Waste Rock Dump Dam and not to the pit). However, at closure runoff from WRSA adjacent to Panda and Koala/Koala North and Fox pits may enter the pits. At Fox the WRSA was designed to flow to the pit lake at closure. However, at the Panda and Koala/Koala North WRSAs, the runoff from the waste rock that will report to the pit lake at closure is not well defined. An estimate of catchment area for each pit lake has been made based on pre-development topography and information provided in Table 3-2.

The closure method for the WRSAs is described in the 2011 ICRP. The core of the WRSA will freeze and only the upper few metres are expected to be hydrologically active. During operation runoff rates from WRSAs are low. BHP Billiton (2011a) estimates runoff coefficients for WRSAs to be of the order of 0.05 to 0.3 (i.e., only 5 – 30%) of precipitation is converted to runoff. Based on data from the Misery WRSA the best estimated runoff coefficient was considered to be around 0.2. This value is used to estimate runoff from WRSAs reporting to Panda, Koala/Koala North and Fox pit lakes.

The water balance model was run assuming average annual precipitation in every year. This assumption was made so the water balance was consistent with the assumptions used in the calculations of pit wall runoff chemistry completed by SRK Consulting for this study (see Section 4.3.3). The concentrations and loadings predicted by their geochemical analyses could not be easily scaled for other annual precipitation totals. However, an assessment of the effect of changing the annual precipitation total on the pit water balances was undertaken (Chapter 5) and the results indicated that the main inflow volume to all the pit lakes was likely to be water pumped from source lakes, such that the assumption of average annual precipitation in every year was unlikely to have an important effect on the modelled long-term results.

The pit lakes load balance models run on a monthly time step with monthly inflows modelled as:

Average Monthly Inflow (m^3/mon) = Total Annual Flow Volume (m^3) × Percentage of Annual Flow Occurring in Month (/mon)

The monthly distribution of the annual totals is provided in Table 4.2-3.

Table 4.2-3. Estimates of Ekati Monthly Precipitation, Runoff and Evaporation

Variable	Percentage by Month (%)						Total
	May	Jun	Jul	Aug	Sep	Oct	
Effective Precipitation[a]	5	55	9	21	6	4	100
Runoff[b]	7	53	23	8	8	1	100
Evaporation[c]	0	40	30	22	7	1	100

[a] *Based on Ekati data from 2004 to 2009, assuming that precipitation in winter is retained as snow and melts during freshet.*
[b] *Based on Ekati stream flow data from 1994 to 2009.*
[c] *Based on observed Ekati data from 2004 to 2007.*

<u>Estimation of Precipitation and Evaporation for Pit Lake Surfaces</u>

Annual net inflows due to precipitation on, and evaporation from, the surface of a pit lake are based on:

Annual Net Flow to Lake Surface (m^3/year) =
(Total Annual Precipitation (m/year) – Total Annual Evaporation (m/year)) × Lake Area (m^2)

Return period annual precipitation totals are provided in Table 4.2-1. However, the water balance model was run considering average evaporation and precipitation in every year for reasons outlined in the previous section.

The model predicts the change in pit lake area over time as it fills, based on relationships relating lake area with pit lake volume. Over time the pit lake area will increase as the pit fills and submerges the pit walls.

The pit lakes load balance models run on a monthly time step with monthly precipitation and evaporation totals modelled as:

Average Monthly Inflow/Outflow (m^3/mon) = ((Total Annual Precipitation (m) × Percentage of Effective Precipitation Occurring in Month (/mon)) – (Total Annual Evaporation (m) × Percentage Evaporation Occurring in Month (/mon)) × Lake Area (m^2)

The monthly distribution of the annual totals is provided in Table 4.2-3. It should be noted that an “effective” precipitation monthly distribution is defined in Table 4.2-3. These percentages reflect the impact of snowmelt and rainfall on the lake surface. All precipitation falling in the winter months is assumed to be snow, and that this snow melts during May and June. Hence, in Table 4.2-3 the winter monthly percentages equal zero (i.e., precipitation is stored as snow) and the high monthly percentages in May and June reflect snowmelt.

4.2.2 Groundwater

Most of the Ekati site is underlain by permafrost, which can extend to around 300 to 500 m depth. Typically pits that do not extend below the permafrost zone experience no groundwater inflows. As a result, there are no groundwater inflows to Misery, Beartooth and Pigeon open pits. However, some of the open pits extend to a depth that groundwater inflows can occur. Underground workings extend below the permafrost and receive groundwater inflows that are pumped to the surface.

Based on observations and previous studies (e.g., EBA 2006) it is assumed that Panda, Koala/Koala North and Fox Pits and/or their underground workings can be affected by groundwater inflows. Groundwater inflows for all other pits are assumed to be zero.

Observed annual totals of water pumped from underground workings are outlined in Table 4.2-4 with annual totals converted into instantaneous flow rates (L/s). From 2004 to 2012 annual average flow rates from underground have ranged between 9.6 L/s to 17.8 L/s, with an average of 13.7 L/s over these years.

Table 4.2-4. Annual Totals of Water Discharged from Underground

Year	Underground Water (m^3)	Underground Water (L/s)
1999	0	0
2000	0	0
2001	0	0
2002	0	0
2003	54,631	[a]-
2004	302,045	9.6
2005	438,015	13.9
2006	535,001	17.0
2007	325,598	10.3
2008	503,067	16.0
2009	352,772	11.2
2010	401,611	12.7
2011	562,411	17.8
2012	456,823	14.4
Average	[b]**430,816**	[b]**13.7**

[a] *Not complete year of data.*
[b] *Average of years 2004 to 2012.*

There is a high degree of uncertainty associated with the estimation of future groundwater inflow rates to the pits.

EBA (2006) undertook modelling work based on data from Klohn Crippen (2001) and calculated the following peak groundwater inflow rates:

- Panda, inflow to underground = 14 L/s and through the pit base = 7.5 L/s;
- Koala North, inflow of 4 L/s;
- Koala, inflows assumed the same as Panda (i.e., inflow to underground = 14 L/s; through the pit base = 7.5 L/s) although Klohn Crippen updated their estimate of groundwater flow into Koala to 20 L/s in 2005 (reported in Rescan 2006a); and
- Fox, inflow only through base of the pit = 7.5 L/s.

The EBA (2006) estimates give a total inflow rate of 32 L/s for Panda and Koala/Koala North, which is over 300% higher than the present day observed flow rate. Based on EBA (2006) the annual volume of underground water from Panda and Koala/Koala North would be around 1.4 Mm^3/year, compared to an observed average of around 0.43 Mm^3/year. The EBA (2006) values are upper estimates of underground flow rates once the pits are at full development and the Base Case model scenario in this report are based on the EBA (2006) values for underground inflows to the pit lakes during the pit infilling period. However, sensitivity runs are considered for lower underground flow rates, including runs based on current observed data.

At the time of this report, the base of Fox pit has not extended below the permafrost layer, so there are no observed measurements of groundwater inflow into this pit. However, once fully developed the base of the pit will pass through the permafrost. The Base Case model run for Fox pit uses the EBA (2006) estimate of groundwater inflows. However, given that EBA (2006) estimates for Panda and Koala/North pits appear high compared to observed data, a similar pattern would be expected for Fox pit. Hence, the groundwater inflows to Fox pit used in the Base Case model run should be considered conservative (high).

A key issue related to groundwater is how the flow rates will vary over time as the pit lakes fill, with the outcome depending on the pit lake level relative to the regional groundwater head. There are no published direct measurements of the regional groundwater head at the Ekati site, nor regional groundwater modeling results. This is not unexpected for sites in the Arctic where obtaining head information from deep boreholes is very difficult. In the absence of other data the water levels in larger natural lakes are often considered to be representative of the regional groundwater head. Such large lakes are assumed to be connected to the deep groundwater system through “talik” zones or windows in the permafrost under the lakes. It is not clear from surface observations as to which lakes in the Ekati area have a talik zone at depth. Clearly the largest lakes such as Lac de Gras would be expected to have some connection to groundwater; however, smaller lakes (e.g., Upper Exeter or the old lakes under Panda and Koala/Koala North pits) may also have a sufficiently deep talik zone. Hence, this provides us with a range of possibilities for the variation in groundwater flow rate over time:

1. Once full, the pit lakes are be expected to have a water elevation greater than Lac de Gras (approximately at 420 masl) and Upper Exeter (approximately at 440 masl). If these two lakes are taken as being representative of the regional groundwater system, then as each pit infills the groundwater inflow rate would tend to zero and the pit lake could become a net source of water to the groundwater system.
2. If local lake levels close to each pit lake are representative of the regional groundwater system then when the pit lakes are full there would likely be a zero net flux between the pit lake and the underground system.
3. If the regional groundwater head was greater than the full pit lake levels, there would be a net flux from the deep groundwater to the pit lakes even once the pit lakes had filled, with consequences for the long-term salinization of pit lake water.

It is unclear which of the above input options is the most realistic, although given the relative elevations of the full pit lakes and water levels in large lakes close to the site one would expect options 1 or 2 to be more likely. However, option 3 is likely to produce the most significant conditions in terms of the producing meromixis within pit lakes and for increasing TDS loads to the pit lakes given that groundwater has higher concentrations of many water quality variables (including TDS) compared to natural lake water in the Ekati area. Under input option 3 there will be highest groundwater inflow rates, with groundwater inflows continuing through the closure period.

For the purpose of this assessment, the Base Case model run assumes that groundwater inflows tend to zero once the pit fills (input option 2). As the pit fills the groundwater flow rate decreases linearly with the increase in depth within the pit lake. For example, when the pit lake or underground workings are empty of water the groundwater flow rate will be the full rate, as shown above. The inflow rate will decrease as the pit lake fills, reaching zero once the pit lake is full. In the model sensitivity analysis a simulation is run which considers option 3 above, where groundwater flow rates decrease linearly with increasing depth in the pit lake to a minimum flow rate of 5% of the initial flow rate for an empty pit lake. A further sensitivity run is undertaken considering lower groundwater inflow rates based on observed data and assuming flow rates tend to zero as the pit lake fills.

No model runs were undertaken assuming a flux from the pit lakes to the underground. More detailed information on flow rates and the local groundwater system would be required before such predictions could be made.

4.2.3 Pumped Inflows

Given the relatively low annual precipitation rates at the Ekati site (338 mm/year) and the large volume of the open pits, it would require tens to hundreds of years to fill the open pits at the site if precipitation and natural runoff were the only sources of water used to fill the pit lakes. Hence, the ICRP describes pit infilling using pumping from source lakes to accelerate the infilling process (BHP Billiton 2011a).

The Base Case considered in this report is that water will be pumped from selected source lakes to actively fill the pit lakes. The physical data for the source lakes are provided in Table 4.2-5. Pumping from the source lakes is planned to occur during the open water season only from June to October every year. There is no pumping during the winter months. An average pumping rate of 0.4 m^3/s is considered in this report for all pit lakes except from Sable, where a lower rate is considered (0.2 m^3/s). These values are based on the ICRP and should be considered indicative only as they are based on initial estimates (BHP Billiton 2011a). Predictions of rates of pit infilling are being developed by others working on the engineering aspects of pit infilling and the potential effects of pumping water from the source lakes will be quantified elsewhere as part of a reclamation research study.

Table 4.2-5. Physical Data for Potential Source Lakes

Source Lake	Drainage Area (km^2)	Lake Water Area (km^2)	Estimated Volume (m^3)	Target Pit
Lac de Gras	4,000	572	6.7×10^9	Beartooth, Panda, Koala/Koala North, Fox, Misery
Ursula Lake	95	22.5	n/a	Sable
Upper Exeter Lake	230	12.8	n/a	Pigeon and possibly Beartooth

[a] *From EBA (2006).*

4.2.4 Outflows from Pit Lakes

Once the pit lakes are filled they will overspill into a neighbouring watercourse or downstream pit as indicated in Table 3-2. The plan is for the pits to become hydrologically linked components within the natural watersheds.

The model used in this study accounts for overflows from the full pit lakes to downstream water bodies; however, the model does not predict impact on the quantity or quality of water within these downstream water bodies.

4.2.5 Ice

Lake ice in the Ekati area can thicken to 2 m by the middle of winter. For small water bodies, the volume of water held as ice in winter can be a significant proportion of the total lake water volume. Ice formation and melting has a limited net impact on the annual lake water balance, as water frozen during winter months is returned to the lake in spring. However, ice is nearly pure water, with chemical constituents in the lake water excluded from the ice and left in the un-frozen lake water below the ice. This can have an important concentrating effect on water quality variables in lake water during winter months as the volume of free water decreases, but the total mass of chemical constituents in the water remains the same; this results in increased concentrations in the water below the ice and decreased concentrations in the ice melt.

The rate of ice formation in the LLCF and downstream lakes is based on field measurements taken during winter water quality sampling during two winters in the LLCF. Table 4.2-6 shows how the depths of ice vary linearly over time.

Table 4.2-6. Ice Thickness Values Used in Model, Based on Measurements at the LLCF from Winters 2005/2006 and 2006/2007

Date	Ice Thickness (m)
September 15	0
October 15	0.25
December 15	1.25
January 15	1.7
April 15	1.7
May 15	1
June 1	0

The impact of ice formation and ice melt is included in the multi-layered model. The model uses October 15 as the date of ice-on and June 1 for ice-off. It should be noted that the results of the model are not sensitive to these dates. The model assumes that 80% of the ice thickness is comprised of black (transparent) ice with the rest being white (snow) ice or slush with high pit lake water content (Pieters and Lawrence 2009a). The model assumes that 90% of the solute content of dense black ice is excluded from the ice during ice growth. Taking into account these factors, the ice creates a fresh water layer that is equivalent to 1.4 m of pure black ice. It should be noted that melting of snow accumulated on the ice will also contribute to the fresh water cap; in the model snow is accounted for in calculations related to precipitation.

4.2.6 Climate Change

The model does not consider the effects of global climate change on climatic variables. Climatic variables such as precipitation and evaporation used in the model are based on average values calculated from historical data and assumed to be representative of present day and future conditions within the time periods modelled.

4.3 WATER QUALITY INPUTS

The key sources of water quality loadings to the pit lakes model are:

- natural water inflows (watershed runoff and precipitation on pit lake surface);
- pumped inflows;

- loadings from loose material lying on base of pit;
- runoff from exposed pit walls, including flow through broken rock on pit wall benches;
- groundwater flows;
- residual mine related chemicals (e.g., Ammonium Nitrate/Fuel Oil [ANFO]); and
- other loadings (e.g., runoff from waste rock piles).

This section also considers pH and TSS within the pit lakes and discusses the modelling approach to chemical reactions and decay.

4.3.1 Natural Water Inflows

Natural water inflows include runoff from watersheds adjacent to the pit lakes (termed natural runoff) and precipitation landing on the pit lake surface.

The chemistry of natural runoff is based on data obtained from the Ekati AEMP for Vulture Lake outflow channel (Vulture-Polar Stream). Vulture Lake is considered to be a reference lake outside of the influence of the LLCF. The water quality for Vulture-Polar is shown in Table 4.3-1.

Natural water in the Ekati area is near pristine with very low concentrations of all water quality variables. No additional loadings are considered for runoff over disturbed catchments adjacent to the open pits. Most of the pit catchments are un-disturbed, with disturbed areas limited to areas close to the pit rim. There is insufficient data on the impact of disturbed land on runoff quality; however, as surface water runoff is a minor contributor during the infilling process compared to pumped inflows from natural lakes any uncertainties introduced by not explicitly considering disturbed areas will be very minor.

Precipitation falling on the pit lake surfaces is assumed to be pure with zero loadings of all water quality variables.

4.3.2 Pumped Inflows

In order to speed up the process of pit lake infilling, water will be pumped from natural source lakes and/or the LLCF into the pit lakes (BHP Billiton 2011a).

The quality of pumped water from natural source lakes is modelled as being equivalent to the quality of Vulture Lake, which is sampled as part of the AEMP. Vulture is considered to be a reference lake outside of the influence of the LLCF. Water quality values for Vulture Lake are provided in Table 4.3-1.

4.3.3 Initial Loadings due to Loose Material Lying on Base of Pit

Fox, Misery, Pigeon and Sable pits are open pits with no underground workings and are not planned to be filled with FPK or mine water at closure. They will have some loose waste material piled at the bottom of the pit and some pit sump water will likely accumulate prior to active infilling. In addition, when the first water enters the pit during filling, it is likely that there will be a release of loadings from the loose material into solution, with fine-grained sediment becoming suspended within the water. In the early months of pit infilling the pit water may be murky with high suspended sediment loads. Over time, with the addition of fresh water with very low natural suspended solids and settling of solids as the pit lake gets deeper, the amount of suspended material within the pit lake is expected to decrease. However, as a result of the disturbance of sediment and the dissolution and mixing with sump water at the bottom of the pit, the dissolved load in the earliest phase of infilling is expected to be greater than predicted from natural runoff alone.

Table 4.3-1. Natural Water Quality, LLCF Water Quality, and Sump Water Quality Inputs

Variable	[a]Vulture Lake	[a]Vulture/Polar Stream	[b]LLCF End of Operations	[b]LLCF 30 Years after End of Operations	Sump [c]Sable	Sump [d]Pigeon	Sump [e]Misery	Sump [f]Fox
Ammonia - N	0.0025	0.0070	0.019	0.0075	2.1	8.9	5.8	2.1
Chloride	0.25	0.25	200	12	22	10	10	22
Nitrate - N	0.0030	0.0030	5.1	1.5	18	29	23	18
Nitrite – N	0.00050	0.00075	0.013	0.0029	0.86	0.88	0.88	0.86
Phosphate	0.0025	0.0056	0.0027	0.0024	0.029	0.046	0.046	0.029
Sulphate	1.2	1.2	76	19	230	60	160	230
TDS	6.6	8.0	480	120	1200	530	530	1200
Aluminum	0.0078	0.039	0.065	0.042	0.020	0.0093	0.010	0.020
Antimony	0.000050	0.000050	0.0033	0.0012	0.0011	0.0023	0.0023	0.0011
Arsenic	0.00012	0.00019	0.0020	0.00065	0.0059	0.0016	0.0033	0.0059
Barium	0.0022	0.0034	0.037	0.017	0.053	0.073	0.073	0.053
Boron	0.00062	0.0010	0.0047	0.0077	0.098	0.048	0.048	0.098
Cadmium	0.000025	0.000025	0.00016	0.000057	0.00012	0.00026	0.00026	0.00012
Chromium	0.000070	0.00024	0.00071	0.00034	0.0012	0.028	0.00050	0.0012
Copper	0.00030	0.0010	0.0011	0.0011	0.0019	0.00066	0.0042	0.0019
Iron	0.0050	0.10	0.043	0.017	0.015	0.042	0.042	0.015
Lead	0.000025	0.000025	0.000072	0.000036	0.00012	0.95	0.000050	0.00012
Manganese	0.0018	0.0041	0.012	0.0076	0.026	0.21	0.21	0.026
Molybdenum	0.000030	0.000030	0.090	0.020	0.32	0.13	0.12	0.32
Nickel	0.00032	0.00068	0.0041	0.0024	0.016	3.5	0.047	0.016
Potassium	0.44	0.48	23	5.6	58	14	14	58
Selenium	0.000050	0.000050	0.00058	0.00020	0.0034	0.0044	0.0044	0.0034
Strontium	0.0048	0.0054	1.2	0.13	0.92	0.49	0.49	0.92
Uranium	0.000020	0.000040	0.00048	0.000064	0.014	0.0019	0.0019	0.014
Vanadium	0.000025	0.00011	0.0035	0.00082	0.0087	0.00080	0.00080	0.0087
Zinc	0.00050	0.0010	0.0018	0.0021	0.0025	0.050	0.0030	0.0025

Notes: Shaded values are higher than Water Quality Benchmarks. For Vulture Lake, Vulture/Polar Stream and Sump data, Water Quality Benchmarks are based on hardness of 4 mg/L for all varibales except chloride (where hardness is 25 mg/L), as outlined in Section 2.5. For LLCF Water Quality Benchmarks are based on hardness values predicted for LLCF in Rescan (2012).

[a] *Median concentration of data 2004 to 2010.*

[b] *Based on average concentrations within model predictions for selected years of operations in Rescan (2012).*

[c] *Sable based on Fox pit sump data due to similarity in Fox and Sable pit wall rock types.*

[d] *Pigeon based on predicted Pigeon pit sump predictions for selected variables (Al, As, Cr, Cu, Pb, Mo, Ni, Zn, NH_4, NO_4, SO_4). For other variables values set equal to Misery pit sump data as rock in Misery pit walls is closest to rock types in Pigeon pit walls.*

[e] *Misery based on Median concentrations of sump data from 2000 to 2005, when Misery was in operations.*

[f] *Fox based on Median concentrations of data from 2003 to 2010.*

Data from Misery Pit allow an assessment of the water quality within a pit lake during the early months of natural pit infilling. In the summer of 2005, the Misery Pit was temporarily closed and water was allowed to build up naturally at the bottom of the pit, due to precipitation landing on the pit surface. This “mini pit lake" was allowed to develop until mid-September 2006 when the pit lake was pumped out and the water sent to the King Pond Settling Facility. At the time the pit lake was drained it had reached 10 m depth with a volume of 58,800 m^3, approximately 0.2% of the total pit lake volume in Table 3-1. Water quality sampling was undertaken in September 2006, before the water was removed from the pit and these data were compared to sump water that was collected and pumped from the base of Misery Pit during mining operations, from September 2000 to September 2004 (see Appendix 2).

The key conclusion of the assessment was that for most water quality variables the average concentration in the mini pit lake was less than the concentration in average pit sump water, representing a dilution of around 1.5 or 2 compared to average sump water. The results showed that there were some variables that had higher average concentrations within the pit lake compared to average sump water, which indicates the high degree of variability within the available data. However, the overall conclusion is that even with a small pit lake (0.2% of total pit lake volume) the quality of water in the lake is expected to be better (i.e., lower concentrations) than typical pit sump water collected during operations. This is due to dilution effects and the submergence of material (sediment) at the bottom of the pit that could produce dissolved loadings into the pit lake water.

Within the model the Base Case for Fox, Misery, Pigeon and Sable pits takes a conservative assumption that until the pit is 1% full all pumped inflows and natural runoff take on the chemistry of typical pit sump water. During this time runoff (run in) over the exposed pit walls is calculated as outlined in Section 4.2.1 providing additional loadings. The effect of this parameter on predicted concentrations is tested using sensitivity analysis, runs undertaken assuming that the initial water in the pit lake has the same chemistry as natural runoff.

Sump water quality data were obtained from samples taken during the lifetime of operational pits. Data used in the model are summarized in Table 4.3-1. The quality of sump water varies among the pits and depends on a number of factors such as whether sump water had been diluted by rainfall prior to sampling. As a result there is a high degree of uncertainty associated with these values and this uncertainty is considered when discussing model results.

In Panda and Koala/Koala North pits the bottom of the pits are linked to underground workings, so that by closure any loadings at the bottom of the pits will have been flushed through to the underground. As a result, no additional loading due to loose material on the base of these pits are considered in the model.

Beartooth pit will be filled to within 30 m of the surface with FPK before the onset of active infilling. Active infilling of this pit may result in re-suspension of FPK material, but the infilling mechanism will be designed to control re-suspension. However, over time, with the addition of fresh water with very low natural suspended solids and settling of solids as the pit lake gets deeper, the amount of suspended FPK and extra fine processed kimberlite (EFPK) material within the pit lake is expected to decrease.

4.3.4 Runoff over Exposed Pit Walls (including Broken Rock on Pit Wall Benches)

On exposure to air and water, rock will be subject to leaching over time, such that water running over the rock exposed on pit walls will accumulate loadings of water quality variables that have leached from the exposed rock. Leaching will continue until the exposed rocks are submerged in the infilling pit lake. Once submerged oxidation rates are reduced by orders of magnitude compared to a subaerial environment, and leaching is effectively stopped. Estimates of the loadings from exposed pit walls are based on calculations provided by SRK Consultants, with details of methods and results given in Appendix 3. The analysis considers inputs from geochemical modelling, humidity cell data and other site observations (e.g., sump water quality data).

Within each pit lake the exposed pit wall area will decrease over time as the pits fill. The model predicts the decrease in pit area over time as the pit lake level rises, based on a relationship between exposed pit wall area and water depth in the pit lake. For existing pits these relationships are based on GIS analysis of existing pit data. For future pits the relationships are based on projected pit dimensions. Once the pit lakes are filled there will be some pit walls exposed above the water surface, as the spill point from the pit lakes are typically lower than the highest pre-development ground level around the edge of the pit lake. Hence, even once the pit lake has been filled there will be some exposed pit wall that will provide loadings to the full pit lake.

SRK undertook geochemical calculations for each of the key rock types exposed in pit walls at the Ekati mine. For less-reactive rock types (e.g., granite, diabase, kimberlite) SRK undertook predictions based on scaling of laboratory results to field conditions following methods described in Appendix 3. For these rock types the key variables were considered to be the volume of reactive rock on the pit wall surface (defined as the surface area multiplied by a thickness of reactive rock) and a correction factor to address differences between laboratory and site conditions. Runoff chemistry predictions were also corrected to ensure consistency with field waste rock seepage data.

Pit walls are composed of near vertical sections of bare rock with some fracturing and flat pit wall benches, on which there will be expected to be broken and disturbed rock. Much of the leaching will occur within the exposed benches and as a result predictions are provided for scenarios considering different thicknesses of the reactive rock parallel to the pit wall. These thickness values represent broken rock and fractures within vertical sections of the wall and broken rock on the benches, with predictions given for 2 m and 4 m deep thicknesses of rock that can provide loadings to the pit sump or pit lake. Results are also given for scenarios considering 'low' and 'high' leach rates based on comparisons with the 50th percentile (low) or 95th percentile (high) of the observed seepage data.

For less reactive rock types the Base Case scenario is considered to be the scenario with 2 m rock thickness and low leach rates. A "Worst Case" scenario is also considered within this report equivalent to 4 m rock thickness and high leach rates. For these less reactive rock types it is assumed that annual leach rates do not vary over time with a constant leach rate in every year of the pit infilling process and every year post-infilling. In reality leach rates will decrease over time as exposed rock is depleted in material that can be leached. For less reactive rock types (e.g., granite, diabase, kimberlite) the time scale over which this depletion could occur is likely to be long (thousands of years) and depletion rates for these rock types are not quantified in the source term estimates used for the modelling (Appendix 3).

Misery pit contains reactive meta-sediments (schist) within its pit walls. As there is a risk of acidic runoff associated with these rock types, SRK undertook more detailed geochemical modelling work to obtain predictions for Misery meta-sediment. However, much of the methodology used for meta-sediments remained the same as for less reactive rock types. The analysis, described in Appendix 3, highlights the importance of jarosite (a weathering product of biotite) on the runoff chemistry. In the case of jarosite formation it would be expected that acidic runoff chemistry could be sustained for a longer period, with leaching at a constant rate over a time period of more than 100 years (see Section 3.2.4 of Appendix 3 for more details on jarosite formation). If jarosite was not formed it is assumed that leaching of the meta-sediments would be more rapid initially, but would decrease rapidly over time as leaching products were exhausted in the host rock. Within around 60 years (assuming first order decay equation in Appendix 3) runoff from the meta-sediment is predicted to become less acidic with markedly lower concentrations of most water quality variables, compared to concentrations during operations or soon after closure.

Appendix 3 provides details of calculations whereby time-varying pit wall runoff leach rates are considered for meta-sediments. The Base Case model runs assume control with jarosite (with average leach rates) and a constant leach rate over time. However, scenario runs were undertaken assuming time varying leach rates without jarosite control, based on a first-order decay equation, with leach rates varying over 100 years. A Scenario run is also undertaken assuming control with jarosite and extreme, high leach rates.

Results for the Base Case scenario are presented in Table 4.3-2. The results are presented as an average concentration of pit wall runoff water entering the pit lake. These values are based on calculating a total annual leach rate (kg/year) for each rock type and dividing this by the annual precipitation falling on the pit lakes (mm/year). The calculations assume that all available leached material is able to be washed into the pit lake so there are no residual loadings once the pit walls are submerged, i.e., there is no “flush” of leachate as the pit walls are submerged.

An attempt was made to try and compare pit wall runoff estimates with observed pit sump data, with results reported in Appendix 4. The analysis did not produce consistent results. The pit wall runoff predictions appear to be reasonably consistent with observed sump data for Fox, Panda and Koala/Koala North pits, once groundwater inputs are added to the calculations. However, for Misery pit the pit wall runoff estimates appear to severally over-estimate sump quality for all variables except molybdenum and arsenic. Hence, model predictions of Misery pit wall runoff may be conservative (high) and should be viewed with caution.

Table 4.3-2. Base Case Pit Wall Runoff Quality

	Concentration (mg/L)						
Variable	**Koala/Koala North**	**Panda**	**Sable**	**Beartooth**	**Pigeon**	**Misery**	**Fox**
Ammonia - N	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093
Chloride	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Nitrate - N	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095
Nitrite – N	0	0	0	0	0	0	0
Phosphate	0	0	0	0	0	0	0
Sulphate	29	29	31	43	40	160	45
TDS	140	140	100	140	120	210	190
Aluminum	0.0039	0.0039	0.0016	0.0024	0.0012	1.4	0.0043
Antimony	0.00005	0.00005	0.0014	0.0032	0.012	0.0048	0.00083
Arsenic	0.00027	0.00027	0.00084	0.0009	0.0061	0.0059	0.00089
Barium	0.044	0.044	0.043	0.044	0.13	0.12	0.052
Boron	0.0096	0.0096	0.0096	0.011	0.050	0.036	0.0096
Cadmium	0.000040	0.000040	0.000058	0.000067	0.00057	0.0015	0.00021
Chromium	0.00040	0.00040	0.00050	0.00059	0.0014	0.0017	0.00062
Copper	0.0013	0.0013	0.0027	0.0023	0.0094	0.21	0.0024
Iron	0.0020	0.0020	0.0020	0.0019	0.0020	10	0.0020
Lead	0.000050	0.000050	0.000059	0.000068	0.0015	0.0015	0.0046
Manganese	0.023	0.023	0.051	0.0050	0.63	1.1	0.15
Molybdenum	0.00070	0.00070	0.0042	0.0046	0.00047	0.00048	0.0017

(continued)

Table 4.3-2. Base Case Pit Wall Runoff Quality (completed)

Variable	Concentration (mg/L)						
	Koala/Koala North	Panda	Sable	Beartooth	Pigeon	Misery	Fox
Nickel	0.0080	0.0080	0.0088	0.0019	0.85	1.8	0.027
Potassium	5.3	5.3	6.4	9.3	17	2.5	6.8
Selenium	0.00010	0.00010	0.00036	0.00058	0.0024	0.0032	0.00068
Strontium	0.64	0.64	0.18	0.18	0.16	0.47	0.47
Uranium	0.00039	0.00039	0.00039	0.00073	0.0020	0.0055	0.00039
Vanadium	0.00030	0.00030	0.0012	0.0019	0.0025	0.0030	0.00097
Zinc	0.0070	0.0070	0.016	0.0093	0.29	0.81	0.019

Notes:
Shaded values are higher than Water Quality Benchmarks, with Water Quality Benchmarks based on hardness of 4 mg/L for all variables except chloride (where hardness is 25 mg/L), as outlined in Section 2.5.
Values based on analyses by SRK Consultants; see Appendix 3 for more details.
Distribution of rock types for each pit wall:

- *Panda and Koala/Koala North: 100% granite.*
- *Sable: 90% granite, 5% diabase, 5% kimberlite.*
- *Beartooth: 85% granite, 5% kimberlite, 5% schist, 5% diabase.*
- *Pigeon: 50% granite, 50% schist.*
- *Misery: 52% schist, 48% granite.*
- *Fox: 90% granite, 5% kimberlite, 5% diabase.*

4.3.5 Groundwater

Groundwater quality is based on analysis of recent (2010 to 2012) data from underground water being pumped from the underground workings to Beartooth pit. These samples are considered the best available data for groundwater and underground quality for the Ekati area. Previous data collected from the underground sumps within Panda and Koala underground were typically sampled for total metals only. With high TSS concentrations in sump water, the total metals samples did not provide reliable information on dissolved metals concentrations in the underground water. The new data set is sampled for dissolved metals. In total 31 samples were used in the analysis with median concentrations of the data set shown in Table 4.3-3.

Table 4.3-3. Groundwater Quality Inputs and Beartooth Pit Mine Water Quality

Variable	Groundwater and Underground Water (mg/L)	[c]Beartooth Pit Mine Water (mg/L)
Ammonia - N	[b]6.3	0.92
Chloride	3700	4,300
Nitrate - N	[b]31	16
Nitrite – N	1.8	0.26
Phosphate	0.30	0.10
Sulphate	580	470
TDS	9300	7,300
Aluminum	[a]0.010	0.045
Antimony	[a]0.0025	0.0066
Arsenic	[a]0.00090	0.0026
Barium	0.17	0.31

(continued)

Table 4.3-3. Groundwater Quality Inputs and Beartooth Pit Mine Water Quality (completed)

Variable	Groundwater and Underground Water (mg/L)	[c]Beartooth Pit Mine Water (mg/L)
Boron	[a]0.10	0.097
Cadmium	[a]0.00010	0.00092
Chromium	0.0025	0.0074
Copper	[a]0.0016	0.0018
Iron	0.030	0.066
Lead	[a]0.00025	0.00084
Manganese	0.082	0.13
Molybdenum	0.26	0.39
Nickel	0.0099	0.0094
Potassium	120	140
Selenium	0.00064	0.00093
Strontium	26	33
Uranium	0.0039	0.0023
Vanadium	[a]0.0050	0.0038
Zinc	[a]0.010	0.0074

Notes:
No values are higher than Water Quality Benchmarks, with Water Quality Benchmarks based on hardness of 4 mg/L for all variables except chloride (where hardness is 25 mg/L), as outlined in Section 2.5.
[a] Many individual samples recorded concentrations below detection limit. Values below detection limit are assumed to have concentrations equal to half the detection limit.
[b] Values of nitrate and ammonia are set to zero once the underground workings are filled and are considered zero for inflows through pit bottoms, see text for details.
[c] From model developed for Rescan (2012).

The key characteristic of groundwater in the Ekati region is its high salinity, reflected in high concentrations of TDS and other related water quality variables such as chlorides. The deep groundwater in many areas of Northern Canada, including the Ekati area is known to have high salinity (Dickin, Mills and Freed 2008). Underground water quality data at the Ekati site indicates that TDS concentrations commonly exceed 10,000 mg/L, with the median concentration in Table 4.3-3 calculated as 9,300 mg/L. These high TDS concentrations (virtually equivalent to salinity in these samples) will have an influence on pit lake water density and the potential for meromixis.

Groundwater samples from the underground workings include relatively high concentrations of nitrate and ammonia, see Table 4.3-3. These reflect the sampling locations for underground water (i.e., within the workings) and are thought to represent input from incompletely combusted or spilled ANFO and not the quality of natural underground water. Pre-development drillhole data support the conclusion that natural levels of nitrates and ammonia are low in groundwater compared to sources from sumps (Rescan 2006a).

In terms of the modelling, groundwater with high concentrations of nitrate and ammonia are input into the model during the initial infilling of the underground workings. When the workings are infilled ammonia and nitrate values are set to zero for subsequent groundwater inflows. For groundwater inflows through the bottom of open pits the ammonia and nitrate concentrations are set to zero throughout the runs.

The available water quality data for groundwater are from Panda and Koala/Koala North underground workings. There are no data for groundwater inflows to Fox pit at present, as the bottom of Fox pit has yet to pass below the permafrost depth. Hence, for the purpose of this assessment data from Panda and Koala/Koala North are used for Fox pit groundwater inflows.

4.3.6 Residual Mine Related Chemicals (i.e., ANFO)

For Fox, Misery, Pigeon and Sable pits residual mine related chemicals associated with pit walls and within material at the bottom of the pit are considered within the sump chemistry used in Section 4.3.5. This assumes all remaining ANFO is washed off the pit wall surfaces in these pits during the initial infilling of the pit and the available sump water quality data provide a reasonable estimate of the loadings expected to report to the bottom of the pit lake.

For Panda and Koala/Koala North pits and underground workings, loadings from residual ANFO are considered through underground water chemistry. As noted in Section 4.3-5, underground water used in the model has high ammonia and nitrate values reflecting an influence from blasting residues. These high nitrate and ammonia values are applied to underground inflows until the underground workings are filled.

At closure Beartooth pit will be filled to within 30 m of the surface with FPK. No additional ANFO inputs are considered for this pit lake.

4.3.7 FPK and Mine Water within Beartooth Pit

During operations Beartooth pit will be filled with FPK and mine water (FPK supernatant and underground water), so that by the end of operations, Beartooth pit will be filled to within 30 m of the pit surface with FPK solids. The current plan is to pump mine water that is above the FPK solids out of Beartooth pit and into the LLCF. Following this fresh water would be pumped into the pit to fill the pit lake to the surface. Hence, there would be a 30 m thick water cover above the FPK solids comprised of a mixture of mine water and fresh water. The relative percentages of mine water and fresh water are not known at present and model runs were undertaken with a range of different contributions from the two sources. Mine water chemistry used in the model is based on results from the LLCF Load Balance Model (Rescan 2012) which contains a sub-model that simulates the quality of mine water in Beartooth pit. The concentrations of mine water used in the model are provided in Table 4.3-3.

4.3.8 Other Inflows

Most of the pit lakes are not expected to receive runoff from waste rock piles, as waste rock is either not located adjacent to the pit or runoff from the waste rock is not diverted to the pit. However, runoff from WRSAs is expected to flow towards Fox, Panda, and Koala/Koala North pit lakes.

The WRSAs were designed to freeze after deposition. The upper 2 to 4 m of the rock piles can thaw out during the summer months allowing precipitation to enter into the pore space. However, for waste rock piles with potentially reactive material the reclamation plan proposes to cover the piles with 5 m of non-reactive granite to limit leaching. For the purposes of this modelling study runoff from WRSAs is considered equivalent to natural runoff, reflecting the low reactivity of the granite cap.

4.3.9 Estimation of pH within Pit Lakes

The mass balance model used in this study does not predict the pH within pit lake waters. However, the pH of pit lake water can have an important control on loadings, e.g., from dissolution of re-suspended sediment within the pits. Low pH will tend to promote leaching of metals from the sediment and additional leaching from submerged pit walls.

The pH of various key inflows to the pit lakes is reviewed below. Prediction of pH is not possible without detailed stoichiometric calculations and/or modelling beyond a mass loading approach.

A review of data from the pre-development period of Sable Lake and Beartooth Lake indicates pH values on the order of 6.4 to 6.7 for Sable and 6.1 for Beartooth (BHP-Diamet 2000). PH values for other water bodies are expected to be similar at slightly less than neutral levels.

Estimates of the quality of pit wall runoff are based on results presented in Appendix 3 and are discussed in more detail in Section 4.3.3. The pH results for each rock type and pit are summarized in Table 4.3-4. The results indicate that for most pits the dominant rock type within the pit walls is granite and the pH of runoff passing over granite lies within the range of 8.1 to 9.3. The exceptions to this are Pigeon and Misery Pit where runoff from meta-sediment (schist) has pH of around 3.2 to 3.6.

Table 4.3-4. Summary of pH Predictions for Runoff over Pit Walls

Pit	Rock Type	Percentage	pH
Koala/Koala North	Granite	100%	8.6 to 8.9
Panda	Granite	100%	8.6 to 8.9
Misery	Schist	52%	3.2 to 3.6
	Granite	48%	8.6 to 8.9
Fox	Diabase	5%	7.9 to 8.0
	Granite	90%	8.5 to 8.6
	Kimberlite	5%	9.6 to 9.8
Beartooth	Diabase	5%	8.2 to 8.5
	Granite	85%	8.4 to 8.6
	Kimberlite	5%	9.1 to 9.3
	Schist	5%	8.2
Pigeon	Granite	50%	8.3 to 9.3
	Schist	50%	3.2 to 3.6
Sable	Diabase	5%	8.2 to 8.4
	Granite	90%	8.1 to 8.4
	Kimberlite	5%	9.2 to 9.4

Note: see Appendix 3 for details.

Data from 51 groundwater samples are provided in Appendix B of Rescan (2006a). The range in pH values for the site is 6.7 to 12.5, but with most of the values clustered close to the median value of 7.4. The standard deviation of the full sample is 1.0.

Data from 6 samples of Misery sump water collected on June 9, 2005, indicate pH values ranging from 6.9 to 7.7, with a median value of 7.6. Average Panda sump water also show a pH of 7.6 based on the available observed data set.

The results indicate that for most pits the input of groundwater, pit wall runoff and sump water are expected to have near neutral or slightly alkaline pH. Natural water pumped from source lakes is expected to have near neutral or slightly acidic pH. However, pit wall runoff for Pigeon and Misery Pits could be acidic due to the presence of meta-sediment in the pit walls.

Given the large volume of natural lake water that will be pumped into the pit lakes during the infilling process it is anticipated that near neutral conditions will develop in the pit lakes once filled. However, due to the presence of potentially acid generating meta-sediments in the walls of Pigeon and Misery pits, there may be a concern related to pH for these pit lakes, although sump water within Misery pit does not show acidic conditions, which may indicate that geochemical calculations for meta-sediment runoff chemistry may be conservative and produce overly low predictions for pH.

4.4 SUMMARY OF MODEL INPUTS AND DISCUSSION OF SCENARIO RUNS

4.4.1 Summary of Model Inputs

The key inputs to the Base Case model are summarized in Table 4.4-1.

Table 4.4-1. Summary of Base Case Model Inputs

Model Parameter	Methodology
Water Balance	
Local catchment runoff	Annual precipitation (mm) × catchment area (m^2) × runoff coefficient, divided into monthly totals based on monthly runoff distribution. Runoff coefficient = 0.5
Runoff from pit walls	Annual precipitation (mm) × area of pit walls (m^2) × runoff coefficient, divided into monthly totals based on monthly effective precipitation distribution. Runoff coefficient = 0.85. Areas of pit walls vary over time.
Runoff from WRSAs	Annual precipitation (mm) × WRSA area (m^2) × runoff coefficient, divided into monthly totals based on monthly effective precipitation distribution. Runoff coefficient = 0.2
Lake surface water balance	Annual Precipitation (mm) – Total Annual Evaporation (mm) × Lake Area (m^2), divided into monthly totals based on monthly runoff distribution. Areas of pit walls vary over time.
Groundwater	Base Case inputs are based on groundwater inflow rates from EBA (2006). Base Case assumes groundwater inflow rate tends to zero as pit lakes fill.
Pumped inflows	Constant rate during open water season (June to October).
Storage	Pit lakes fill over time according to water balance and storage/elevation curve for each pit.
Overflow	Load balance model predicts water balance and chemistry to point that pit lakes are full. Predictions of water quality overflowing from pit lakes are made by multi-layer model presented in Chapter 7.
Water Quality	
Precipitation directly on pit lake	Assumed to be pristine water
Natural runoff directly entering pit lake from upstream watersheds	Assumed equal to typical natural stream water from AEMP dataset
Runoff from disturbed areas within mine area	No additional loadings
Pumped water from source lakes	Assumed to be natural lake water from AEMP dataset.
Runoff from waste rock piles	Waste rock piles assumed to be frozen with non-reactive granite cap. Runoff assumed equivalent to natural runoff for this assessment
Leaching from pit walls	Data based on SRK geochemical analyses, applicable for average precipitation case.

(continued)

Table 4.4-1. Summary of Base Case Model Inputs (completed)

Model Parameter	Methodology
Water Quality ***(cont'd)***	
Flush of leachate from walls as they are submerged	Zero, assumption from geochemical analyses is that walls are flushed of available leached water quality variables on annual basis, so no additional loading is available at submergence
Leaching from submerged pit walls	Zero, once walls are submerged there is zero additional loading
Groundwater	Average underground water quality data, but only applicable for Fox, Koala/Koala North and Panda pits
Initial Flush/loadings from material at bottom of pits	Assume that until 1% of the pit volume has been filled pumped inflows and watershed runoff take on sump water quality
Residual mine related chemicals	Assumed to be included within assumptions for initial loadings from material at the bottom of the pits (i.e., sump water and initial groundwater inflows)
Chemical Reactions/Decay of Variables	All water quality variables are assumed conservative and inert except for nutrients

5. Model Scenarios for Pit Infilling Models and Long-term Water Quality Predictions

Engineers and Scientists

5. Model Scenarios for Pit Infilling Models and Long-term Water Quality Predictions

Key model inputs and assumptions were described in Chapter 4, which concluded with a description of the model Base Case scenario. Although a set of Base Case or best estimate model inputs can be derived there are uncertainties associated with each of the model inputs. In order to assess how these uncertainties affect model results a series of model sensitivity runs were undertaken for the pit infilling process and for long-term water quality model runs. Within each sensitivity run a key model input or assumption is varied and results are compared to the Base Case scenario. In this way the key model inputs that have the greatest impact on water quality results can be identified and an assessment can be made of the overall uncertainty associated with the water quality predictions. The results of the sensitivity analyses can be used to identify data gaps, guide future work and guide data collection activities at Ekati.

Sensitivity analyses were undertaken for both the pit infilling models and long-term water quality prediction models. Different scenarios were identified for each of these models.

The future pit lakes at Ekati do not have the same sensitivities to model inputs, e.g., some pit lakes will have groundwater inflows while filling, while others have meta-sediment exposed within the pit walls. Hence, the pit lakes are divided into four groupings in Section 5.1. Sensitivity analyses are then developed for each of these groupings in Sections 5.2 and 5.3.

5.1 GROUPING OF PIT LAKES FOR SCENARIO MODEL RUNS

Based on the model inputs described above the pit lakes at Ekati can be divided into four groups:

1. *Open pit with no groundwater inflows and no meta-sediments within the pit walls.* The only pit lake within this group is ***Sable pit***. For this pit lake there is no source of water with high TDS (i.e., groundwater) which would tend to promote the formation of meromixis. In addition, the pit walls are dominated by relatively unreactive rock (i.e., granite, diabase and kimberlite).
2. *Open pits with no groundwater inflows and with meta-sediments within the pit walls.* The pit lakes within this group are ***Misery pit and Pigeon pit***. For these pit lakes there are no sources of water with high TDS (i.e., groundwater) which would tend to promote the formation of meromixis. However, the pit walls have exposure of meta-sediments, which are considered to have the potential to leach relatively higher loadings of many dissolved metals, with a risk of elevating concentrations within the forming pit lake.
3. *Open pits that have groundwater inflows.* The pit lakes within this group are ***Panda pit (and underground workings), Koala/Koala North (and underground workings) and Fox pit***. For these pit lakes groundwater is expected to be a source with high TDS which would tend to promote the formation of meromixis. However, the pit walls are expected to be dominated by relatively unreactive rock (i.e., granite, diabase and kimberlite).
4. *Open pit which will be partially infilled with mine water and mine solids.* The only pit lake within this group is ***Beartooth pit***. Beartooth will be filled to within 30 m of its spill point with FPK solids. There will be a water cover above the solids.

5.2 MODEL SCENARIOS FOR PIT INFILLING MODELS

In order to assess the effect of varying the model inputs on water quality in the full pit lakes a series of scenario runs were undertaken for each of the model groupings outlined in Section 5.1. The model scenarios are described in Tables 5.2-1 to 5.2-4. A description of the key parameters that were varied is provided below:

- ***Pit wall runoff quality***. The Base Case assumes pit wall runoff has the quality of best estimate predictions as outlined in Section 4.3.4. For all pit lakes model sensitivity runs were undertaken assuming higher loadings from the exposed pit walls, based on Worst Case pit wall runoff quality from SRK. The purpose of these runs was to identify how uncertainties in the pit wall chemistry predictions impacted water quality in the full pit lakes. In addition for Misery and Pigeon pits, which have meta-sediment (schist) exposed in the pit walls two additional sensitivity runs were undertaken considering a time varying input from the schist to the pit lake, as discussed in Section 4.3-4and Appendix 3. One additional run was undertaken for these two pit lakes using observed Misery sump data as a surrogate for pit wall runoff. This was done as there were concerns that pit wall runoff predictions might be overly conservative (high) and Misery sump water may be an appropriate data set to reflect actual pit wall runoff conditions within Misery and Pigeon pits.
- ***Quality of initial water entering pit lake***. The Base Case assumes that until a pit has filled over 1% of its volume, pumped inflows and natural runoff take on the quality of typical sump water. This is to account for flushing of material at the bottom of the pit (see Section 4.3.3). Model sensitivity runs were undertaken assuming initial water accumulating in pit had water quality equivalent to natural runoff only (i.e., no additional loadings due to flushing of material at the bottom of the pit). The purpose of these runs was to identify how uncertainties in the quality of initial loadings to the pit impacted water quality in the full pit lakes.
- ***Pumped inflow***. The Base Case assumes that pumped inflows range from 0.2 to 0.4 m^3/s and that the source of water is from natural lakes. If the pumping rate is decreased the time of infilling will be increased and the quality of the pit lake water would be expected to deteriorate due to increased loadings from pit walls (which are exposed for a long period of time) and increased groundwater inflows. Hence, three sensitivity runs were undertaken for each pit lake assuming (i) zero pumped inflow, (ii) pumped inflows at half the rate in the Base Case, and (iii) pumped inflows at double the rate in the Base Case. The purpose of these runs was to identify how uncertainties in the pumping rates impacted water quality in the full pit lakes. For Panda and Koala/Koala North pit lakes a further set of sensitivity runs was completed by varying the time between the end of operations and the beginning of active infilling of the pit lakes. The Base Case assumes that pumping commences 13 years after the end of operations at Ekati and during this time the pit lakes begin to fill with groundwater and surface water runoff. Sensitivity runs were completed assuming that pumping begins immediately after the end of operations at the mine site.
- ***Variable groundwater inflow***. Groundwater affects Panda Koala/Koala North and Fox pit lakes only. The Base Case scenario considered groundwater flow rates presented by EBA (2006) and assumes that the groundwater inflow rate decreases over time to zero as the pit lakes fill. Sensitivity runs are undertaken assuming lower groundwater flow rates based on observed data and that the groundwater inflow rate decreases linearly as the pit lake fills, to a minimum of 5% of the initial inflow rate. As a result the pit receives groundwater inflows even when filled, as if the regional groundwater table is above the pit lake. The purpose of these runs was to identify how uncertainties in groundwater inflow rates impact water quality in the full pit lakes.

- ***Infilling of Beartooth pit lake***. Beartooth pit lake will be filled with FPK solids to within 30 m of the spill point of the pit lake. There will be a 30 m cover of water over the FPK solids. The water cover will be a combination of mine water sitting above the FPK solids (a mixture of underground water and FPK supernatant) and fresh water from a source lake. The relative contribution of mine water and fresh water is not known at present and will depend on the quality of the mine water and physical limits to the volume of mine water that can be pumped from above the FPK solids. As a result, scenarios were run considering different thicknesses of the mine water layer above the FPK solids. In the Base Case it is assumed that there will be 5 m depth of mine water above the FPK solids. Sensitivity runs were undertaken considering scenarios with a 10 m thick layer of mine water and 1 m thick layer. For all scenarios it is assumed that the remaining volume up to the spill point of Beartooth pit is filled with fresh water from a source lake.

Table 5.2-1. Scenario Runs for Pit Infilling Sensitivity Analysis; Sable Pit Lake

Scenario	Base Case
Base Case	As outlined in Chapter 4 and Table 4.4.1
Scenario G1.1	Pit wall runoff quality varied from Base Case; ***Worst case 4 m results from SRK***
Scenario G1.2	Initial Loadings to Sump varied from Base Case; ***No initial loadings from pit sump***
Scenario G1.3a	Pumped inflow rate to pit lake varied from Base Case; ***Zero pumped inflow from source lake***
Scenario G1.3b	Pumped inflow rate to pit lake varied from Base Case; ***Half pumped inflow from source lake***
Scenario G1.3c	Pumped inflow rate to pit lake varied from Base Case; ***Double pumped inflow from source lake***

Table 5.2-2. Scenario Runs for Pit Infilling Sensitivity Analysis; Misery and Pigeon Pit Lakes

Scenario	Base Case
Base Case	As outlined in Chapter 4 and Table 4.4.1
Scenario G2.1a	Pit wall runoff quality varied from Base Case; ***Worst case 4 m results from SRK***
Scenario G2.1b	Pit wall runoff quality varied from Base Case; ***Schist loadings decay over time (First order rapid decay)***
Scenario G2.1c	Pit wall runoff quality varied from Base Case; ***Schist loadings decay over time (First order slow decay)***
Scenario G2.1d	Pit wall runoff quality varied from Base Case; ***Misery sump water quality used for pit wall runoff***
Scenario G2.2	Initial Loadings to Sump varied from Base Case; ***No initial loadings from pit sump***
Scenario G2.3a	Pumped inflow rate to pit lake varied from Base Case; ***Zero pumped inflow from source lake***
Scenario G2.3b	Pumped inflow rate to pit lake varied from Base Case; ***Half pumped inflow from source lake***
Scenario G2.3c	Pumped inflow rate to pit lake varied from Base Case; ***Double pumped inflow from source lake***

Table 5.2-3. Scenario Runs for Pit Infilling Sensitivity Analysis; Panda, Koala/Koala North and Fox Pit Lakes

Scenario	Base Case
Base Case	As outlined in Chapter 4 and Table 4.4.1
Scenario 1	Pit wall runoff quality varied from Base Case; ***Worst case 4 m results from SRK***
Scenario 2	Initial Loadings to Sump varied from Base Case; ***No initial loadings from pit sump***
Scenario G3.3a	Pumped inflow rate to pit lake varied from Base Case; ***Zero pumped inflow from source lake***
Scenario G3.3b	Pumped inflow rate to pit lake varied from Base Case; ***Half pumped inflow from source lake***

(continued)

Table 5.2-3. Scenario Runs for Pit Infilling Sensitivity Analysis; Panda, Koala/Koala North and Fox Pit Lakes (completed)

Scenario	Base Case
Scenario G3.3c	Pumped inflow rate to pit lake varied from Base Case; ***Double pumped inflow from source lake***
Scenario G3.3d	Time scale for pumped inflows varied from Base Case; ***Pumped inflows begin immediately after end of operations at the mine site***
Scenario G3.4a	Groundwater inflow varied from Base Case; ***groundwater flow rates based on observed data from underground workings***
Scenario G3.4b	Groundwater inflow varied from Base Case; ***groundwater inflows are assumed when pit lakes are full (5% of maximum)***

Table 5.2-4. Scenario Runs for Pit Infilling Sensitivity Analysis; Beartooth Pit Lake

Scenario	Base Case
Base Case	As outlined in Chapter 4 and Table 4.4.1. Run assumes 5 m of mine water above FPK solids in pit
Scenario G4.1a	Remaining mine water above FPK solids varied from baseline; 10 m of mine water assumed above FPK solids in pit lake
Scenario G4.1b	Remaining mine water above FPK solids varied from baseline; 1 m of mine water assumed above FPK solids in pit

Results for these scenario runs are presented in Section 6.1.

5.3 MODEL SCENARIOS FOR LONG-TERM WATER QUALITY PREDICTIONS

Not all scenario runs undertaken for the pit infilling model are considered for the long-term water quality predictions due to the time required to set-up and run the layered pit lake models. In addition, initial model runs identified key sensitivities for each of the pit lakes. Hence, for long-term water quality predictions the Base Case is run for all pits, with selected scenarios based on varying the key model inputs expected to impact long-term water quality within the pit lakes.

5.3.1 Open Pit with No Groundwater Inflows and No Meta-sediments within the Pit Walls (Sable Pit Lake)

The Base Case run only was undertaken for Sable pit, as pit infilling and layered model results indicated that predicted water quality in the surface layers were well below Water Quality Benchmarks and no meromixis was predicted.

5.3.2 Open Pits with No Groundwater Inflows and with Meta-sediments within the Pit Walls (Misery and Pigeon Pit Lakes)

Initial model runs indicated that the key control on long-term water quality within Misery and Pigeon pit lakes was loadings to the pit lake from runoff over pit walls sub-aerially exposed above the final pit lake water level. As outlined in Section 4.3.4 the pit walls for Misery and Pigeon pits have a high percentage (around 50%) of meta-sediments which are reactive when exposed to air and can generate high loadings of many metals. The Base Case model run considers a conservative situation where loadings from the pit walls are constant over time. Scenario runs are also undertaken assuming that loadings from meta-sediments exposed in the pit walls would decrease over time.

Scenario 1 considers a first order decay rate for all chemical constituents, such that concentrations are reduced to 1/40 of the initial leach rate by year 100, with details of the methods and rate of decay provided in Appendix 3. Scenario 1 assumes a high total mass of loadings available to be leached compared to Scenario 2. It is noted that although leach rates decay over time to levels that are less than the constant rates assumed in the Base Case, the scenario runs predict higher initial leach rates than the Base Case run. Details of the geochemical modelling approach are provided in SRK (2013) presented in Appendix 3.

Scenario 1 considers a first order decay rate for all chemical constituents, such that concentrations are reduced to 1/2000 of the initial leach rate by year 100, with details of the methods and rate of decay provided in Appendix 3. Scenario 2 assumes a lower total mass of loadings available to be leached compared to Scenario 1. It is noted that although leach rates decay over time to levels that are less than the constant rates assumed in the Base Case, the scenario runs predict higher initial leach rates than the Base Case run.

5.3.3 Open Pits that Have Groundwater Inflows (Panda, Koala/Koala North and Fox Pit Lakes)

Initial model runs indicated that the key controls on long-term water quality and the potential for meromixis within pit lakes affected by groundwater inflows were the rate of groundwater inflow during the infilling process and assumptions related to the presence or absence of stratification within the infilled pit lake. Hence, three scenarios are undertaken for each of these pit lakes:

- Scenario 1 assumes that the pit lake is fully mixed at the point infilling is complete, which is the same assumption as in the Base Case. However, the run considers the initial condition whereby the pit was filled in response to a lower groundwater inflow rate than considered in the Base Case, with groundwater flows equivalent to observed flows, similar to Scenario G3.4a for the pit infilling models. The purpose of this scenario was to consider the impact of lower groundwater flow rates and lower salinity within the full pit lake on long-term evolution of meromixis in the pit lake.
- Scenario 2 assumes that during filling the pit lake is completely mixed up to an elevation of approximately 30 m below the spill point. To assist with long term stability a 30 m cover of water will be placed over this in a way that does not cause additional mixing. Hence, in the model it is assumed that there is a 30 m fresh water cover (with chemistry of natural lake water from Table 4.3-1) on top of a fully mixed pit lake, with chemistry predicted by the load balance model for infilling. The purpose of this scenario is to assess the impact that such a cover would have on long-term stability of meromixis in the pit lake and on the quality of water in the surface layer.
- Scenario 3 assumes that at the end of pit infilling the salinity in the pit lake is distributed linearly within the pit lake; with the highest concentrations at the bottom of the pit lake and lowest concentrations at the surface. The average concentration (i.e., fully mixed concentration) will occur close to the mid-point of the pit lake. The purpose of this scenario is to assess whether the formation of stratification within the pit lake during the infilling period would have a major effect on the long-term stability of meromixis in the pit lake and on the quality of water in the surface layer.

5.3.4 Open Pit which will be Partially Infilled with Mine Water and Mine Solids (Beartooth Pit Lake)

Two model scenarios are considered with different assumptions related to the amount of mine water that is left above the tailings solids before flooding of the pit lake with fresh water. Scenarios are run considering a 5 m layer of mine water (25 m layer of freshwater on top) and a 10 m layer of mine water (20 m layer of freshwater on top).

6. Predictions of Likelihood of Meromixis in Pit Lakes

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6. Predictions of Likelihood of Meromixis in Pit Lakes

This chapter provides a detailed definition of meromixis (Section 6.1), provides a conceptual model of the evolution of meromixis in pit lakes (Section 6.2) and reviews available information from existing pit lakes that can be used to inform predictions of the likelihood of occurrence of meromixis in the pit lakes at the Ekati site (Sections 6.3 to 6.5). Model predictions of meromixis in the Ekati pit lakes are then presented (Section 6.6) along with a sensitivity analysis of key parameters that can affect the likelihood of meromixis for the Ekati pit lakes (Section 6.7).

6.1 DEFINITION OF MEROMIXIS

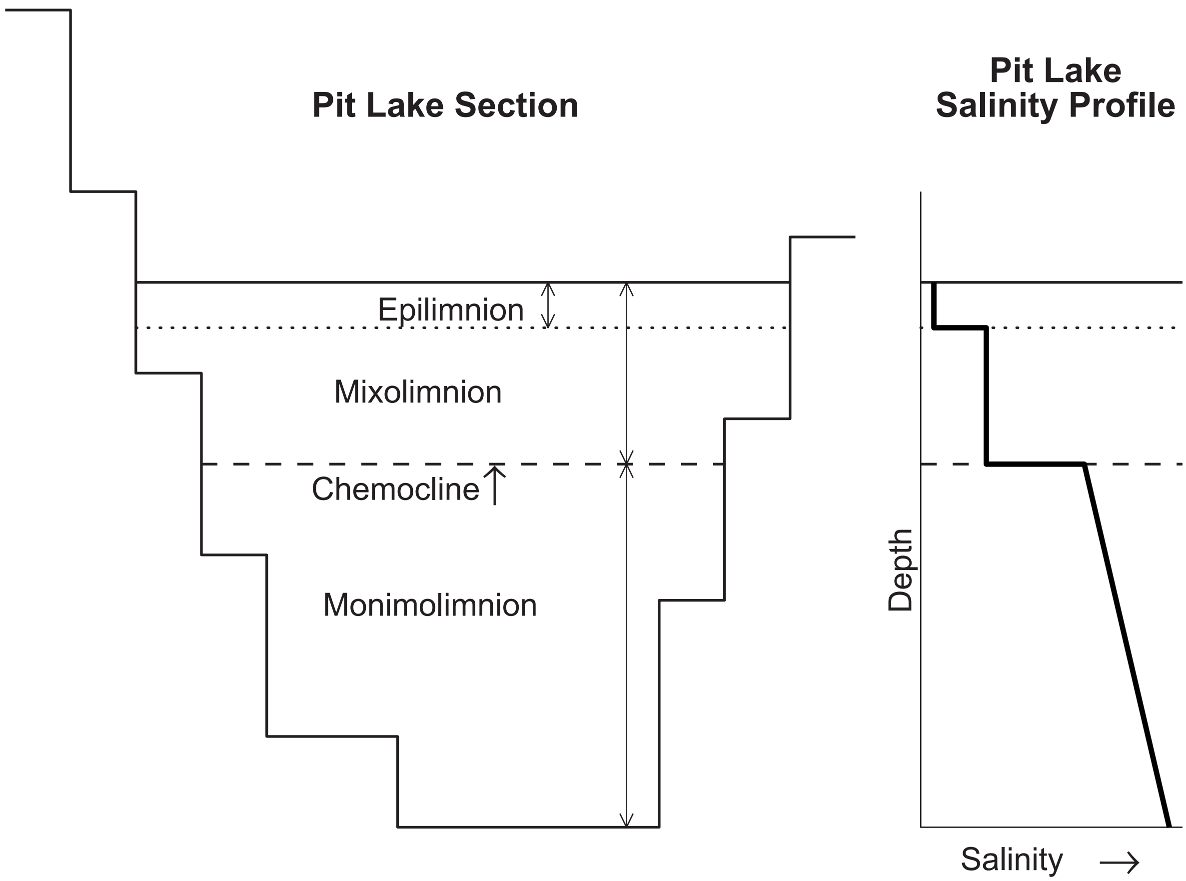
While there are exceptions, temperate lakes are usually temperature stratified in summer, and turnover occurs in both spring and fall. Such lakes are termed dimictic lakes. Hence, natural lakes in the Ekati area would be expected to turnover twice every year. However, pit lakes are often deep, have a small surface area, and are more saline than surrounding natural waters. These factors predispose pit lakes to meromixis, meaning they are likely to be permanently stratified.

Meromixis refers to lakes that “do not undergo complete circulation” (Wetzel 2001) and that are “not completely mixed” (Walker and Likens 1975). However, the absence of complete mixing does not preclude the transfer of water between the deep layer (monimolimnion) and the overlying water (mixolimnion). This transport may result from, for example, groundwater inflow, brine currents generated as ice forms, or the surface mixed layer eroding the top of the deep water. In addition, even in lakes that exhibit meromixis at depth, physical and temperature stratification can form and break down in the surface layers of these lakes in response to ice melt and summer heating of the lake surface. Hence, there can be mixing within the surface layers of these pit lakes, even if full mixing to depth does not occur.

It is useful to distinguish between two types of meromixis. The term “weak meromixis” is used here to describe cases where complete mixing is absent, but there is some degree of transport to depth, and “strong meromixis” to describe cases where the deep water is isolated and there is negligible transport with the overlying water.

The status of mixing can change over time as local hydrological and meteorological conditions vary. For example, the lake may be subject to intermittent meromixis, i.e., it may mix one year and not the other.

Figure 6.1-1 shows the layers in a meromictic lake. The defining feature of meromixis is the large increase in salinity, usually called the chemocline (Hutchinson 1957, Wetzel 2001) which is also sometimes referred to as the halocline (salinity gradient) or pycnocline (density gradient). The chemocline separates the mixolimnion (seasonally mixed surface water) from the monimolimnion (isolated deep water). Figure 6.1-1 shows the salinity just after ice-off, in which the epilimnion (surface layer) is fresher as a result of ice-melt and runoff. The epilimnion mixes down, slowly through the summer and more rapidly in the fall, until the surface layer includes, typically, the entire mixolimnion. Further deepening of the mixolimnion is resisted by the chemocline, leaving the monimolimnion relatively isolated throughout the year.



Note: The chemocline (large increase in salinity) separates the mixolimnion (surface water that mixes seasonally) from the monimolimnion (isolated deep water).

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Schematic of Meromixis for a Pit Lake with Ice Cover

Figure 6.1-1

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In a meromictic lake, dissolved and suspended substances make the monimolimnion (deep water) denser than the mixolimnion above. This stratification makes it less likely that the natural sources of mixing (typically wind, surface cooling and inflows) can provide enough energy to break down the density stratification and mix the entire lake. In temperate climates, the exclusion of salt from ice cover and freshet inflow can provide a cap of fresh water sufficient to resist spring turnover (Pieters and Lawrence 2009a). During summer, warming of the surface means that the pit lake stability is augmented by temperature. However, it is in late fall, once the surface layer has deepened and cooled to the temperature of maximum density (TMD), ~4ºC, that the pit lake is most vulnerable to turnover. At this time the temperature is nearly uniform and stability is provided by changes in salinity alone.

In a similar way, right after ice-off is also a time when the stratification is maintained by the salinity alone and the surface mixed layer is vulnerable to the additional energy provided by wind mixing. However, because of significant solar heating at high latitudes in spring, the surface layer warms quickly, and temperature becomes the dominant source of stability (e.g., Pieters and Lawrence 2009a).

Ice cover at high latitude is both thick and dominated by black ice, which excludes a high degree of salt (e.g., Pieters and Lawrence 2009a). Ice cover at high latitude can play a dual role. On the one hand, the low salinity of the ice melt can create a cap of fresh water sufficient to suppress turnover in spring and fall. On the other hand, as the ice grows in winter, the salt excluded from the ice induces convection which can, under certain conditions, overcome meromixis.

Beside wind, salinity and ice cover, there are often additional natural and anthropogenic processes at work in pit lakes, such as groundwater inflows, sludge inflows or rock falls that can also affect the stratification, some examples of which are provided in this chapter.

The model developed for this study will estimate the magnitude of those factors that enhance the stability of the lake (e.g., the salinity of the water column, and the introduction of buoyant water at the surface by ice-melt and runoff) and compares them to the primary factors that induce mixing (wind, surface cooling, and inflows).

6.2 CONCEPTUAL MODEL OF THE EVOLUTION OF STRONG MEROMIXIS WITH ICE COVER

A schematic of strong meromixis in a lake with ice cover is shown in Figure 6.2-1. The left column shows temperature and the right column shows conductivity[1].

In spring (Figure 6.2-1a, b) ice melt and freshet runoff generate a low conductivity surface layer (0 to 2 m, Figure 6.2-1b). The resulting contrast in conductivity between the surface layer and the rest of the mixolimnion prevents mixing of the entire mixolimnion in spring. As spring and summer progress this thin surface layer will warm and deepen slightly.

In fall (Figure 6.2-1c, d) the surface layer cools and is mixed deeper by wind and penetrative convection[2]. Most or all of the mixolimnion (0 to 15 m, Figure 6.2-1d) is now included in the surface layer.

[1] Conductivity, C25, is a measure of salinity (TDS), S[mg/L] ≈ 0.7 C25[μS/cm].
[2] Penetrative convection results from surface cooling which creates plumes of cooler water that can erode the pycnocline.

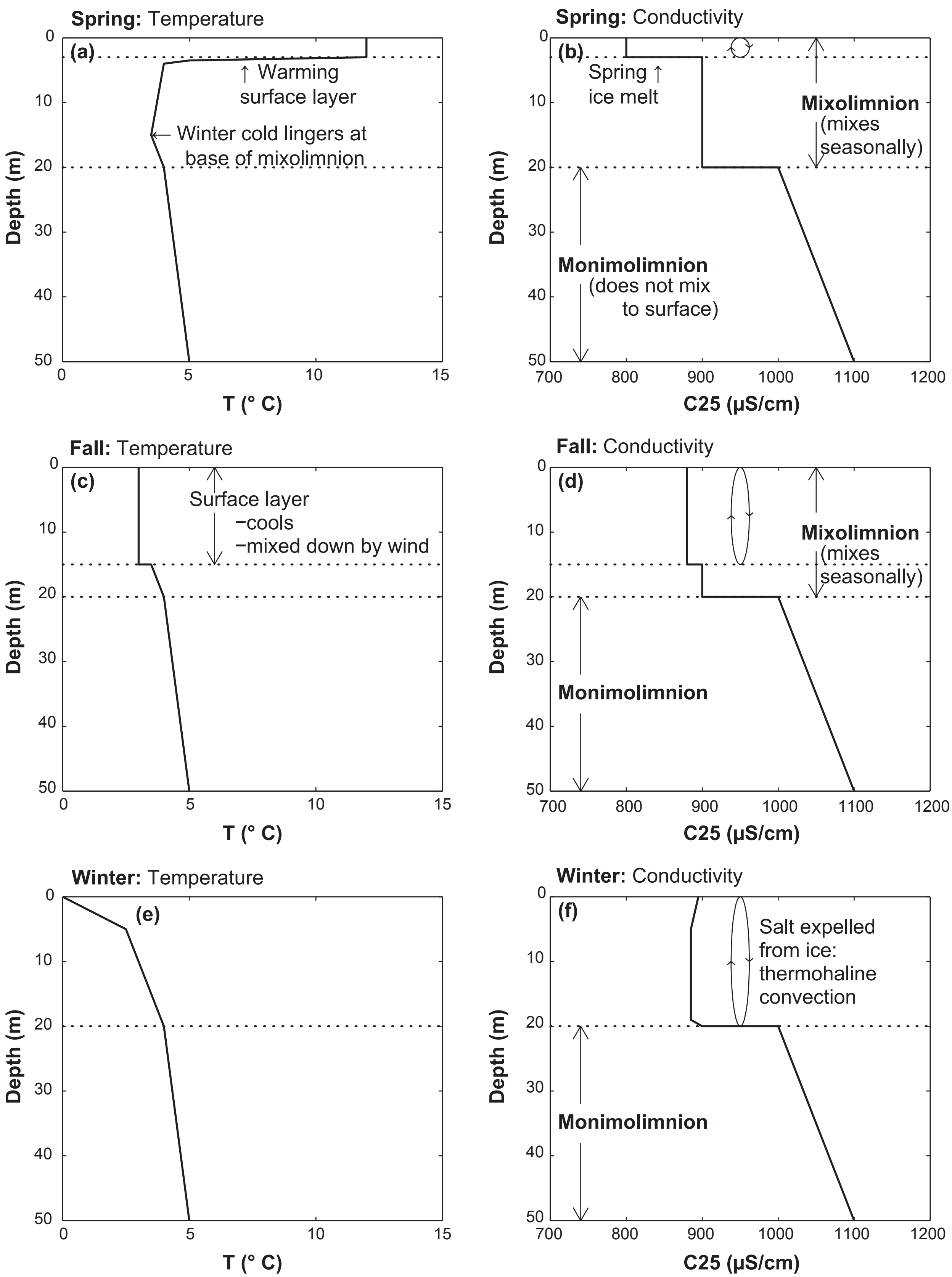

Figure 6.2-1

Schematic of Seasonal Circulation in Strong Meromixis with Ice Cover

The density of fresh water is highest at ~ 4ºC[3]. As the surface of the lake cools below 4ºC, it becomes "reverse" stratified: cold (< 4ºC), less-dense water forms a surface layer floating on the deeper, more-dense water nearer to 4ºC. It should be noted that reverse stratification in winter is much weaker than thermal stratification in summer.

In winter (Figure 6.2-1e, f) salt excluded from the ice can result in thermohaline convection. This can complete the mixing of the mixolimnion if that had not already taken place in the fall. The salt excluded from the ice increases the salinity of the mixolimnion.

The under-ice convection is episodic. When ice forms, the temperature of the surface layer is reverse stratified with buoyant water at ~0ºC[4] just under the ice (Figure 6.2-1e). As a result of the reverse temperature stratification, the salt excluded from the ice will initially remain just under the ice.

However, the accumulation of salt just under the surface of the ice will eventually overcome the reverse temperature stratification and convection through the mixolimnion will occur. The heat flux through the ice will then cool water below the ice and re-establish reverse temperature stratification. As a result, under ice mixing is episodic and depends on the growth of ice to generate sufficient saline water to induce convection.

In spring, the coldest point in the water column occurs in the lower part of the mixolimnion (Figure 6.2-1a). This minimum is a remnant of the reverse stratification of winter (Figure 6.2-1e). The presence of this temperature minimum in summer confirms that spring overturn did not occur and examples of this are given in the next section.

We now look at the defining feature of meromixis, a chemocline. If the lake is meromictic, there is a significant step in conductivity between the mixolimnion and the monimolimnion (at 20 m in Figure 6.2-1b). This step in conductivity prevents the mixolimnion from eroding the top of the monimolimnion. For the pit lake to remain meromictic, this step in conductivity must be larger than the increase in conductivity of the mixolimnion due to exclusion of salt from the ice. This is used as a criterion for meromixis in the next section.

A secondary feature that is often observed in meromixis is the gradual increase in conductivity with depth in the monimolimnion (Figure 6.2-1b). Note that this increase in conductivity stabilizes the increase in temperature that is often observed with depth (Figure 6.2-1a). A gradient in conductivity is observed in the deep water of meromictic lakes (e.g., Gibson 1999) and, as discussed in the next section, in those pits that are more strongly meromictic.

6.3 EXAMPLES OF PIT LAKE BEHAVIOUR

The following section describes conductivity-temperature-depth (CTD) profiles from six pit lakes of varying stability to illustrate meromixis and other processes that are potentially important to the proposed Ekati pit lakes. The characteristics of the example pit lakes are summarized in Table 6.3-1.

The six examples are located at three different sites. Three — Faro, Grum and Vangorda — are located at the Faro mine site in the Anvil Range, Yukon (Pieters and Lawrence 2006). The Main Zone and Waterline pit lakes are located on the Equity mine site near Houston, British Columbia, Canada (Crusius et al. 2003, Leung 2003, Whittle 2004, and Pieters et al. 2010). Zone 2 Pit is located at the Colomac Mine site, 200 km N of Yellowknife, NWT (Pieters and Lawrence 2009b, 2011).

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[3] The TMD, T_{MD} [ºC], depends slightly on salinity (TDS), S [g/L], T_{MD} = 3.98-0.22 S for S<2.

[4] The freezing point of water, T_f [ºC], only varies slightly with salinity, S [g/L]; over the range of S observed at EKATI, T_f = -0.054 S.

Table 6.3-1. Pit Lake Characteristics

Pit	Faro[a]	Grum[a]	Vangorda[a]	Water-line[b]	Main Zone[b]	Z2P[c]
Water level (masl)	1,066	1,185	1,089	1,265	1,260	332.3
Status of filling	Not full	Not full	Not full	Filled	Not full	Not full
Water level variation (m)	~3, pumped		Pumped	< 0.2	~2, pumped	~1 m
Max. depth (m)	~90	~50	~50	40	120	110
Surface area (m^2)	510,000	95,000	59,000	26,000	205,000	153,000
Volume (Mm^3)	~30	~2	~1	0.48	9.7	7.1
Est. inflow (m^3/y)	5.9×10^4	n/a	2.4×10^6	$\sim 2 \times 10^5$	$\sim 5 \times 10^5$	1.5×10^5
Bulk retention time (y)	50	n/a	0.4	2.4	20	~50
Total ice thickness (m)	0.5			~0.7		0.8
Mictic status	Strong	-	-	Weak	-	Weak

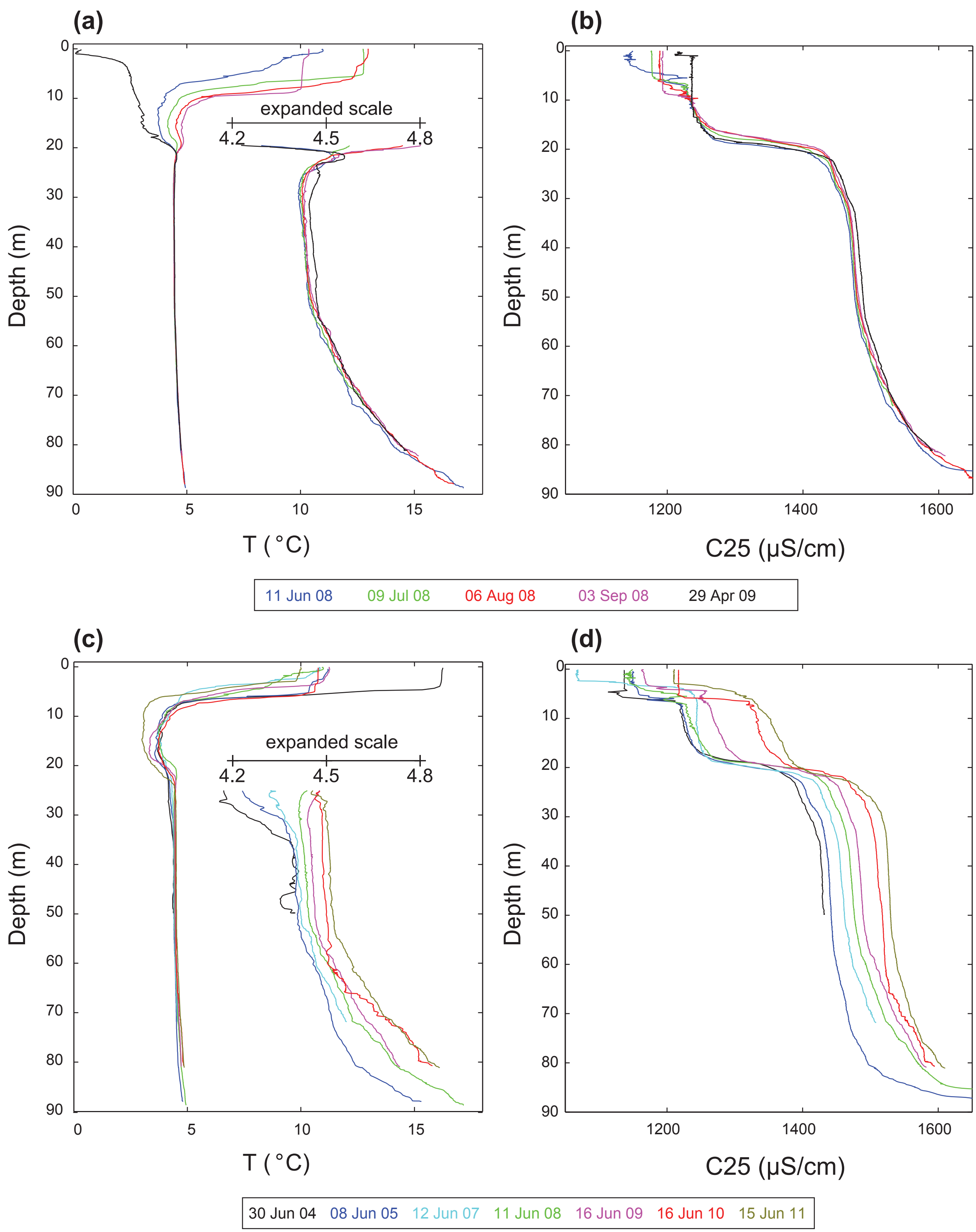
[a] *Faro mine site, 200 km north of Whitehorse, Yukon (62.353 N, 133.364 W).*
[b] *Equity Silver mine site, 30 km southeast of Houston B.C. (54.189 N, 126.263 W).*
[c] *Colomac mine site, 250 km north of Yellowknife, NWT (64.397 N, 115.089 W).*

Faro pit lake (Figure 6.3-1) displays characteristics of strong meromixis and follows the pattern described in the previous section. Of primary importance is the distinct chemocline at 20 m. Below the chemocline, the conductivity increases with depth in the monimolimnion. Above the chemocline, the June profile shows a fresh, warm surface layer to ~5 m depth (Figure 6.3-1a, b). Of particular note in June, is the temperature minimum in the mixolimnion at approximately 15 m; this relict from winter indicates that spring overturn did not occur. As summer progresses to fall, the surface layer deepens.

The first profiles of the open-water season in Faro pit lake are shown for 2004 to 2011 in Figure 6.3-1c, d. While there is little discernible change in temperature and conductivity in the deep water during any given year, there is a small, gradual increase in both temperature (~0.02ºC/y) and conductivity (~14 µS/cm/y) from 2004 to 2011. The cause of these increases is not known, but possibilities include groundwater inflow, geothermal heating, and remineralization (decomposition of organic matter to inorganic forms). Despite these small changes, the profiles suggest a high degree of isolation for the Faro deep water.

A second pit lake that displays meromixis is the Equity Waterline (Figure 6.3-2). There is a chemocline around 19 m and the conductivity increases below the chemocline. The spring profiles show a warm fresh surface layer (0 to 4 m) and a temperature minimum at the base of the mixolimnion (from 8 to 15 m). Isolation of the deep water is suggested by relatively constant temperature and conductivity and by the absence of dissolved oxygen (not shown). Note the results for Waterline are complicated by inflow of water at 17 m and possibly 32 m depth from adits connected to collapsed underground mine workings.

The Equity Main Zone pit lake provides a startling contrast to the Waterline as a result of acid rock drainage (ARD) neutralization sludge that enters the surface of the pit and sinks to the bottom (Pieters et al. 2010). This inflow effectively stirs the entire deep water of the pit as indicated by the uniform profiles of temperature and conductivity (Figure 6.3-3a, b). Besides mixing the deep water, the sludge also entrains water from the warm fresh surface layer and carries this surface water to depth. This weakens the summer stratification and results in the early onset of fall overturn. As a result of fall overturn the Main Zone is holomictic. A holomictic lake mixes completely at least once a year.



Notes: (a) Temperature and (b) conductivity profiles over one season, June 2008 to April 2009. The chemocline is located at 20 m.
(c) Temperature and (d) conductivity profiles, spring or early summer, 2004 to 2011. A warm fresh epilimnion can be seen in the top 5 m.

Figure 6.3-1

Faro Pit Lake Temperature and Conductivity Profiles, 2004 to 2011

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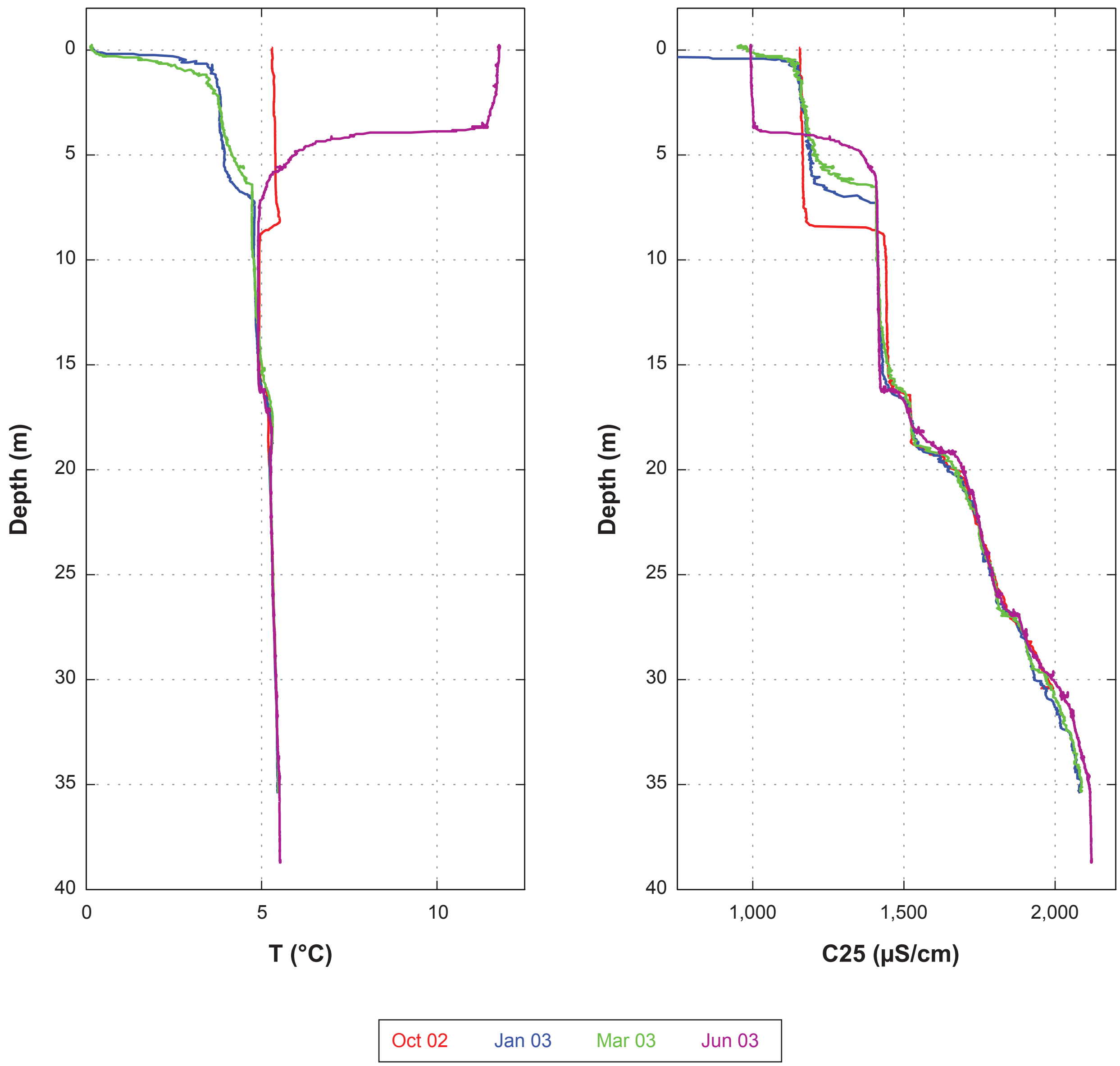

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Equity Silver Waterline Pit Lake Temperature and Conductivity Profiles, 2002 and 2003

Figure 6.3-2

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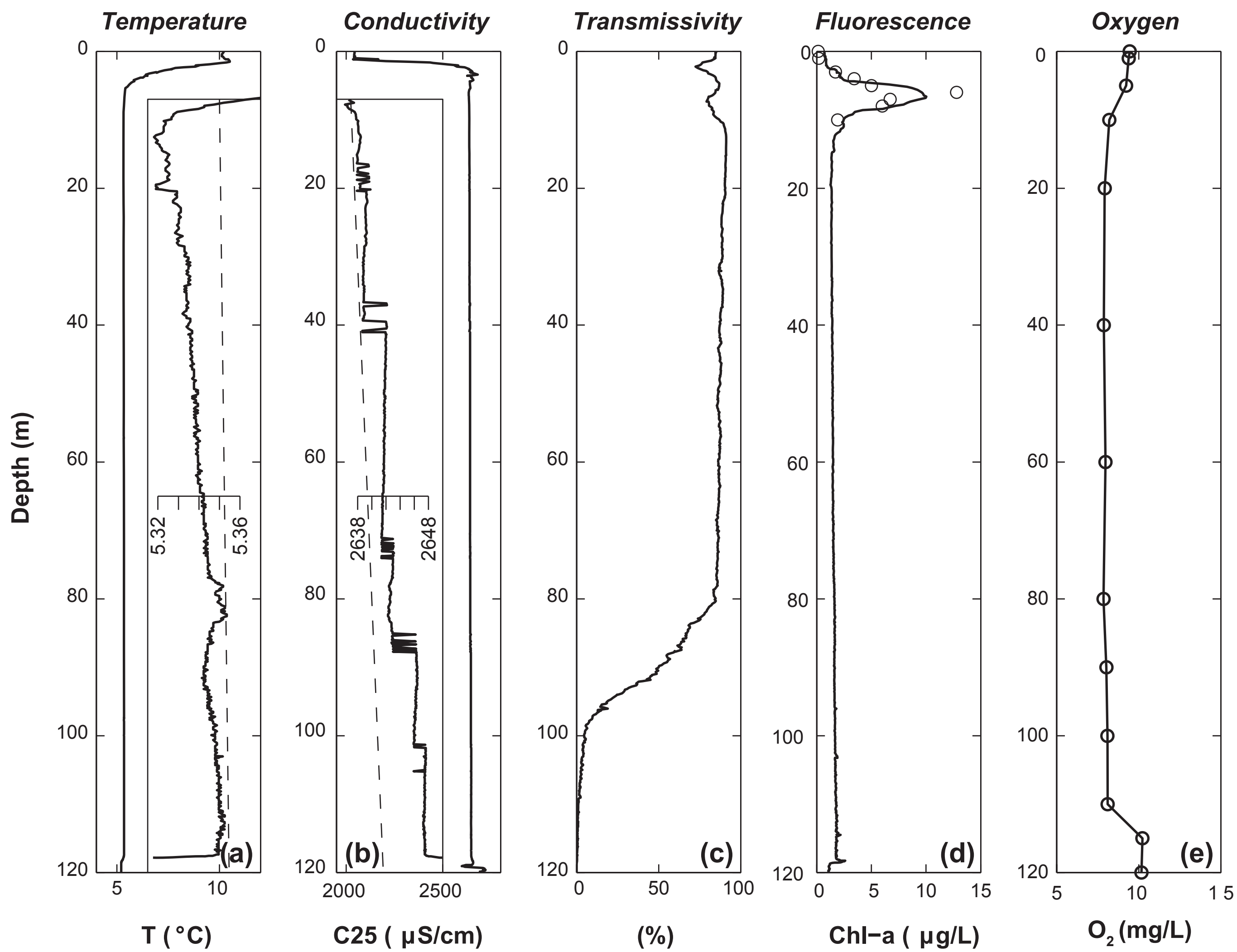

Figure 6.3-3

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Equity Silver Main Zone Pit Lake, June 25, 2001

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A signature of the sludge entering Main Zone can be seen in the light transmission (Figure 6.3-3c), with dramatically reduced transmission below 80 m. The height of this sludge "cloud" above the bottom varied with the rate of sludge inflow. The sludge cloud settled completely a few days after sludge inflow stopped. In addition to sludge, dissolved oxygen was also highest near the bottom, being carried to depth by the sludge inflow (Figure 6.3-3e).

Data from Grum pit appear similar to that from Main Zone and suggest that a similar process may be at work (Figure 6.3-4). While the volume of water flowing into Grum was low, the likely source of disturbance in Grum pit is the gradual failure of the east wall which is composed of till and which showed signs of active creep. Ongoing slumping, either above or below the water surface, likely explains the significant mixing observed.

Like Main Zone, the spring profiles in Grum show a fresh, warm surface layer but no chemocline (Figure 6.3-4). Also like Main Zone the temperature and conductivity profiles are relatively uniform with noise suggestive of active mixing. In addition, the temperature and conductivity of the deep water varies significantly with time indicating these waters are not isolated.

In contrast to Main Zone where fall overturn occurred, temperature chain data through fall 2004 indicate that overturn did not occur in Grum in fall 2004. What remains to be seen is whether spring overturn occurs in Grum. Based on Main Zone where spring overturn did not occur, we suggest that spring overturn with complete mixing is unlikely and tentatively classify Grum as weakly meromictic.

Vangorda, also on the Faro site, is used for storage of ARD from around the mine site and has a small retention time of 0.4 year. Profiles from the pit are shown in Figure 6.3-5. Unlike Grum and Main Zone the conductivity profiles appear to have a distinct chemocline at 13 to 18 m. However, what is immediately striking is that the conductivity and temperature of the deep water, and the depth of the chemocline, varies significantly over the year. There is also little gradient in temperature and conductivity in the deep water. The processes that lead to these changes in Vangorda are not known, but may result from pumping of water to and from the pit lake. Vangorda lacks temperature data from which to assess spring and fall overturn; we tentatively classify Vangorda as weakly meromictic.

In the Colomac Zone 2 Pit, the ice melt and freshet inflow are sufficient to suppress both spring and fall turnover. However, significant groundwater inflow at around 60 m depth (the elevation at which groundwater became a problem during mining, SRK 2000) has prevented Zone 2 Pit from developing strong meromixis (Figure 6.3-6). As the pit has filled, the conductivity of the pit lake has declined from 2004 to 2009; as the pit has approached full, the flow of groundwater has decreased and the conductivity of the pit has changed less rapidly. There is no significant chemocline, other than occasional small steps around 20 m (e.g., 2005 and 2009).

Indicators of meromixis: The main indicator of meromixis is the ability of the chemocline to resist mixing in fall, discussed in the next section. Here we examine two additional indicators. First, we evaluate the strength of the conductivity step at the chemocline against winter mixing. We ask what thickness of black ice would be needed to make the water above the chemocline (mixolimnion) as saline as the deep water (monimolimnion). This is the point at which mixing into the deep water could begin. We define δ to be the ratio of this hypothetical ice thickness needed to initiate mixing divided by the observed ice thickness. Values of δ are given in Table 6.3-2.

For Faro and Waterline with isolated deep water, $\delta > 1$ and it would take many times the observed ice thickness to initiate mixing into the deep water during winter. In contrast, for Zone 2 Pit in 2004/05, $\delta = 0.9$ and mixing occurred between the surface layer and the monimolimnion. However, for Zone 2 Pit in the subsequent winter, 2005/06, which was mild with less ice and poorer salt exclusion, $\delta = 1.4$, and no mixing with the monimolimnion occurred.

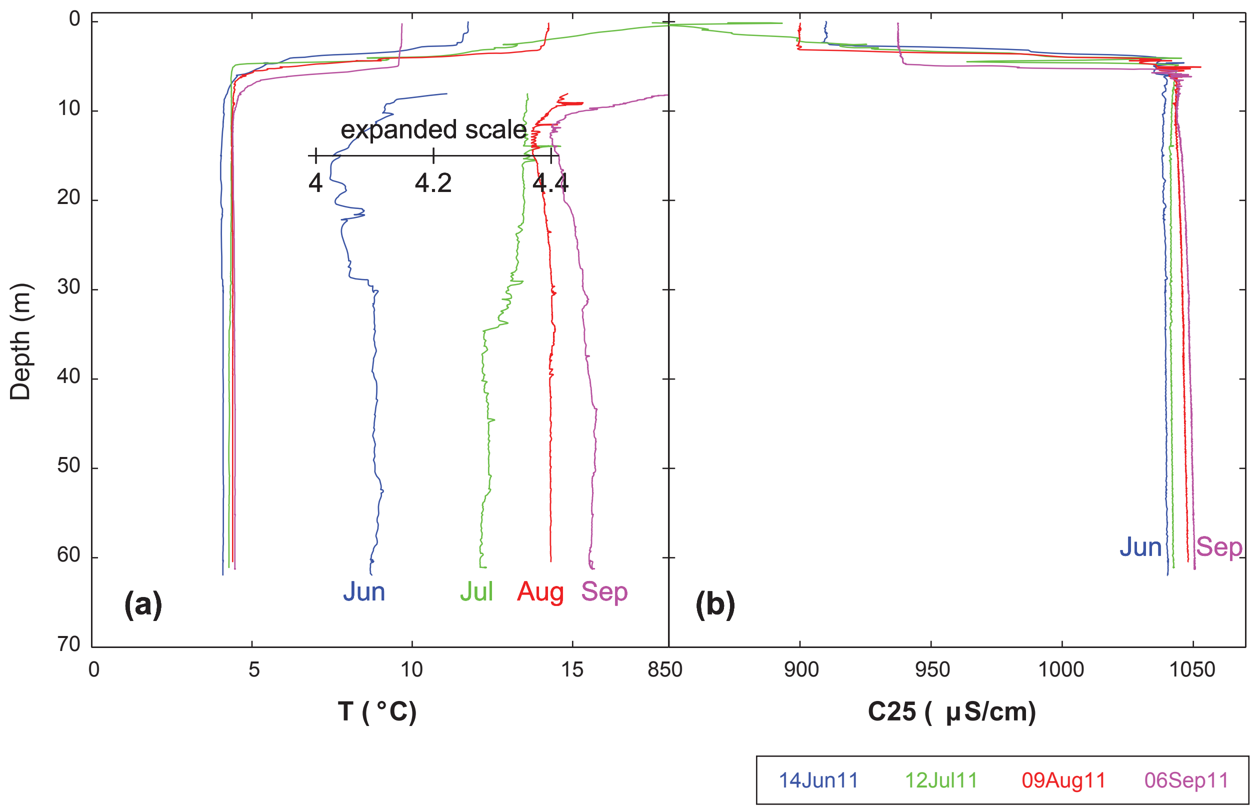

Figure 6.3-4

Grum Pit Lake Temperature and Conductivity Profiles, 2011

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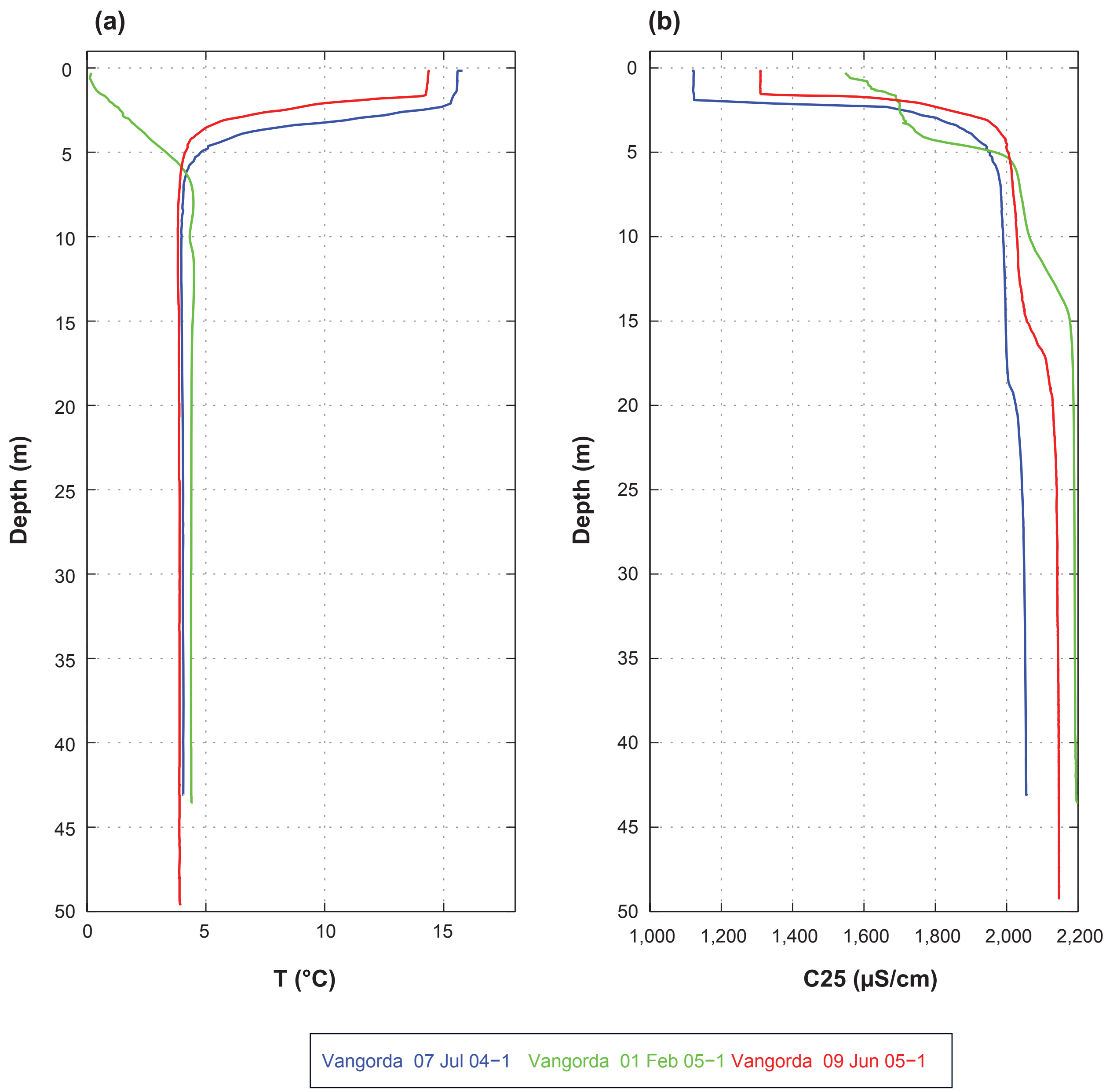

Vangorda Pit Lake Temperature and Conductivity Profiles, 2004 and 2005

Figure 6.3-5

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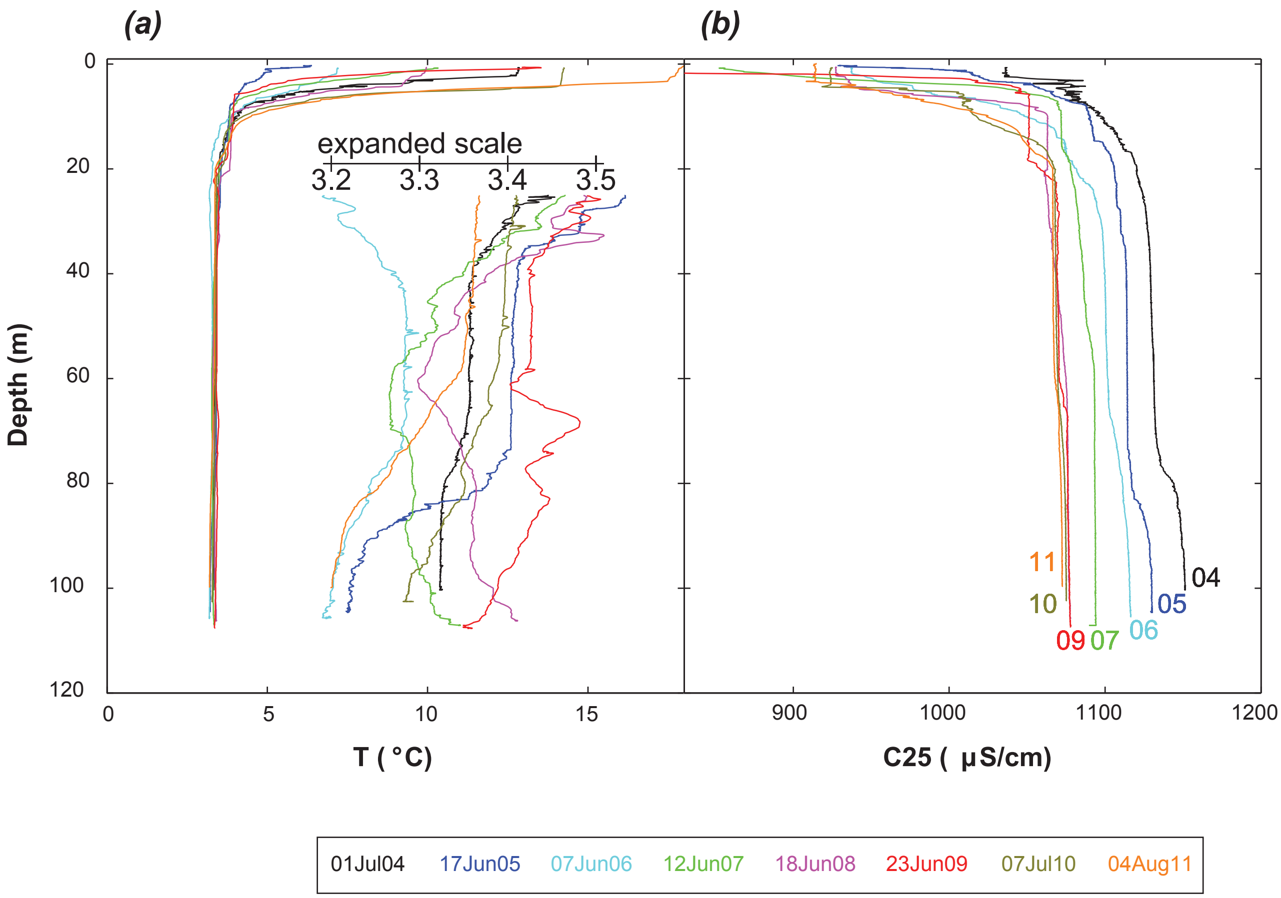

Figure 6.3-6

Zone 2 Pit Lake Temperature and Conductivity Profiles, Spring 2004-2011

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Table 6.3-2. Salinity Characteristics of the Example Pit Lakes

Pit lake	δ Ice-thickness Required to Initiate Mixing Divided by Measured Ice-thickness	Gradient in C25 in Deep Water (μS/cm m^{-1})	Mixing
Faro	11	1.7	Strong meromixis
Waterline	3	35[a]	Weak meromixis
Vangorda	1.4	0.2	Meromixis unlikely
Grum	1	0.2	Meromixis unlikely
Zone 2 Pit	0.9 (2004/05) 1.4 (2005/06)	0.2	Weak meromixis
Main Zone	n/a	0.1	Holomixis

[a] *Enhanced by groundwater inflows.*

The second feature is a conductivity gradient in the monimolimnion. The approximate gradient of conductivity in the monimolimnion (deep water) is given in Table 6.3-2. This change in conductivity with depth is large in the Faro and Waterline pit lakes that have potentially isolated deep water. In contrast, pit lakes that are known to be actively mixing (e.g., Main Zone) display little increase in conductivity with depth.

6.4 SALINITY STABILITY AND THE MEROMICTIC RATIO

The previous sections provided a qualitative description of how salinity differences between a fresh surface layer and the deep water can cause meromixis; this section provides a way to quantify these processes. To start, the stability of a lake is defined, and this stability is divided into temperature and salinity components. The salinity stability in summer is then compared to the reduction in salinity stability during the fall.

The stability of a lake gives the amount of energy needed to mix the entire lake (Wetzel 2001); this energy is usually divided by the area of the lake to give units of J/m^2. In a stratified lake, the surface layer is less dense and the deep water is denser. Stratification may result from temperature, salt or both. When the entire lake is mixed, the dense deep water is lifted and mixed throughout the lake: this raises the center of mass of the water in the lake, doing work against gravity. The stability integrates the amount of work that must be done against gravity.

In the middle of summer, pit lakes will be stratified in both temperature and salinity. However, just before freeze up, the lake will have cooled until the temperature is relatively uniform and temperature will no longer contribute significantly to stability. During this time, salinity stability alone resists mixing. Therefore, it is the salinity stratification that determines whether or not meromixis will occur.

The stability due to both temperature and salinity is given by:

$$St_{TOT} = \frac{g}{A_0}\int_0^H (\rho(z) - \bar{\rho})\, z\, A(z)\, dz \quad [\mathrm{J\ m^{-2}}] \qquad (1)$$

where z is the depth from the surface, $\rho(z)$ is the density, $\bar{\rho} = \frac{1}{V}\int_0^H \rho(z)\, A(z)\, dz$ is the mean density, *A(z)* is the area of the pit, $A_o = A(0)$ is the surface area, *H* is the total depth, *V* is the total volume, and *g* is gravity.

For salinities of interest at the Ekati site, density can be separated into temperature and salinity components following Chen and Millero (1986):

$$\rho(z) = \rho(z)_{S=0} + \beta\, S(z) \;\; [\mathrm{kg/m^3}] \tag{2}$$

where $\beta \approx 0.8$ and S [mg/L] is salinity (TDS). Similarly, the mean density can be separated into temperature and salinity components:

$$\overline{\rho} = \overline{\rho}_{S=0} + \beta\, \overline{S} \tag{3}$$

where $\overline{\rho}_{S=0} = \dfrac{1}{V}\displaystyle\int_0^H \rho(z)_{S=0}\, A(z)\, dz$ and $\overline{S} = \dfrac{1}{V}\displaystyle\int_0^H S(z)\, A(z)\, dz$. Substituting (2) and (3) into (1) gives:

$$St_{TOT} = St_T + St_S \tag{4}$$

where St_T gives the stability due to temperature, and St_S give the stability due to salinity:

$$St_T = \frac{g}{A_0}\int_0^H (\rho(z) - \overline{\rho}_{S=0})\, z\, A(z)\, dz$$

$$St_S = \frac{g\beta}{A_0}\int_0^H \left(S(z) - \overline{S}\right) z\, A(z)\, dz$$

To determine the stability in the fall, we start with the salinity stability at the approximate end of the warming period (late August), which we define as St_S^*. The salinity stability in summer, St_S^*, excludes the large and changing effect of temperature. St_S, is then compared to typical changes of salinity stability over the fall, ΔSt_S, observed at other sites. If $St_S^* >> \Delta St_S$, meromixis is likely and if $St_S^* \sim \Delta St_S$ then meromixis is unlikely.

The salinity stability at the end of the warming period, St_S^*, for Waterline is approximately 200 J/m^2. We wish to compare St_S^* with the reduction in salinity stability during the cooling period, ΔSt_S. For the Waterline pit lake in fall 2001, ΔSt_S was approximately 13 J/m^2. The meromictic ratio M = $St_S^*/\Delta St_S$ (15 for Waterline) is an indicator of the likelihood of meromixis. The higher M, the more likely the lake is to be meromictic. For the proposed Ekati pit lakes the average value from the Waterline, Z2P and Faro pit lakes of ΔSt_S = 20 J/m^2 is used as a point of comparison (Table 6.4-1).

Table 6.4-1. Meromictic Ratio for Comparison Sites

Site	Mictic Status	Year	St_S^* (J/m^2)	ΔSt_S (J/m^2)	M = $St_S^*/\Delta St_S$
Waterline	Weakly meromictic	2001	200	13	15
Z2P	Weakly meromictic	2004	140	25	6
		2005	145	~19	8
Faro	Meromictic	2004	700	~20	~35

6.5 FACTORS THAT AFFECT MEROMIXIS

6.5.1 Factors that Enhance Stability

6.5.1.1 Relative Depth

Pit lakes are characterized by a small surface area relative to their maximum depth. This reduces the ability of wind stress and surface cooling to affect mixing. The relative depth scales the maximum depth by the equivalent diameter of the surface area:

$$h_r = \frac{h_{\max}}{2\sqrt{A/\pi}}$$

where $h_{\max}$ is the maximum depth of the pit lake and A is the surface area. A high relative depth indicates a small surface area.

Most lakes have a small relative depth, $h_r < 0.02$ and lakes that are considered deep with a small surface area have $h_r > 0.04$ (Wetzel 2001). The relative depth of the example and Ekati pit lakes is given in Table 6.5-1. The relative depth of the example pits is much higher than 0.04, averaging 0.19. The relative depth of the Ekati pit lakes is higher yet, averaging 0.37. This is consistent with the circular shape and very steep slopes in the Ekati pits that reflects the nature of the kimberlite pipes.

Table 6.5-1. Relative Depth of the Example and Ekati Pit Lakes

Pit	Relative Depth
Example Pits[a]	
Faro	0.11
Grum	0.14
Vangorda	0.18
Waterline	0.22
Main Zone	0.23
Zone 2 Pit	0.25
Ekati Pits	
Sable	0.33
Misery	0.34
Pigeon	0.40
Panda	0.44
Koala/Koala North	0.40
Fox	0.36
Beartooth	0.45

[a] *See Section 6.3 for detail.*

6.5.1.2 Pit Lake Salinity and Ice Cover

While relative depth is important, it does not predict meromixis. Rather the key factor predicting meromixis is an increase in salinity between the surface and deep water. As seen for the example pit lakes, the chemocline must provide sufficient density difference to resist mixing in fall, and the salinity step must be large enough to prevent the surface layer from becoming as saline as the deep water in winter.

For northern pit lakes, the primary source of a chemocline is melting of relatively fresh ice. There is only a handful of data on salt exclusion from lake-ice (see references in Pieters and Lawrence 2009a). However, data from the Colomac site in 2004/2005 gave 97 to 99% of salt excluded from four water bodies ranging in salinity from 50 to 960 mg/L, which suggests that the proportion of salt excluded from ice is independent of the salinity.

Increasing the salinity increases the density contrast between the freshwater layer and the deep water. Increasing the thickness of ice increases the amount of fresh ice-melt the next summer. As a result the summer stability increases with both salinity and the thickness of the ice.

6.5.1.3 Inflow Salinity and Volume

The Ekati site is located in a region of relatively low annual precipitation (338 mm) and most of the Ekati pit lakes have relatively small drainage areas. As a result the inflow from the surrounding drainage to these pit lakes is relatively small, and is less important than ice cover in establishing a fresh-water layer on the surface of the pit. However, the inflows can play an important role in flushing the surface layer of the pit lake and, in the long run, this inflow can increase the stability significantly.

The salinity of the inflow is also important. If the salinity of the inflow is lower than that of the surface mixed layer, then inflows reduce the salinity of the surface mixed layer and increase stability. However, if the salinity of the inflow is higher than that of the surface mixed layer, the inflow makes the surface mixed layer more saline, reducing the stability and making under-ice mixing more likely the following winter.

6.5.2 Factors that Induce Mixing

6.5.2.1 Wind and Cooling

In the open water season mixing occurs as the surface layer deepens, driven by wind and surface cooling. Wind drives turbulence, shear at the pycnocline, and upwelling; while surface cooling drives penetrative convection. All of these processes can act to deepen the surface mixed layer. As the surface layer deepens, it becomes more saline as it entrains deeper water, decreasing the salinity stability.

6.5.2.2 Ice

The dual role of ice in both stabilizing and destabilizing meromixis has already been discussed in Section 6.3. Not only can the fresh ice-melt create meromixis, but, under special circumstances, salt excluded from the ice can induce mixing into the monimolimnion under the ice. As discussed, this would occur when sufficient salt was excluded from the ice to raise the salinity of the mixolimnion to that of the monimolimnion ($\delta \leq 1$). This would be possible in pit lakes with no runoff, or when saline runoff displaces fresh water in the surface layer. This is unlikely to occur in the pit lakes predicted to be meromictic at the Ekati site because natural runoff has low salinity, and while the drainage areas are small, the volume of runoff is sufficient to flush the surface layer over time.

6.5.2.3 Other Factors

Of the six examples discussed, only one displays strong meromixis (Faro) and one shows evidence of strong meromixis despite inflow from submerged mine workings (Waterline). The remaining pits, as well as other pit lakes not discussed here, illustrate a wide variety of potential disturbances to meromixis:

- rock falls (observed in Zone 2 Pit);
- active creep and subsidence of till wall (Grum);

- injection of water through underground mine workings (Waterline) or conveyor shafts (Island Copper; Fisher and Lawrence 2006);
- groundwater inflow (Zone 2 Pit and Brenda; Stevens and Lawrence 1998);
- restoration of diverted creek flow (planned for Faro and Grum);
- pumping water out of the pit lake from a selected depth (Grum and Main Zone);
- disposal of fresh water runoff around the mine site (Grum, Vangorda);
- disposal of dense sludge to the surface (Main Zone); and
- injection of ARD to depth (Island Copper, see Pelletier et al. 2009).

6.6 BASE CASE RESULTS

The previous sections discussed meromixis and the factors that control meromixis. This and following sections will describe the results of the multi-layer model described in Section 4.1.2 for the long-term evolution of each filled pit lake.

This section considers the Base Case of the pit-infilling analysis (Section 5.2). As the pit filled, this Base Case included sump water, pit wall runoff, pumped inflow from natural lakes, and groundwater. This resulted in pit lakes with initial salinities summarized in Table 6.6-1. The quality of water flowing from the filled pit lakes is discussed in the next chapter.

Table 6.6-1. Pit Lake Stability Results, Base Case

Pit	Max. Pit Depth (m)	Initial Model Salinity (mg/L)	M Year 1	M Year 250	Mictic Status
Sable	234	20	0.6	0.5	Not meromicitic
Misery	275	10	0.2	0.3	Not meromictic
Pigeon	179	9	0.1	0.4	Not meromictic
Panda	294	1,630	82	900	Strong meromixis
Koala/Koala North	249	1,400	61	760	Strong meromixis
Fox	310	135	6	95	Weak meromixis at first, developing into strong meromixis
Beartooth	30	790	8.2	0.1	Not meromicitic

Once the pit lakes have filled, the Base Case for pit lake evolution assumes that all groundwater inflows cease, with groundwater flows tending to zero as the pit lakes fill. The effect of pit-wall runoff and groundwater inflow, along with other factors is discussed in subsequent sections.

The results for each pit lake are summarized in Figures 6.6-1 to 6.6-8. In the first panel (a), the blue line is shown with two different scales, giving the salinity stability, St_S^* (blue line read from the left scale), and the meromictic ratio, M (blue line read from the right scale), both on August 31 of each year, which assesses the likelihood of meromixis (Section 6.4). The dash line marks M = 1. If M ≤ 1 the pit is unlikely to be meromicitic and mixing during the fall is likely to extend to the bottom of the pit lake. If M >> 1 then meromixis is likely and mixing will not extend to the bottom. The second panel (b) gives the predicted depth to which the surface layer mixed in the fall, at the time of ice-on. The third panel (c) gives the predicted salinity of the surface layer (red) and deep water (blue) of the pit lake at ice-on. Included in this panel are the initial salinity of the pit lake (dashed line) and the mean salinity of all inflow (dotted line). The results for all eight pit lakes are summarized in Table 6.6-1.

6.6.1 Group 1: Open Pits with No Groundwater and No Meta-sediments within the Pit Walls

6.6.1.1 Sable Pit Lake

Sable pit has a small local drainage of 0.6 km^2 and no stream inflow (Table 3-2). Sable pit will have a depth of 234 m and the predicted initial salinity of Sable pit for the Base Case is very low, 20 mg/L, with a relatively low variability in potential initial salinity values, even with changes to inflow parameters (as discussed in Section 7.1.2.1). The predicted salinity stability at maximum heat content (31 August) was also very low, 10 to 11 J/m^2 (Figure 6.6-1a). As this is less than the change in salinity stability through the fall, ΔSt_S = 20 J/m^2, the model mixed to the bottom by the time of ice-on every year (Figure 6.6-1b) and meromixis does not occur.

Figure 6.6-1c shows the salinity of the surface and deep water of the pit at ice-on for each year; because the pit mixes to the bottom the surface salinity (red line) is the same as that of the deep water (blue line). The salinity of the pit lake gradually declines with time, due to the inflow of natural runoff and precipitation on the pit lake surface. The dashed line at the top give the initial salinity of the pit, and the dotted line marks the flow-weighted average salinity of all the inflows, which is ~10 mg/L for Sable. The initial water in the pit lake is gradually being flushed by the inflow with a timescale of ~1,000 years.

The flushing in the model takes longer than the bulk flushing time of the pit lake, V/q_{in} ~ 300 years, where V is the pit volume and q_{in} is the net inflow. The actual flushing takes longer because the pit lake is stratified during the open water season and the inflow flushes only the surface mixed layer and not the whole pit. In effect, the inflow short-circuits through the shallow surface layer and the outflow carries away less salt than if the inflow were mixed throughout the pit.

6.6.2 Group 2: Open Pits with No Groundwater and with Meta-sediments in the Pit Walls

6.6.2.1 Misery Pit Lake

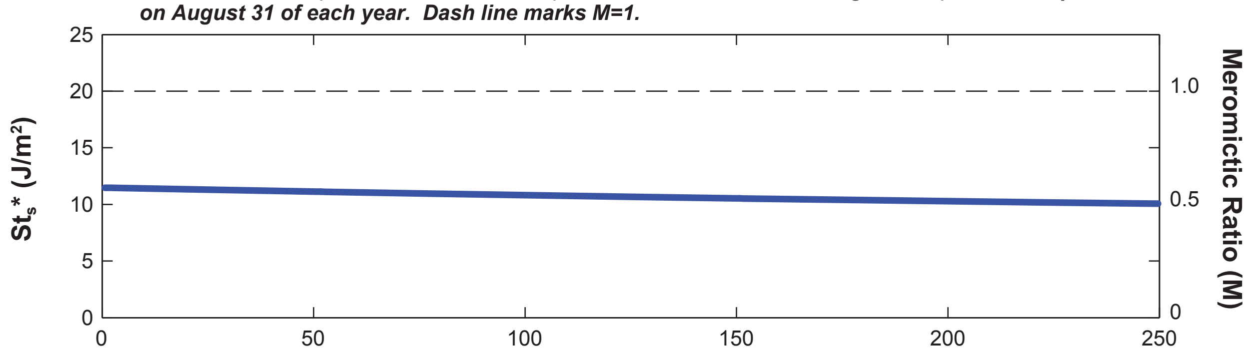
The final depth of Misery pit will be 275 m (Table 3-1). Misery pit has a very small drainage area of 0.02 km^2, limited to ground adjacent to the pit and which slopes into the pit lake.

The predicted initial salinity of the full pit lake is only 10.1 mg/L. The predicted salinity stability for August 31 of the first model year was 3 J/m^2, much less than ΔSt_S = 20 J/m and as a result meromixis is not predicted (Figure 6.6-2a). Over time post-infilling, the salinity of the pit lake is predicted to increase slightly as a result of loadings from exposed pit walls, but this is insufficient to produce meromixis within the pit lake. As the mean salinity of the inflow is 56 mg/L the final pit lake salinity cannot exceed this value and will likely be much lower as loadings from pit wall runoff would be expected to decrease over time (Figure 6.6-2c).

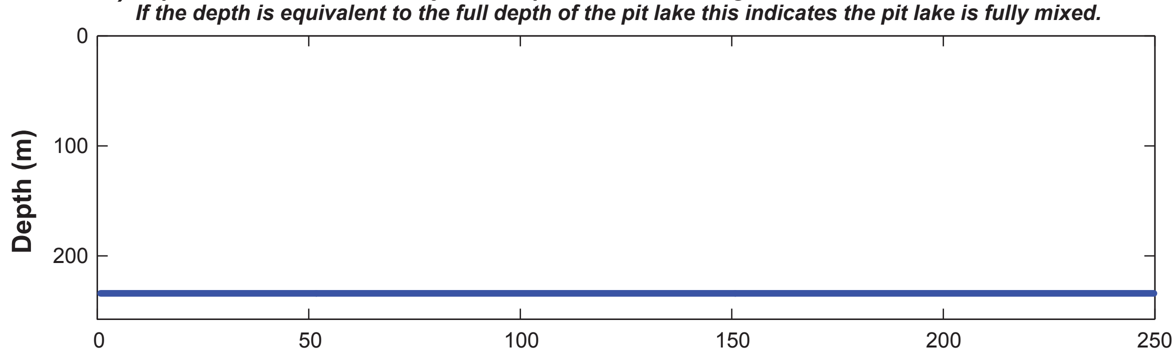
6.6.2.2 Pigeon Pit Lake

Mining at Pigeon has yet to commence. Of the three potential pit layouts outlined in EBA (2010), V17 is considered here; the predicted behaviour of V20 and V26 will be very similar. While Pigeon Pit has a large drainage (10.5 km^2), most of this is planned to flow around the pit lake through the Pigeon stream diversion. The diversion channel is planned to remain open after closure (BHP Billiton 2011a). The remaining area draining to Pigeon Pit (V17) is small, only 0.11 km^2.

a) *The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.*



b) *Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.*



c) *Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).*

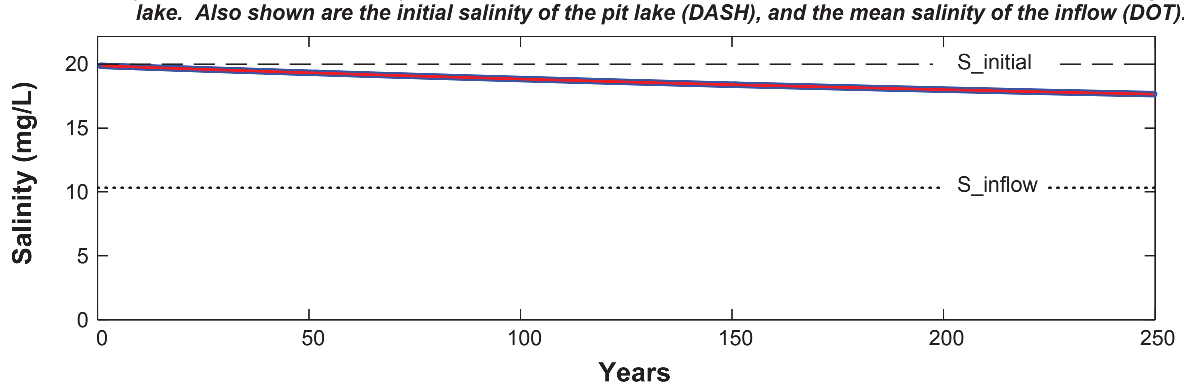
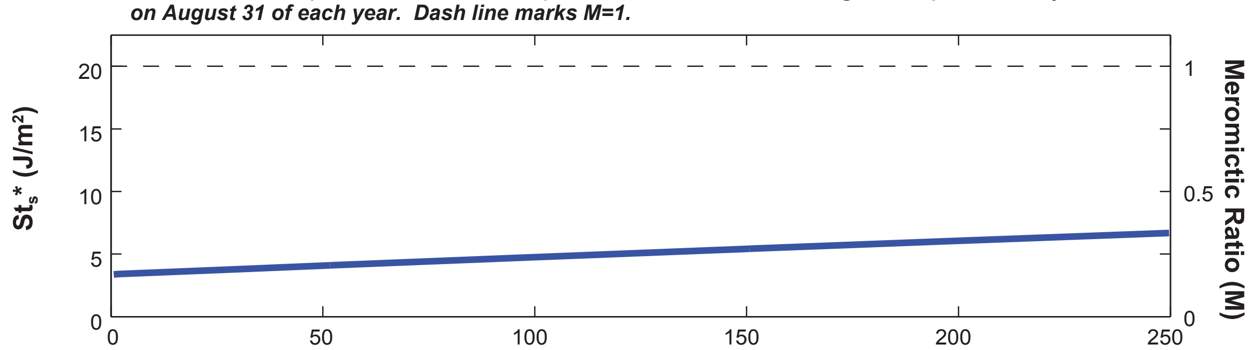


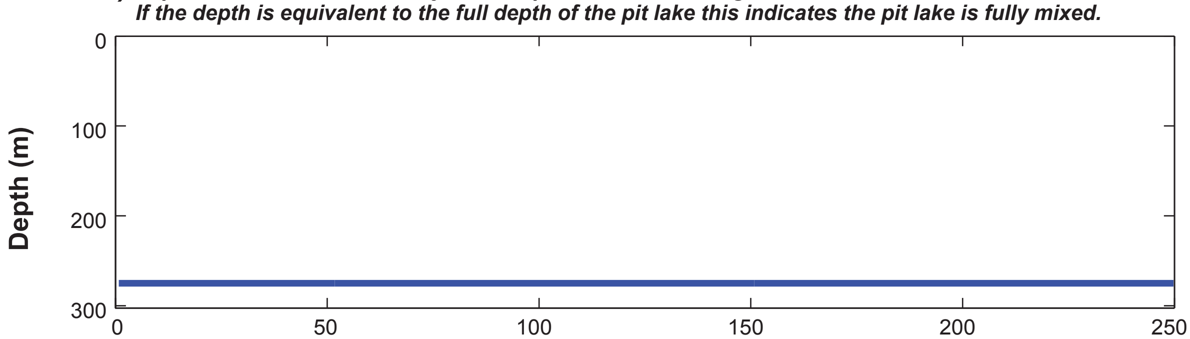
Figure 6.6-1

Predicted Stability of Sable Pit Lake

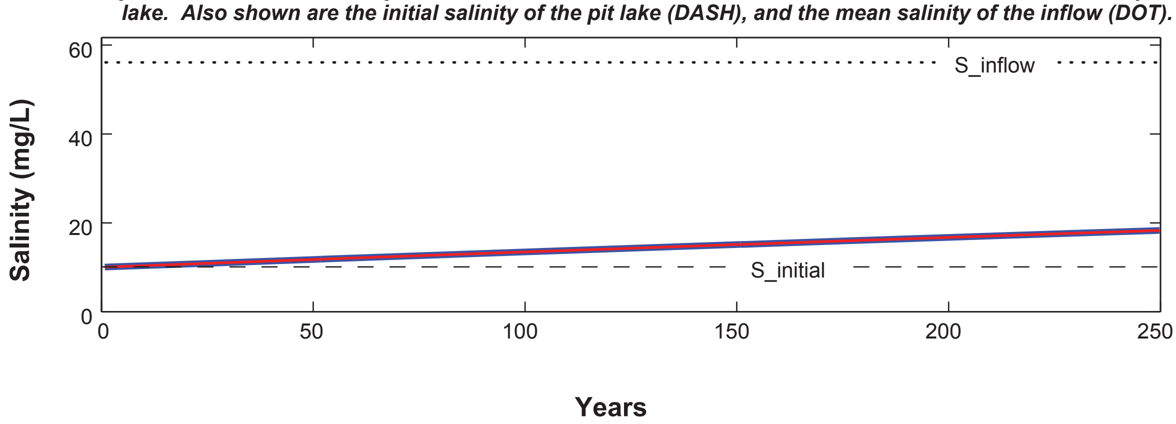
a) *The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.*



b) *Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.*



c) *Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).*



Predicted Stability of Misery Pit Lake

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Pigeon Pit Lake will have a depth of 179 m and, like Sable, is predicted to have a low initial salinity of 9 mg/L. The salinity stability in Pigeon Pit at the end of August was very low, 1 to 8 J/m^2 (Figure 6.6-3a), much less than ΔSt_S = 20 J/m^2, and meromixis is not predicted. Pigeon is predicted to mix to the bottom each year (Figure 6.6-3b). Over time post-infilling, the salinity of the pit lake is predicted to increase slightly as a result of loadings from exposed pit walls, but this is insufficient to produce meromixis within the pit lake. As the mean salinity of the inflow is 36 mg/L the final pit lake salinity cannot exceed this value and will likely be much lower as loadings from pit wall runoff would be expected to decrease over time.

6.6.3 Group 3: Open Pits that Have Groundwater Inflows

6.6.3.1 Panda Pit Lake

Panda and Koala/Koala North pit lakes are connected at depth through underground workings. At the surface, while there is a relatively large watershed upstream of Panda Pit, most of the runoff from the watershed will flow around the pit lake through the Panda Diversion Channel, which will be retained after closure. As a result, the remaining area draining to Panda pit is 1.6 km^2 (Table 3-2).

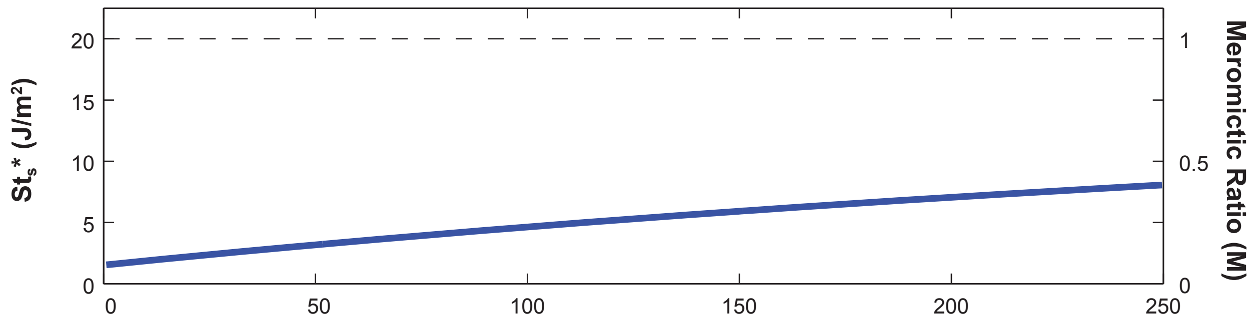
The predicted initial salinity for the Base Case for Panda pit lake is 1,630 mg/L, with the high salinity values resulting from groundwater inflows into the filling pit lake. The salinity stability on August 31 of the first model year was 1,600 J/m^2 which is larger than ΔSt_S = 20 J/m^2 and gives M = 80, predicting meromixis (Figure 6.6-4a). The surface layer initially mixes to just over 5 m and deepens slowly with time (Figure 6.6-4b). As time progresses the salinity of the surface layer decreases as a result of flushing with fresh inflow (Figure 6.6-4c). This increases the stability significantly, so that after 250 years M ~900, and strong meromixis is predicted into the future. It should be noted that meromixis is predicted assuming there are no additional groundwater inflows into the pit lake once full. As outlined in Chapter 4, the Base Case assumption is that groundwater inflows tend to zero as the pit fills.

6.6.3.2 Koala/Koala North Pit Lake

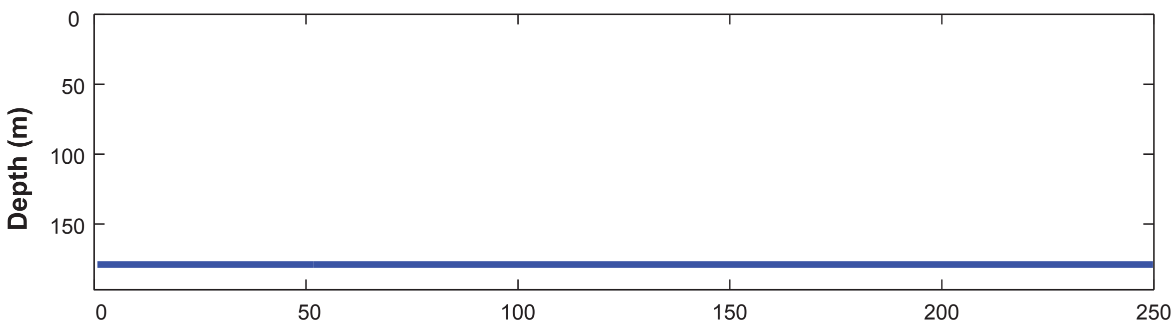
Koala/Koala North pit lake is connected at depth to Panda pit lake through underground workings. At the surface the pit lake will receive runoff from a local drainage of 0.64 km^2, plus the outflow from Panda pit lake. The initial salinity of Koala/Koala North pit lake was predicted to be 1,400 mg/L. The salinity stability on 31 August of the first model year is predicted to be 1,200 J/m^2, much greater than ΔSt_S = 20 J/m^2, giving M = 60, indicating meromixis (Figure 6.6-5a). The surface layer is initially 6 m deepening over time to 21 m (Figure 6.6-5b). Like Panda pit lake, as the surface layer is flushed, and as the salinity of the surface layer decreases (Figure 6.6-5c), the stability rises significantly to give M > 700 indicating strong meromixis. It should be noted that meromixis is predicted assuming there are no additional groundwater inflows into the pit lake once full. As outlined in Chapter 4, the Base Case assumption is that groundwater inflows tend to zero as the pit fills.

Once filled Koala/Koala North pit lake will have a single surface expression and they are considered as a single pit lake in this analysis. However, the Koala North pit is significantly shallower than Koala pit. A series of model runs were undertaken to assess whether the meromixis would extend to include the Koala North pit area. Results indicated that meromixis would occur (Figure 6.6-6a). After year 150, deepening of the surface layer causes the stability of the meromixis in Koala North to gradually decline. Predicting whether Koala North will gradually mix significantly deeper over time scales longer than 250 years is unlikely to be reliable; but it would appear that meromixis is likely to occur for periods of at least 150 years, see also discussion of groundwater in Section 6.7.

a) ***The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.***



b) ***Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.***



c) ***Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).***

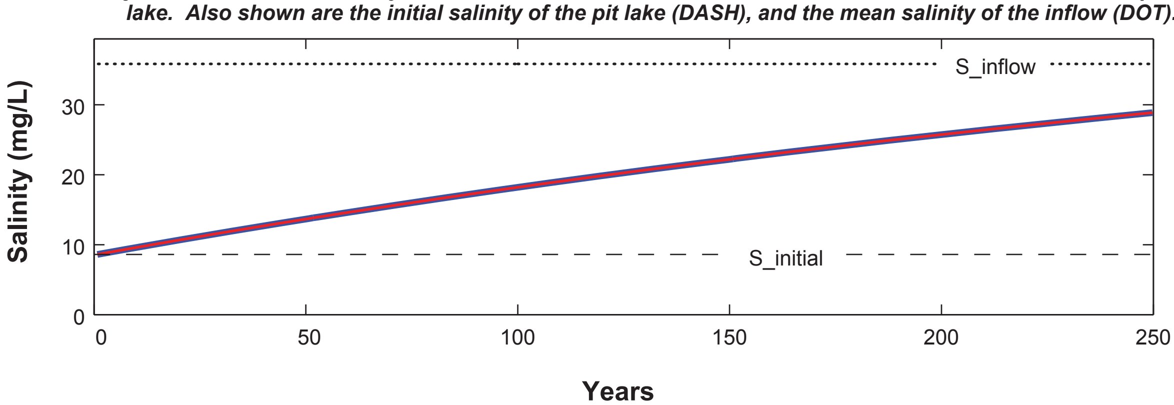


Figure 6.6-3

Predicted Stability of Pigeon Pit Lake

a) *The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.*

b) *Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.*

c) *Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).*

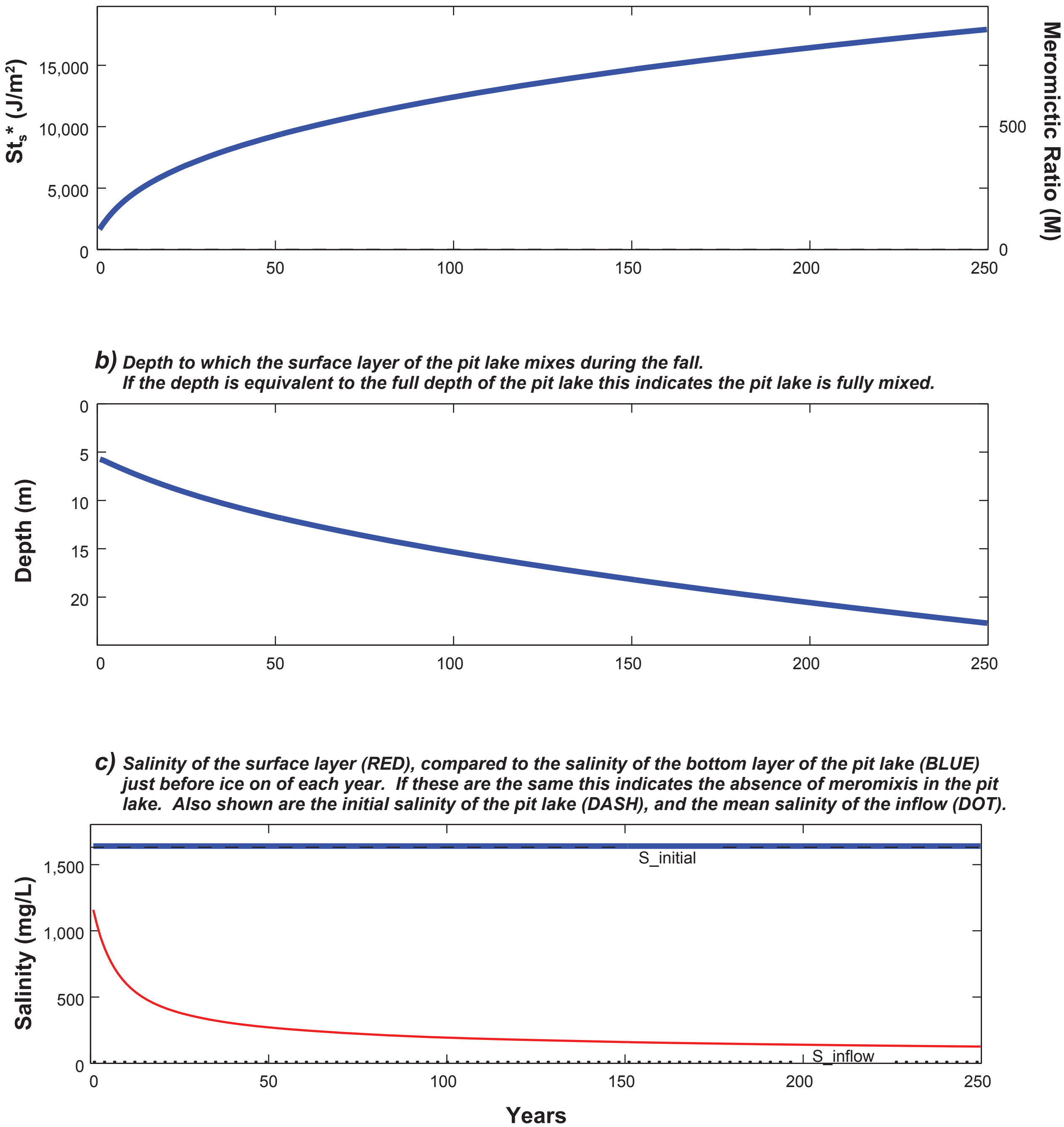


Figure 6.6-4

Predicted Stability of Panda Pit Lake

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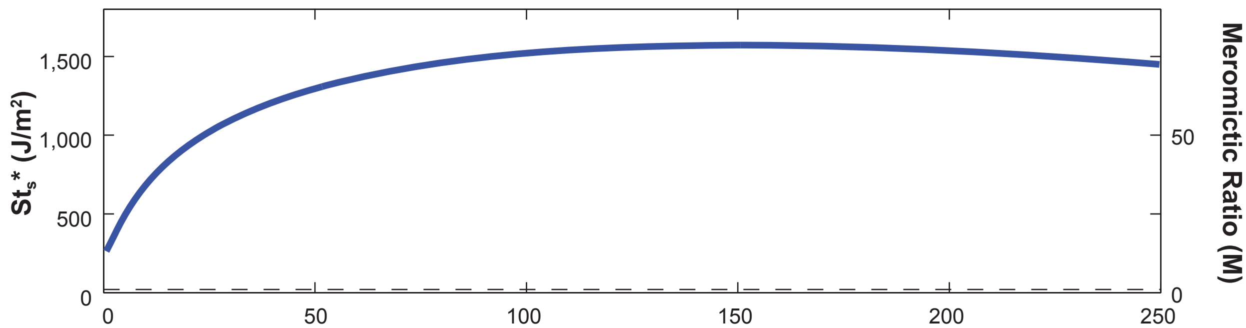
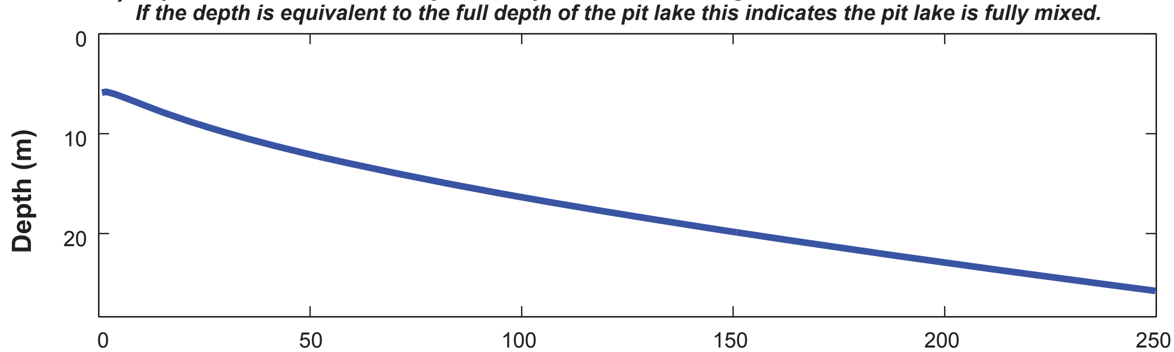
a) The blue line is shown with two different scales giving the salinity stability (St_s, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.*



b) Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.



c) Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).

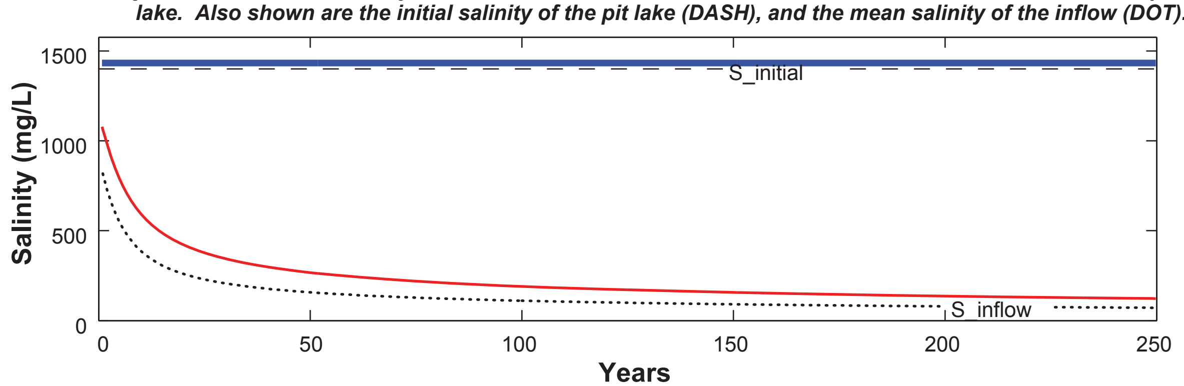
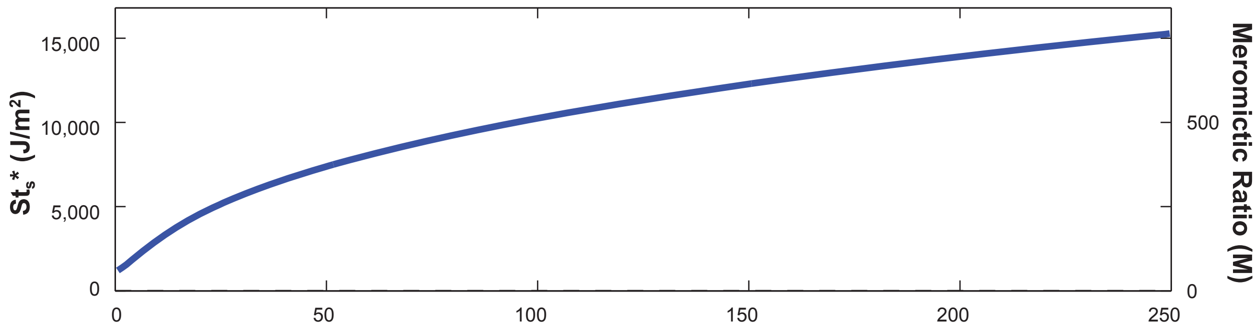


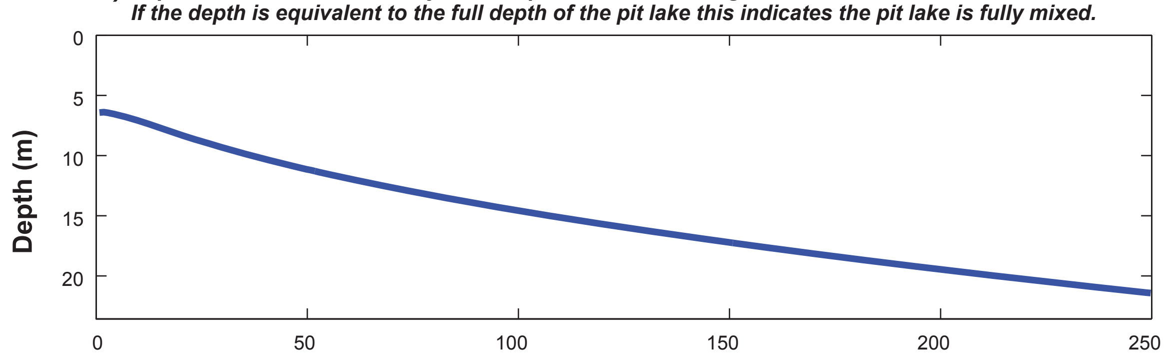
Figure 6.6-5

Predicted Stability of Koala Pit Lake

a) The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.



b) Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.



c) Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).

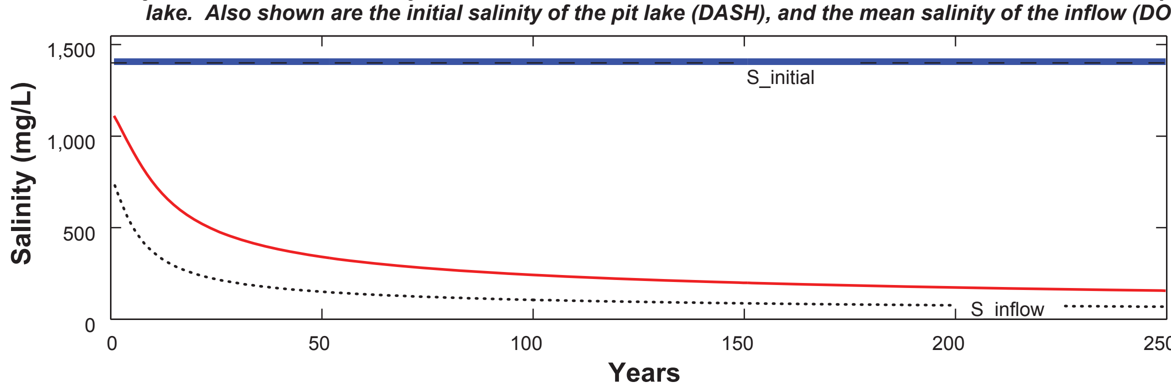


Figure 6.6-6

Predicted Stability of Koala North Pit Lake

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6.6.3.3 Fox Pit Lake

Fox pit will have a maximum depth of 310 m and will be the deepest of the open pits. While Fox has a large natural drainage area of almost 11 km^2, all but 0.28 km^2 will remain diverted around the pit at closure. The drainage to Fox also includes 2 km^2 of WRSA. The predicted initial salinity for the Base Case for Fox pit is 135 mg/L. The predicted salinity stability for 31 August of the first model year for Fox pit is 120 J/m^2, larger than $\Delta St_S = 20\ J/m^2$, and giving M = 6 (Figure 6.6-7a). As a result weak meromixis is predicted.

The initial salinity stability in Fox pit lake is less than that of Panda and Koala/Koala North, the other three pit lakes that receive groundwater inflows. Fox pit lake has lower salinity as groundwater inflow rates are predicted to be lower for Fox that for the other two pit lakes. In keeping with this lower salinity stability, the depth of the initial surface mixed layer in Fox is deeper, beginning at 32 m (Figure 6.6-7b), while the surface layer in Panda and Koala/Koala North began at around 5 m in depth. The stability of Fox pit lake increases as the surface layer is flushed (Figure 6.6-7c), increasing to M = 94 suggesting meromixis with a mixolimnion of 60 to 70 m depth.

6.6.4 Group 4: Open Pit Partially Infilled with Mine Water and Mine Solids

6.6.4.1 Beartooth Pit Lake

Mining is complete at Beartooth, and the pit will be used to store FPK solids and mine water (FPK supernatant and underground water) during operations. At closure remaining mine water will be pumped from the pit lake and a cover of fresh water will be pumped into the pit lake. Hence, the Base Case scenario for Beartooth pit considers the pit filled to within 30 m of the surface with FPK solids. It is assumed that the cap is composed of 25 m of fresh water and 5 m of residual mine water. It is assumed that not all of the mine water was able to be physically removed at the end of operations.

The initial salinity of Beartooth pit lake for the Base Case is predicted to be 790 mg/L. The salinity stability of Beartooth Pit lake at the end of the first year is expected to be 160 J/m^2, giving M = 8 (Figure 6.6-8a). In the first year the surface layer is predicted to mix to only 6 m, however in subsequent years the surface layer will continue to deepen until just after year 150 the surface layer reached the bottom and meromixis is no long predicted (Figure 6.6-8b). Due to inter-annual variability (Section 6.6.10), the depth to which the pit will mix is likely to vary significantly from year to year and intermittent meromixis would be expected.

The loss of meromixis would occur because Beartooth is shallow (30 m deep); at first the stability increases as the surface layer gets deeper and the fresh water cover increases (year 0 to 40, Figure 6.6-8a). However, once the surface mixed layer reaches half depth around year 40, the stability begins to decline as the surface layer deepens.

Beartooth has a small local drainage of 0.21 km^2 and receives outflow from Bearclaw Lake draining 1.66 km^2 s (Table 3-2). Flows from this relatively large drainage flushes the surface layer of the pit lake and salinity in the upper layer drops rapidly (Figure 6.6-8c). At first this contributes to the increased stability, until the surface layer depth reaches about 15 m. However, as the surface layer deepens past 15 m, more of the pit lake is flushed until the salinity of the entire pit lake is less than 100 mg/L after year 150 (Figure 6.6-8c), and meromixis is no longer likely.

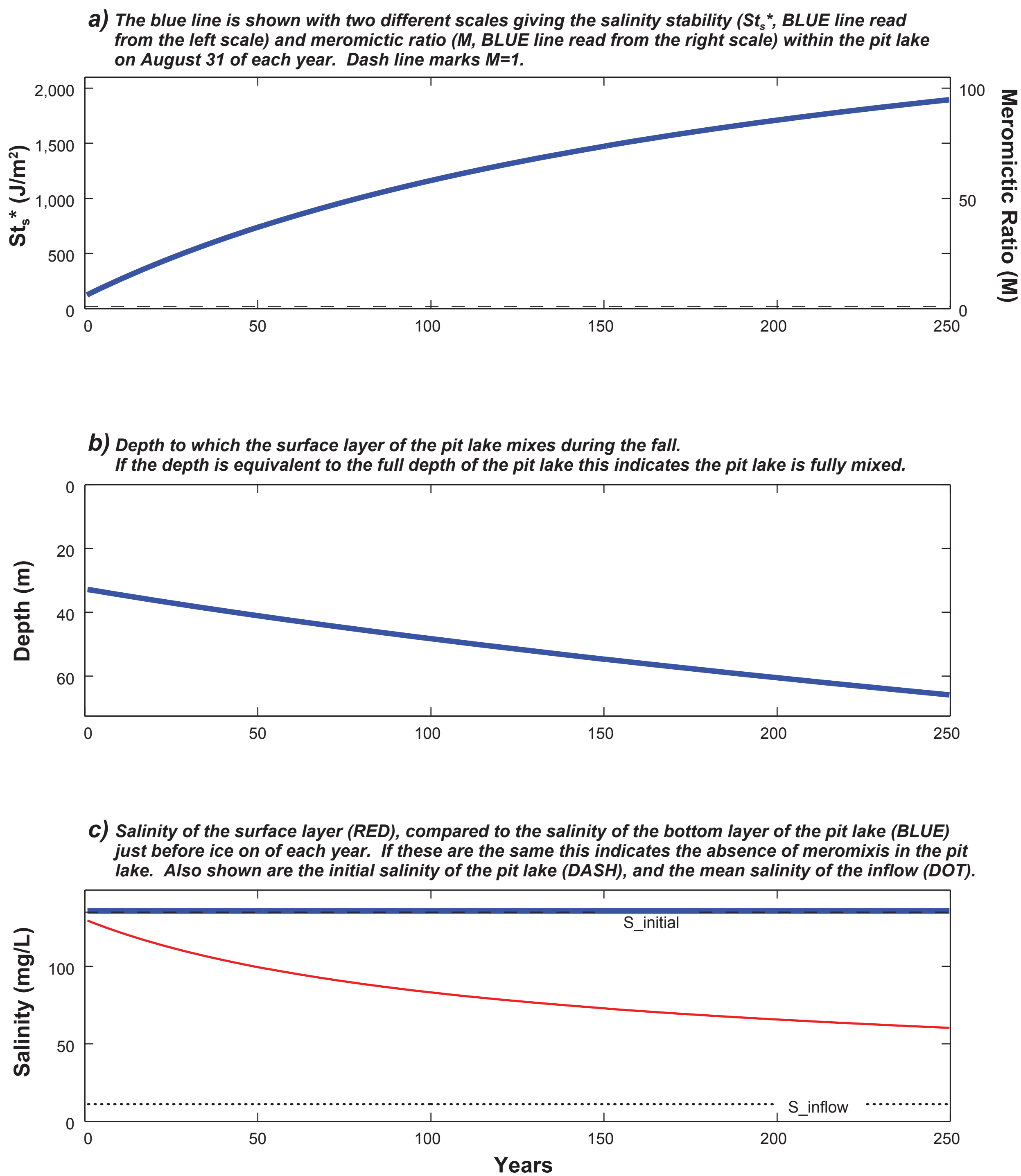
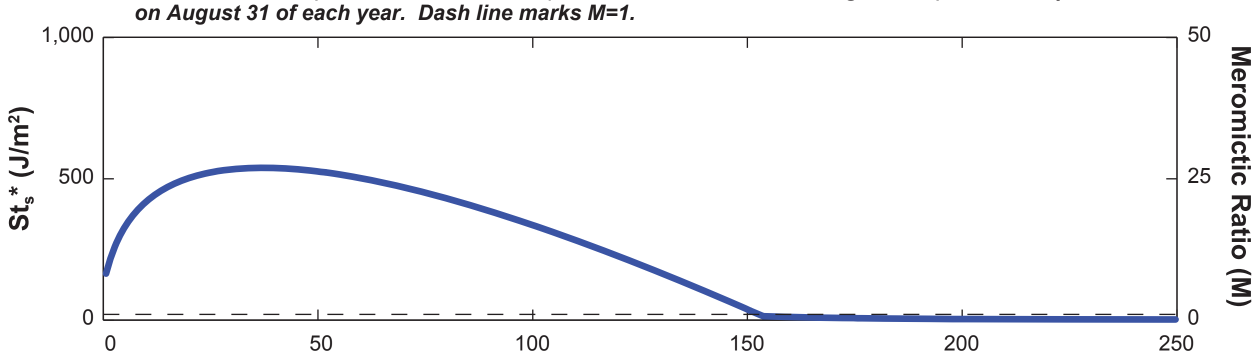


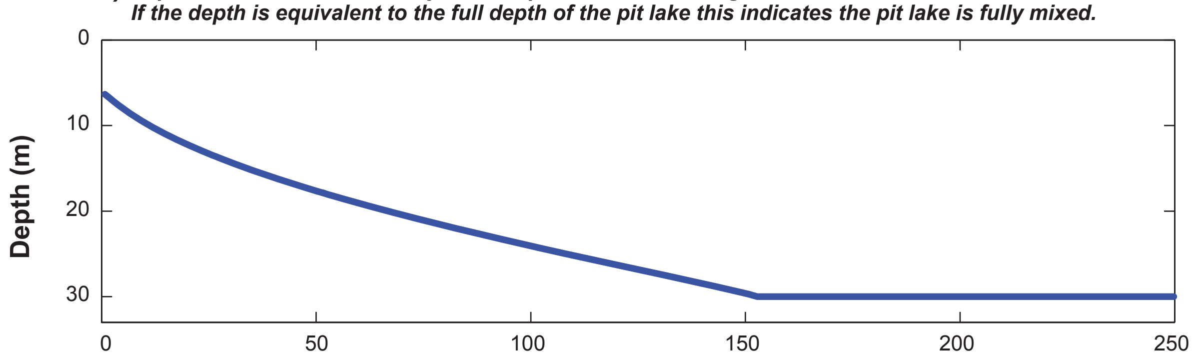
Figure 6.6-7

Predicted Stability of Fox Pit Lake

a) ***The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.***



b) ***Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.***



c) ***Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).***

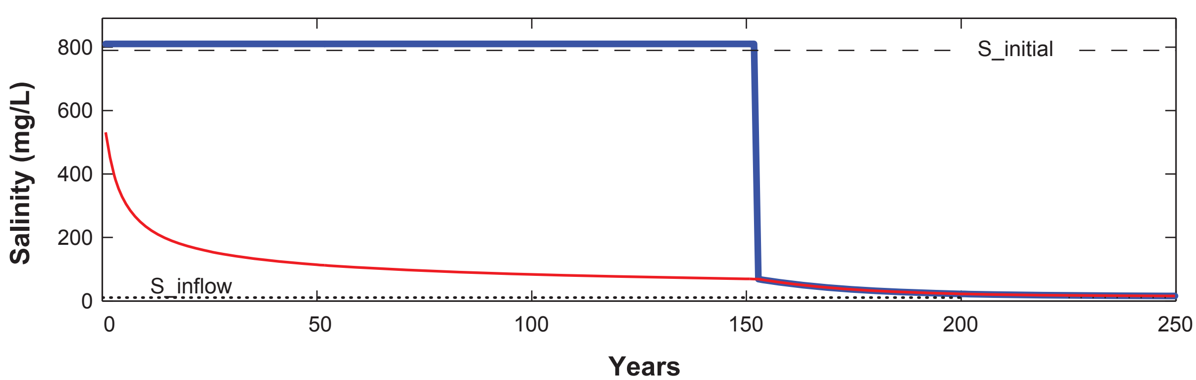


Figure 6.6-8

Predicted Stability of Beartooth Pit Lake

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6.6.5 Effect of Assumption Related to Initial Pit Lake Salinity Distributions

As described in Section 2.2.2, the initial stratification of the filled pit lake depends on the degree of mixing during filling which is difficult to predict. Three scenarios are considered for the initial stratification of the three pit lakes (Panda, Koala/Koala North and Fox) for which meromixis is predicted:

- Base case — The base case considers the initial pit to be completely mixed. This case is conservative as all constituents are mixed throughout the pit lake.
- Scenario 1 — This scenario assumes complete mixing until the pit lake has filled to 30 m from the overflow level, at which point natural water (TDS = 10 mg/L) is added while minimizing mixing to establish a 30 m cover of low salinity water.
- Scenario 2 — Linear stratification: this would be intermediate to the Base Case and Scenario 1. If mixing is incomplete during filling this can give rise to gradient in salinity, which can be represented by linear stratification. Note also that stratification that approximately linear stratification is observed in the deep water, for example, of Faro (Figure 6.3-1) and Water line (Figure 6.3-2) pit lakes, as well as other meromictic lakes (e.g., Gibson 1999).

The initial salinity profiles for Panda pit are shown in Figure 6.6-9; all three scenarios have the same volume averaged TDS of 1,630 mg/L. The stability with the 30 m cover is significantly higher than that for the Base Case (Figure 6.6-10a) as would be expected because of the increased salinity contrast between the surface and deep water. With a 30 m cover the depth of the surface layer increases gradually (Figure 6.6-10a), and the salinity of the surface layer increases a little, until a balance is reached between surface deepening and flushing of the surface layer by runoff. In the Base Case the salinity of the outflow began well over 1,000 mg/L, while for the case of a 30 m cover the salinity remained below 100 mg/L.

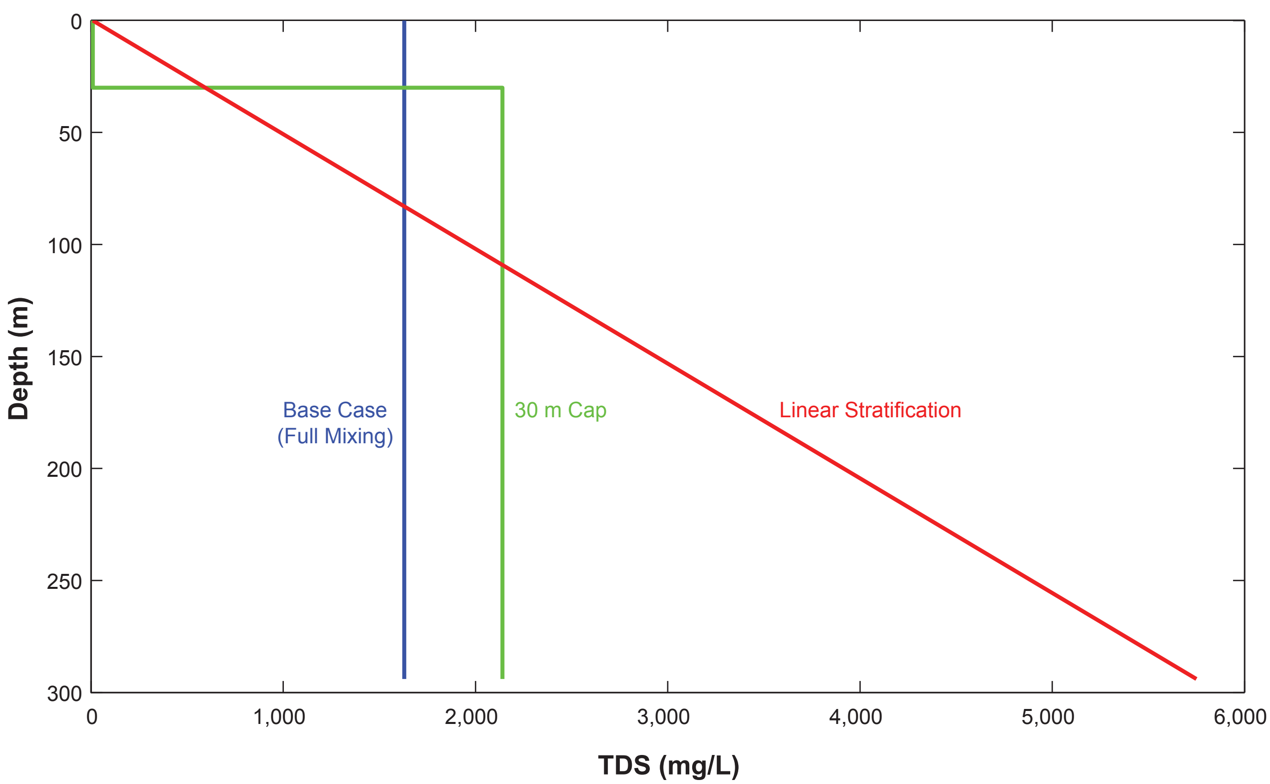
With linear stratification a significant proportion of the saline water remains at depth, and as a consequence the stability is higher than for the Base Case and for Scenario 1 (Figure 6.6-10a). The surface layer deepens rapidly at first and then more gradually as it reaches about 30 m depth (Figure 6.6-10a). The salinity of the surface layer increases slightly to a peak of 160 mg/L after the first seven years. However, in the long term the salinity of the surface layer is similar to that of the 30 m cover (80 mg/L). Results are summarized in Table 6.6-2.

Table 6.6-2. Pit Lake Stability Results, Panda Lake Base Case and Initial Stratification Scenarios

Pit case	Initial Stratification	Initial Model Salinity (mg/L)	M Year 1	M Year 250	Mictic Status
Base Case	Fully mixed	1,630 mg/L	15	250	Strong meromixis
Scenario 1	30 m fresh water cover	0 to 30 m 10 mg/L > 30 m 2,140 mg/L	1,550	1,700	Strong meromixis
Scenario 2	Linear	0 to 5,750 mg/L	3,300	3,500	Strong meromixis

6.6.6 Effect of Groundwater Flow Rate for Pit Lakes with Groundwater Inflows

As described in Section 4.2.2, groundwater inflow is possible in three of the filled pit lakes, Panda, Koala/Koala North and Fox. For each of these pit lakes, the Base Case described in the previous section used conservative (high) flow estimates based on work reported EBA (2006), and assumed groundwater inflows tend to zero as pit is filled.



Initial Profile of TDS with Depth in Panda Pit Lake for the Base Case (Full Mixing) and Two Alternative Scenarios; 30 m Cover, and Linear Stratification

Figure 6.6-9

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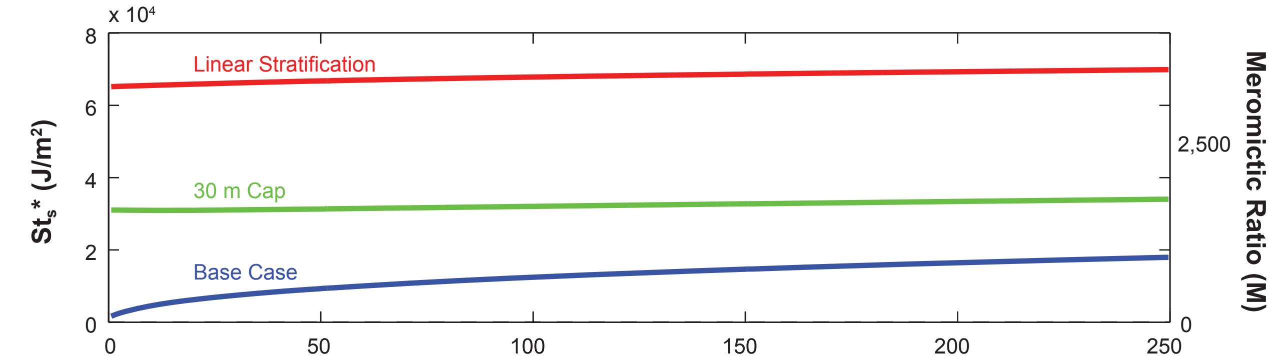
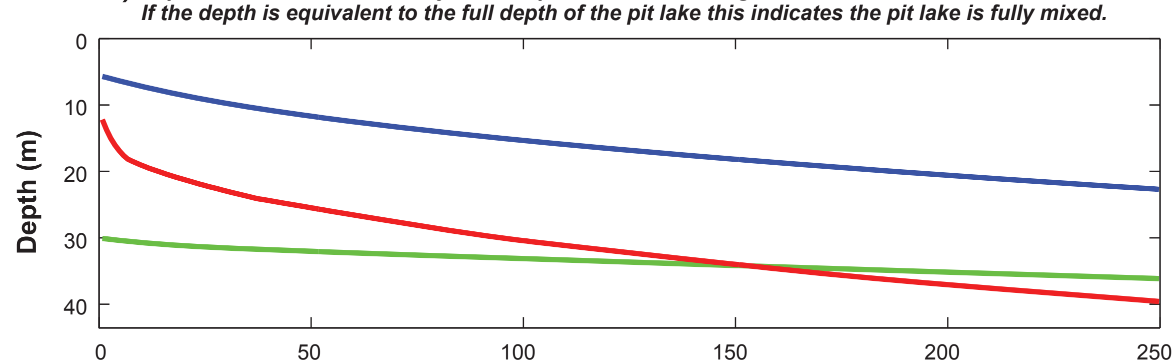
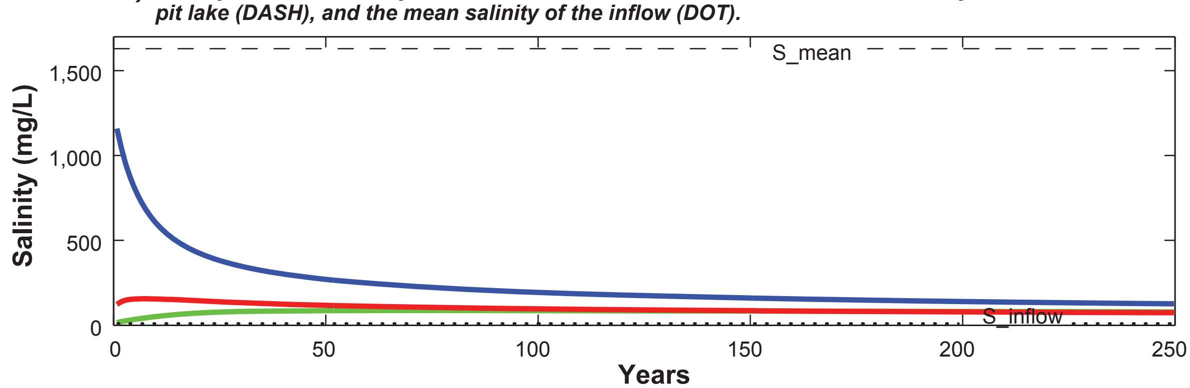
***a)** For each run the line is shown with two different scales giving the salinity stability (St_s*, left scale) and meromictic ratio (M, right scale) within the pit lake on August 31 of each year. Dash line marks M=1.*



***b)** Depth to which the surface layer of the pit lake mixes during the fall.*
If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.



***c)** Salinity of the surface layer for each run. Also shown are the initial mean salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).*



Predicted Stability of Panda Pit Lake Comparing the Base Case Using Alternative Initial Stratification of a 30 m Cover and Linear Stratification

Figure 6.6-10

There are two ways in which sensitivity to groundwater is explored:

1. During pit lake filling, scenarios considered lower and higher rates of inflow of groundwater to the pit lakes (Table 5.2-3). These different flow rates resulted in different initial pit lake salinities, and the effect of this is discussed in Section 6.6.9.
2. Groundwater may continue to flow into the pit lakes after they have filled. In this case, groundwater inflow results in an increase in the salinity of the deep water for each of the pit lakes.

Here we consider the effect of groundwater inflow reporting directly to the pit lakes by considering 5% off the maximum groundwater inflow to continue once the pit lakes have filled, and assuming that groundwater is distributed throughout the deep water. The stability of the four pit lakes with groundwater is shown in Figures 6.6-11 to 6.6-14.

Groundwater inflow once the pit lakes have been filled results in an increase in the salinity of the deep water for each of the pit lakes. For example, the salinity of the lower layer of Panda pit lake increases from 1,630 to 2,300 mg/L in 250 years (Figure 6.6-11). The surface layer deepened to just over 15 m (Figure 6.6-11b) slightly shallower than 23 m without groundwater (Figure 6.6-4b). Because of the increase in salinity, the stability at year 250 increased slightly from M = 900 without groundwater (Figure 6.6-4a) to M=940 with groundwater (Figure 6.6-11a).

The groundwater inflow increases the volume of the lower layer. For example, in Panda the chemocline would be expected to rise by more than 0.03 m/y (Table 6.6-3) or 3 m over 100 years if there was no entrainment. However, the chemocline is eroded when the surface layer mixes down in fall. There will be a balance between the rising of the chemocline due to groundwater inflow and erosion of the chemocline by surface mixing. With groundwater the chemocline is slightly shallower than without.

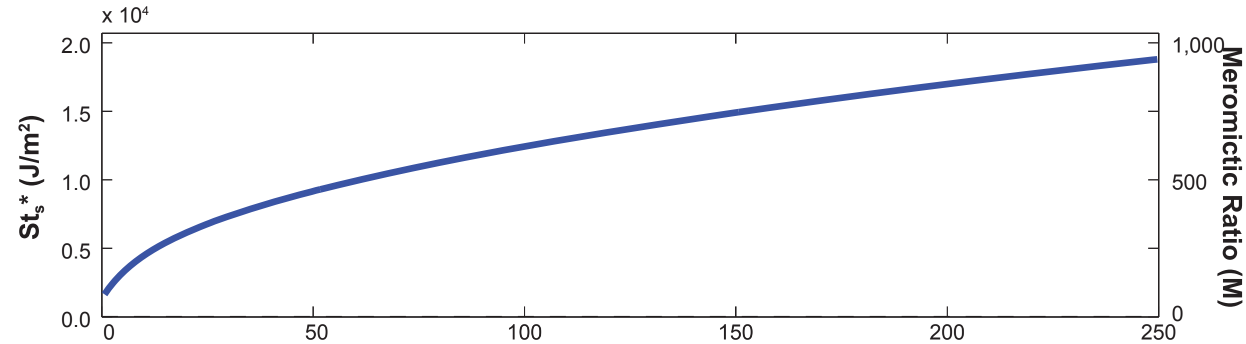
Table 6.6-3. Ekati Pit Lakes with Groundwater

	Panda	Koala/Koala North	Fox
Max pit lake depth (m)	300	249	330
Max depth of UG workings[a] (m)	535	630	-
UG Volume[b] (Mm^3)	1.8	5.4	-
Groundwater inflow reporting directly to the empty pit[b] (L/s)	7.5	7.5	7.5
Groundwater inflow reporting to the empty UG (L/s)	14	20	-
Annual increase in surface water level due to groundwater reporting directly to the pit lake, using 5% (m)	0.03	0.02	0.02
Annual increase in surface water level due to groundwater reporting to the UG, using 5% (m)	0.06	0.06	
Bulk residence time in the pit lake of groundwater reporting directly to the pit lake, using 5% (y)	3,300	2,800	6,100

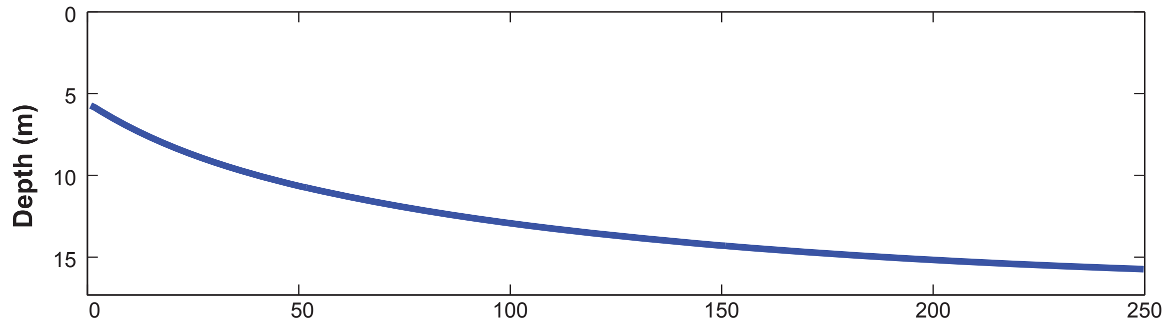
[a] *ICRP (BHP Billiton 2011a)*
[b] *EBA (2006)*

Erosion of the chemocline affects the salinity of the surface mixed layer. While the salinity of the surface layer decreases as a result of flushing with runoff, it doesn't decrease as much as in the case without groundwater.

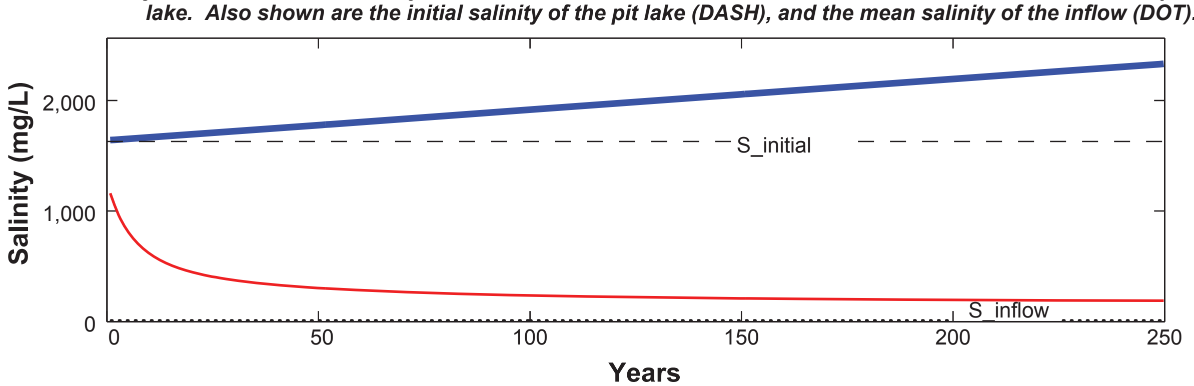
a) *The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.*



b) *Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.*



c) *Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).*



Predicted Stability of Panda Pit Lake with Groundwater Input

Figure 6.6-11

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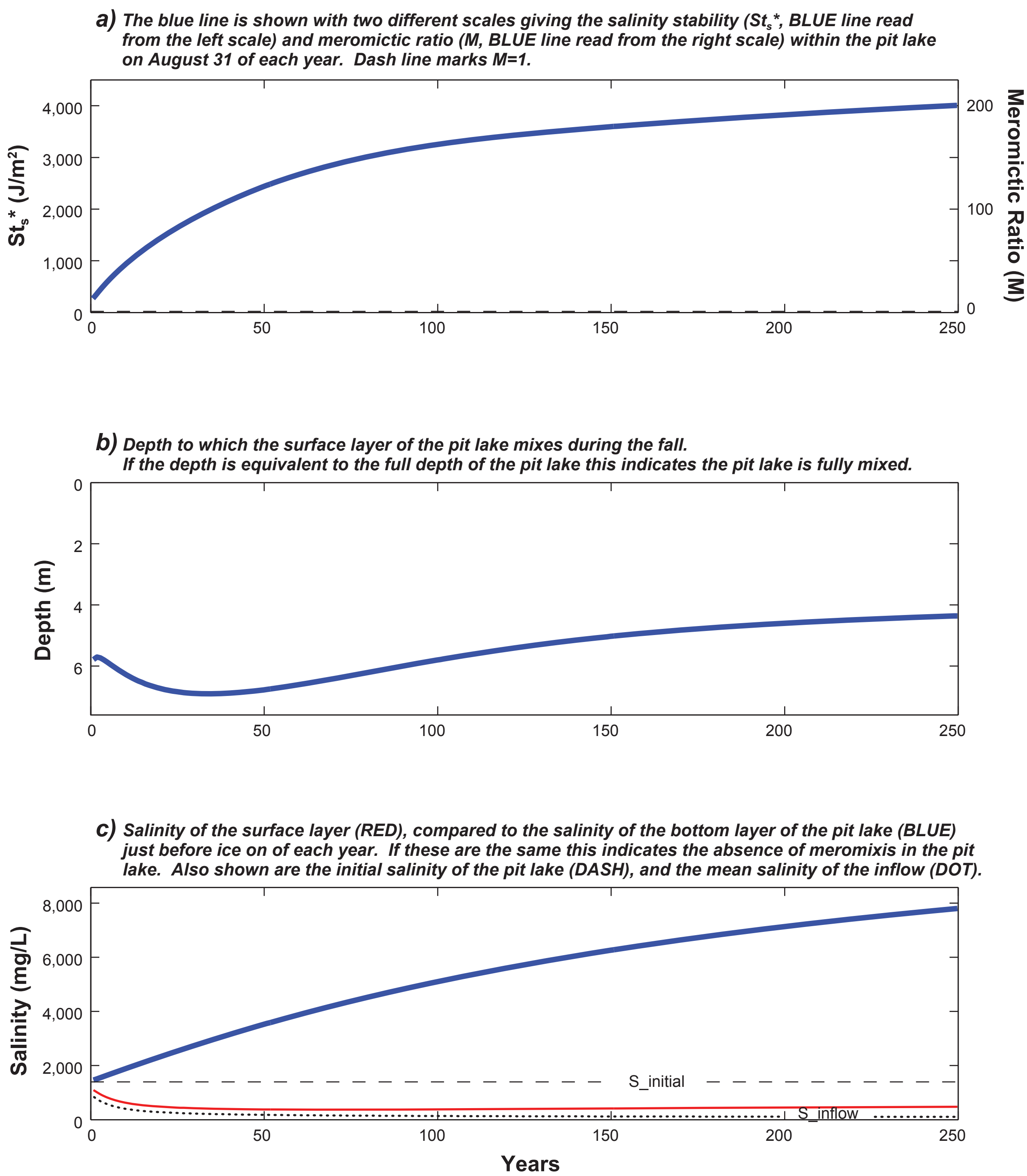

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Predicted Stability of Koala North Pit Lake with Groundwater Input

Figure 6.6-12

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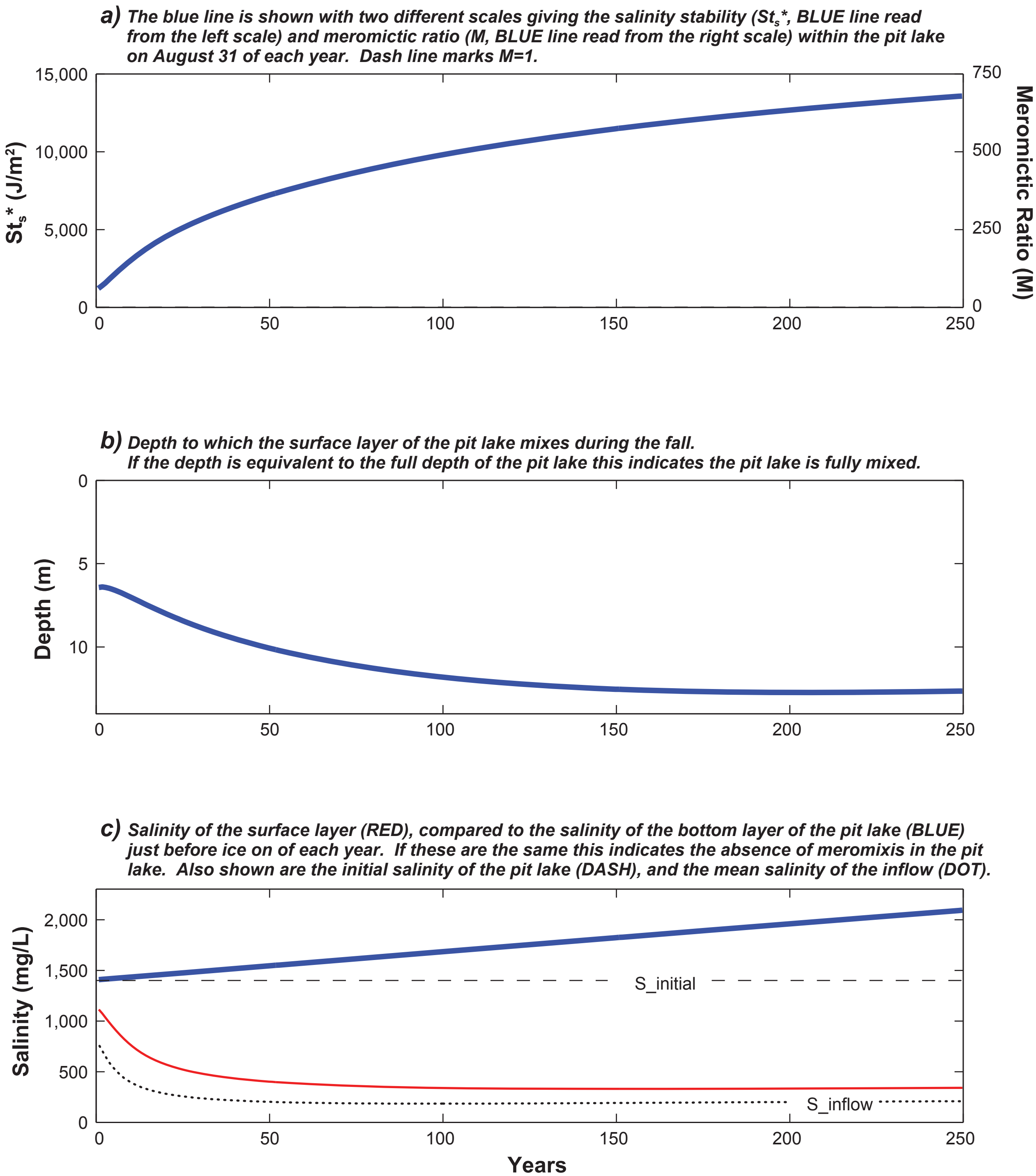

Figure 6.6-13

Predicted Stability of Koala Pit Lake with Groundwater Input

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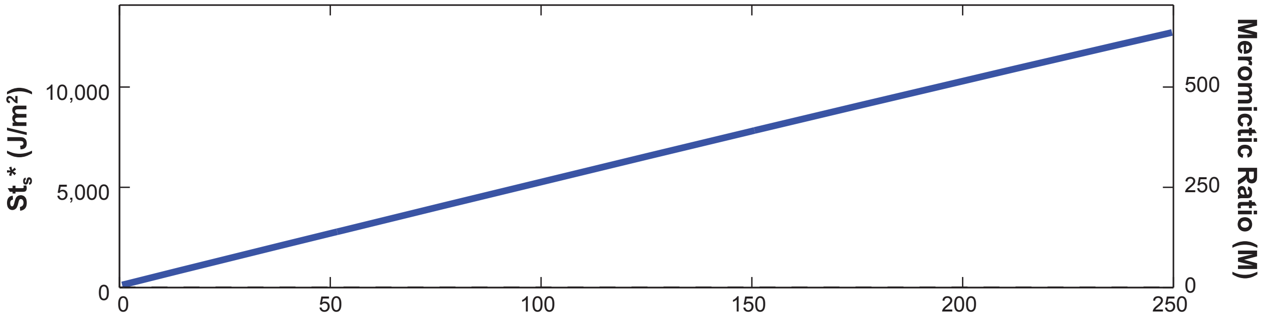
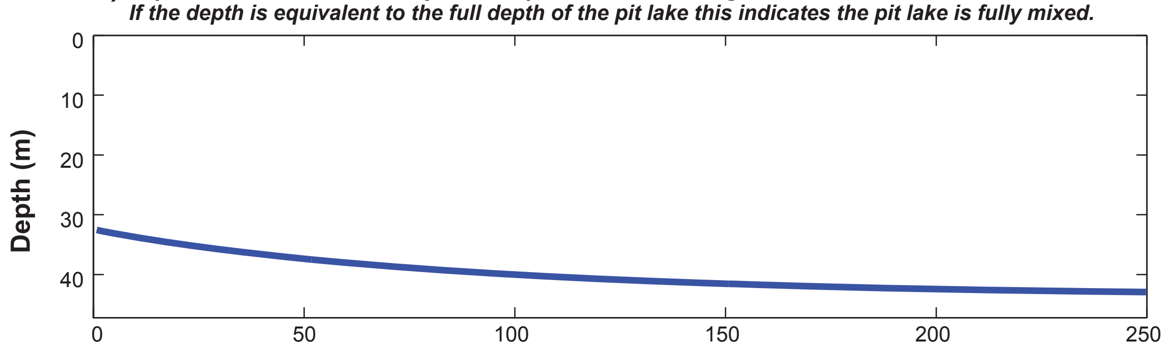
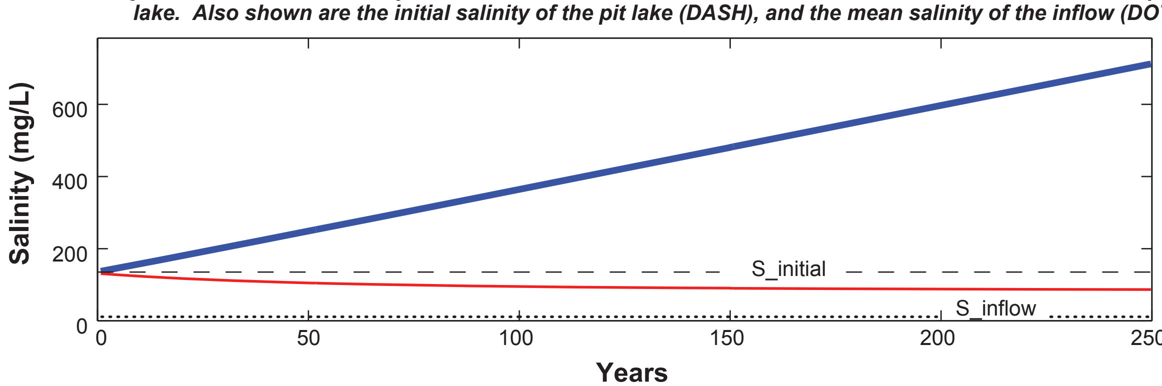
a) ***The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.***



b) ***Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.***



c) ***Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).***



Predicted Stability of Fox Pit Lake with Groundwater Input

Figure 6.6-14

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The increase in the stability of the four pit lakes with groundwater inflow is shown in Table 6.6-4.

Table 6.6-4. Change in Surface Mixed Layer Depth and Meromictic Ratio for Pit Lakes with Groundwater after 250 Years

	Without Groundwater		With Groundwater	
Pit Lake	**Surface Mixed Layer Depth before Ice-on (m)**	**M**	**Surface Mixed Layer Depth before Ice-on (m)**	**M**
Panda	23	900	16	940
Koala North	26	72	4	200
Koala	21	760	13	680
Fox	66	95	43	640

For pit lakes predicted to be meromictic, the chemocline gradually erodes deeper (Figures 6.6-4 to 6.6-7). The effect of groundwater in arresting this erosion has already been noted. Potential groundwater inflow not only replenishes the volume of the lower layer, but increases the salinity of the lower layer, increasing the salinity stability.

In the above, groundwater was mixed throughout the monimolimnion providing an upper bound to the export of groundwater from the pit. Alternatively, depending on the details of how groundwater enters the pit lake, the groundwater reporting directly to the pit may pool at the bottom of the pit lake. For example if the groundwater enters at or near the bottom, there may be little or no mixing with the water above. In this case the groundwater may accumulate at the bottom, forming a distinct layer that is strongly stratified.

If groundwater reporting to the underground workings continues to flow once the pits are filled, this groundwater will raise the interface between the saline groundwater in the underground workings and the less saline water in the pit lake. As a result a deep saline layer may be formed in the lower part of the pit. The groundwater reporting directly to the pit lakes may also contribute to this layer if it tends to pool at the bottom rather than mix through the deep water.

The bulk residence time of the pit lakes is estimated in Table 6.6-5 for Panda and Koala/Koala North. It should be noted that the Koala North pit is much shallower than Koala pit and so formation of a saline deep layer would occur in Koala first and might not reach the level of Koala North. With the estimated groundwater to the underground workings it would take 1,800 and 1,100 years to replace all the water in Panda and Koala with groundwater, respectively. This time would decrease if groundwater reporting to the pits contributed as well. This suggests that if groundwater continues to flow once the pits are filled, groundwater would be important to the long-term evolution of the pit lakes. These estimates used a groundwater flow rate of 5% of groundwater inflow when empty; a key uncertainty is the rate of groundwater inflow to the filled pit lake.

Table 6.6-5. Bulk Residence Time of Possible Groundwater Inflow Reporting to the Underground Workings

	Units	**Panda**	**Koala**
Pit Volume	m^3	39.9E+06	33.6E+06
Current flow to UG	L/s	14	20
5% of current flow to UG	m^3/y	22,000	32,000
Bulk residence time of the pit lake	y	1,800	1,100

6.6.7 Salinity of Inflows

In order to provide an indication of the effect of saline inflow from the watershed and exposed pit wall, the salinity of the combined natural and pit wall runoff is given in Table 6.6-6, where it is compared to the initial pit salinity. Except for Misery, the area of the pit-walls is small relative to the watershed (Tables 3-1 and 3-2). In the case of Koala North and Koala, the inflow is dominated by outflow from the upstream Panda pit lake. The mean salinity of the inflow is less than the initial salinity of the pit lakes with the exception of Pigeon and Misery pit lakes.

Table 6.6-6. Inflow Salinity

Pit	Potential for Meromixis in Long Term? (Base Case)	Salinity of Pit-wall Runoff (mg/L)	Estimated Mean Salinity Watershed and Pit-wall Runoff (mg/L)	Initial Pit Salinity (Base Case) (mg/L)
Sable	Low	100	10	20
Misery	Low	289	56	10
Pigeon	Low	286	36	9
Panda	High	140	11	1,630
Koala/Koala North	High	140	130	1,400
Fox	High	190	11	135
Beartooth	Low	140	10	790

For pit lakes with a high potential to be meromictic, at the start of summer the surface mixed layer is about twice the depth of the ice melt (Pieters and Lawrence 2009b), and, as a result, the salinity of the surface mixed layer is about half the salinity of the mixolimnion; here we briefly consider the early years when the salinity of the mixolimnion is close to the initial salinity of the pit lake. If the mean salinity of the inflow remains less than about half the initial salinity of the pit lake, the inflow will continue to reduce the surface mixed layer salinity, and increase stability. The inflow salinity is less than half the pit lake salinity for all of the pit lakes except Sable, Pigeon and Misery.

For pit lakes with inflows having salinity greater than the surface mixed layer, the effect of the inflow will be to displace fresh water with more saline water. This, along with salt exclusion under ice, gradually increases the net salinity of the entire pit lake as observed for Misery (Figure 6.6-2c) and Pigeon (Figure 6.6-3c). However, this increase is not large enough to lead to meromixis.

For pit lakes where meromixis is predicted, sufficient input of salinity from runoff could result in the loss of meromixis. Potential sources for runoff salinity are disturbed areas such as mill sites, WRSAs, and roads.

6.6.8 Rate and Timing of Freshwater Pumping

For Panda and Koala/Koala North, the Base Case assumes that the pit lakes are filled 13 years after the end of operations at Ekati. During this 13 year period there will be surface water and groundwater inflows to the pit lakes. These initial groundwater inflows results in elevated salinities in the final pit lake of between 1,400 to 1,600 mg/L for the Base Case. However, if filling of the pit lakes by pumping of fresh water were to commence upon completion of mining the initial salinity could be reduced to 300 to 400 mg/L. In this case, meromixis is still predicted, with M = 100 to 300, at year 250, although the strength of the meromixis would be decreased. The surface layer would also be slightly deeper, between 40 and 50 m.

6.6.9 Discussion of Sensitivity to Other Input Parameters

In addition to groundwater inflows and inflow salinity the evolution of meromixis is also sensitive to:

- the depth of the pit lake;
- the initial pit lake salinity, S;
- the thickness of ice, hi;
- the degree of fall mixing, ΔStS;
- the volume and salinity of surface inflow; and
- the volume and salinity of groundwater inflow.

The first four factors — depth, salinity, ice thickness and fall mixing — are summarized in Figure 6.6-15. Increasing depth and increasing salinity results in an increased likelihood of meromixis in the first year, and this is given by the region above the solid line. Below the dashed line, meromixis is unlikely in the first year. Between the dashed and solid line is a transition zone.

Each of the proposed pit lakes is marked using the salinity predicted from both the Base Case (solid) and scenarios of Tables 5.2-1 to 5.2-4. For Beartooth, two scenarios are considered, the Base Case with initial mine water 5 m deep (initial salinity 790 mg/L), and a scenario with initial mine water 10 m deep (initial salinity 1,650 mg/L). Shown above the line are the pit lakes that are likely to be meromictic (i.e., Panda, Koala/Koala North and Fox). The other pits, Sable, Pigeon, Beartooth and Misery lie near or below the dashed line and are unlikely to be meromictic.

The solid and dashed lines originate by considering variation in ice thickness and fall mixing, ΔSt_S. Maximum ice thickness on nearby Contwoyto Lake varied from 1.2 and 2.2 m depth; this range was used to bound the natural variability in ice thickness. In the example pit lakes ΔSt_S varied from 13 to 25 J/m^2 (Table 6.4-1); ΔSt_S=20 J/m^2 was used in the model. Higher ΔSt_S — increased fall mixing — could result, for example, from higher winds before ice-on. To explore the effect of variation in ice-thickness and ΔSt_S, the boundary of meromixis is shown in Figure 6.6-15 for two cases: (1) low ice and high ΔSt_S (solid line) which reduces the range of meromixis and (2) high ice and low ΔSt_S (dash line) which increases the range of meromixis.

6.6.10 Interannual Variability

The effect of interannual variability is shown by comparing the results for Sable Pit lake, both without (Figure 6.6-16) and with (Figure 6.6-17) variability in ice thickness. An initial pit lake salinity of 50 mg/L was chosen to best illustrate the variability.

To generate variability, the ice thickness was varied from year to year using 14 years of data from Contwoyto Lake. In addition, the degree of fall mixing, ΔSt_S, was set to 10, 20, or 30 J/m^2. At a time of thinner ice and larger ΔSt_S, the stability in the fall would be significantly reduced, and conversely for thicker ice and lower ΔSt_S. While Figure 6.6-17 resembles Figure 6.6-16 the net effect was to reduce the stability. In effect, continuous meromixis is likely outside of the upper bound of Figure 6.6-15, while intermittent meromixis is likely between the bounds shown.

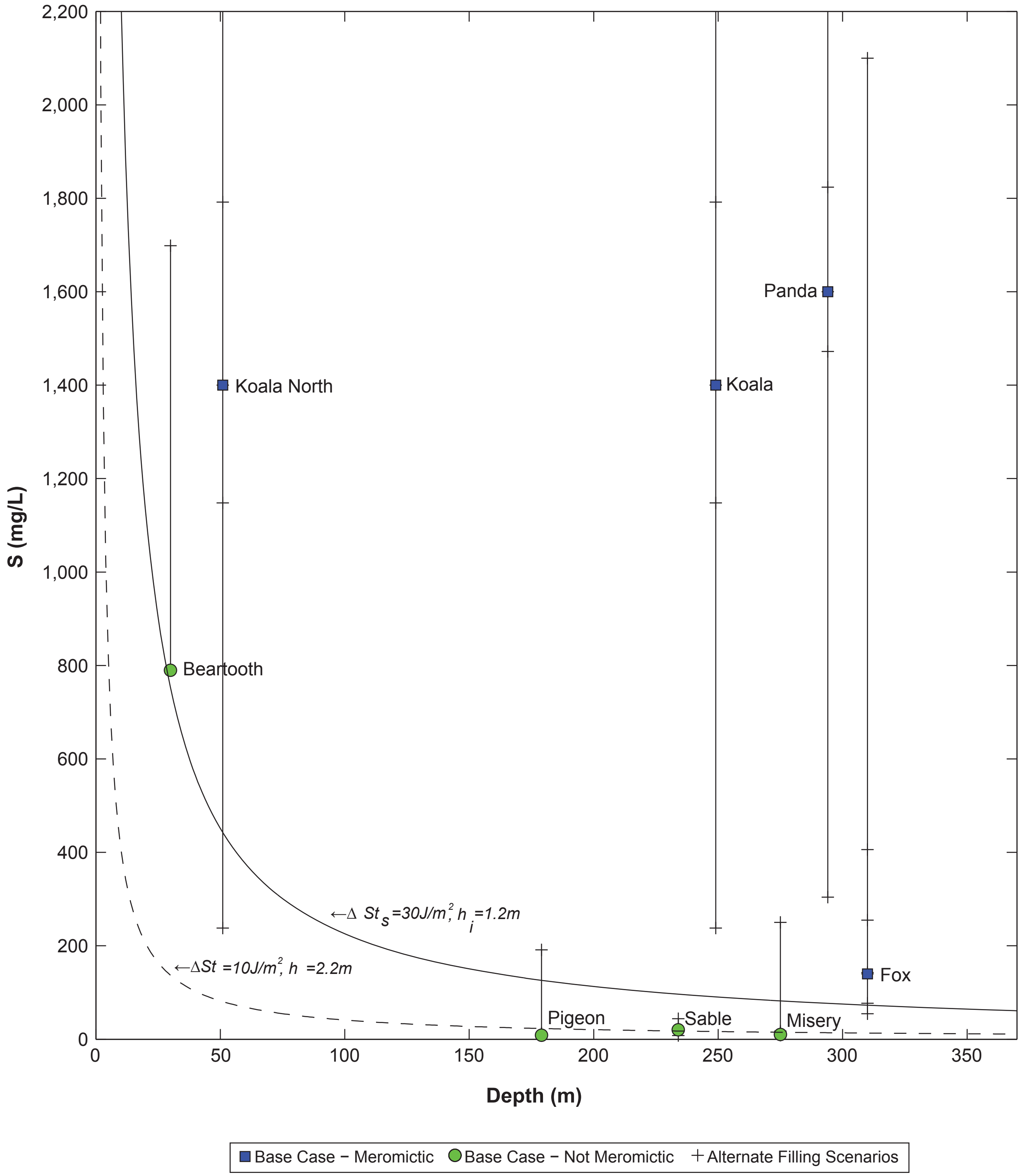

Figure 6.6-15

Dependence of Meromixis on Salinity and Depth for Ekati Pit Lakes

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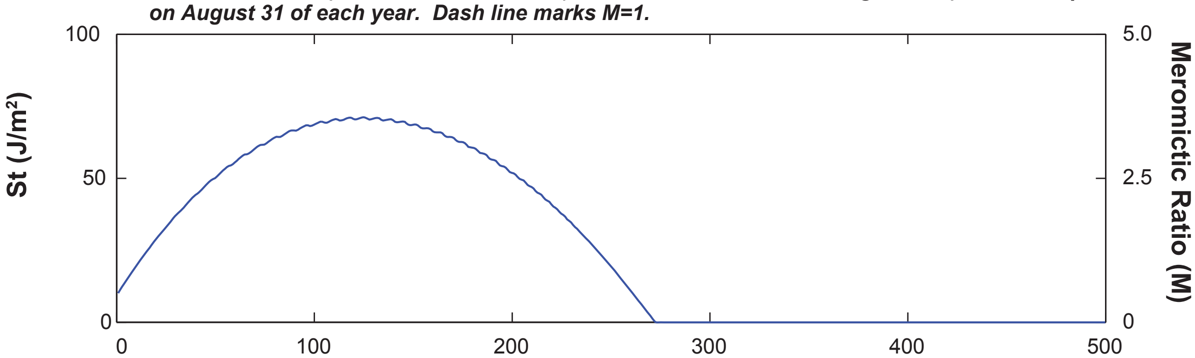
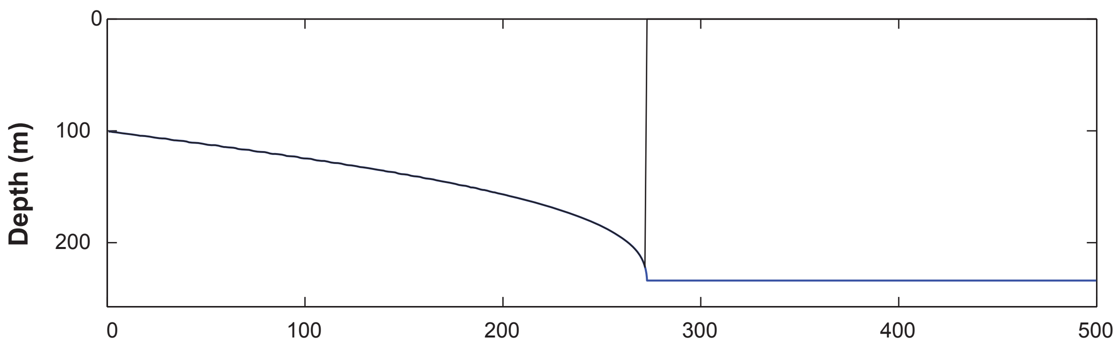
***a)** The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year. Dash line marks M=1.*



***b)** Depth to which the surface layer of the pit lake mixes during the fall. If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.*



***c)** Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).*

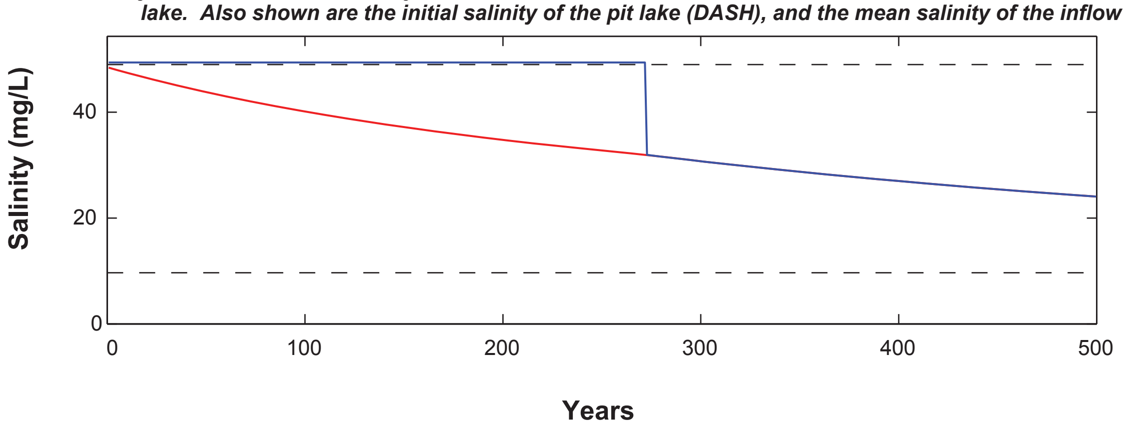
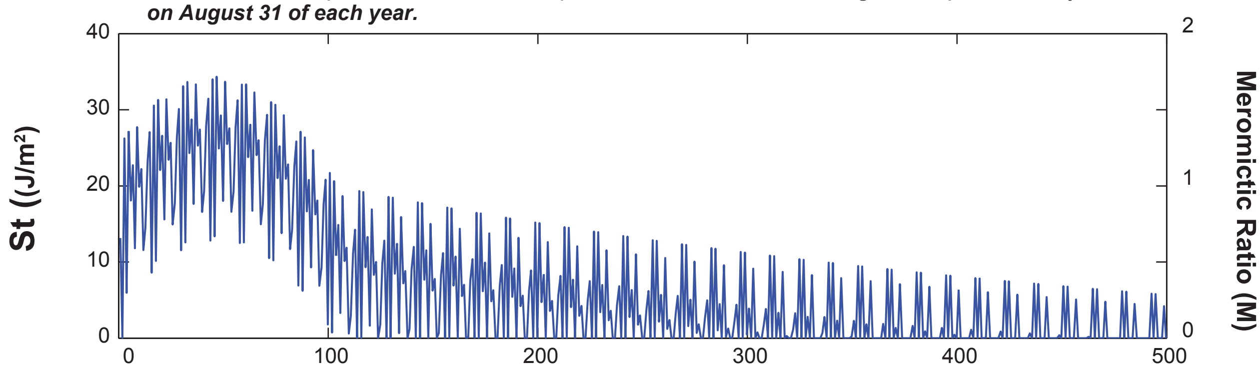


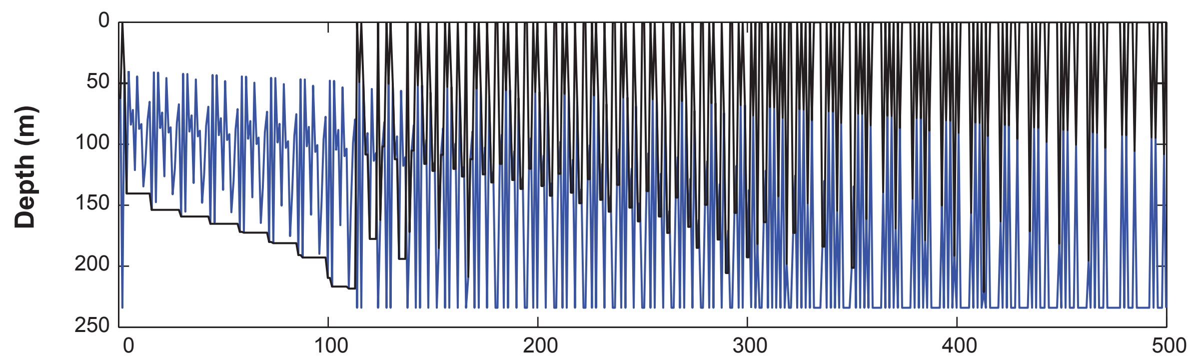
Figure 6.6-16

Predicted Stability of Sable Pit Lake for Comparison with Figure 6.6-17

a) *The blue line is shown with two different scales giving the salinity stability (St_s*, BLUE line read from the left scale) and meromictic ratio (M, BLUE line read from the right scale) within the pit lake on August 31 of each year.*



b) *Depth to which the surface layer of the pit lake mixes during the fall.*
If the depth is equivalent to the full depth of the pit lake this indicates the pit lake is fully mixed.



c) *Salinity of the surface layer (RED), compared to the salinity of the bottom layer of the pit lake (BLUE) just before ice on of each year. If these are the same this indicates the absence of meromixis in the pit lake. Also shown are the initial salinity of the pit lake (DASH), and the mean salinity of the inflow (DOT).*

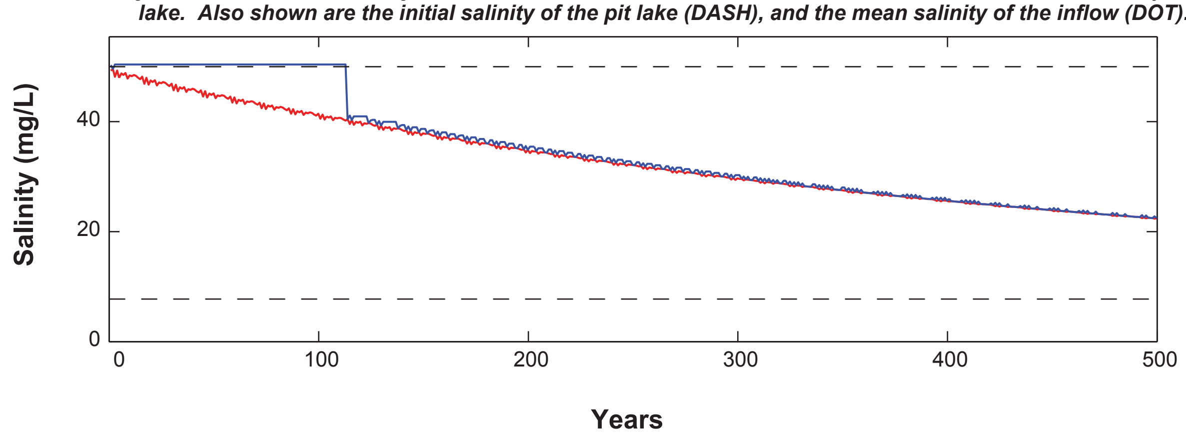


Figure 6.6-17

Stability of Sable Pit Lake with Variation in Ice Thickness and ΔS

6.7 SUMMARY AND DISCUSSION OF MEROMIXIS MODEL RESULTS

The Ekati pit lakes generally divide into those with low initial salinity (12-20 mg/L) that are not meromictic (Groups 1 and 2), and those with higher salinity (> 100 mg/L) that are likely meromictic (Group 3). Within the group of pit lakes which are predicted to be meromictic it is noted that Fox pit lake has relatively lower initial salinity (135 mg/L) and sits close to the boundary of likely meromixis shown in Figure 6.7-7. In contrast, Panda and Koala/Koala North pit lakes have high initial salinity for the Base Case (1,400 to 1,630 mg/L) and for these pit lakes there is a higher likelihood of the formation of meromixis over the long term. Beartooth pit lake is the exception (Group 4). Beartooth is saline but shallow and is not predicted to be meromictic in the long term. Although meromixis is predicted for some pit lakes at Ekati, it should be noted that salinities within the pit lakes at Ekati is much lower than the salinity of some natural meromictic lakes. For example, the salinity of Mahoney Lake is approximately 40,000 mg/L (Ward et al. 1990). There are several reasons, why meromixis might occur at lower salinities in pit lakes. These include the unusually high relative depth of the proposed pit lakes, as well as thick ice with a high degree of salt exclusion. As a result permanent stratification is predicted to occur at much lower salinities than might otherwise be expected.

Surface inflows play an important role in flushing the surface mixed layer and increasing the stability of the pit lake over time. Just after filling of the pit lake, the stability is maintained by the fresh ice melt, from ice of thickness, h_i. After flushing of the mixolimnion the stability is maintained by the fresh surface mixed layer of depth, h_{sml}. In the limit of $h_{sml} << h_{max}$, where h_{max} is the full depth of the lake, flushing of the surface layer increases the stability by a factor of about h_{sml}/h_i. For Panda and Koala pit lakes, h_i ~ 2 m and h_{sml} ~ 20 m; as a result the stability increases over time by a factor of ten due to surface layer flushing.

Model results were presented for a Base Case scenario, with further runs undertaken varying key model inputs. The results indicated that although meromixis was predicted for three pit lakes, there are a number of parameters (e.g., groundwater inflows, initial pit lake chemistry, surface inflows) that will impact the long-term stability of meromixis.

7. Pit Lake Water Quality Predictions

7. Pit Lake Water Quality Predictions

This chapter provides predictions of the water quality of the pit lakes at completion of filling (Section 7.1) and up to 250 years following end of infilling of each pit lake (Section 7.2). The key model results are provided in Section 7.2, which relate to the water quality in the surface layer of the full pit lakes. Water in the surface layer can flow from the pit lakes to the receiving environment. These results are compared to Water Quality Benchmarks for the receiving environment.

Prior to discussing the surface layer water quality predictions, Section 7.1 provides results of a sensitivity analysis that models the impact of changing key model input parameters on initial bulk water quality within the pit lakes up to the point that the lakes are full. These pit lake infilling model predictions provide the initial conditions for the multi-layer models used (Chapter 6) to predict the likelihood of meromixis in each pit lake and which predict the long-term water quality in the surface layers of each pit lake.

The model scenarios considered in Sections 7.1 and 7.2 were outlined in Chapter 5.

7.1 RESULTS FOR PIT INFILLING LOAD BALANCE MODEL

The pit infilling load balance model was used to generate initial conditions (water quality at the point the pit lakes are full) for the multi-layer model. This section outlines the Base Case predictions from this model and describes the results of a model sensitivity analysis which identifies parameters that have the greatest influence on pit lake chemistry. A model sensitivity analysis provides an illustration of the effect of changing key model parameters on important model outputs. By re-running the model for a range of scenarios and changing one input parameter for each model run, the effect of each input on the model results can be isolated. If model parameters are varied within the range of possible input values, then a sensitivity analysis can also provide an indication of uncertainty associated with the model predictions.

Base Case inputs and scenarios for the sensitivity analysis were outlined in Chapters 4 and 5 respectively.

7.1.1 Water Balance Results for Pit Infilling

Considering the Base Case scenario for pit lake infilling, Figures 7.1-1a and 7.1-1b illustrate the percentage contribution to the full pit volume from each water source. The results clearly indicate that the key input to each pit lake is the pumped inflow volumes with pumped inflows contributing in excess of 80% of the total inflow for all pit lakes. This is not unexpected given the relatively small catchment areas flowing to each pit lake and the generally low annual precipitation totals in the Ekati region. In addition, groundwater flows are at maximum of around 32 L/s (0.032 m^3/s) for the Koala/ Panda/Koala North pits, which is less than 10% of the assumed pumped flow rate of 0.4 m^3/s. Even considering that pumped flows are only discharged to the pit lakes for half of the year the underground flows contribute around 16% of the annual flow.

Sensitivity runs varying key input parameters such as annual precipitation totals, runoff coefficients, evaporation rates and groundwater inflow rates indicated that changes to these parameters had a minor impact on the rate of infilling of the pit lakes compared to the effect of changing the pumped inflow rate.

The main conclusion from the water balance calculations for pit infilling is that the rate of pumped inflows to the pit lakes from donor lakes is the key input deciding the rate of infilling of the pit lake.

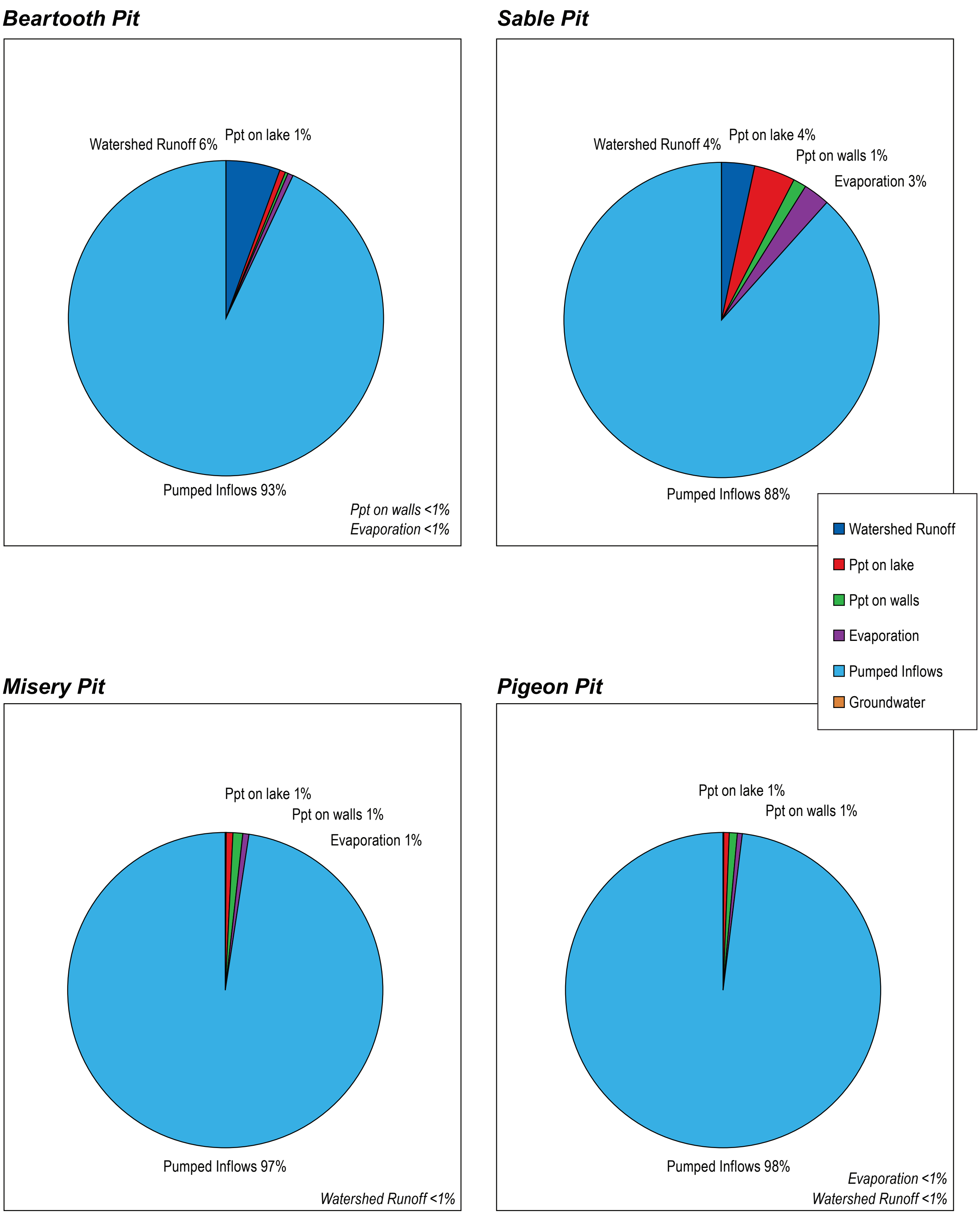
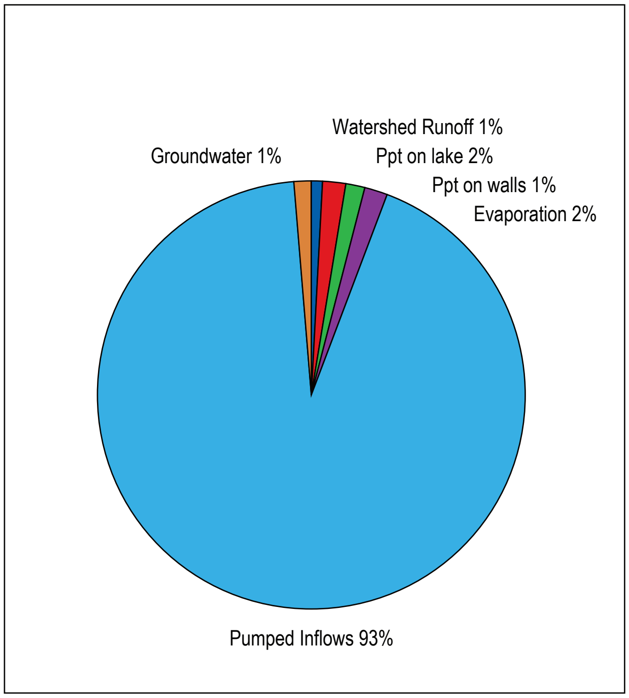


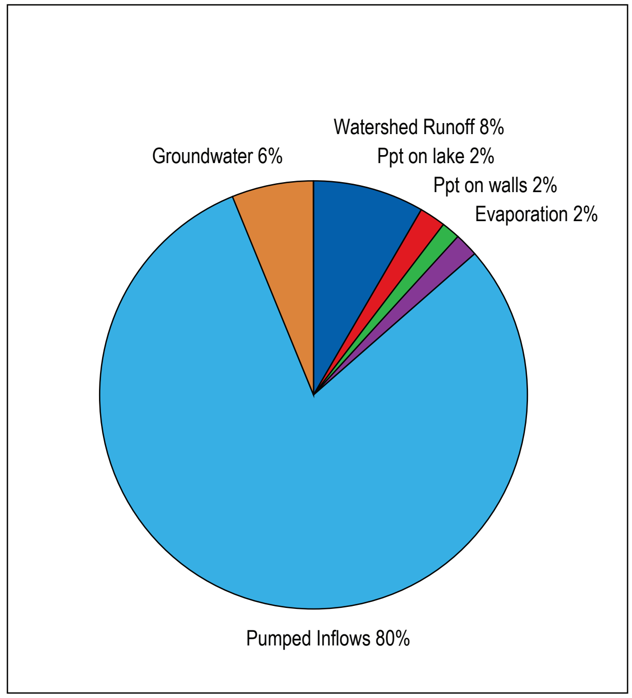
Figure 7.1-1a

Proportion of Inflows to Pits during Infilling Period

Fox Pit



Panda Pit - 0.2 m³/s pumping



Koala/Koala North Pit - 0.2 m³/s pumping

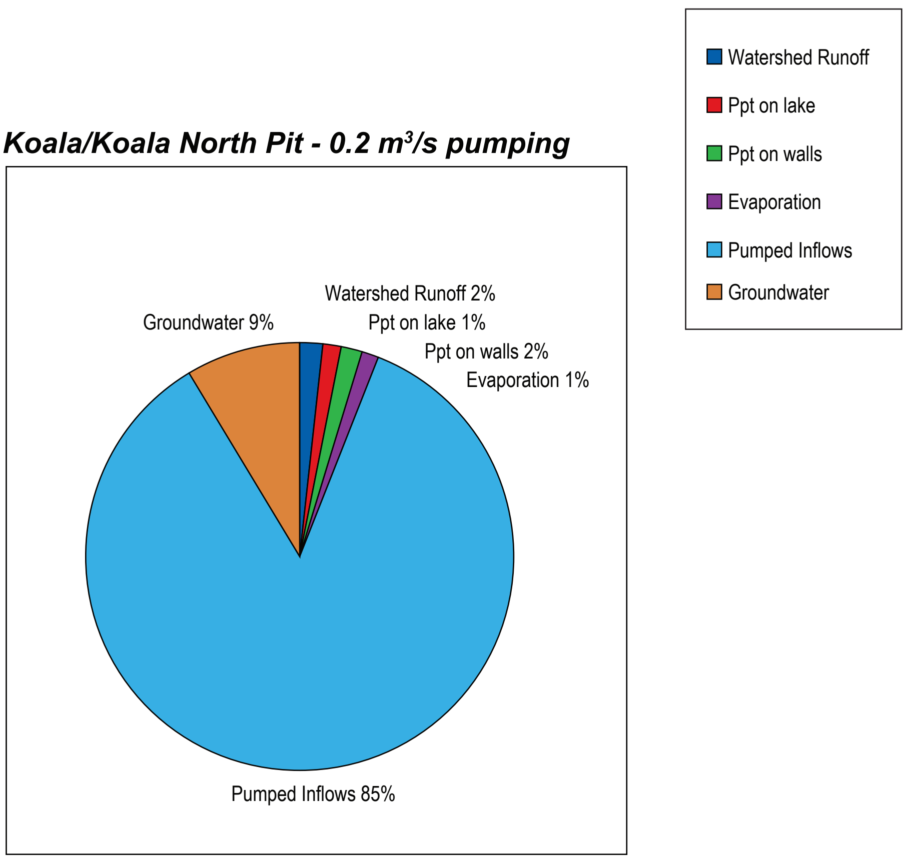


Figure 7.1-1b

Proportion of Inflows to Pits during Infilling Period

DOMINION DIAMOND

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7.1.2 Water Quality Results for Pit Infilling

Predictions of bulk (i.e., averaged) water quality in each pit lake when full are provided for the Base Case in Tables 7.1-1 to 7.1-7. The tables also provide results for each of the scenarios outlined in Chapter 5, with results presented as the percentage change in predicted concentrations from the Base Case. Results for each pit lake are discussed below.

7.1.2.1 Results for Group 1 — Open Pit with No Groundwater Inflows and No Meta-sediments within the Pit Walls (Sable Pit Lake)

Results for Sable pit lake are presented in Table 7.1-1. The results indicate that cadmium is the only water quality variable that is predicted to exceed Water Quality Benchmarks for the Base Case or any of the scenario runs. Concentrations of all other water quality variables are below Water Quality Benchmarks.

Table 7.1-1. Sensitivity Analysis for Pit Infilling Water Quality — Sable Pit

Variable	[a]Water Quality Benchmark (mg/L)	Base Case (mg/L)	Percentage Change from Base Case				
			Scenario G1.1	Scenario G1.2	Scenario G1.3a	Scenario G1.3b	Scenario G1.3c
Ammonia - N	0.59	0.024	0	-88	19	1	0
Chloride	[b]170	0.47	0	-46	11	1	0
Nitrate - N	0.49	0.18	0	-98	1	0	0
Nitrite – N	0.06	0.0091	0	-94	0	0	0
Phosphate		0.0028	0	-9	44	98	-1
Sulphate	20	3.9	12	-58	190	10	-5
TDS	-	20	9	-60	120	6	-4
Aluminum	0.10	0.0089	0	-1	200	10	-5
Antimony	0.02	0.000080	60	-13	430	22	-12
Arsenic	0.005	0.00019	18	-30	120	6	-3
Barium	1	0.0033	37	-15	330	17	-9
Boron	1.5	0.0017	29	-56	140	8	-3
Cadmium	0.0000021	0.000026	20	-4	27	1	-1
Chromium III	0.0089	0.000022	58	-12	230	12	-7
Chromium VI	0.0010	0.000073	58	-12	230	12	-6
Copper	0.0020	0.00038	-1	-4	280	14	-8
Iron	0.30	0.0085	0	-1	700	36	-19
Lead	0.0010	0.000026	0	-4	28	1	-1
Manganese	0.62	0.0028	160	-8	490	25	-13
Molybdenum	19	0.0033	16	-97	32	2	-1
Nickel	0.025	0.00061	82	-26	390	20	-11
Potassium	41	1.1	23	-52	140	7	-4
Selenium	0.0010	0.000088	94	-38	87	4	-2
Strontium	6.2	0.017	16	-56	270	13	-8
Uranium	0.015	0.00017	11	-81	140	7	-3
Vanadium	0.015	0.00013	25	-66	270	14	-7
Zinc	0.03	0.00076	420	-2	560	30	-15

[a] Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.
[b] Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).
Scenarios are defined in Table 5.2-1.

The sensitivity analysis indicates that most water quality variables are sensitive to assumptions related to the initial flush of loadings at the beginning of infilling of Sable pit (Scenario G1.2) and the rate of pumping of fresh water into Sable pit (Scenarios G1.3 to G1.5). Decreasing the pumping rate of fresh water to zero (Scenario G1.3) increases concentrations of many variables by more than 100%; however, no concentrations are predicted to rise above Water Quality Benchmarks even for this extreme scenario. Given the relatively small volume of Sable pit, halving or doubling the pumped inflow rate (Scenarios G1.4 and G1.5) makes limited impact on the bulk chemistry of the full pit, as even with a relatively low pumped inflow the volume of water from donor lakes dominate the water budget of the pit lake. Most metals (apart from aluminum, copper, iron and lead) are sensitive to changes in pit wall chemistry (Scenario G1.1).

In summary, the sensitivity analysis suggests that concentrations in the full Sable pit lake could vary by around ± 100% if input parameters were varied. However, even with this variation cadmium concentrations only are predicted to exceed Water Quality Benchmarks, and the cadmium value is known to be low Rescan (2012). Overall, the model predicts that the water quality within the full Sable pit will be of good quality with low TDS concentrations.

7.1.2.2 Results for Group 2 — Open Pits with No Groundwater Inflows and with Meta-sediments within the Pit Walls (Misery and Pigeon Pit Lakes)

<u>Pigeon Pit</u>

The results for Pigeon pit lake are presented in Table 7.1-2. The results suggest exceedances of Water Quality Benchmarks values for cadmium only for the Base Case scenario.

The key model sensitivity is to pumped inflow rate with significantly higher (two to three orders of magnitude) concentrations predicted in the scenario with no pumped inflows (Scenario G2.3a). In this case pit wall runoff chemistry dominates the full pit, resulting in high concentrations of all metals, with concentrations of aluminum, cadmium, copper, iron, manganese, nickel, selenium, sulphate and zinc exceeding Water Quality Benchmarks. Increasing the rate of pumping lowers the concentrations in the pit lake (Scenario G2.4c), although the effect is limited as Pigeon pit fills quickly with the Base Case pumped inflow rate, such that an increase in the rate has only a marginal impact on concentrations.

The Base Case scenario produces lower concentrations of most water quality variables within the full pit lake (expect phosphate and vanadium) compared to scenarios with different pit wall loading chemistries (i.e., Scenarios G2.1a to G2.1c). The three other pit wall loading scenarios produce similar initial pit lake chemistries, with significant increases in concentrations predicted for a number of variables. It should be noted that scenarios G2.1b and G2.1b predict time varying loadings from pit walls, with higher initial loadings compared to the Base Case, but with the loadings decreasing over time. The effect of long-term changes in loadings is considered in Section 7.2. The scenario which replaces predictions of pit wall runoff chemistry with observed Misery sump water quality (Scenario G2.4d) produces significantly lower concentrations for most variables (except nitrate and molybdenum), suggesting that if pit wall runoff predictions are overly conservative (high) water quality in the full pit lake might better than predicted in the Base Case.

Changing the initial loadings to the pit lake (Scenario G2.2) decreases concentrations for some variables, but the effects are minor (i.e., from 0 to 13%). For Pigeon (and Misery) pit lake sump water is of better quality than pit wall runoff, such that the removal of initial loadings to the pit lake equivalent to sump water quality has limited impact on overall pit lake water quality.

Table 7.1-2. Sensitivity Analysis for Pit Infilling Water Quality — Pigeon Pit

Variable	[a]Water Quality Benchmark (mg/L)	Base Case (mg/L)	Percentage Change from Base Case							
			Scenario G2.1a	Scenario G2.1b	Scenario G2.1c	Scenario G2.1d	Scenario G2.2	Scenario G2.3a	Scenario G2.3b	Scenario G2.3c
Ammonia - N	0.59	0.00078	0	0	0	170	-2	-100	-31	160
Chloride	[b]170	0.25	0	0	0	29	0	130	1	0
Nitrate - N	0.49	0.0045	0	0	0	4000	-13	2200	27	-13
Nitrite - N	0.06	0.00027	0	0	0	410	-3	-99	-27	71
Phosphate		0.0054	-30	-20	-20	-86	0	-89	1	24
Sulphate	20	2.4	94	160	160	4	0	4400	36	-16
TDS	-	8.7	31	51	50	24	0	2100	18	-8
Aluminum	0.10	0.013	730	730	730	-39	0	3500	28	-13
Antimony	0.02	0.000087	-14	-23	-23	-21	0	3800	31	-14
Arsenic	0.005	0.00016	87	83	83	-7	0	2100	17	-8
Barium	1	0.0031	5	-5	-5	-11	0	2600	21	-9
Boron	1.5	0.00086	67	51	51	16	0	2500	21	-9
Cadmium	0.0000021	0.000035	57	52	52	-23	0	2500	21	-9
Chromium III	0.0089	0.000019	24	6	6	-78	0	1300	11	-4
Chromium VI	0.0010	0.000064	24	6	6	-78	0	1300	11	-5
Copper	0.0020	0.0015	430	430	430	-78	0	7200	58	-26
Iron	0.30	0.0088	39	760	760	-40	0	3800	31	-14
Lead	0.0010	0.000035	57	51	51	-28	0	2600	21	-9
Manganese	0.62	0.0098	66	48	48	-65	0	7300	59	-27
Molybdenum	19	0.000037	150	-1	-1	2600	-8	1100	15	-7
Nickel	0.025	0.012	250	240	240	-94	0	8700	71	-32
Potassium	41	0.46	22	77	77	20	0	340	3	-1
Selenium	0.0010	0.000072	64	33	33	18	0	2700	22	-10
Strontium	6.2	0.0064	11	4	4	-26	0	2300	18	-8
Uranium	0.015	0.000055	190	190	190	-37	0	5700	46	-21
Vanadium	0.015	0.000048	-3	-15	-15	-35	0	4300	35	-16
Zinc	0.03	0.0054	340	320	320	-90	0	8100	66	-30

[a] Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.
[b] Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001). Scenarios are defined in Table 5.2-2.

In summary, the sensitivity analysis suggests that concentrations in the full pit lake could vary by more than 1,000% if inflow pumping rates were significantly reduced. As it is unlikely that pumping rates will be reduced the key uncertainty associated with Pigeon pit lake is from pit wall runoff quality, with result indicating that different assumptions with respect to pit wall chemistry could result in exceedances of Water Quality Benchmarks for a number of variables. However, overall the sensitivity analysis indicates that the predicted infilled pit lake chemistry has a high degree of uncertainty associated with pit wall chemistry predictions and the rate of pit infilling. As a result, uncertainties associated with predicted water quality within the Base Case scenario are likely to be on the order of one or two orders of magnitude.

Misery Pit

The results for Misery pit lake are presented in Table 7.1-3.

The key model sensitivity is to pumped inflow rate with significantly higher (two to three orders of magnitude) concentrations predicted in the scenario with no pumped inflows (Scenario G2.3a). In this case pit wall runoff chemistry dominates the full pit, resulting in high concentrations of all metals, with concentrations of aluminum, cadmium, chromium VI, copper, iron, lead, manganese, nickel, selenium, sulphate and zinc exceeding Water Quality Benchmarks. Increasing the rate of pumping lowers the concentrations in the pit lake (Scenario G2.4c).

The Base Case scenario produces lower concentrations of most variables within the full pit lake (expect phosphate and vanadium) compared to scenarios with different pit wall loading chemistries (i.e., Scenarios G2.1a to G2.1c). The three other pit wall loading scenarios produce similar initial pit lake chemistries, with significant increases in concentrations predicted for a number of water quality variables. It should be noted that scenarios G2.1b and G2.1b predict time varying loadings from pit walls, with higher initial loadings compared to the Base Case, but with the loadings decreasing over time. The effect of long-term changes in loadings is considered in Section 7.2. The scenario which replaces predictions of pit wall runoff chemistry with observed Misery sump water quality (Scenario G2.4d) produces significantly lower concentrations for most variables (except nitrate and molybdenum), suggesting that if pit wall runoff predictions are overly conservative (high) water quality in the full pit lake might be better than predicted in the Base Case.

Changing the initial loadings to the pit lake (Scenario G2.2) has negligible impact on concentrations. For Misery pit lake, sump water is of better quality than pit wall runoff, such that the removal of initial loadings to the pit lake equivalent to sump water quality has limited impact on overall pit lake water quality.

In summary, the sensitivity analysis suggests that concentrations in the full pit lake could vary by more than 1,000% if inflow pumping rates were significantly reduced. As it is unlikely that pumping rates will be reduced the key uncertainty associated with Misery pit lake is due to pit wall runoff quality, with result indicating that different assumptions with respect to pit wall chemistry could result in exceedances of Water Quality Benchmarks for a number of variables. However, overall the sensitivity analysis indicates that the predicted infilled pit lake chemistry has a high degree of uncertainty associated with pit wall chemistry predictions and the rate of pit infilling. As a result, uncertainties associated with predicted water quality within the Base Case scenario is likely to be of the order of one or two orders of magnitude.

There is the potential for low pH water to develop in Misery pit lake, depending on the pH of pit wall runoff. The pH of inflows to the pond are estimated to be; natural water (pH ~6.5); sump water (pH = 7.6); pit wall runoff (pH ~3.6). Based on the water balance results, pit wall runoff is only 1% of the annual water budget during pit infilling. Pit wall runoff is about 1,000 times more acidic than natural pumped water (pH being measured on a log scale) and as a result, on an order of magnitude basis, it would appear that the pH within Misery pit lake could be mildly acidic. More detailed assessments of pit wall runoff are required to make predictions of pH within the pit lake.

Table 7.1-3. Sensitivity Analysis for Pit Infilling Water Quality — Misery Pit

Variable	[a]Water Quality Benchmark (mg/L)	Base Case (mg/L)	Percentage Change from Base Case							
			Scenario G2.1a	Scenario G2.1b	Scenario G2.1c	Scenario G2.1d	Scenario G2.2	Scenario G2.3a	Scenario G2.3b	Scenario G2.3c
Ammonia - N	0.59	0.00037	0	0	0	760	0	-99	-66	47
Chloride	[b]170	0.26	0	0	0	45	0	160	2	-1
Nitrate - N	0.49	0.0048	0	0	0	5900	-8	2300	33	-17
Nitrite - N	0.06	0.00013	0	0	0	890	0	-97	-60	52
Phosphate		0.0028	-29	-20	-20	-72	0	15	-52	24
Sulphate	20	3.1	120	200	200	1	0	4300	54	-28
TDS	-	10	44	73	73	31	0	2400	30	-15
Aluminum	0.10	0.016	970	970	970	-51	0	3600	46	-23
Antimony	0.02	0.00011	-19	-30	-30	-29	0	3900	49	-24
Arsenic	0.005	0.00018	130	120	120	-11	0	2300	30	-15
Barium	1	0.0037	6	-7	-7	-16	0	2800	35	-18
Boron	1.5	0.0010	91	72	72	19	0	2700	34	-18
Cadmium	0.0000021	0.000041	79	73	73	-33	0	2800	35	-18
Chromium III	0.0089	0.000021	34	9	9	-16	0	1500	19	-10
Chromium VI	0.0010	0.000070	34	9	9	-16	0	1500	19	-10
Copper	0.0020	0.0023	470	470	470	-85	0	6100	77	-39
Iron	0.30	0.011	52	980	980	-51	0	3900	49	-25
Lead	0.0010	0.000042	78	71	71	-40	0	2900	36	-18
Manganese	0.62	0.015	70	53	53	-71	0	6200	79	-40
Molybdenum	19	0.000038	230	-2	-2	3900	-5	1200	17	-9
Nickel	0.025	0.020	250	250	250	-95	0	6900	87	-44
Potassium	41	0.47	32	120	120	30	0	400	5	-3
Selenium	0.0010	0.000086	86	46	46	21	0	3000	37	-19
Strontium	6.2	0.0074	16	6	6	-36	0	2500	31	-16
Uranium	0.015	0.000079	220	220	220	-45	0	5200	66	-34
Vanadium	0.015	0.000063	-5	-19	-19	-45	0	4200	53	-27
Zinc	0.03	0.0086	350	340	340	-94	0	6600	84	-42

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001). Scenarios are defined in Table 5.2-2.

7.1.2.3 *Results for Group 3 — Open Pits with Groundwater Inflows (Panda, Koala/Koala North and Fox Pit Lakes)*

Panda Pit Lake

The Base Case model scenario for Panda pit lake predicts exceedances of Water Quality Benchmarks for chloride, nitrate, sulphate and cadmium (Table 7.1-4). As discussed in Rescan (2012) the cadmium benchmark is known to be excessively low and is based on the CCME interim guideline. Nitrate exceedances result from the infilling of underground workings with blast residues and sulphate exceedances result from groundwater inflows to the pit lakes.

As with other pit lakes, the model results are sensitive to the rate of pumping of fresh water into the pit lake during infilling. If zero pumped inflows are modelled (Scenario G3.3a) there is predicted to be > 100% change to many water quality variables as there is a greater influence of groundwater and pit wall runoff on the pit lake water quality. Higher pumping rates (Scenario G3.3c) result in lower concentrations. The time between the end of operations and the beginning of pumping is also an important parameter. The Base Case assumes pumping commences 13 years after the end of operations, while Scenario G3.3d assumes that pumping commences immediately at the end of operations. Predicted concentrations of most water quality variables are significantly lower for Scenario G3.3d than for the Base Case, as the pit lake fills more quickly with less time for loadings from groundwater and pit wall runoff into the filling pit lake. For Scenario 3.3d cadmium and sulphate concentrations only exceed Water Quality Benchmarks.

Running the model with worst case pit wall chemistry (i.e., 4 m thick layer of broken rock on pit bench surfaces compared to 2 m thick layer in the Base Case and higher weathering rate than Base Case) produces higher concentrations of most water quality variables, but for many variables changes are relatively low, indicating a low sensitivity to the pit wall runoff chemistry. Even for variables (e.g., selenium and zinc) where predicted concentrations increase by above 100%, predicted concentrations do not exceed Water Quality Benchmarks.

Changing the groundwater flow rate (Scenarios G3.4a and G3.4b) has an effect on almost all variables (except aluminum). Lowering the groundwater flow rate (Scenario G3.4a) decreases concentrations of all variables, indicating that groundwater has higher concentrations of most variables compared with natural surface water. Increasing the groundwater flow rate and maintaining a positive flow rate once the pit lake is filled (Scenario G3.4b) predicts an increase in all variables.

If it is assumed that pumped flows to Panda pit lake will not be zero, the results for Panda pit lake indicate that the predictions of full pit lake chemistry are not overly sensitive to model inputs, with changes in modelled concentrations of less than an order of magnitude with changes in pit wall runoff and groundwater inflows. The key issues with respect to Panda pit lake will be potential for the formation of meromixis due to high TDS concentrations and the effect this will have on the water quality in the surface layers within the pit lake.

Koala/Koala North Pit Lake

Results for Koala/Koala North pit lake are similar to those described above for Panda pit lake, Table 7.1-5. This is not surprising as the pit lakes are linked at depth and are of similar size with groundwater inflows through the bottom of the open pit and into the underground workings.

Fox Pit

The results for Fox pit lake are presented in Table 7.1-6. The Base Case model scenario for Fox pit lake predicts exceedances of Water Quality Benchmarks for cadmium only. As discussed in Rescan (2012) the cadmium benchmark is known to be excessively low.

Table 7.1-4. Sensitivity Analysis for Pit Infilling Water Quality — Panda Pit

Variable	[a]Water Quality Benchmark (mg/L)	Base Case (mg/L)	Percentage Change from Base Case							
			Scenario G3.1	Scenario G3.2	Scenario G3.3a	Scenario G3.3b	Scenario G3.3c	Scenario G3.3d	Scenario G3.4a	Scenario G3.4b
Ammonia - N	0.59	0.000032	-70	-70	-65	-69	-73	-49	-65	80
Chloride	[b]170	650	0	0	130	14	-8	-78	-81	89
Nitrate - N	0.49	0.94	0	0	130	14	-8	-91	-81	89
Nitrite - N	0.06	0.000020	-45	-45	-90	-71	16	-41	-65	75
Phosphate	-	0.00030	-35	-36	-77	-53	-14	-56	-35	70
Sulphate	20	100	1	0	130	15	-8	-77	-80	87
TDS	-	1600	0	0	130	14	-8	-78	-81	88
Aluminum	0.1	0.012	1	4	88	10	-6	-14	-6	1
Antimony	0.02	0.00048	14	0	120	13	-7	-70	-72	79
Arsenic	0.005	0.00027	24	1	79	9	-4	-41	-41	44
Barium	1	0.034	12	0	120	14	-7	-72	-73	79
Boron	1.5	0.018	7	0	130	14	-8	-75	-77	85
Cadmium	0.0000021	0.000038	130	1	46	5	-3	-27	-28	30
Chromium III	0.0089	0.00051	26	0	110	12	-7	-67	-69	75
Chromium VI	0.001	0.00051	26	0	110	12	-7	-67	-69	75
Copper	0.002	0.00055	-3	1	62	7	-4	-35	-33	36
Iron	0.3	0.0092	0	1	59	7	-4	-36	-38	42
Lead	0.001	0.000065	25	0	80	9	-5	-48	-49	54
Manganese	0.62	0.017	4	0	120	13	-7	-68	-68	74
Molybdenum	19	0.046	1	0	130	14	-8	-78	-81	89
Nickel	0.025	0.018	2	0	130	14	-8	-76	-79	86
Potassium	41	22	4	0	130	14	-8	-76	-79	87
Selenium	0.001	0.00016	120	1	89	10	-5	-53	-55	60
Strontium	6.2	4.6	0	0	130	14	-8	-78	-81	89
Uranium	0.015	0.00071	9	0	130	14	-8	-76	-78	85
Vanadium	0.015	0.00092	5	0	130	14	-8	-75	-77	85
Zinc	0.03	0.0024	240	0	110	12	-7	-59	-57	59

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001). Scenarios are defined in Table 5.2-3.

Table 7.1-5. Sensitivity Analysis for Pit Infilling Water Quality — Koala/Koala North Pit

Variable	[a]Water Quality Benchmark (mg/L)	Base Case (mg/L)	Percentage Change from Base Case							
			Scenario G3.1	Scenario G3.2	Scenario G3.3a	Scenario G3.3b	Scenario G3.3c	Scenario G3.3d	Scenario G3.4a	Scenario G3.4b
Ammonia - N	0.59	0.00014	0	0	-93	-43	27	-58	-62	95
Chloride	[b]170	560	0	0	200	28	-18	-80	-84	120
Nitrate - N	0.49	0.85	0	0	200	28	-18	-98	-84	120
Nitrite - N	0.06	0.000046	0	0	-98	-55	130	-57	-56	85
Phosphate	-	0.00034	2	0	-94	-44	62	-27	-31	80
Sulphate	20	89	1	0	200	28	-18	-78	-82	120
TDS	-	1400	0	0	200	28	-18	-79	-83	120
Aluminum	0.1	0.010	1	4	110	10	-5	-14	-6	0
Antimony	0.02	0.00042	15	0	180	25	-16	-70	-73	100
Arsenic	0.005	0.00025	24	1	110	15	-9	-40	-40	55
Barium	1	0.029	12	0	190	27	-17	-72	-74	100
Boron	1.5	0.016	7	0	190	27	-17	-76	-79	110
Cadmium	0.0000021	0.000037	120	1	63	9	-5	-25	-25	36
Chromium III	0.0089	0.00044	27	0	170	24	-15	-66	-69	97
Chromium VI	0.001	0.00044	27	0	170	24	-15	-66	-69	97
Copper	0.002	0.00052	-3	1	86	12	-8	-32	-31	43
Iron	0.3	0.0086	0	1	83	12	-7	-34	-36	52
Lead	0.001	0.000059	25	1	120	17	-10	-46	-48	67
Manganese	0.62	0.015	5	0	180	25	-16	-68	-70	97
Molybdenum	19	0.039	1	0	200	28	-18	-80	-84	120
Nickel	0.025	0.015	3	0	200	28	-18	-77	-81	110
Potassium	41	19	4	0	190	27	-18	-78	-81	120
Selenium	0.001	0.00014	130	1	130	19	-11	-51	-53	76
Strontium	6.2	3.9	1	0	200	28	-18	-79	-83	120
Uranium	0.015	0.00061	9	0	190	28	-17	-76	-80	110
Vanadium	0.015	0.00079	6	0	200	27	-17	-77	-80	110
Zinc	0.03	0.0022	250	0	160	23	-14	-58	-57	77

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001). Scenarios are defined in Table 5.2-3.

Table 7.1-6. Sensitivity Analysis for Pit Infilling Water Quality — Fox Pit

Variable	[a]Water Quality Benchmark (mg/L)	Base Case (mg/L)	Percentage Change from Base Case						
			Scenario G3.1	Scenario G3.2	Scenario G3.3a	Scenario G3.3b	Scenario G3.3c	Scenario G3.4a	Scenario G3.4b
Ammonia - N	0.59	0.00015	0	0	-65	-71	95	-71	50
Chloride	[b]170	47	0	0	1,600	93	-52	-70	220
Nitrate - N	0.49	0.17	0	-3	1,100	64	-36	-50	150
Nitrite - N	0.06	0.00018	0	0	-62	-71	140	-76	55
Phosphate	-	0.000047	-21	0	-71	-59	73	-34	210
Sulphate	20	11	5	-2	1,100	65	-36	-46	140
TDS	-	140	2	0	1400	82	-45	-61	190
Aluminum	0.1	0.0089	0	0	170	10	-5	0	1
Antimony	0.02	0.00010	39	-1	650	38	-21	-21	66
Arsenic	0.005	0.00020	18	-2	170	9	-5	-3	11
Barium	1	0.0056	30	-1	790	47	-26	-27	84
Boron	1.5	0.0029	16	-3	740	43	-24	-30	93
Cadmium	0.0000021	0.000029	76	0	180	10	-5	-2	7
Chromium III	0.0089	0.000027	47	-1	490	29	-16	-18	56
Chromium VI	0.001	0.000093	47	-1	490	29	-16	-18	56
Copper	0.002	0.00036	-2	0	190	11	-6	-3	10
Iron	0.3	0.0054	0	0	77	5	-2	-4	13
Lead	0.001	0.000093	75	0	1,100	62	-34	-1	5
Manganese	0.62	0.0052	41	0	920	53	-29	-13	41
Molybdenum	19	0.0062	3	-4	810	47	-27	-38	110
Nickel	0.025	0.0020	30	0	1,200	73	-40	-42	130
Potassium	41	2.4	16	-1	1,100	63	-35	-45	140
Selenium	0.001	0.000097	89	-3	240	13	-8	-5	17
Strontium	6.2	0.35	2	0	1500	90	-50	-67	200
Uranium	0.015	0.00020	12	-5	400	22	-13	-17	52
Vanadium	0.015	0.00018	16	-4	640	37	-21	-24	74
Zinc	0.03	0.00092	260	0	660	38	-21	-9	28

[a] Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.
[b] Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001). Scenarios are defined in Table 5.2-3.

As with other pit lakes, the model results are sensitive to the rate of pumping of fresh water into the pit lake during infilling. If zero pumped inflows are modelled (Scenario G3.3a) there is predicted to be > 500% change in many water quality variables as there is a greater influence of groundwater and pit wall runoff on the pit lake water quality. However, halving the pumping rate (Scenario G3.3b) has a much lesser impact on water quality. Higher pumping rates (Scenario G3.3c) result in lower concentrations.

Running the model with worst case pit wall chemistry (i.e., 4 m thick layer of broken rock on pit bench surfaces compared to 2 m thick layer in the Base Case and higher weathering rate than Base Case) produces higher concentrations of most water quality variables, but for many variables changes are relatively low, indicating a low sensitivity to the pit wall runoff chemistry. Even for zinc, where predicted concentrations increase by above 100%, predicted concentrations does not exceed Water Quality Benchmarks.

Changing the groundwater flow rate (Scenarios G3.4a and G3.4b) has an effect on almost all variables (except aluminum). Lowering the groundwater flow rate (Scenario G3.4a) decreases concentrations of all variables, indicating that groundwater has higher concentrations of most variables compared with natural surface water. Increasing the groundwater flow rate and maintaining a positive flow rate once the pit lake is filled (Scenario G3.4b) predicts an increase in all variables.

If it is assumed that pumped flows to Fox pit lake will not be zero, the results for Fox pit lake indicate that the predictions of full pit lake chemistry are not overly sensitive to model inputs, with changes in modelled concentrations of less than an order of magnitude with changes in pit wall runoff and groundwater inflows. The key issue with respect to Fox pit lake will be whether meromixis forms in the pit lake, with greater TDS values (140 mg/L) in the Base Case compared to pit lakes with no groundwater inflow. However, the Fox pit lake TDS values are not as high as those predicted for Panda or Koala/Koala North pit lakes.

7.1.2.4 Results for Group 4 — Open Pit which Will Be Partially Infilled with Mine Water and Mine Solids (Beartooth Pit Lake)

Unlike the other pit lakes at the Ekati site, Beartooth pit lake will be substantially filled with FPK solids at the end of operations. Above the FPK solids there will be a 30 m water cover that will a mixture of fresh water and mine water. The relative volumes of fresh water and mine water in the pit lake will depend on the quality of the mine water and the volume of mine water that is pumped out of the pit lake prior to the addition of fresh water. Three scenarios are considered; one where there is assumed to be a 5 m thick layer of mine water above the FPK solids which is then mixed with a 25 m thick layer of fresh water, and others where the mine water layer is considered to be 10 m and 1 m thick. Results for Beartooth pit lake are provided in Table 7.1-7 and they indicate that the presence of mine water above the FPK solids can have an impact on water quality in the pit lake. If 5 m depth of mine water remains the bulk chemistry in the pit lake shows exceedances of chloride, nitrate, phosphate, sulphate and cadmium. If the layer of mine water is thicker (10 m), concentrations of chromium (VI) and strontium are also predicted to exceed Water Quality Benchmarks. In contrast, if only 1 m of mine water remains concentrations of nitrate and cadmium only are predicted to exceed Water Quality Benchmarks. Clearly if all of the mine water is removed at the end of operations then concentrations would tend to natural water. However, the physical limit to this may be the ability of pumping equipment to remove all the mine water from the pit lake.

7.1.3 Summary of Pit Infilling Results

This section has presented predictions of the water balance and water quality of each pit lake during the infilling process. The model predictions were based on a conservative box modelling approach that considered the key inputs and outputs into each pit lake during the infilling process.

Table 7.1-7. Pit Infilling Water Quality Predictions — Beartooth Pit

Variable	[a]Water Quality Benchmark	5 m Thick Layer of Mine Water (mg/L)	10 m Thick Layer of Mine Water (mg/L)	1 m Thick Layer of Mine Water (mg/L)
Ammonia - N	0.59	0.10	0.21	0.034
Chloride	[b]170	470	980	150
Nitrate - N	0.49	1.7	3.5	0.54
Nitrite - N	0.06	0.028	0.058	0.0093
Phosphate		0.013	0.025	0.0059
Sulphate	20	52	110	17
TDS	-	790	1700	260
Aluminum	0.10	0.012	0.016	0.0091
Antimony	0.02	0.00076	0.0015	0.00028
Arsenic	0.005	0.00039	0.00069	0.00021
Barium	1	0.035	0.072	0.013
Boron	1.5	0.011	0.023	0.0040
Cadmium	0.0000021	0.00012	0.00023	0.000056
Chromium III	0.0089	0.00020	0.00040	0.000074
Chromium VI	0.0010	0.00067	0.0013	0.00025
Copper	0.0020	0.00046	0.00064	0.00027
Iron	0.30	0.012	0.019	0.0055
Lead	0.0010	0.00011	0.00021	0.000041
Manganese	0.62	0.016	0.031	0.0048
Molybdenum	19	0.042	0.089	0.011
Nickel	0.025	0.0013	0.0024	0.00049
Potassium	41	15	31	4
Selenium	0.0010	0.00015	0.00025	0.000063
Strontium	6.2	3.5	7.4	0.88
Uranium	0.015	0.00027	0.00054	0.000077
Vanadium	0.015	0.00043	0.00087	0.00012
Zinc	0.03	0.0012	0.0021	0.00057

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).
Scenarios are defined in Table 5.2-4.

It should be noted that the predictions presented here are bulk averaged chemistry within the filled pit lakes. The model used to predict the water quality of the infilling pit lakes does not simulate stratification or layering within the pit lake. Such processes are represented in the multi-layer model, with predictions of surface layer water quality presented in Section 7.2.

The results of the water quality modelling indicate that for most water quality variables the bulk chemistry in the full pit lakes is not expected to exceed Water Quality Benchmarks for the Base Case model runs, with some exceptions.

Exceedances of cadmium are predicted in all pit lakes. The cadmium benchmark is based on the interim CCME guideline value which is known to be unrealistically low (Rescan 2012). A draft CCME guideline for cadmium has been published and it is significantly higher than the interim guideline. However, the draft guideline has yet to be formally endorsed so is not considered in this report. The model predictions for cadmium are lower than the draft guideline. This is the case for all pit lakes and not just pit lakes with higher cadmium loadings from meta-sediments.

In all the calculations presented in the section, hardness dependent Water Quality Benchmarks (except chloride) are calculated based on a low hardness value of 4 mg/L, which is consistent with background water quality for the Ekati area. Low hardness values result in low Water Quality Benchmarks.

Chloride, nitrate and sulphate are predicted to exceed Water Quality Benchmarks in Panda and Koala/Koala North as a result of high concentrations of these water quality variables in underground water. The same variables are predicted to exceed the Water Quality Benchmark for Beartooth pit as a result of residual mine water within the pit lake at the end of operations.

Copper is predicted to exceed Water Quality Benchmarks in Misery pit as a result of relatively high loadings from meta-sediment exposed in the Misery pit wall.

Sensitivity model runs undertaken that vary key model inputs produced exceedances for other water quality variables. The largest number of exceedances occurred for Misery and Pigeon pit lakes where sensitivity runs that resulted in higher loadings from reactive meta-sediments within the pit walls were seen to produce exceedances of Water Quality Benchmarks for a number of metals (e.g., aluminum, copper, nickel, zinc).

The main conclusion from the sensitivity analysis was that the key parameter affecting water quality results for each pit lake was the rate of freshwater pumping to the pit; the higher the rate of pumping the closer the quality in the pit lake tended to natural lake water.

For Panda and Koala/Koala North pit lakes the time delay from the end of operations to the onset of active infilling of the pit lakes impacted concentrations of a number of water quality variables and especially those associated with groundwater. The longer the delay in the onset of pumping the higher the concentrations of these water quality variables in the full pit lake. Based on the ICRP, the time between the end of operations and the onset of pumping for other pit lakes are not as long as for Panda and Koala/Koala North, so they were not considered in detail in this study. However, if future changes to the ICRP result in more time before the onset of pumping, higher concentrations in the pit lakes are predicted due to surface water runoff over exposed pit walls. These impacts would be expected to be greatest for Misery and Pigeon pit lakes which have meta-sediment in their pit walls.

For pits with groundwater inflows (especially for variables such as TDS) results were sensitive to assumptions related to the groundwater inflow rate and how the inflow rate changes (decreases) over time as the pits fill. It should be noted that the model does not consider a scenario where the pit lake becomes a source of discharge to groundwater (i.e., lake level is greater than regional groundwater head resulting in flows from lake to groundwater). There are limited data on groundwater flow rates and none on the regional groundwater head. Improved knowledge of these variables would assist in refining the current estimates. This is especially important in assessing whether the pit lakes will become sources or sinks for groundwater once the lakes are filled.

As outlined above, estimates of pit wall chemistry for Pigeon and Misery pit lakes have an important influence on final pit lake chemistry. Both Misery and Pigeon pits walls contain meta-sediments which are predicted to produce high loadings in pit wall runoff. However, comparison of pit wall runoff predictions with observed Misery sump water would suggest that the pit wall runoff predictions may over-estimate the loadings from pit walls (see Section 4.3.4) and as a result high metals loadings in Misery and Pigeon pits should be viewed with caution as they may be conservative (high).

The model assumes that runoff from waste rock piles has the chemistry of natural runoff as reactive waste rock is assumed to be contained in a frozen core with the hydrologically active part of WRSAs composed of non-reactive granite. This assumption should be reviewed when more information on WRSA design is available and further work is undertaken on the WRSAs reporting to each pit lake.

There is the potential that water from the LLCF could be used to infill pit lakes either as an alternative to or within a blend with natural lake water. A detailed assessment of the impact of LLCF water on pit lake chemistry is beyond the scope of this assessment. However, natural background water quality is of better quality than the LLCF water, and as a result the LLCF has the potential to influence the ultimate quality of water in full pit lakes.

7.2 LONG-TERM PREDICTIONS OF WATER QUALITY IN SURFACE LAYER OF PIT LAKE

Outflows from the pit lakes will occur during the open water season when the lakes are ice-free and there is a net surplus of water. The outflow to surface water bodies will be through natural, uncontrolled spill points, such that overflow will only take place within the surface layer of the pit lakes. Hence, predictions are required of the water quality in the surface layer of the pit lake over time.

Water quality predictions have been made for two periods in each year, post infilling:

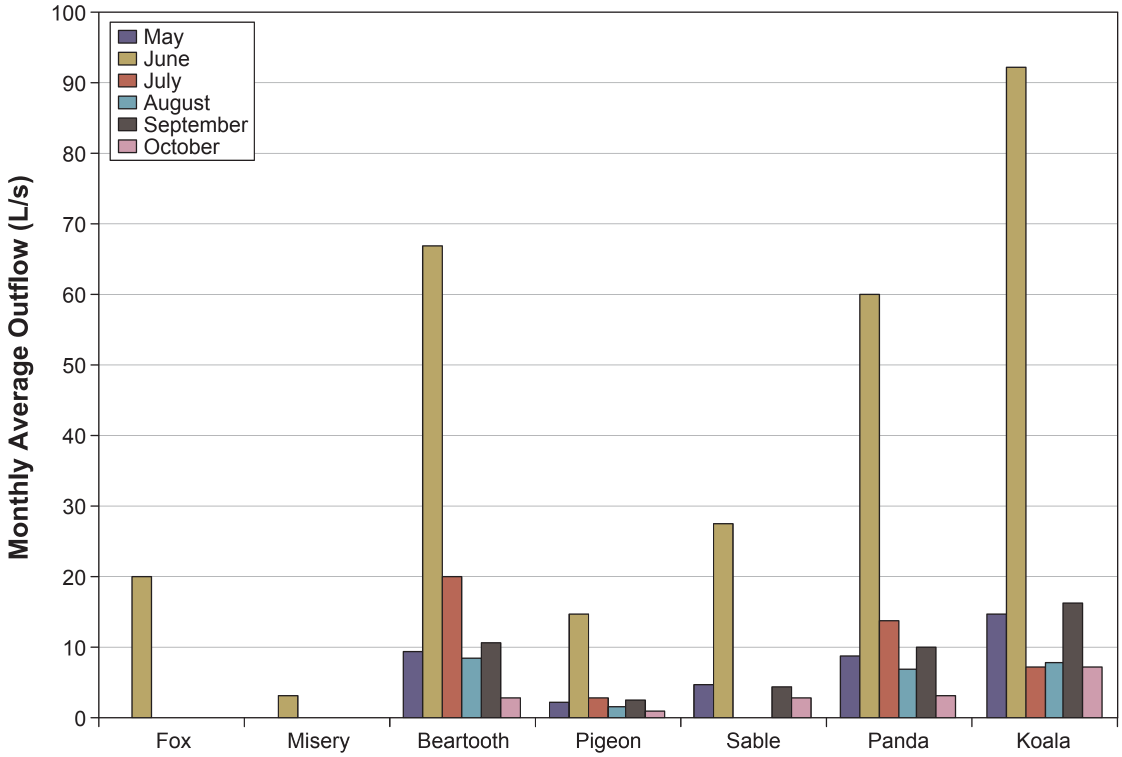
- spring and summer (June, July, August) when a surface layer forms due to ice melt following freshet; and
- fall (September, October) when full mixing is expected to occur following warming and cooling of the upper layer (for cases with no meromixis).

Upper layer concentrations of most water quality variables would be expected to be lower during spring and summer due to the diluting effect of ice melt and freshwater runoff into each pit lake. Concentrations of most variables increase in the fall as the surface layer deepens and entrains water from below.

7.2.1 Long-term Water Balance Results

Once a pit lake is full and water levels have reached the overspill level from the pit lake, excess water from the pit lake will flow out of the lake to a downstream pit lake, natural lake or watercourse (natural or man-made). Estimates of annual water volumes discharged from each pit lake under average, dry and wet conditions are provided in Table 7.2-1. Estimates of monthly average flows for a year with average precipitation and runoff are presented in Table 7.2-2 and shown in Figure 7.2-1.

With the pit diversion channels remaining in place at closure (i.e., Pigeon Diversion Channel and Panda Diversion Channel), the water balance results indicate that outflows from most pit lakes will be relatively low, primarily due to the small catchment areas draining to the pit lakes and the effect of evaporation from the pit lake surfaces. For some pit lakes (Fox, Misery and Sable) evaporation from the pit lake surface results in the outflow from the lake tending to zero during some months as the lake surface is drawn down below the spill level. For all pit lakes the summer outflows are substantially lower than flows during freshet, even if flow can be maintained during these months. For all lakes outflows are greatest during June at the height of snowmelt. These results are consistent with the observed flow hydrographs at gauged streams at the Ekati site.



DOMINION DIAMOND

Figure 7.2-1

Average Monthly Flows out of Each Pit Lake for Average Annual Precipitation and Runoff Condition

Rescan
Engineers & Scientists

Table 7.2-1. Estimates of Annual Discharge from Each Pit Lake Post-infilling

Pit Lake	Annual Discharge Volume (m^3)		
	Dry[a]	Average[b]	Wet[c]
Sable	0	105,000	363,000
Pigeon (Pigeon Diversion Channel in place)	5,800	65,000	183,000
Pigeon (Pigeon Diversion Channel removed)	601,000	1,810,000	4,420,000
Beartooth	81,000	313,000	802,000
Misery	0	9,000	105,000
Fox	0	54,000	286,000
Panda	36,000	271,000	750,000
Koala/Koala North[d]	17,000	382,000	1,110,000

Notes: Zero groundwater inflow once pits have filled. Runoff values assume Panda Diversion Channel remain in place.
[a] *Annual average precipitation = 162 mm/year, runoff coefficient = 0.35.*
[b] *Annual average precipitation = 338 mm/year, runoff coefficient = 0.5.*
[c] *Annual average precipitation = 621 mm/year, runoff coefficient = 0.65.*
[d] *Koala/Koala North receives runoff from Panda Pit lake.*

Table 7.2-2. Average Monthly Flows from Each Pit Lake (Average Precipitation and Runoff)

Pit Lake	Average Monthly Flow (L/s)					
	May	June	July	August	September	October
Fox	0	20	0	0	0	0
Misery	0	3.0	0	0	0	0
Beartooth	9	67	20	8	11	3
Pigeon (Pigeon Diversion Channel in place)	2	15	3	2	2	1
Pigeon (Pigeon Diversion Channel removed)	25	190	79	28	29	4.2
Sable	4.7	28	0	0	4.3	2.9
Panda	8.8	60	14	6.7	10	3.2
Koala/Koala North	15	92	7.3	7.7	16	7.3

7.2.2 Long-term Model Results for Group 1 — Open Pit with no Groundwater Inflows and No Meta-sediments within the Pit Walls (Sable Pit Lake)

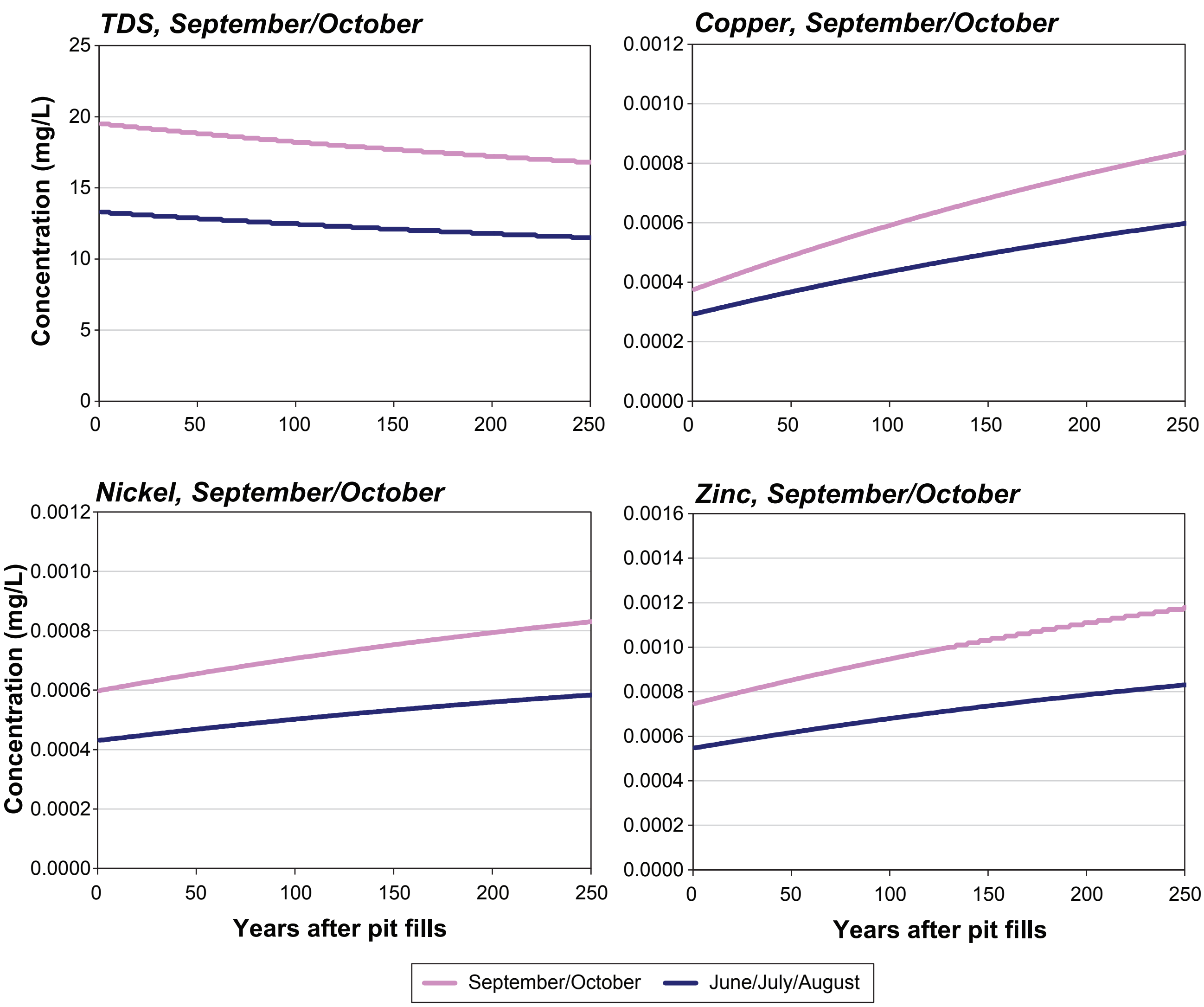
Sable pit is an isolated open pit that will be filled with freshwater. Long-term water quality predictions in the surface water layer of Sable pit lake for Base Case conditions are provided in Table 7.2-3, with time series graphs for key water quality variables in Figure 7.2-2. The results indicate that all model water quality variables, apart from cadmium, are predicted to be below Water Quality Benchmarks. As discussed in Rescan (2012), the cadmium Water Quality Benchmark is known to be unrealistically low.

Concentrations of dissolved anions (e.g., sulphate and TDS) are predicted to decrease over time, with concentrations of some metals are predicted to increase. However, the rate of increase is low and concentrations are orders of magnitude below Water Quality Benchmarks. For many metals the initial concentrations in the full Sable pit lake were lower than concentrations used for natural runoff into the pit lake at closure. This results from the assumption that pumped water to infilling pit lake is equivalent to observed water quality in Vulture Lake, while surface runoff is set equivalent to observed stream water quality in Vulture/Polar stream. Concentrations in Vulture/polar stream are higher than those in Vulture Lake for many variables (Table 4.3-1), but all concentrations are well below Water Quality Benchmarks. Hence, if the pit lake models were run long enough into the future concentrations would tend to the natural water quality of Vulture/Polar stream.

Table 7.2-3. Predicted Concentration in Overflow Discharge from Sable Pit Lake, Base Case

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Years	Year 1	10 Year	100 Year	250 years
Ammonia - N	0.59	0.023	0.023	0.021	0.018	0.016	0.016	0.014	0.012
Chloride	[b]170	0.46	0.46	0.44	0.41	0.31	0.31	0.30	0.28
Nitrate - N	0.49	0.18	0.17	0.14	0.10	0.12	0.11	0.093	0.067
Nitrite – N	0.06	0.0089	0.0087	0.0073	0.0055	0.0059	0.0058	0.0048	0.0036
Phosphate		0.0028	0.0029	0.0038	0.0049	0.0021	0.0021	0.0027	0.0035
Sulphate	20	3.8	3.8	3.5	3.2	2.6	2.6	2.4	2.2
TDS	-	20	19	18	17	13	13	13	12
Aluminum	0.10	0.0089	0.0098	0.018	0.028	0.0076	0.0082	0.014	0.02
Antimony	0.02	0.000078	0.000079	0.000083	0.000088	0.000055	0.000055	0.000058	0.000061
Arsenic	0.005	0.00019	0.00019	0.00021	0.00023	0.00013	0.00013	0.00014	0.00016
Barium	1	0.0032	0.0033	0.0037	0.0043	0.0023	0.0024	0.0026	0.0030
Boron	1.5	0.0017	0.0017	0.0017	0.0016	0.0012	0.0012	0.0011	0.0011
Cadmium	0.0000021	0.000025	0.000026	0.000028	0.000030	0.000018	0.000018	0.000019	0.000021
Chromium III	0.0089	0.0000053	0.0000068	0.000020	0.000037	0.000006	0.0000069	0.000016	0.000027
Chromium VI	0.0010	0.000018	0.000023	0.000067	0.00012	0.000020	0.000023	0.000053	0.000090
Copper	0.0020	0.00038	0.00040	0.00059	0.00084	0.00029	0.00031	0.00044	0.00060
Iron	0.30	0.0089	0.012	0.035	0.065	0.010	0.012	0.028	0.047
Lead	0.0010	0.000025	0.000026	0.000028	0.000030	0.000018	0.000018	0.000019	0.000021
Manganese	0.62	0.0028	0.0028	0.0036	0.0045	0.0020	0.0021	0.0026	0.0032
Molybdenum	19	0.0032	0.0032	0.0026	0.0019	0.0021	0.0021	0.0017	0.0012
Nickel	0.025	0.00060	0.00061	0.00071	0.00083	0.00043	0.00044	0.00050	0.00058
Potassium	41	1.1	1.1	1.0	0.96	0.73	0.73	0.70	0.66
Selenium	0.0010	0.000086	0.000086	0.000084	0.000082	0.000059	0.000059	0.000058	0.000057
Strontium	6.2	0.017	0.017	0.016	0.014	0.011	0.011	0.011	0.0098
Uranium	0.015	0.00017	0.00016	0.00015	0.00012	0.00011	0.00011	0.000098	0.000082
Vanadium	0.015	0.00013	0.00013	0.00014	0.00015	0.000090	0.000090	0.000096	0.00010
Zinc	0.03	0.00075	0.00077	0.00095	0.0012	0.00055	0.00056	0.00068	0.00083

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).



Long Term Water Quality in Sable Pit Lake for TDS, Copper, Nickel, and Zinc

Figure 7.2-2

In summary, for Sable pit the model results predict there will be no meromixis within the pit lake, although there will be natural stratification at times of the year in response to air temperature and snow melt. The water quality within the surface layer of Sable pit lake and flowing into downstream water bodies is expected to be below Water Quality Benchmarks for all variables.

7.2.3 Long-term Model Results for Group 2 — Open Pits with No Groundwater Inflows and with Meta-sediments within the Pit Walls (Misery and Pigeon Pit Lakes)

7.2.3.1 Misery Pit Lake

Long-term water quality predictions in the surface water layer of Misery pit lake for Base Case conditions are provided in Table 7.2-4a, with time series graphs for key water quality variables in Figure 7.2-3. For the Base Case exceedances of Water Quality Benchmarks for cadmium and copper are predicted in the early years after the pit lake has been filled. Over time concentrations of most metals are predicted to increase, resulting in exceedances of the Water Quality Benchmark for nickel and zinc around 250 years after the pit has been filled. This is a result of the Base Case assumption that pit wall runoff leach rates for meta-sediment, exposed in the Misery pit wall, do not vary over time. The area of pit wall exposed above the full Misery pit lake is a significant portion (40%) of the total catchment flowing to Misery pit lake, so loadings from the exposed pit wall at closure is an important driver for future water quality in the pit lake. For the Base Case scenario, concentrations in Misery pit lake are predicted to increase into the future until the pit lake quality approached that of the pit wall runoff (adjusted for the diluting effects of natural inflows).

The assumption of constant leach rates for meta-sediment over the full 250 years of the model simulation may not be realistic. The Base Case for meta-sediment leaching assumes that jarosite (formed by the weathering of biotite) is able to prolong acidic runoff conditions for meta-sediments in perpetuity. However, even if jarosite was formed leach rates would be expected to decrease over time as weathering products were exhausted, although the geochemical modelling undertaken (Appendix 3) was not able to quantify this decay for the jarosite case, although values given in Appendix 3 are considered valid for up to 100 years post-closure. Hence, Scenarios 1 and 2 were run assuming no control with jarosite and a time varying leach rate. Scenario 2 considered higher leach rates compared to Scenario 1. It is noted that although runs with no jarosite do produce predictions with a decreasing leaching rate over time, the initial leach rate associated with these scenarios are higher than for the Base Case. Jarosite control (Base Case) results in reduced leach rates over the short-term, but prolongs the release of the weathering products over the longer-term.

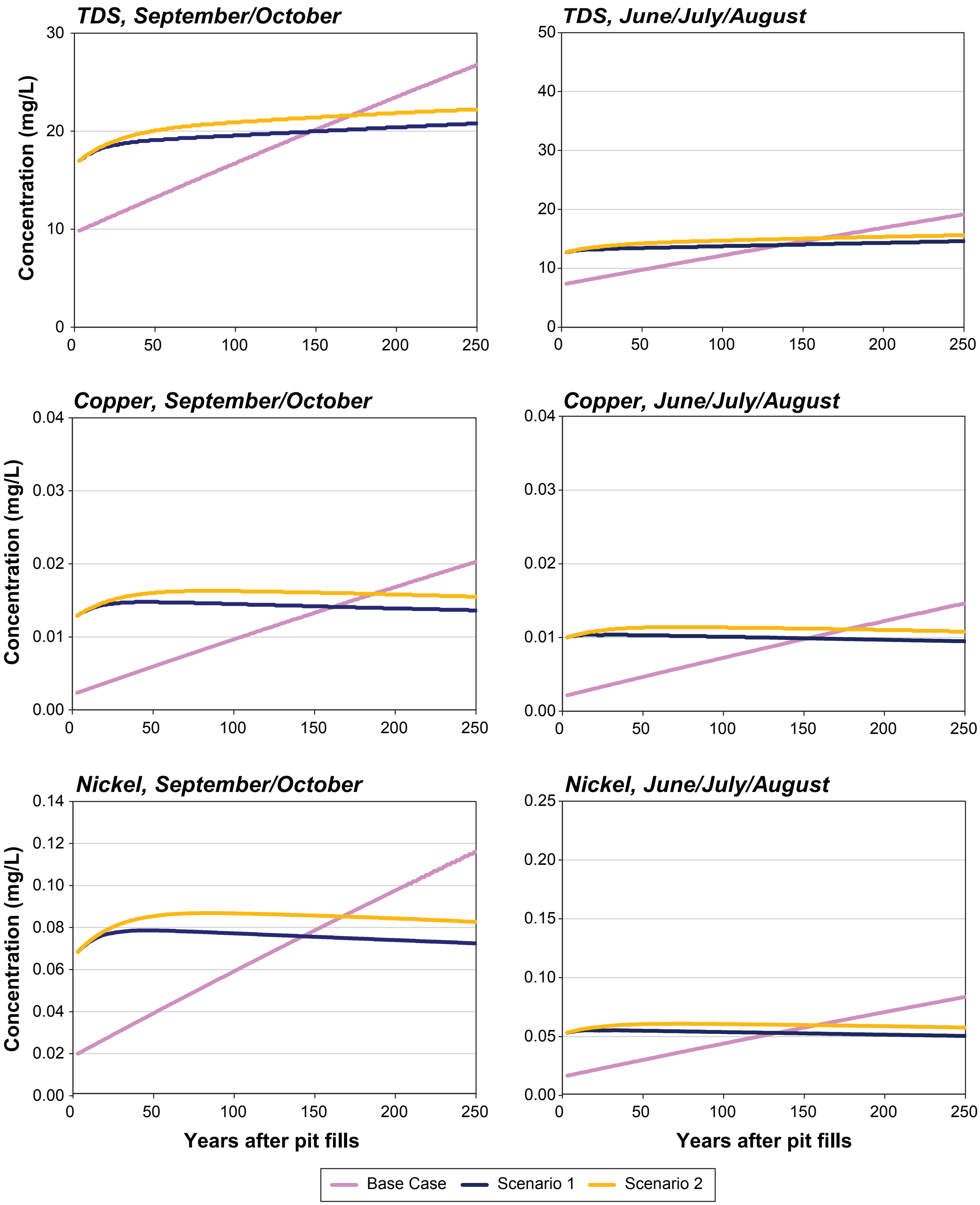
Long-term water quality predictions in the surface water layer of Misery pit lake for Scenarios 1 and 2 are provided in Tables 7.2-4b and 7.2-4c, with time series graphs for key variables in Figure 7.2-3. The results for Scenarios 1 and 2 show an initial increase in concentrations in the pit lake for the first 50 to 100 years after the pit lake is filled, but with concentrations gradually decreasing from that point onwards. This is more realistic than the trend of increasing concentrations predicted for the Base Case. However, for Scenarios 1 and 2 the initial concentrations of many variables within the pit lake are higher than those predicted for the Base Case, which is consistent with what would be expected for scenarios with no jarosite control. As a result exceedances of Water Quality Benchmarks for aluminum, cadmium, copper, nickel and zinc are predicted for Scenarios 1 and 2.

The long-term water quality predictions for Misery pit lake indicate the potential for exceedances of Water Quality Benchmarks for some variables in the surface layers of the pit lake. However, the long-term predictions for Scenarios 1 and 2 clearly illustrate the influence of initial pit lake chemistry on the long-term predictions. If concentrations in the initial pit lake are significantly lower than predicted for Scenarios 1 and 2, then concentrations in the pit lake might not exceed Water Quality Benchmarks.

Table 7.2-4a. Predicted Concentration in Overflow Discharge from Misery Pit Lake, Base Case

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Years	Year 1	10 Year	100 Year	250 Years
Ammonia - N	0.59	0.00036	0.00037	0.00041	0.00047	0.00026	0.00026	0.00029	0.00033
Chloride	[b]170	0.25	0.25	0.24	0.22	0.17	0.17	0.17	0.16
Nitrate - N	0.49	0.0047	0.0047	0.0045	0.0042	0.0033	0.0033	0.0031	0.0029
Nitrite - N	0.06	0.00012	0.00012	0.00012	0.00012	0.000086	0.000086	8.6E-05	8.7E-05
Phosphate		0.0027	0.0027	0.0026	0.0026	0.0019	0.0019	0.0018	0.0018
Sulphate	20	3.1	3.6	7.8	14	2.5	2.8	5.8	10
TDS	-	9.8	10	17	27	7.4	7.8	12	19
Aluminum	0.10	0.017	0.026	0.11	0.25	0.019	0.025	0.086	0.18
Antimony	0.02	0.00011	0.00011	0.00012	0.00014	7.6E-05	0.000077	8.4E-05	9.6E-05
Arsenic	0.005	0.00018	0.00019	0.00033	0.00056	0.00014	0.00014	0.00024	0.00040
Barium	1	0.0036	0.0036	0.0040	0.0047	0.0026	0.0026	0.0029	0.0033
Boron	1.5	0.0010	0.0011	0.0016	0.0025	0.00074	0.00078	0.0012	0.0018
Cadmium	0.0000021	4.1E-05	4.3E-05	0.000067	0.00010	3.0E-05	0.000032	4.9E-05	7.4E-05
Chromium III	0.0089	2.0E-05	2.0E-05	2.3E-05	2.8E-05	1.4E-05	0.000014	1.6E-05	1.9E-05
Chromium VI	0.0010	6.8E-05	6.8E-05	7.8E-05	9.2E-05	4.8E-05	0.000049	5.5E-05	6.5E-05
Copper	0.0020	0.0024	0.0030	0.0098	0.020	0.0022	0.0026	0.0074	0.015
Iron	0.30	0.012	0.019	0.082	0.18	0.013	0.018	0.062	0.13
Lead	0.0010	4.1E-05	4.4E-05	6.8E-05	0.00010	3.1E-05	0.000032	0.000049	7.5E-05
Manganese	0.62	0.015	0.016	0.027	0.043	0.011	0.012	0.019	0.031
Molybdenum	19	3.7E-05	3.6E-05	3.6E-05	3.5E-05	2.6E-05	0.000026	2.5E-05	2.4E-05
Nickel	0.025	0.020	0.024	0.060	0.12	0.017	0.019	0.045	0.084
Potassium	41	0.46	0.49	0.80	1.3	0.35	0.37	0.58	0.91
Selenium	0.0010	8.5E-05	8.9E-05	0.00013	0.00018	6.2E-05	0.000065	9.1E-05	0.00013
Strontium	6.2	0.0073	0.0074	0.0084	0.0099	0.0052	0.0052	0.0059	0.0070
Uranium	0.015	7.9E-05	9.1E-05	0.00021	0.00040	6.4E-05	0.000073	0.00016	0.00029
Vanadium	0.015	6.1E-05	6.2E-05	7.4E-05	9.1E-05	4.4E-05	0.000045	5.2E-05	6.5E-05
Zinc	0.03	0.0087	0.011	0.030	0.061	0.0076	0.0090	0.023	0.044

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).



Long Term Water Quality in Misery Pit Lake for TDS, Copper, and Nickel

Figure 7.2-3

DOMINION DIAMOND

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Table 7.2-4b. Predicted Concentration in Overflow Discharge from Misery Pit Lake, Scenario 1

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Years	Year 1	10 Year	100 Year	250 Years
Ammonia - N	0.59	0.00036	0.00037	0.00041	0.00047	0.00026	0.00026	0.00029	0.00033
Chloride	[b]170	0.25	0.25	0.24	0.22	0.17	0.17	0.17	0.16
Nitrate - N	0.49	0.0047	0.0047	0.0045	0.0042	0.0033	0.0033	0.003	0.0029
Nitrite - N	0.06	0.00012	0.00012	0.00012	0.00012	0.000086	0.000086	8.63E-05	8.7E-05
Phosphate		0.0021	0.0021	0.0021	0.0021	0.0015	0.0015	0.0015	0.0015
Sulphate	20	9.2	9.9	10	10	7.1	7.3	7.2	6.9
TDS	-	17	18	20	21	13	13	14	15
Aluminum	0.10	0.17	0.18	0.19	0.18	0.13	0.14	0.13	0.12
Antimony	0.02	7.6E-05	7.8E-05	7.8E-05	0.000073	5.5E-05	0.000056	5.4E-05	5.1E-05
Arsenic	0.005	0.00039	0.00041	0.00042	0.00039	0.00029	0.00030	0.00029	0.00028
Barium	1	0.0034	0.0034	0.0034	0.0032	0.0024	0.0024	0.0024	0.0022
Boron	1.5	0.0017	0.0018	0.0018	0.0017	0.0013	0.0013	0.0013	0.0012
Cadmium	0.0000021	7.1E-05	7.4E-05	7.6E-05	0.000071	0.000053	0.000054	5.3E-05	5.0E-05
Chromium III	0.0089	2.2E-05	2.2E-05	2.2E-05	2.2E-05	1.6E-05	0.000016	1.6E-05	1.5E-05
Chromium VI	0.0010	7.3E-05	7.5E-05	7.5E-05	7.2E-05	5.3E-05	0.000053	5.2E-05	5.0E-05
Copper	0.0020	0.013	0.014	0.014	0.014	0.010	0.010	0.010	0.0095
Iron	0.30	0.12	0.13	0.14	0.13	0.094	0.097	0.095	0.090
Lead	0.0010	7.1E-05	7.5E-05	7.6E-05	7.1E-05	5.3E-05	0.000054	5.3E-05	5.0E-05
Manganese	0.62	0.023	0.024	0.025	0.024	0.018	0.018	0.018	0.017
Molybdenum	19	0.000036	0.000036	3.5E-05	3.2E-05	2.5E-05	0.000025	2.4E-05	2.3E-05
Nickel	0.025	0.068	0.074	0.077	0.072	0.053	0.055	0.054	0.050
Potassium	41	1.0	1.1	1.1	1.0	0.77	0.79	0.76	0.72
Selenium	0.0010	0.00012	0.00013	0.00013	0.00012	9.3E-05	0.000094	9.2E-05	8.6E-05
Strontium	6.2	0.0077	0.0078	0.0078	0.0073	0.0055	0.0056	0.0054	0.0051
Uranium	0.015	0.00025	0.00026	0.00028	0.00026	0.00019	0.00020	0.00019	0.00018
Vanadium	0.015	0.000050	5.2E-05	5.3E-05	5.1E-05	3.7E-05	0.000038	3.7E-05	3.5E-05
Zinc	0.03	0.037	0.040	0.042	0.039	0.029	0.030	0.029	0.027

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-4c. Predicted Concentration in Overflow Discharge from Misery Pit Lake, Scenario 2

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Years	Year 1	10 Year	100 Year	250 Years
Ammonia - N	0.59	0.00036	0.00037	0.00041	0.00047	0.00026	0.00026	0.00029	0.00033
Chloride	[b]170	0.25	0.25	0.24	0.22	0.17	0.17	0.17	0.16
Nitrate - N	0.49	0.0047	0.0047	0.0045	0.0042	0.0033	0.0033	0.0031	0.0029
Nitrite - N	0.06	0.00012	0.00012	0.00012	0.00012	0.000086	0.000086	8.6E-05	8.7E-05
Phosphate		0.0021	0.0021	0.0021	0.0021	0.0015	0.0015	0.0015	0.0015
Sulphate	20	9.2	10	11	11	7.1	7.4	8.0	7.8
TDS	-	17	18	21	22	13	13	15	16
Aluminum	0.10	0.17	0.18	0.21	0.20	0.13	0.14	0.15	0.14
Antimony	0.02	7.6E-05	7.8E-05	8.2E-05	7.7E-05	5.5E-05	0.000056	5.7E-05	5.4E-05
Arsenic	0.005	0.00039	0.00041	0.00046	0.00044	0.00029	0.00030	0.00032	0.00030
Barium	1	0.0034	0.0034	0.0036	0.0034	0.0024	0.0025	0.0025	0.0023
Boron	1.5	0.0017	0.0018	0.0020	0.0019	0.0013	0.0013	0.0014	0.0013
Cadmium	0.0000021	7.1E-05	7.5E-05	8.2E-05	0.000078	5.3E-05	0.000055	5.7E-05	5.4E-05
Chromium III	0.0089	2.2E-05	2.2E-05	2.3E-05	2.2E-05	1.6E-05	0.000016	1.6E-05	1.6E-05
Chromium VI	0.0010	7.3E-05	7.5E-05	7.8E-05	7.5E-05	5.3E-05	0.000054	5.4E-05	5.2E-05
Copper	0.0020	0.013	0.014	0.016	0.016	0.010	0.010	0.011	0.011
Iron	0.30	0.12	0.13	0.15	0.15	0.094	0.099	0.11	0.10
Lead	0.0010	7.1E-05	0.000075	8.2E-05	7.8E-05	5.3E-05	0.000055	5.8E-05	5.4E-05
Manganese	0.62	0.023	0.025	0.028	0.027	0.018	0.018	0.020	0.019
Molybdenum	19	0.000036	0.000036	3.5E-05	3.3E-05	2.5E-05	0.000025	2.4E-05	2.3E-05
Nickel	0.025	0.068	0.075	0.087	0.083	0.053	0.056	0.060	0.058
Potassium	41	1.0	1.1	1.2	1.1	0.77	0.80	0.82	0.78
Selenium	0.0010	0.00012	0.00013	0.00014	0.00014	9.2E-05	0.000096	9.9E-05	0.000094
Strontium	6.2	0.0077	0.0079	0.0081	0.0076	0.0055	0.0056	0.0056	0.0053
Uranium	0.015	0.00025	0.00027	0.00031	0.00029	0.00019	0.00020	0.00021	0.00020
Vanadium	0.015	0.000050	5.2E-05	5.6E-05	5.4E-05	3.7E-05	0.000038	3.9E-05	3.8E-05
Zinc	0.03	0.037	0.041	0.047	0.045	0.029	0.030	0.033	0.031

[a] Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.
[b] Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

The impact of model assumptions on the water quality of the infilling pit lake was discussed in Section 7.1. It was noted that comparisons between pit wall runoff predictions for Misery pit lake and observed Misery sump water quality suggested that the pit wall runoff predictions were significantly higher than the observed sump water quality. This suggests that model predictions (i.e., Base Case and Scenarios 1 and 2) based on the pit wall runoff predictions could be overly conservative (high). These observations clearly suggest that the focus on future work for Misery pit lake should be on initial pit lake water quality predictions.

It should be noted that given the small catchment surrounding Misery pit lake that water balance predictions (Section 7.2.1) indicated that outflow rates from Misery pit lake would be expected to be very low. Hence, even if exceedances of Water Quality Benchmarks were predicted for the pit lake, the downstream loadings from these elevated concentrations may not be significant. Predictions of the downstream influence of flows from Misery pit lake were not considered in this study.

In summary, the model predictions suggest the potential for exceedances of Water Quality Benchmarks in the surface layer of Misery pit lake. The results indicate the sensitivity of long-term water quality predictions to the initial water quality within the pit lake when full and to the area of pit wall exposed and the quality of pit wall runoff.

7.2.3.2 Pigeon Pit Lake

Long-term water quality predictions in the surface water layer of Pigeon pit lake for Base Case conditions are provided in Table 7.2-5a, with time series graphs for key water quality variables in Figure 7.2-4. Results for modelled Scenarios 1 and 2 are provided in Tables 7.2-5b and 7.2-5c. The general results and observations for Pigeon pit lake are similar to those for Misery pit lake, although concentrations in the pit lake are slightly lower than for Misery due to the larger natural catchment flowing into Pigeon pit lake compared to that for Misery pit lake.

The Base Case model run predicts exceedances of cadmium and copper in the early years after the filling of the pit lake. However, over time concentrations of many variables are predicted to increase due to the assumption of constant leach rates from meta-sediment exposed in the Pigeon pit wall. By 250 years after the pit has filled the Base Case predicts exceedances of Water Quality Benchmarks for sulphate, aluminum, cadmium, copper, iron, nickel, and zinc.

As discussed for Misery pit lake the assumption of constant leach rates for meta-sediment over time is not realistic and Scenarios 1 and 2 were run considering a time varying leach rate. The results for Scenarios 1 and 2 show an initial increase in concentrations in the pit lake for the first 50 to 100 years after the pit lake is filled, but with concentrations gradually decreasing from that point onwards. As before, the initial concentrations of many variables for Scenarios 1 and 2 within the pit lake are higher than those predicted for the Base Case. Although the leach rates used in Scenarios 1 and 2 show a decreasing rate over time, the initial leach rates during pit lake infilling and for early years post-infilling are higher than those used in the Base Case (see Appendix 3). As a result, exceedances of Water Quality Benchmarks for aluminum, cadmium, copper, nickel and zinc are predicted for Scenarios 1 and 2.

In summary the model predictions suggest the potential for exceedances of Water Quality Benchmarks in the surface layer of Pigeon pit lake. However, these exceedances result from model runs based on predicted pit wall runoff inputs, which may be conservative (high). The results indicate the sensitivity of long-term water quality predictions to the initial water quality within the pit lake when full and to the area of pit wall exposed and the quality of pit wall runoff.

Table 7.2-5a. Predicted Concentration in Overflow Discharge from Pigeon Pit Lake, Base Case

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Years	Year 1	10 Year	100 Year	250 Years
Ammonia - N	0.59	0.00076	0.00079	0.0010	0.0013	0.00053	0.00054	0.00070	0.00089
Chloride	[b]170	0.24	0.24	0.21	0.16	0.16	0.16	0.14	0.11
Nitrate - N	0.49	0.0044	0.0043	0.0036	0.0027	0.0028	0.0028	0.0024	0.0018
Nitrite - N	0.06	0.00026	0.00026	0.00025	0.00024	0.00017	0.00017	0.00016	0.00016
Phosphate		0.0053	0.0052	0.0047	0.0041	0.0035	0.0034	0.0031	0.0027
Sulphate	20	2.9	6.2	36	72	4.4	6.5	26	49
TDS	-	9.3	14	59	110	9.9	13	42	78
Aluminum	0.10	0.025	0.092	0.69	1.4	0.066	0.11	0.50	0.98
Antimony	0.02	8.6E-05	9.6E-05	0.00018	0.00029	6.4E-05	0.000077	0.00013	0.00020
Arsenic	0.005	0.00017	0.00028	0.0013	0.0025	0.00020	0.00027	0.00090	0.0017
Barium	1	0.0031	0.0034	0.0067	0.011	0.0023	0.0026	0.0047	0.0073
Boron	1.5	0.00091	0.0014	0.0052	0.010	0.00093	0.0012	0.0037	0.0069
Cadmium	0.0000021	3.7E-05	5.6E-05	0.00022	0.00043	3.8E-05	0.000051	0.00016	0.00029
Chromium III	0.0089	1.9E-05	2.1E-05	4.2E-05	6.8E-05	1.4E-05	0.000016	2.9E-05	4.6E-05
Chromium VI	0.0010	6.2E-05	7.0E-05	0.00014	0.00023	4.7E-05	0.000052	9.9E-05	0.00016
Copper	0.0020	0.0024	0.0076	0.054	0.11	0.0054	0.0088	0.039	0.076
Iron	0.30	0.017	0.066	0.50	1.0	0.047	0.079	0.36	0.70
Lead	0.0010	3.8E-05	5.6E-05	0.00022	0.00043	3.9E-05	0.000051	0.00016	0.00029
Manganese	0.62	0.011	0.019	0.094	0.19	0.014	0.019	0.067	0.13
Molybdenum	19	3.5E-05	3.5E-05	3.4E-05	3.3E-05	2.3E-05	0.000023	2.3E-05	2.2E-05
Nickel	0.025	0.017	0.045	0.29	0.60	0.032	0.050	0.21	0.41
Potassium	41	0.48	0.72	2.8	5.4	0.50	0.65	2.0	3.7
Selenium	0.0010	0.000075	0.00010	0.00037	0.00070	0.000072	0.000092	0.00026	0.00048
Strontium	6.2	0.0064	0.0072	0.015	0.024	0.0049	0.0054	0.010	0.017
Uranium	0.015	7.0E-05	0.00016	0.00099	0.0020	0.00012	0.00018	0.00071	0.0014
Vanadium	0.015	4.8E-05	5.8E-05	0.00014	0.00025	3.9E-05	0.000045	0.00010	0.00017
Zinc	0.03	0.0080	0.023	0.16	0.32	0.016	0.026	0.11	0.22

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

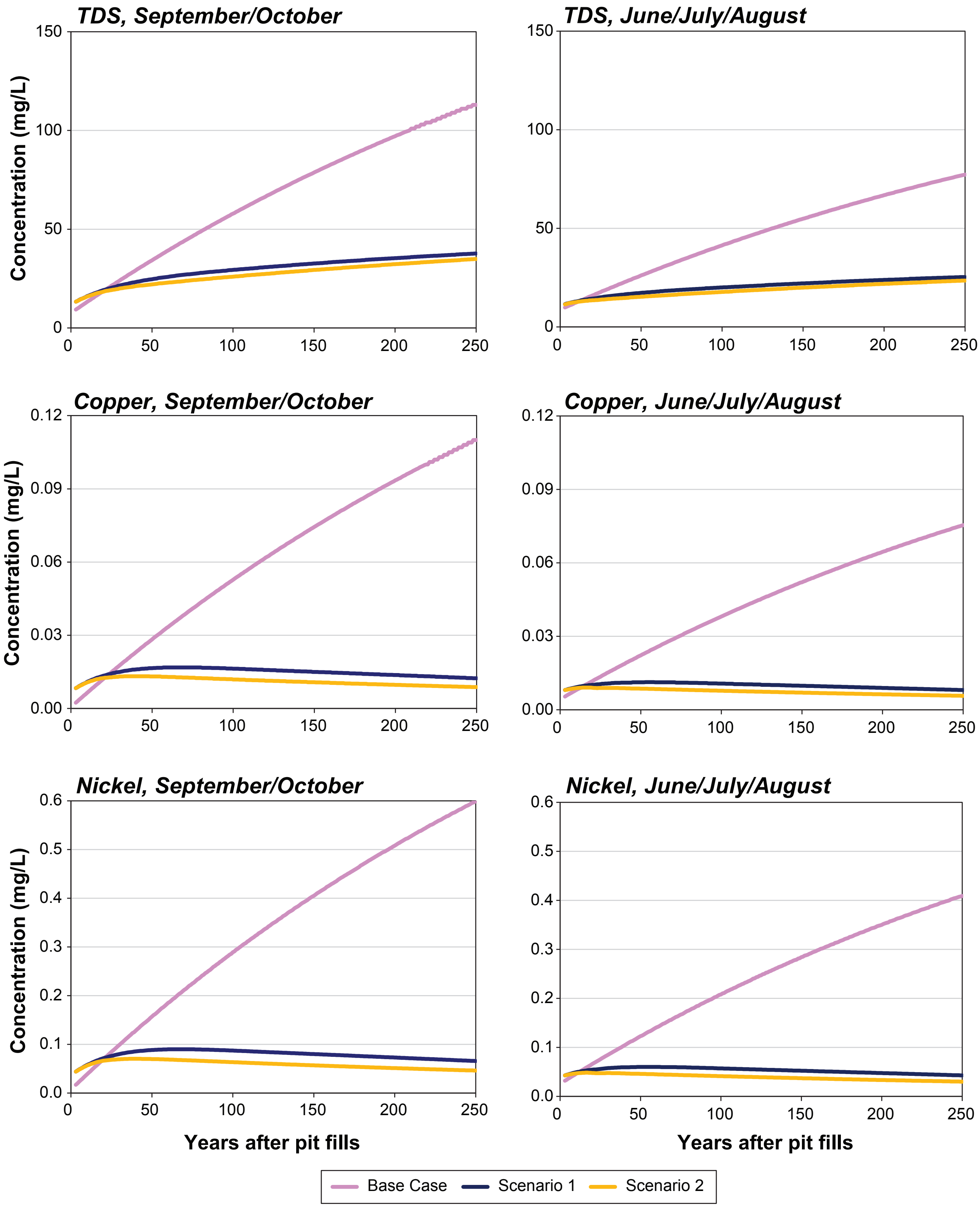

Figure 7.2-4

Long Term Water Quality in Pigeon Pit Lake for TDS, Copper, and Nickel

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Table 7.2-5b. Predicted Concentration in Overflow Discharge from Pigeon Pit Lake, Scenario 1

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Years	Year 1	10 Year	100 Year	250 Years
Ammonia - N	0.59	0.00076	0.00080	0.0012	0.0016	0.00054	0.00056	0.00079	0.0011
Chloride	[b]170	0.24	0.24	0.21	0.18	0.16	0.16	0.14	0.12
Nitrate - N	0.49	0.0044	0.0043	0.0037	0.0029	0.0029	0.0028	0.0024	0.0019
Nitrite - N	0.06	0.00026	0.00026	0.00026	0.00027	0.00017	0.00017	0.00018	0.00018
Phosphate		0.0042	0.0042	0.0041	0.0039	0.0028	0.0028	0.0027	0.0026
Sulphate	20	6.4	8.4	12	12	5.9	6.8	8.3	7.6
TDS	-	13	17	33	46	12	14	23	31
Aluminum	0.10	0.11	0.15	0.22	0.17	0.11	0.12	0.14	0.14
Antimony	0.02	6.6E-05	0.000072	7.7E-05	6.1E-05	4.9E-05	5.1E-05	5.0E-05	4.0E-05
Arsenic	0.005	0.00029	0.00036	0.00045	0.00035	0.00025	0.00028	0.00030	0.00023
Barium	1	0.0029	0.0031	0.0033	0.0028	0.0021	0.0022	0.0022	0.0018
Boron	1.5	0.0013	0.0016	0.0020	0.0016	0.0011	0.0012	0.0013	0.0010
Cadmium	0.0000021	5.4E-05	6.5E-05	8.0E-05	6.2E-05	4.5E-05	5.0E-05	5.2E-05	4.0E-05
Chromium III	0.0089	2.0E-05	2.1E-05	2.4E-05	2.4E-05	1.4E-05	1.5E-05	1.6E-05	1.6E-05
Chromium VI	0.0010	6.6E-05	7.1E-05	8.2E-05	7.8E-05	4.8E-05	5.0E-05	5.4E-05	5.2E-05
Copper	0.0020	0.0084	0.012	0.016	0.012	0.0081	0.0095	0.011	0.0080
Iron	0.30	0.079	0.11	0.16	0.13	0.076	0.090	0.10	0.086
Lead	0.0010	5.4E-05	6.5E-05	0.000080	6.2E-05	4.5E-05	5.0E-05	5.2E-05	4.0E-05
Manganese	0.62	0.015	0.020	0.028	0.022	0.014	0.016	0.018	0.014
Molybdenum	19	0.000035	3.5E-05	3.1E-05	2.5E-05	2.3E-05	2.3E-05	2.0E-05	1.6E-05
Nickel	0.025	0.044	0.061	0.087	0.066	0.043	0.050	0.057	0.043
Potassium	41	0.82	0.96	1.1	0.91	0.66	0.72	0.75	0.59
Selenium	0.0010	9.6E-05	0.00012	0.00014	0.00011	7.9E-05	8.7E-05	9.0E-05	7.0E-05
Strontium	6.2	0.0066	0.0071	0.0074	0.0059	0.0048	0.0050	0.0048	0.0039
Uranium	0.015	0.00016	0.00022	0.00031	0.00023	0.00016	0.00018	0.00020	0.00015
Vanadium	0.015	4.1E-05	0.000047	5.9E-05	5.5E-05	3.2E-05	0.000035	3.9E-05	3.7E-05
Zinc	0.03	0.024	0.033	0.047	0.036	0.023	0.027	0.031	0.023

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-5c. Predicted Concentration in Overflow Discharge from Pigeon Pit Lake, Scenario 2

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Years	Year 1	10 Year	100 Year	250 Years
Ammonia - N	0.59	0.00076	0.00080	0.0012	0.0016	0.00054	0.00056	0.00079	0.0011
Chloride	[b]170	0.24	0.24	0.21	0.18	0.16	0.16	0.14	0.12
Nitrate - N	0.49	0.0044	0.0043	0.0037	0.0029	0.0029	0.0028	0.0024	0.0019
Nitrite - N	0.06	0.00026	0.00026	0.00026	0.00027	0.00017	0.00017	0.00018	0.00018
Phosphate		0.0042	0.0042	0.0041	0.0039	0.0028	0.0028	0.0027	0.0026
Sulphate	20	6.4	8.2	9.8	9.3	5.9	6.5	6.5	6.1
TDS	-	13	17	30	43	12	13	20	29
Aluminum	0.10	0.11	0.15	0.16	0.12	0.11	0.12	0.10	0.078
Antimony	0.02	6.6E-05	7.1E-05	6.7E-05	5.3E-05	4.9E-05	5.0E-05	4.4E-05	3.5E-05
Arsenic	0.005	0.00029	0.00035	0.00036	0.00028	0.00025	0.00026	0.00023	0.00018
Barium	1	0.0029	0.0031	0.0030	0.0025	0.0021	0.0022	0.0020	0.0016
Boron	1.5	0.0013	0.0016	0.0016	0.0012	0.0011	0.0012	0.0010	0.00081
Cadmium	0.0000021	5.4E-05	6.4E-05	6.4E-05	4.8E-05	4.5E-05	4.8E-05	4.2E-05	3.2E-05
Chromium III	0.0089	2.0E-05	2.1E-05	2.2E-05	2.2E-05	1.4E-05	1.5E-05	1.5E-05	1.4E-05
Chromium VI	0.0010	6.6E-05	7.0E-05	7.4E-05	7.3E-05	4.8E-05	4.9E-05	4.9E-05	4.8E-05
Copper	0.0020	0.0084	0.011	0.012	0.0088	0.0080	0.0090	0.0078	0.0057
Iron	0.30	0.079	0.11	0.12	0.097	0.076	0.085	0.078	0.064
Lead	0.0010	5.4E-05	6.4E-05	6.4E-05	4.8E-05	4.5E-05	4.8E-05	4.2E-05	3.2E-05
Manganese	0.62	0.015	0.020	0.021	0.016	0.014	0.016	0.014	0.010
Molybdenum	19	0.000035	3.5E-05	3.0E-05	2.4E-05	2.3E-05	2.3E-05	2.0E-05	1.6E-05
Nickel	0.025	0.044	0.059	0.063	0.046	0.043	0.048	0.041	0.030
Potassium	41	0.82	0.94	0.94	0.74	0.66	0.69	0.61	0.49
Selenium	0.0010	9.6E-05	0.00011	0.00011	0.000085	7.9E-05	8.4E-05	7.3E-05	5.6E-05
Strontium	6.2	0.0066	0.0070	0.0066	0.0052	0.0048	0.0049	0.0043	0.0034
Uranium	0.015	0.00016	0.00022	0.00023	0.00017	0.00016	0.00017	0.00015	0.00011
Vanadium	0.015	4.1E-05	4.6E-05	5.1E-05	4.8E-05	3.2E-05	0.000034	3.4E-05	3.2E-05
Zinc	0.03	0.024	0.032	0.034	0.025	0.023	0.026	0.022	0.016

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

7.2.4 Long-term Model Results for Group 3 — Open Pits that Have Groundwater Inflows (Panda, Koala/Koala North and Fox Pit Lakes)

7.2.4.1 Panda Pit Lake

Long-term water quality predictions in the surface water layer of Panda pit lake for Base Case conditions are provided in Table 7.2-6a, with time series graphs for key water quality variables in Figure 7.2-5. The results indicate exceedances of Water Quality Benchmarks for cadmium, chloride, nitrate and sulphate in the surface layer within the pit lake. The cadmium Water Quality Benchmark is known to be low (Rescan 2012), so exceedances of this water quality variable are not unexpected.

However, high concentrations of chloride, nitrate and sulphate reflect groundwater inflows into the pit lake during pit infilling. Note that high nitrate concentrations may reflect conservative assumptions regarding how much explosives residue is left at the end of operations, and may be an over-estimate. Over time (after 10 years post-infilling) concentrations of these variables fall below Water Quality Benchmarks as loadings of these variables are flushed from the pit lake. It is noted that once the pit lake is full the model assumes there are no additional groundwater flows into the pit lakes.

Results for Scenario 1 are given in Table 7.2-6b, with time series data for key water quality variables in Figure 7.2-5. This scenario considers pit infilling with lower groundwater flow rates. Results for this scenario show exceedances of Water Quality Benchmarks for cadmium only. In this case there are no exceedances of any of the salts (e.g., chloride, sulphate) associated with groundwater. Predictions of most variables are lower than the Base Case indicating the influence of groundwater inflows on initial water quality in the pit lake.

Results for Scenario 2 are given in Table 7.2-6c, with time series data for key water quality variables in Figure 7.2-5. This scenario considers a management option whereby the pit lake is filled with a 30 m surface fresh water cover. This scenario typically produces lower concentrations than the Base Case and similar to Scenario 1, with concentrations of cadmium exceeding Water Quality Benchmarks. For many variables concentrations in the surface layer increase in the first few years after the pit is filled as water with higher concentrations below the fresh water cover, mixes with the fresh surface layer. However, the concentrations reach an approximate equilibrium after around 100 years.

Results for Scenario 3 are given in Table 7.2-6d, with time series data for key water quality variables in Figure 7.2-5. This scenario considers an initial condition in the pit lake where pit lake salinity is linearly distributed within the pit lake at the point the pit lake is full. The model predicts exceedances of Water Quality Benchmarks for cadmium only. Predicted concentrations are lower than the Base Case for all water quality variables. Modelling indicates that a linear distribution in initial salinity promotes the formation of meromixis within the pit lake, with higher concentrations of all variables in the lower layer in the pit lake, and lower concentrations in the surface layer of the pit lake.

Overall the predictions suggest that water quality in the surface layer of Panda pit lake has the potential to have exceedances of water quality variables associated with groundwater, such as chloride and sulphate. These variables exceed Water Quality Benchmarks for the Base Case. However, scenario runs with potentially more realistic model inputs (e.g., scenario with groundwater flows more reflective of observed flows (Scenario 1) and scenarios with development of stratification within the pit lake (Scenario 3) do not produce exceedances for these variables. The results also suggest that placing a fresh water cover at the top of the pit lake can result in lower concentrations in the surface water layer compared to scenarios without this layer.

Table 7.2-6a. Predicted Concentration in Overflow Discharge from Panda Pit Lake, Base Case

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.0011	0.0048	0.0080	0.0085	0.00091	0.0042	0.0062	0.0064
Chloride	[b]170	420	210	63	40	380	180	46	28
Nitrate - N	0.49	0.61	0.30	0.094	0.061	0.55	0.26	0.069	0.042
Nitrite - N	0.06	0.00014	0.00052	0.00084	0.00091	0.00012	0.00045	0.00066	0.00068
Phosphate		0.00096	0.0039	0.0063	0.0068	0.00082	0.0033	0.0049	0.0051
Sulphate	20	67	34	12	8.0	60	29	8.5	5.7
TDS	-	1100	530	170	110	950	440	120	77
Aluminum	0.10	0.014	0.030	0.045	0.048	0.012	0.026	0.035	0.036
Antimony	0.02	0.00032	0.00019	0.00010	9.0E-05	0.00029	0.00016	7.8E-05	6.6E-05
Arsenic	0.005	0.00020	0.00022	0.00024	0.00025	0.00018	0.00019	0.00019	0.00019
Barium	1	0.022	0.013	0.0075	0.0066	0.020	0.011	0.0057	0.0049
Boron	1.5	0.012	0.0066	0.0030	0.0024	0.011	0.0056	0.0022	0.0018
Cadmium	0.0000021	2.9E-05	3.0E-05	0.000032	3.3E-05	2.6E-05	2.5E-05	2.5E-05	2.5E-05
Chromium III	0.0089	8.4E-05	7.5E-05	7.4E-05	7.4E-05	7.5E-05	6.4E-05	5.7E-05	5.6E-05
Chromium VI	0.0010	0.00028	0.00025	0.00025	0.00025	0.00025	0.00022	0.00019	0.00019
Copper	0.0020	0.00051	0.00086	0.0012	0.0012	0.00045	0.00074	0.00092	0.00094
Iron	0.30	0.021	0.071	0.11	0.12	0.018	0.061	0.088	0.092
Lead	0.0010	0.000046	3.8E-05	3.5E-05	3.5E-05	4.1E-05	3.2E-05	2.7E-05	2.6E-05
Manganese	0.62	0.012	0.0084	0.0064	0.0062	0.010	0.0071	0.0050	0.0046
Molybdenum	19	0.030	0.015	0.0045	0.0029	0.027	0.012	0.0033	0.0020
Nickel	0.025	0.012	0.0062	0.0026	0.0020	0.010	0.0052	0.0019	0.0014
Potassium	41	15	7.5	2.8	2.0	13	6.4	2.0	1.4
Selenium	0.0010	0.00011	8.4E-05	7.2E-05	7.1E-05	9.7E-05	7.2E-05	5.5E-05	5.3E-05
Strontium	6.2	3.0	1.5	0.46	0.29	2.7	1.2	0.33	0.20
Uranium	0.015	0.00047	0.00026	0.00012	9.5E-05	0.00042	0.00022	8.8E-05	6.9E-05
Vanadium	0.015	0.00061	0.00037	0.00021	0.00019	0.00055	0.00031	0.00016	0.00014
Zinc	0.03	0.0018	0.0015	0.0014	0.0014	0.0016	0.0013	0.0011	0.0011

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*

[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*

Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

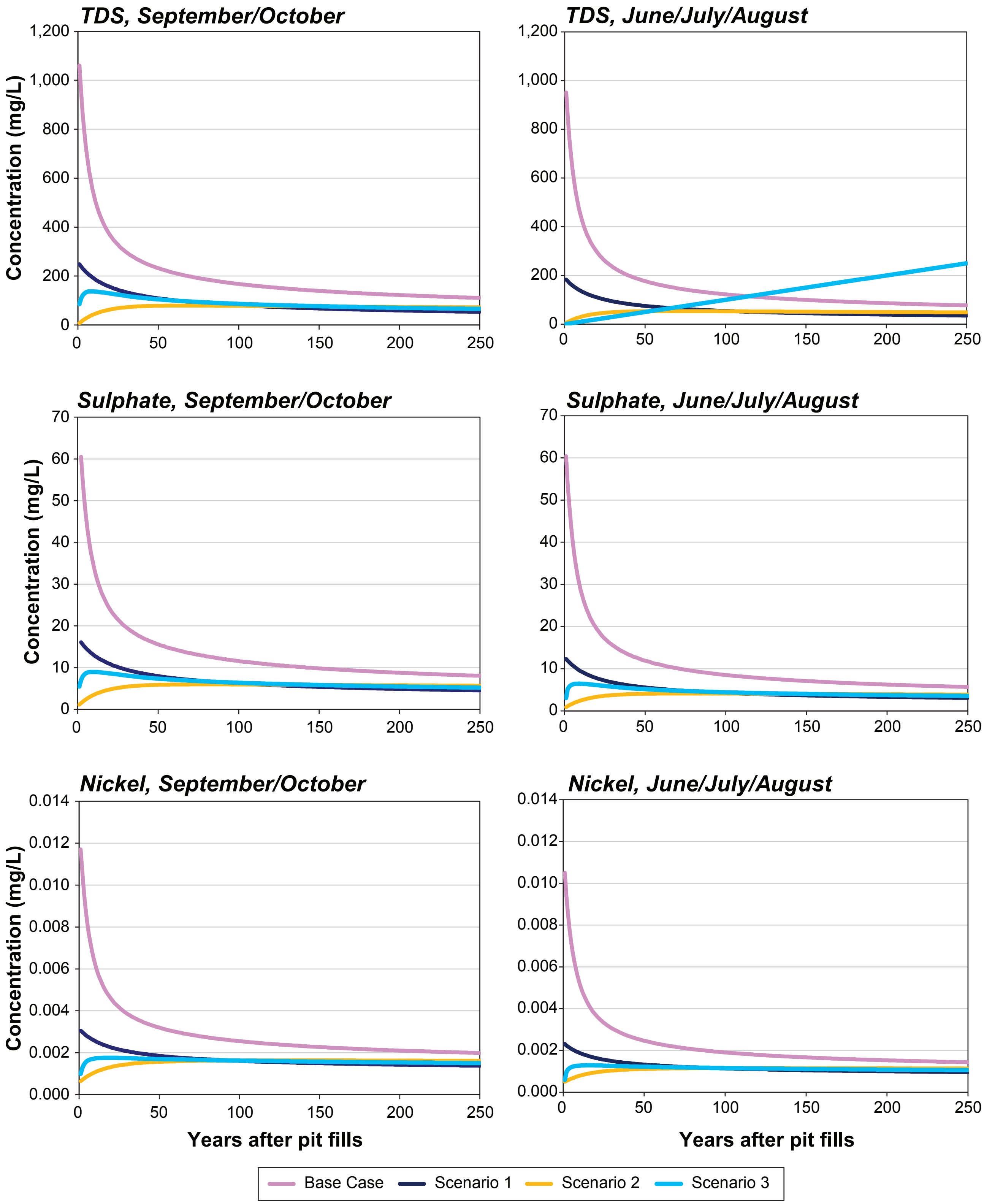

Figure 7.2-5

Long Term Water Quality in Panda Pit Lake for TDS, Sulphate, and Nickel

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Table 7.2-6b. Predicted Concentration in Overflow Discharge from Panda Pit Lake, Scenario 1

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00066	0.0028	0.0070	0.0081	0.00092	0.0025	0.0053	0.0059
Chloride	[b]170	96	73	28	17	71	52	19	11
Nitrate - N	0.49	0.20	0.15	0.062	0.039	0.15	0.11	0.041	0.025
Nitrite - N	0.06	8.6E-05	0.00031	0.00075	0.00086	0.00011	0.00027	0.00057	0.00063
Phosphate		0.00065	0.0023	0.0056	0.0065	0.00082	0.0020	0.0042	0.0047
Sulphate	20	17	13	6.2	4.6	12	9.4	4.2	3.1
TDS	-	250	190	81	54	180	140	54	35
Aluminum	0.10	0.013	0.022	0.042	0.046	0.012	0.019	0.031	0.034
Antimony	0.02	0.00011	0.00010	8.1E-05	7.7E-05	8.5E-05	7.5E-05	5.8E-05	5.4E-05
Arsenic	0.005	0.00014	0.00017	0.00023	0.00024	0.00012	0.00014	0.00017	0.00018
Barium	1	0.0076	0.0070	0.0058	0.0056	0.0058	0.0052	0.0042	0.0040
Boron	1.5	0.0034	0.0029	0.0020	0.0018	0.0026	0.0022	0.0014	0.0013
Cadmium	0.0000021	2.4E-05	2.6E-05	3.2E-05	0.000033	1.9E-05	2.1E-05	2.3E-05	2.4E-05
Chromium III	0.0089	3.4E-05	4.4E-05	6.4E-05	7.0E-05	2.8E-05	3.5E-05	4.8E-05	5.0E-05
Chromium VI	0.0010	0.00011	0.00015	0.00021	0.00023	9.5E-05	0.00012	0.00016	0.00017
Copper	0.0020	0.00038	0.00062	0.0011	0.0012	0.00034	0.00051	0.00081	0.00088
Iron	0.30	0.014	0.043	0.10	0.12	0.016	0.038	0.076	0.084
Lead	0.0010	2.8E-05	3.0E-05	3.3E-05	3.4E-05	2.2E-05	0.000023	2.4E-05	2.4E-05
Manganese	0.62	0.0046	0.0049	0.0055	0.0057	0.0037	0.0038	0.0040	0.0041
Molybdenum	19	0.0068	0.0052	0.0020	0.0012	0.0050	0.0037	0.0013	0.00080
Nickel	0.025	0.0031	0.0026	0.0016	0.0014	0.0023	0.0019	0.0011	0.00096
Potassium	41	3.7	3.0	1.6	1.2	2.8	2.1	1.1	0.85
Selenium	0.0010	6.0E-05	6.2E-05	6.7E-05	6.8E-05	4.8E-05	0.000048	4.9E-05	4.9E-05
Strontium	6.2	0.69	0.52	0.21	0.13	0.51	0.38	0.14	0.087
Uranium	0.015	0.00013	0.00011	7.9E-05	7.2E-05	9.8E-05	8.3E-05	5.6E-05	5.0E-05
Vanadium	0.015	0.00017	0.00017	0.00016	0.00016	0.00013	0.00013	0.00012	0.00011
Zinc	0.03	0.00094	0.0010	0.0013	0.0014	0.00076	0.00083	0.00096	0.00098

[a] Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.
[b] Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-6c. Predicted Concentration in Overflow Discharge from Panda Pit Lake, Scenario 2

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00067	0.0026	0.0075	0.0086	0.0050	0.0053	0.0064	0.0067
Chloride	[b]170	0.29	14	27	24	0.18	9.7	18	16
Nitrate - N	0.49	0.0033	0.12	0.23	0.20	0.0022	0.081	0.15	0.14
Nitrite - N	0.06	0.00071	0.00076	0.00095	0.00099	0.00054	0.00057	0.00070	0.00072
Phosphate		0.0053	0.0055	0.0069	0.0072	0.0040	0.0042	0.0051	0.0053
Sulphate	20	1.2	3.5	6.0	5.7	0.90	2.5	4.1	3.9
TDS	-	7.7	44	78.	72	5.9	30	53	48
Aluminum	0.10	0.037	0.039	0.048	0.050	0.028	0.029	0.035	0.037
Antimony	0.02	4.7E-05	6.0E-05	8.1E-05	8.2E-05	3.6E-05	4.4E-05	5.8E-05	5.9E-05
Arsenic	0.005	0.00018	0.00019	0.00024	0.00026	0.00014	0.00015	0.00018	0.00019
Barium	1	0.0032	0.0042	0.0059	0.0061	0.0025	0.0031	0.0043	0.0044
Boron	1.5	0.00095	0.0014	0.0021	0.0021	0.00073	0.0010	0.0015	0.0015
Cadmium	0.0000021	2.4E-05	2.5E-05	3.2E-05	3.4E-05	1.8E-05	1.9E-05	2.4E-05	2.5E-05
Chromium III	0.0089	5.2E-05	5.7E-05	7.3E-05	7.6E-05	4.0E-05	4.3E-05	5.3E-05	5.5E-05
Chromium VI	0.0010	0.00017	0.00019	0.00024	0.00025	0.00013	0.00014	0.00018	0.00018
Copper	0.0020	0.00094	0.0010	0.0012	0.0013	0.00072	0.00076	0.00092	0.00096
Iron	0.30	0.094	0.099	0.12	0.13	0.072	0.075	0.090	0.094
Lead	0.0010	2.4E-05	0.000026	3.3E-05	3.5E-05	1.8E-05	2.0E-05	2.4E-05	2.5E-05
Manganese	0.62	0.0039	0.0044	0.0059	0.0061	0.0030	0.0034	0.0043	0.0044
Molybdenum	19	3.2E-05	0.0010	0.0019	0.0018	2.2E-05	0.00070	0.0013	0.0012
Nickel	0.025	0.00065	0.0011	0.0016	0.0016	0.00050	0.00078	0.0012	0.0011
Potassium	41	0.46	0.97	1.6	1.5	0.35	0.70	1.1	1.0
Selenium	0.0010	4.7E-05	5.3E-05	6.8E-05	7.0E-05	3.6E-05	4.0E-05	5.0E-05	5.2E-05
Strontium	6.2	0.0058	0.11	0.20	0.18	0.0046	0.072	0.14	0.12
Uranium	0.015	3.8E-05	5.6E-05	8.1E-05	8.2E-05	2.9E-05	0.000041	0.000058	5.8E-05
Vanadium	0.015	0.00010	0.00013	0.00017	0.00018	8.0E-05	9.6E-05	0.00013	0.00013
Zinc	0.03	0.00095	0.0010	0.0014	0.0014	0.00073	0.00080	0.0010	0.0010

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-6d. Predicted Concentration in Overflow Discharge from Panda Pit Lake, Scenario 3

Variable	[a]Water Quality Benchmark (mg/L)	September to October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00067	0.0026	0.0075	0.0086	0.00089	0.0023	0.0056	0.0063
Chloride	[b]170	34	54	31	22	18	38	21	15
Nitrate - N	0.49	0.049	0.078	0.47	0.035	0.026	0.055	0.032	0.023
Nitrite - N	0.06	7.6E-05	0.00027	0.00079	0.00091	9.6E-05	0.00025	0.00060	0.00067
Phosphate		0.00056	0.0020	0.0059	0.0068	0.00071	0.0018	0.0045	0.0050
Sulphate	20	5.5	9.0	6.4	5.2	3.0	6.4	4.4	3.6
TDS	-	85	140	86	66	46	97	58	44
Aluminum	0.10	0.0045	0.015	0.042	0.048	0.0053	0.014	0.032	0.035
Antimony	0.02	3.0E-05	5.8E-05	0.000076	7.8E-05	2.0E-05	4.4E-05	5.5E-05	5.6E-05
Arsenic	0.005	3.3E-05	9.1E-05	0.00022	0.00024	3.2E-05	7.8E-05	0.00016	0.00018
Barium	1	0.0021	0.0041	0.0056	0.0057	0.0014	0.0032	0.0041	0.0041
Boron	1.5	0.0010	0.0019	0.0020	0.0019	0.00064	0.0014	0.0014	0.0014
Cadmium	0.0000021	4.5E-06	1.2E-05	2.9E-05	3.2E-05	4.3E-06	1.0E-05	2.1E-05	2.3E-05
Chromium III	0.0089	1.2E-05	3.0E-05	6.5E-05	7.2E-05	1.0E-05	2.5E-05	4.8E-05	5.2E-05
Chromium VI	0.0010	3.8E-05	9.9E-05	0.00022	0.00024	3.4E-05	8.4E-05	0.00016	0.00018
Copper	0.0020	0.00013	0.00041	0.0011	0.0012	0.00014	0.00036	0.00082	0.00091
Iron	0.30	0.010	0.037	0.11	0.12	0.013	0.033	0.080	0.089
Lead	0.0010	5.8E-06	1.4E-05	3.0E-05	3.3E-05	5.0E-06	1.2E-05	2.2E-05	2.4E-05
Manganese	0.62	0.0013	0.0029	0.0053	0.0058	0.0010	0.0024	0.0040	0.0042
Molybdenum	19	0.0024	0.0038	0.0022	0.0016	0.0013	0.0027	0.0015	0.0010
Nickel	0.025	0.00099	0.0017	0.0016	0.0015	0.00059	0.0013	0.0012	0.0011
Potassium	41	1.2	2.0	1.6	1.4	0.68	1.5	1.1	0.96
Selenium	0.0010	0.000013	0.000031	0.000061	6.7E-05	1.1E-05	2.6E-05	4.5E-05	4.9E-05
Strontium	6.2	0.24	0.38	0.23	0.17	0.13	0.27	0.15	0.11
Uranium	0.015	4.1E-05	7.4E-05	7.9E-05	7.6E-05	0.000025	0.000055	5.7E-05	5.4E-05
Vanadium	0.015	5.8E-05	0.00012	0.00016	0.00017	4.0E-05	9.0E-05	0.00012	0.00012
Zinc	0.03	0.00023	0.00058	0.0012	0.0014	0.00020	0.00049	0.00092	0.0010

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

7.2.4.2 Koala/Koala North Pit Lake

Results for Koala/Koala North pit lake are similar to those for Panda pit lake.

Long-term water quality predictions in the surface water layer of Koala/Koala North pit lake for Base Case conditions are provided in Table 7.2-7a, with time series graphs for key water quality variables in Figure 7.2-6. The results indicate exceedances of Water Quality Benchmarks for cadmium, chloride, nitrate and sulphate in the surface layer within the pit lake. The cadmium Water Quality Benchmark is known to be low, so exceedances of this water quality variable are not unexpected. However, high concentrations of chloride, nitrate and sulphate reflect groundwater inflows into the pit lake during pit infilling. High nitrate concentrations may reflect conservative assumptions regarding how much explosives residue is left at the end of operations, and may be an over-estimate.

Over time (after 10 years post-infilling) concentrations of these variables fall below their Water Quality Benchmarks as loadings of these variables are flushed from the pit lake. Once the pit lake is full the model assumes there are no additional groundwater flows into the pit lakes.

Results for Scenario 1 are given in Table 7.2-7b, with time series data for key water quality variables in Figure 7.2-6. This scenario considers pit infilling with lower groundwater flow rates. Results for this scenario show exceedances of Water Quality Benchmarks for cadmium only. In this case there are no exceedances of any of the salts (e.g., chloride, sulphate) associated with groundwater. Predictions of most variables are lower than the Base Case indicating the influence of groundwater inflows on initial water quality in the pit lake.

Results for Scenario 2 are given in Table 7.2-7c, with time series data for key variables in Figure 7.2-6. This scenario considers a management option whereby the pit lake is filled with a 30 m surface fresh water cover. This scenario typically produces lower concentrations than the Base Case and similar to Scenario 1, with concentrations of cadmium only exceeding Water Quality Benchmarks. For many variables concentrations in the surface layer increase in the first few years after the pit is filled as water with higher concentrations below the fresh water cover, mixes with the fresh surface layer. However, the concentrations reach an approximate equilibrium after around 150 years.

Results for Scenario 3 are given in Table 7.2-7d, with time series data for key water quality variables in Figure 7.2-6. This scenario considers an initial condition in the pit lake where pit lake salinity is linearly distributed within the pit lake at the point the pit lake is full. The model predicts exceedances of Water Quality Benchmarks for cadmium only. Predicted concentrations are lower than the Base Case for all water quality variables. Modelling indicates that a linear distribution in initial salinity promotes the formation of meromixis within the pit lake, with higher concentration of all variables in the lower layer in the pit lake, and lower concentrations in the surface layer of the pit lake.

Overall the predictions suggest that water quality in the surface layer of Koala pit lake has the potential to have exceedances of variables associated with groundwater, such as chloride and sulphate. These variables exceed Water Quality Benchmarks for the Base Case. However, scenario runs with potentially more realistic model inputs (e.g., scenario with groundwater flows more reflective of observed flows (Scenario 1) and scenarios with development of stratification within the pit lake (Scenario 3) do not produce exceedances for these variables. The results also suggest that placing a fresh water cover at the top of the pit lake can result in lower concentrations in the surface water layer compared to scenarios without this layer.

Table 7.2-7a. Predicted Concentration in Overflow Discharge from Koala Pit Lake, Base Case

Variable	[a]Water Quality Benchmark (mg/L)	September to October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00051	0.0035	0.0075	0.0083	0.00045	0.0030	0.0059	0.0062
Chloride	[b]170	410	270	81	51	360	230	60	36
Nitrate - N	0.49	0.62	0.40	0.12	0.079	0.54	0.34	0.091	0.056
Nitrite - N	0.06	9.3E-05	0.00040	0.00081	0.00089	8.1E-05	0.00034	0.00063	0.00067
Phosphate		0.00057	0.0029	0.0060	0.0066	0.00050	0.0025	0.0047	0.0050
Sulphate	20	65	43	14	9.5	56	36	11	6.8
TDS	-	1000	670	210	140	890	570	160	97
Aluminum	0.10	0.0099	0.024	0.043	0.047	0.0086	0.021	0.034	0.035
Antimony	0.02	0.00031	0.00022	0.00011	0.000097	0.00027	0.00019	8.7E-05	7.1E-05
Arsenic	0.005	0.00019	0.00021	0.00024	0.00025	0.00017	0.00018	0.00018	0.00018
Barium	1	0.022	0.018	0.0079	0.0067	0.019	0.013	0.0060	0.0049
Boron	1.5	0.012	0.0080	0.0034	0.0026	0.010	0.0068	0.0025	0.0019
Cadmium	0.0000021	0.000028	2.9E-05	3.2E-05	3.3E-05	2.4E-05	2.5E-05	2.5E-05	2.4E-05
Chromium III	0.0089	7.8E-05	7.6E-05	7.4E-05	7.4E-05	6.7E-05	6.4E-05	5.7E-05	5.6E-05
Chromium VI	0.0010	0.00026	0.00025	0.00025	0.00025	0.00023	0.00022	0.00019	0.00019
Copper	0.0020	0.00044	0.00074	0.0011	0.0012	0.00038	0.00063	0.00089	0.00092
Iron	0.30	0.012	0.054	0.11	0.12	0.011	0.046	0.084	0.089
Lead	0.0010	4.5E-05	0.000040	3.5E-05	3.5E-05	3.9E-05	0.000034	2.7E-05	0.000026
Manganese	0.62	0.011	0.0090	0.0065	0.0062	0.0095	0.0077	0.0050	0.0046
Molybdenum	19	0.029	0.019	0.0058	0.0036	0.025	0.016	0.0043	0.0026
Nickel	0.025	0.011	0.0077	0.0030	0.0022	0.0098	0.0065	0.0022	0.0016
Potassium	41	14	9.4	3.3	2.3	12	8.0	2.4	1.7
Selenium	0.0010	0.00010	9.0E-05	7.3E-05	7.2E-05	9.1E-05	7.7E-05	5.6E-05	5.3E-05
Strontium	6.2	2.9	1.9	0.58	0.36	2.5	1.6	0.43	0.26
Uranium	0.015	0.00045	0.00031	0.00013	0.00010	0.00039	0.00026	9.9E-05	0.000075
Vanadium	0.015	0.00058	0.00043	0.00023	0.00020	0.00050	0.00036	0.00018	0.00015
Zinc	0.03	0.0016	0.0015	0.0014	0.0014	0.0014	0.0013	0.0011	0.0010

[a] Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.
[b] Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

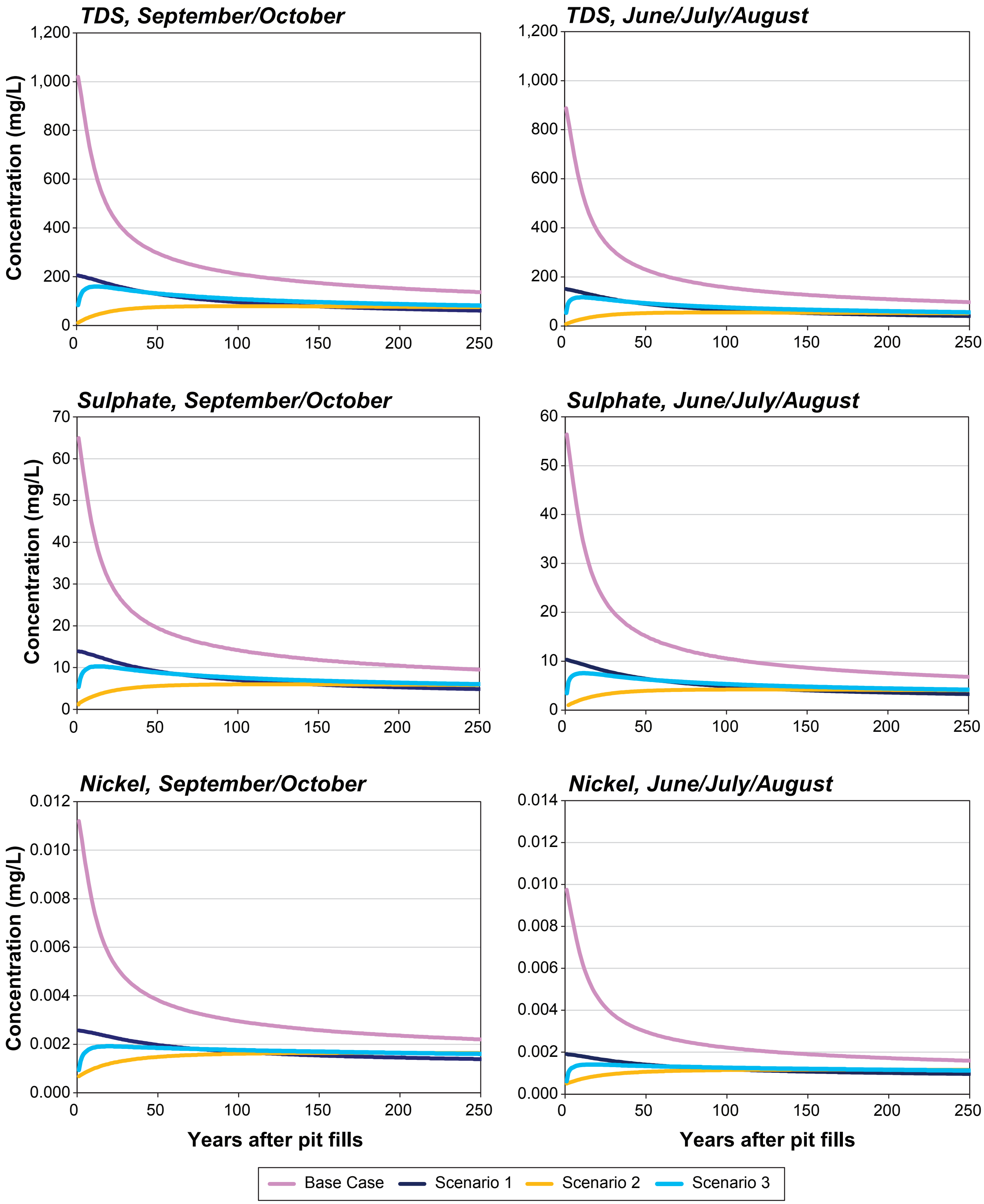

Figure 7.2-6

Long Term Water Quality in Koala Pit Lake for TDS, Sulphate, and Nickel

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Table 7.2-7b. Predicted Concentration in Overflow Discharge from Koala Pit Lake, Scenario 1

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00025	0.0013	0.0061	0.0076	0.00040	0.0012	0.0046	0.0055
Chloride	[b]170	79	73	34	20	58	53	23	13
Nitrate - N	0.49	0.18	0.16	0.076	0.047	0.13	0.11	0.052	0.031
Nitrite - N	0.06	4.8E-05	0.00016	0.00066	0.00082	5.8E-05	0.00015	0.00050	0.00060
Phosphate		0.00036	0.0012	0.0050	0.0062	0.00043	0.0011	0.0037	0.0044
Sulphate	20	14	13	7.0	4.8	10	9.4	4.8	3.3
TDS	-	210	190	95	61	150	140	65	40
Aluminum	0.10	0.0095	0.015	0.038	0.045	0.0082	0.012	0.028	0.032
Antimony	0.02	9.9E-05	9.7E-05	8.3E-05	7.8E-05	7.4E-05	7.2E-05	6.0E-05	5.5E-05
Arsenic	0.005	0.00013	0.00015	0.00022	0.00024	0.00010	0.00012	0.00016	0.00017
Barium	1	0.0067	0.0066	0.0057	0.0054	0.0050	0.0049	0.0041	0.0038
Boron	1.5	0.0029	0.0028	0.0021	0.0018	0.0022	0.0021	0.0015	0.0013
Cadmium	0.0000021	2.4E-05	2.5E-05	3.1E-05	3.2E-05	1.8E-05	1.9E-05	2.2E-05	2.3E-05
Chromium III	0.0089	2.9E-05	3.5E-05	5.9E-05	6.7E-05	2.3E-05	2.7E-05	4.4E-05	4.8E-05
Chromium VI	0.0010	9.7E-05	0.00012	0.00020	0.00022	7.7E-05	9.2E-05	0.00015	0.00016
Copper	0.0020	0.00034	0.00045	0.00099	0.0012	0.00028	0.00037	0.00074	0.00084
Iron	0.30	0.0076	0.022	0.089	0.11	0.0086	0.020	0.067	0.080
Lead	0.0010	2.8E-05	2.8E-05	3.2E-05	3.3E-05	2.1E-05	2.2E-05	2.3E-05	2.4E-05
Manganese	0.62	0.0040	0.0042	0.00520	0.0054	0.0030	0.0032	0.0038	0.0039
Molybdenum	19	0.0056	0.0052	0.0024	0.0015	0.0041	0.0037	0.0017	0.00096
Nickel	0.025	0.0028	0.0025	0.00170	0.0014	0.0019	0.0018	0.0012	0.00096
Potassium	41	3.1	3.0	1.8	1.3	2.3	2.2	1.2	0.90
Selenium	0.0010	5.8E-05	6.0E-05	6.6E-05	6.8E-05	0.000044	4.5E-05	4.8E-05	4.8E-05
Strontium	6.2	0.57	0.53	0.25	0.15	0.42	0.38	0.17	0.10
Uranium	0.015	0.00011	0.00011	8.1E-05	0.000071	8.1E-05	7.8E-05	5.7E-05	5.0E-05
Vanadium	0.015	0.00014	0.00015	0.00016	0.00016	0.00011	0.00011	0.00011	0.00011
Zinc	0.03	0.00084	0.00091	0.0012	0.0013	0.00064	0.00070	0.00088	0.00092

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-7c. Predicted Concentration in Overflow Discharge from Koala Pit Lake, Scenario 2

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.0065	0.0066	0.0083	0.0090	0.0048	0.0049	0.0061	0.0065
Chloride	[b]170	0.27	12	28	26	0.17	8.0	19	18
Nitrate - N	0.49	0.0028	0.028	0.15	0.15	0.0021	0.023	0.11	0.11
Nitrite - N	0.06	0.00070	0.00071	0.00090	0.00098	0.00052	0.00053	0.00066	0.00071
Phosphate		0.0052	0.0053	0.0066	0.0072	0.0039	0.0039	0.0048	0.0052
Sulphate	20	1.1	3.0	6.0	5.8	0.84	2.1	4.2	4.1
TDS	-	7.6	36	79	75	5.6	25	55	52
Aluminum	0.10	0.036	0.037	0.046	0.050	0.027	0.027	0.034	0.036
Antimony	0.02	4.7E-05	5.6E-05	7.9E-05	8.3E-05	3.4E-05	4.1E-05	5.7E-05	5.9E-05
Arsenic	0.005	0.00018	0.00018	0.00024	0.00026	0.00013	0.00014	0.00017	0.00018
Barium	1	0.0032	0.0038	0.0057	0.0061	0.0024	0.0028	0.0042	0.0044
Boron	1.5	0.00093	0.0013	0.0020	0.0021	0.00069	0.00093	0.0014	0.0015
Cadmium	0.0000021	2.3E-05	2.4E-05	3.1E-05	3.4E-05	1.7E-05	0.000018	2.3E-05	2.4E-05
Chromium III	0.0089	5.1E-05	5.4E-05	7.0E-05	7.6E-05	3.8E-05	4.0E-05	5.1E-05	5.5E-05
Chromium VI	0.0010	0.00017	0.00018	0.00024	0.00025	0.00013	0.00014	0.00017	0.00018
Copper	0.0020	0.00093	0.00095	0.0012	0.0013	0.00069	0.00071	0.00088	0.00095
Iron	0.30	0.093	0.094	0.12	0.13	0.069	0.070	0.086	0.093
Lead	0.0010	2.3E-05	2.5E-05	3.2E-05	3.5E-05	1.7E-05	1.8E-05	2.4E-05	2.5E-05
Manganese	0.62	0.0038	0.0042	0.0057	0.0061	0.0028	0.0031	0.0041	0.0044
Molybdenum	19	3.1E-05	0.00084	0.0020	0.0018	2.1E-05	0.00058	0.0014	0.0012
Nickel	0.025	0.00064	0.00096	0.0016	0.0016	0.00047	0.00070	0.0012	0.0012
Potassium	41	0.45	0.85	1.6	1.5	0.33	0.61	1.1	1.1
Selenium	0.0010	4.7E-05	0.000050	6.6E-05	7.0E-05	3.4E-05	0.000037	0.000048	5.1E-05
Strontium	6.2	0.0054	0.086	0.20	0.19	0.0040	0.060	0.14	0.13
Uranium	0.015	3.7E-05	5.0E-05	8.0E-05	8.2E-05	2.8E-05	0.000037	5.7E-05	5.8E-05
Vanadium	0.015	0.00010	0.00012	0.00017	0.00018	7.6E-05	8.8E-05	0.00012	0.00013
Zinc	0.03	0.00093	0.00099	0.0013	0.0014	0.00069	0.00074	0.00097	0.0010

[a] Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.
[b] Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-7d. Predicted Concentration in Overflow Discharge from Koala Pit Lake, Scenario 3

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00028	0.0014	0.0067	0.0083	0.00037	0.0013	0.0051	0.0060
Chloride	[b]170	33	63	40	29	21	46	28	20
Nitrate - N	0.49	0.051	0.096	0.062	0.046	0.032	0.070	0.043	0.032
Nitrite - N	0.06	3.2E-05	0.00015	0.00072	0.00089	4.0E-05	0.00014	0.00054	0.00065
Phosphate		0.00024	0.0011	0.0054	0.0066	0.00030	0.0011	0.0040	0.0048
Sulphate	20	5.4	10	7.6	6.0	3.4	7.5	5.3	4.2
TDS	-	84	160	110	82	53	120	76	56
Aluminum	0.10	0.0022	0.0088	0.038	0.047	0.0024	0.0081	0.029	0.034
Antimony	0.02	2.7E-05	5.7E-05	0.000078	8.1E-05	1.8E-05	4.4E-05	5.7E-05	5.8E-05
Arsenic	0.005	2.2E-05	6.5E-05	0.00020	0.00024	1.9E-05	5.6E-05	0.00015	0.00017
Barium	1	0.0019	0.0040	0.0054	0.0056	0.0013	0.0031	0.0040	0.0040
Boron	1.5	0.00099	0.0020	0.0021	0.0020	0.00065	0.0015	0.0015	0.0014
Cadmium	0.0000021	3.2E-06	8.9E-06	2.6E-05	3.2E-05	2.7E-06	7.6E-06	2.0E-05	2.3E-05
Chromium III	0.0089	8.3E-06	2.2E-05	6.0E-05	7.1E-05	6.7E-06	1.9E-05	4.5E-05	5.1E-05
Chromium VI	0.0010	2.8E-05	7.4E-05	0.00020	0.00024	2.2E-05	6.2E-05	0.00015	0.00017
Copper	0.0020	7.1E-05	0.00025	0.0010	0.0012	7.1E-05	0.00023	0.00075	0.00088
Iron	0.30	0.0044	0.020	0.097	0.12	0.0055	0.019	0.072	0.086
Lead	0.0010	4.5E-06	1.2E-05	2.8E-05	3.3E-05	3.5E-06	9.5E-06	2.09E-05	2.4E-05
Manganese	0.62	0.0010	0.0025	0.0050	0.0056	0.00077	0.0020	0.0037	0.0041
Molybdenum	19	0.0024	0.0044	0.0029	0.0021	0.0015	0.0032	0.0020	0.0014
Nickel	0.025	0.00094	0.0019	0.0018	0.0016	0.00062	0.0014	0.0013	0.0011
Potassium	41	1.2	2.3	1.8	1.6	0.76	1.7	1.3	1.1
Selenium	0.0010	1.0E-05	2.5E-05	5.8E-05	6.6E-05	7.9E-06	2.1E-05	0.000043	0.000048
Strontium	6.2	0.24	0.44	0.29	0.21	0.15	0.32	0.20	0.14
Uranium	0.015	3.8E-05	7.6E-05	8.3E-05	7.9E-05	2.5E-05	5.8E-05	6.0E-05	5.6E-05
Vanadium	0.015	5.1E-05	0.00011	0.00016	0.00017	3.6E-05	8.5E-05	0.00012	0.00012
Zinc	0.03	0.00017	0.00044	0.0011	0.0013	0.00014	0.00037	0.00083	0.00094

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

7.2.4.3 Fox Pit Lake

Long-term water quality predictions in the surface water layer of Fox pit lake for Base Case conditions are provided in Table 7.2-8a, with time series graphs for key water quality variables in Figure 7.2-7. The results indicate that all water quality variables apart from cadmium are predicted to be lower than Water Quality Benchmarks. As discussed in Rescan (2012) the cadmium Water Quality Benchmark is known to be low. Concentrations are predicted to decrease steadily over time for all variables, apart from a few metals. Concentrations of these variables are not predicted to rise above Water Quality Benchmarks and will reach equilibrium between natural inflows and pit wall runoff.

Results for Scenario 1 are given in Table 7.2-8b, with time series data for key water quality variables in Figure 7.2-7. This scenario considers pit infilling with lower groundwater flow rates. As with the Base Case the model predicts exceedances of Water Quality Benchmarks for cadmium only. Predicted concentrations are lower for all variables indicating that groundwater inflows are a key influence on initial water quality in the pit lake.

Results for Scenario 2 are given in Table 7.2-8c, with time series data for key water quality variables in Figure 7.2-7. This scenario considers a management option whereby the pit lake is filled with a 30 m surface fresh water cover. This scenario typically produces the lowest predicted concentrations in the surface water layer and cadmium concentrations only are predicted to exceed Water Quality Benchmarks.

Results for Scenario 3 are given in Table 7.2-8d, with time series data for key water quality variables in Figure 7.2-7. This scenario considers an initial condition in the pit lake where pit lake salinity is linearly distributed within the pit lake at the point the pit lake is full. As with the Base Case the model predicts exceedances of Water Quality Benchmarks for cadmium only. The water quality predictions indicate that for the first 100 to 200 years after the pit has been filled, concentrations of most water quality variables in the surface layer of the pit lake are lower than for the Base Case, which assumes a fully mixed pit lake at the end of the infilling period. However, over time concentrations are seen to rise to an approximate steady state at which point (around 250 years after the end of infilling) concentrations in Scenario 3 can be above those predicted in the Base Case.

In the Base Case there are higher concentrations in the surface layer resulting in a higher rate “flushing out” of loadings from the surface layer compared to Scenario 3, resulting in lower concentrations over time. In contrast, for Scenario 3 there is less flushing and over time and poorer quality water from deep in the pit lake is mixed with surface layers raising the concentrations. However, despite this, cadmium concentrations only exceed the Water Quality Benchmarks for this scenario.

Overall the predictions suggest that water quality in the surface layer of Fox pit lake would not exceed Water Quality Benchmarks (except cadmium). This is the case for all scenarios considered. The results also suggest that placing a fresh water cover at the top of the pit lake can result in lower concentrations in the surface water layer compared to scenarios without this layer.

7.2.5 Long-term Model Results for Group 4 — Open Pit which Will Be Partially Infilled with Mine Water and Mine Solids (Beartooth Pit Lake)

Beartooth pit lake will be filled with FPK solids up to 30 m from the spill level of the pit. Hence, in the closure period Beartooth pit lake will have a water depth of only 30 m. Long-term water quality predictions in the surface water layer of Beartooth pit lake for Base Case conditions are provided in Table 7.2-9. The Base Case scenario assumes that there is a water cover above FPK solids comprised of a mixture of 5 m deep layer of mine water and 25 m deep layer of fresh water.

Table 7.2-8a. Predicted Concentration in Overflow Discharge from Fox Pit Lake, Base Case

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00030	0.00089	0.0041	0.0060	0.00046	0.00089	0.0031	0.0044
Chloride	[b]170	42	40	25	17	31	29	18	12
Nitrate - N	0.49	0.15	0.14	0.093	0.064	0.11	0.10	0.066	0.044
Nitrite - N	0.06	0.00018	0.00023	0.00052	0.00070	0.00016	0.00020	0.00040	0.00052
Phosphate		0.00061	0.0011	0.0035	0.0049	0.00063	0.00096	0.0027	0.0036
Sulphate	20	10	9.5	6.6	5.0	7.3	6.9	4.8	3.5
TDS	-	120	120	78	55	89	84	55	39
Aluminum	0.10	0.0089	0.012	0.027	0.036	0.0078	0.0098	0.020	0.027
Antimony	0.02	9.3E-05	9.2E-05	8.4E-05	7.9E-05	7.0E-05	0.000068	0.000061	5.7E-05
Arsenic	0.005	0.00018	0.00019	0.00021	0.00023	0.00014	0.00014	0.00016	0.00017
Barium	1	0.0051	0.0051	0.0049	0.0049	0.0038	0.0038	0.0036	0.0035
Boron	1.5	0.0026	0.0026	0.0021	0.0019	0.0020	0.0019	0.0016	0.0014
Cadmium	0.0000021	0.000027	2.8E-05	0.000030	3.2E-05	2.0E-05	2.1E-05	2.2E-05	0.000023
Chromium III	0.0089	2.6E-05	2.9E-05	0.000046	5.6E-05	2.1E-05	2.3E-05	3.5E-05	4.1E-05
Chromium VI	0.0010	8.7E-05	9.7E-05	0.00015	0.00019	6.9E-05	7.7E-05	0.00012	0.00014
Copper	0.0020	0.00035	0.00041	0.00076	0.00097	0.00029	0.00033	0.00058	0.00072
Iron	0.30	0.0072	0.015	0.060	0.086	0.0086	0.015	0.046	0.064
Lead	0.0010	8.5E-05	8.2E-05	6.4E-05	5.4E-05	6.2E-05	6.0E-05	4.7E-05	3.9E-05
Manganese	0.62	0.0047	0.0048	0.0051	0.0053	0.0036	0.0036	0.0038	0.0039
Molybdenum	19	0.0056	0.0053	0.0034	0.0023	0.0041	0.0038	0.0024	0.0016
Nickel	0.025	0.0018	0.0018	0.0015	0.0013	0.0014	0.0013	0.0011	0.00094
Potassium	41	2.2	2.1	1.6	1.3	1.6	1.5	1.1	0.91
Selenium	0.0010	8.8E-05	8.7E-05	8.0E-05	7.7E-05	6.6E-05	6.5E-05	5.9E-05	5.6E-05
Strontium	6.2	0.31	0.29	0.19	0.13	0.23	0.21	0.13	0.090
Uranium	0.015	0.00018	0.00018	0.00013	0.00011	0.00013	0.00013	9.5E-05	7.6E-05
Vanadium	0.015	0.00017	0.00016	0.00016	0.00016	0.00012	0.00012	0.00012	0.00011
Zinc	0.03	0.00085	0.00088	0.0011	0.0012	0.00065	0.00067	0.00079	0.00086

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

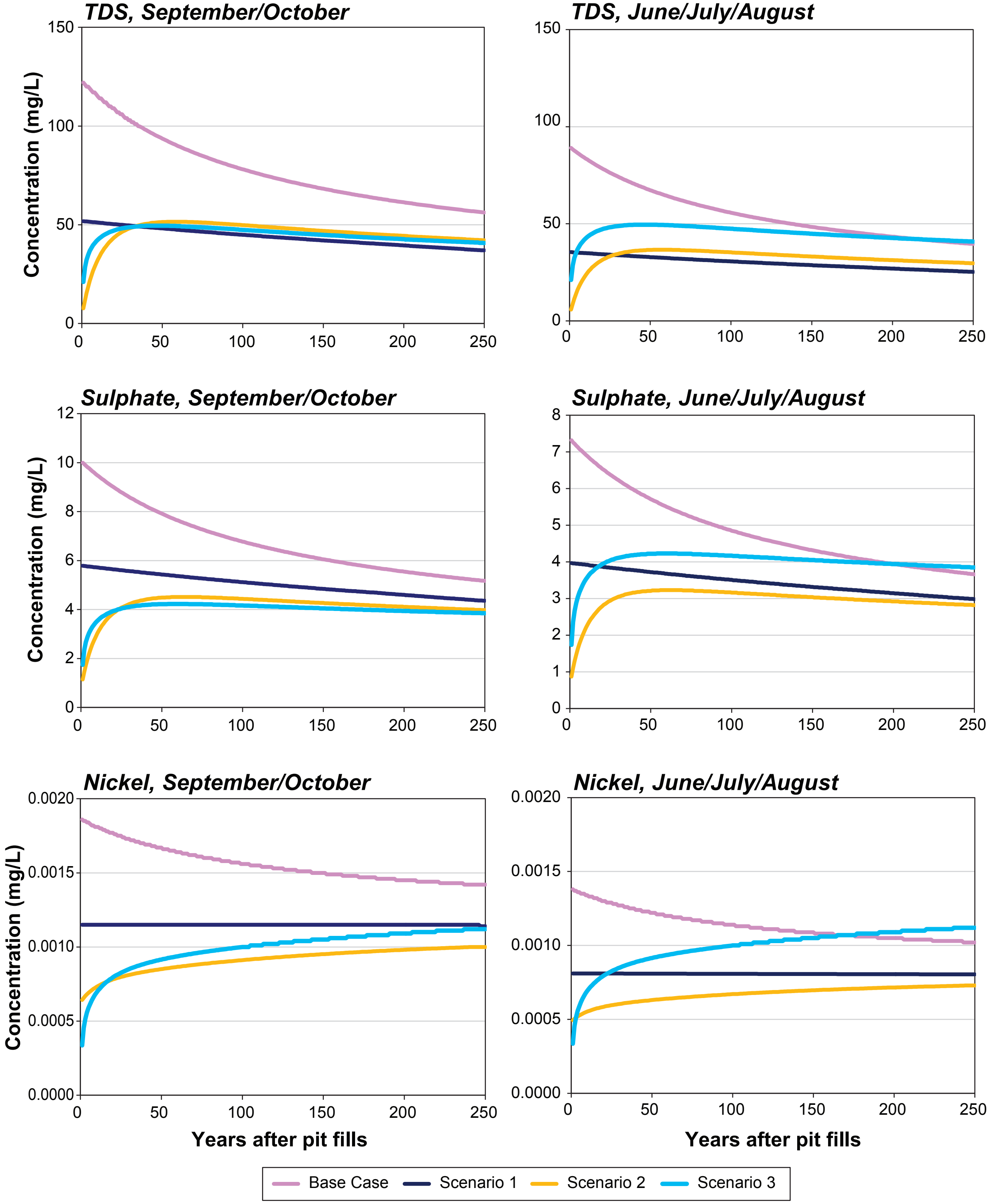

Figure 7.2-7

Long Term Water Quality Fox Pit Lake
for TDS, Sulphate, and Nickel

Table 7.2-8b. Predicted Concentration in Overflow Discharge from Fox Pit Lake, Scenario 1

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00011	0.00029	0.0018	0.0038	0.00040	0.00052	0.0016	0.0029
Chloride	[b]170	13	13	11	8.5	9.1	8.9	7.5	5.7
Nitrate - N	0.49	0.27	0.26	0.22	0.17	0.18	0.18	0.15	0.11
Nitrite - N	0.06	4.8E-05	6.6E-05	0.00022	0.00042	6.6E-05	7.8E-05	0.00018	0.00032
Phosphate		0.00039	0.00057	0.0021	0.0041	0.00060	0.00072	0.0018	0.0031
Sulphate	20	5.8	5.7	5.1	4.4	4.0	3.9	3.5	3.0
TDS	-	52	51	45	37	35	35	31	25
Aluminum	0.10	0.0089	0.0097	0.017	0.026	0.0078	0.0083	0.013	0.019
Antimony	0.02	7.9E-05	7.9E-05	7.8E-05	7.8E-05	5.6E-05	5.6E-05	5.5E-05	5.4E-05
Arsenic	0.005	0.00018	0.00019	0.00020	0.00022	0.00013	0.00013	0.00014	0.00016
Barium	1	0.0040	0.0040	0.0042	0.0044	0.0029	0.0029	0.0030	0.0031
Boron	1.5	0.0020	0.0020	0.0019	0.0018	0.0014	0.0014	0.0013	0.0012
Cadmium	0.0000021	2.8E-05	2.8E-05	2.9E-05	3.1E-05	2.0E-05	2.0E-05	2.1E-05	2.2E-05
Chromium III	0.0089	2.2E-05	2.3E-05	3.2E-05	4.3E-05	1.8E-05	1.8E-05	2.4E-05	3.2E-05
Chromium VI	0.0010	7.4E-05	7.8E-05	0.00011	0.00014	5.8E-05	6.1E-05	8.1E-05	0.00010
Copper	0.0020	0.00035	0.00037	0.00053	0.00075	0.00028	0.00029	0.00041	0.00055
Iron	0.30	0.0058	0.0082	0.029	0.056	0.0084	0.010	0.024	0.042
Lead	0.0010	9.0E-05	8.9E-05	8.6E-05	8.2E-05	6.3E-05	6.2E-05	0.000060	5.7E-05
Manganese	0.62	0.0044	0.0044	0.0048	0.0053	0.0032	0.0032	0.0034	0.0038
Molybdenum	19	0.0038	0.0037	0.0031	0.0024	0.0026	0.0025	0.0021	0.0016
Nickel	0.025	0.0012	0.0012	0.0012	0.0011	0.00081	0.0008	0.00081	0.00080
Potassium	41	1.3	1.3	1.2	1.1	0.90	0.89	0.83	0.75
Selenium	0.0010	8.9E-05	0.000089	8.7E-05	8.4E-05	6.3E-05	6.2E-05	6.1E-05	5.9E-05
Strontium	6.2	0.11	0.11	0.093	0.073	0.075	0.074	0.063	0.049
Uranium	0.015	0.00016	0.00016	0.00014	0.00012	0.00011	0.00011	1.0E-04	8.5E-05
Vanadium	0.015	0.00014	0.00014	0.00014	0.00014	0.000096	9.6E-05	9.9E-05	0.00010
Zinc	0.03	0.00082	0.00083	0.00095	0.0011	0.00060	0.00061	0.00069	0.00078

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-8c. Predicted Concentration in Overflow Discharge from Fox Pit Lake, Scenario 2

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.0066	0.0055	0.0056	0.0068	0.0050	0.0042	0.0042	0.0050
Chloride	[b]170	0.32	14	23	18	0.18	10	16	12
Nitrate - N	0.49	0.0030	0.034	0.055	0.044	0.0022	0.024	0.038	0.030
Nitrite - N	0.06	0.00070	0.00062	0.00065	0.00076	0.00054	0.00047	0.00048	0.00056
Phosphate		0.0053	0.0046	0.0054	0.0068	0.0041	0.0036	0.0040	0.0050
Sulphate	20	1.1	3.0	4.4	4.0	0.87	2.2	3.2	2.8
TDS	-	7.7	32	50	42	5.8	24	35	30
Aluminum	0.10	0.037	0.032	0.034	0.039	0.028	0.024	0.025	0.029
Antimony	0.02	4.7E-05	0.000060	7.5E-05	7.8E-05	3.6E-05	4.5E-05	5.5E-05	5.6E-05
Arsenic	0.005	0.00018	0.00024	0.00030	0.00030	0.00014	0.00018	0.00022	0.00022
Barium	1	0.0032	0.0040	0.0049	0.0051	0.0024	0.0030	0.0036	0.0037
Boron	1.5	0.00094	0.0017	0.0023	0.0021	0.00072	0.0012	0.0016	0.0015
Cadmium	0.0000021	2.4E-05	2.8E-05	3.4E-05	3.5E-05	0.000018	2.1E-05	2.5E-05	2.6E-05
Chromium III	0.0089	5.2E-05	0.00012	0.00018	0.00016	4.0E-05	9.0E-05	0.00012	0.00011
Chromium VI	0.0010	0.00018	0.00041	0.00058	0.00052	0.00013	0.00030	0.00042	0.00037
Copper	0.0020	0.00094	0.00085	0.00090	0.0010	0.00072	0.00064	0.00067	0.00077
Iron	0.30	0.094	0.079	0.080	0.098	0.072	0.060	0.060	0.071
Lead	0.0010	2.4E-05	4.2E-05	6.5E-05	7.0E-05	1.9E-05	3.2E-05	4.8E-05	5.0E-05
Manganese	0.62	0.0039	0.0044	0.0055	0.0060	0.0030	0.0033	0.0040	0.0044
Molybdenum	19	3.8E-05	0.0016	0.0026	0.0020	2.2E-05	0.0011	0.0018	0.0014
Nickel	0.025	0.00064	0.00073	0.00091	0.0010	0.00050	0.00055	0.00067	0.00073
Potassium	41	0.45	0.66	0.86	0.85	0.35	0.49	0.62	0.61
Selenium	0.0010	4.9E-05	0.00034	0.00053	0.00044	0.000036	0.00024	0.00038	0.00030
Strontium	6.2	0.0058	0.11	0.19	0.15	0.0040	0.082	0.13	0.10
Uranium	0.015	3.8E-05	6.9E-05	9.4E-05	8.8E-05	2.9E-05	5.1E-05	6.8E-05	6.3E-05
Vanadium	0.015	0.00010	0.00017	0.00022	0.00021	7.9E-05	0.00012	0.00016	0.00015
Zinc	0.03	0.00094	0.00096	0.0011	0.0013	0.00072	0.00073	0.00083	0.00092

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-8d. Predicted Concentration in Overflow Discharge from Fox Pit Lake, Scenario 3

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	250 Year	Year 1	10 Year	100 Year	250 Year
Ammonia - N	0.59	0.00020	0.00059	0.0030	0.0053	0.00020	0.00059	0.0030	0.0053
Chloride	[b]170	7.2	14	15	12	7.2	14	15	12
Nitrate - N	0.49	0.026	0.053	0.056	0.045	0.026	0.053	0.056	0.045
Nitrite - N	0.06	4.7E-05	0.00011	0.00037	0.00060	4.7E-05	0.00011	0.00037	0.00060
Phosphate		0.00027	0.00072	0.0032	0.0056	0.00027	0.00072	0.0032	0.0056
Sulphate	20	1.7	3.5	4.2	3.8	1.7	3.5	4.2	3.8
TDS	-	21	42	47	41	21	42	47	41
Aluminum	0.10	0.0024	0.0058	0.019	0.031	0.0024	0.0058	0.019	0.031
Antimony	0.02	1.7E-05	3.6E-05	5.6E-05	6.6E-05	1.7E-05	3.6E-05	5.6E-05	6.6E-05
Arsenic	0.005	3.5E-05	7.5E-05	0.00014	0.00019	3.5E-05	7.5E-05	0.00014	0.00019
Barium	1	0.00096	0.0020	0.0033	0.0041	0.00096	0.0020	0.0033	0.0041
Boron	1.5	0.00048	0.00098	0.0014	0.0015	0.00048	0.00098	0.0014	0.0015
Cadmium	0.0000021	5.2E-06	1.1E-05	2.0E-05	2.7E-05	5.2E-06	1.1E-05	2.0E-05	2.7E-05
Chromium III	0.0089	5.7E-06	1.3E-05	3.2E-05	4.8E-05	5.7E-06	1.3E-05	3.2E-05	4.8E-05
Chromium VI	0.0010	1.9E-05	4.3E-05	0.00011	0.00016	1.9E-05	4.3E-05	0.00011	0.00016
Copper	0.0020	8.2E-05	0.00019	0.00054	0.00084	8.2E-05	0.00019	0.00054	0.00084
Iron	0.30	0.0034	0.0094	0.044	0.076	0.0034	0.0094	0.044	0.076
Lead	0.0010	1.6E-05	3.3E-05	5.0E-05	6.0E-05	1.6E-05	3.3E-05	5.0E-05	6.0E-05
Manganese	0.62	0.00092	0.0020	0.0037	0.0049	0.00092	0.0020	0.0037	0.0049
Molybdenum	19	0.00096	0.0019	0.0020	0.0016	0.00096	0.0019	0.0020	0.0016
Nickel	0.025	0.00034	0.00069	0.0010	0.0011	0.00034	0.00069	0.0010	0.0011
Potassium	41	0.39	0.79	1.0	1.0	0.39	0.79	1.0	1.0
Selenium	0.0010	1.6E-05	0.000034	5.4E-05	6.4E-05	1.6E-05	0.000034	5.4E-05	6.4E-05
Strontium	6.2	0.053	0.11	0.11	0.092	0.053	0.11	0.11	0.092
Uranium	0.015	3.2E-05	6.6E-05	0.000083	8.3E-05	3.2E-05	6.6E-05	0.000083	8.3E-05
Vanadium	0.015	0.000031	6.5E-05	0.00011	0.00013	0.000031	6.5E-05	0.00011	0.00013
Zinc	0.03	0.00017	0.00037	0.00075	0.0010	0.00017	0.00037	0.00075	0.0010

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

Table 7.2-9. Predicted Concentration in Overflow Discharge from Beartooth Pit Lake

Variable	[a]Water Quality Benchmark (mg/L)	September, October				June, July, August			
		Year 1	10 Year	100 Year	500 Years	Year 1	10 Year	100 Year	500 Years
Ammonia - N	0.59	0.056	0.028	0.016	0.0095	0.048	0.021	0.011	0.0068
Chloride	[b]170	250	100	35	0.83	220	73	20	0.51
Nitrate - N	0.49	0.92	0.38	0.13	0.0058	0.78	0.27	0.074	0.0039
Nitrite - N	0.06	0.015	0.0068	0.003	0.001	0.013	0.0049	0.0019	0.00074
Phosphate		0.0089	0.0078	0.0078	0.0075	0.0076	0.0062	0.0056	0.0054
Sulphate	20	29	13	5.5	1.9	24	9.1	3.4	1.3
TDS	-	430	180	69	12	360	130	41	8.6
Aluminum	0.10	0.019	0.037	0.048	0.052	0.017	0.031	0.036	0.038
Antimony	0.02	0.00043	0.00022	0.00013	0.000082	0.00037	0.00016	0.000087	0.000059
Arsenic	0.005	0.00027	0.00026	0.00026	0.00026	0.00024	0.00021	0.00019	0.00019
Barium	1	0.02	0.011	0.0069	0.0048	0.017	0.0081	0.0047	0.0034
Boron	1.5	0.0063	0.0033	0.0021	0.0014	0.0053	0.0025	0.0014	0.001
Cadmium	0.0000021	0.000073	0.000049	0.00004	0.000034	0.000062	0.000038	0.000028	0.000024
Chromium III	0.0089	0.00013	0.000093	0.000083	0.000075	0.00011	0.000073	0.000059	0.000054
Chromium VI	0.0010	0.00042	0.00031	0.00028	0.00025	0.00036	0.00024	0.0002	0.00018
Copper	0.0020	0.00058	0.001	0.0013	0.0014	0.00051	0.00083	0.00093	0.00097
Iron	0.30	0.039	0.092	0.12	0.13	0.036	0.077	0.091	0.096
Lead	0.0010	0.000068	0.000047	0.000039	0.000034	0.000058	0.000036	0.000028	0.000024
Manganese	0.62	0.01	0.0072	0.0062	0.0055	0.0085	0.0056	0.0044	0.004
Molybdenum	19	0.023	0.0093	0.0032	0.0001	0.019	0.0066	0.0018	0.000067
Nickel	0.025	0.00093	0.0009	0.00093	0.00092	0.0008	0.00072	0.00068	0.00066
Potassium	41	8.3	3.8	1.7	0.7	7	2.7	1.1	0.5
Selenium	0.0010	0.000098	0.000079	0.000074	0.00007	0.000084	0.000062	0.000053	0.00005
Strontium	6.2	1.9	0.77	0.27	0.012	1.6	0.55	0.15	0.0078
Uranium	0.015	0.00016	0.000097	0.000072	0.000057	0.00014	0.000074	0.00005	0.000041
Vanadium	0.015	0.00027	0.0002	0.00017	0.00016	0.00023	0.00015	0.00012	0.00011
Zinc	0.03	0.00099	0.0012	0.0013	0.0014	0.00086	0.00096	0.00098	0.00099

[a] *Based on hardness of 4 mg/L, which is approximate background hardness of natural waters in Ekati area.*
[b] *Hardness of 4 mg/L is outside of meaningful range for chloride Water Quality Benchmark equation. Hence, a hardness value of 25 mg/L was used to give meaningful benchmark value of 170 mg/L chloride.*
Note: Shaded values are predictions that exceed Water Quality Benchmarks or site Water Licence (W2009L2-0001).

The results indicate that chloride, nitrate and sulphate concentrations only are predicted to exceed their Water Quality Benchmark, one year after closure. Soon after this, the model predicts that the concentration of all water quality variables will be less than Water Quality Benchmarks apart from cadmium, with concentrations lowered due to dilution from the natural watershed lying upstream of Beartooth pit lake. As discussed earlier the cadmium Water Quality Benchmark is known to be low (Rescan 2012). Concentrations of most water quality variables are predicted to decrease steadily over time, with increases predicted for a small number of metals. These increases are due to loadings from exposed pit walls surrounding the pit lakes. As noted previously, the model takes a conservative approach in assuming that the quality of pit wall runoff does not vary over time. In reality, pit wall runoff would be expected to improve over time as the exposed sections of pit wall become depleted in weathering products. Even with these conservative assumptions predicted concentrations of most water quality variables are well below Water Quality Benchmarks.

7.3 SUMMARY AND DISCUSSION OF LONG-TERM WATER QUALITY PREDICTIONS

Water balance and water quality predictions for the upper layers of the pit lakes were made for the period up to 250 years after each pit lake has been infilled. Estimates were made of average overflow rates from each pit lake as well as predictions of the quality of water within the upper layers of each lake. Outflows from the pit lakes will only occur during the open water season when the lakes are ice-free and there is a net surplus of water. The outflow to surface water bodies will be through natural, uncontrolled spill points, such that overflow will only take place within the surface layer of the pit lakes.

The key results of the modelling assessment are summarized below:

- Due to the relatively small watersheds flowing into each pit lake and the high evaporation rate (relative to precipitation rate) predicted for the Ekati area, outflow volumes from each pit lake are expected to be relatively low. For some pit lakes there will be zero outflow during some summer months.
- Cadmium concentrations are predicted to exceed Water Quality Benchmarks in all pit lakes. The cadmium benchmark is based on the interim CCME guideline value which is known to be low. A draft CCME guideline for cadmium has been published and it is significantly higher than the current guideline. However, the draft guideline has yet to be formally endorsed by the CCME and is therefore not considered in this report. The model predictions for cadmium are lower than the draft guideline.
- Apart from cadmium, no other water quality variables are predicted to exceed Water Quality Benchmarks in Sable and Fox pit lakes.
- In Beartooth pit lake a 30 m thick layer of water above FPK solids was modelled. The model predicts that apart from cadmium, only chloride, nitrate and sulphate concentrations exceed Water Quality Benchmarks and only for a few years after pit infilling. The results depend on how much mine water is left within the pit lake prior to the pumping of fresh water to complete a 30 m deep water cover. The lower the volume of mine water the lower the concentrations of all water quality variables.
- In Panda and Koala/Koala North pit lakes, apart from cadmium, only chloride, nitrate and sulphate concentrations (sourced from groundwater during infilling) are predicted to exceed Water Quality Benchmarks for the Base Case scenario, and for less than 100 years after the end of operations. However, exceedances are not predicted for scenarios with lower groundwater flow rates, a fresh water cover, and for scenarios where there is the formation of stratification within the pit lake during infilling. Given the likelihood that groundwater flow rates in the Base

Case are conservative (high) and that a fresh water cover could be considered as a water management option during pit infilling, the modelling study indicates that water in the surface layer of Panda and Koala/Koala North pit lakes would likely meet Water Quality Benchmarks.

- In Pigeon and Misery pit lakes model runs predict exceedances of a number of water quality variables in the closure period as a result of loadings from pit wall runoff. There are uncertainties associated with pit wall runoff predictions, with evidence from observed pit sump chemistry that pit wall runoff predictions used in the model may be conservative (high). Hence, further work is required to better determine pit wall runoff quality for these pit lakes. Irrespective of the quality of water in these pit lakes, outflow rates from these pit lakes are predicted to be very low and tending to zero for Misery pit lake during summer months.

It should be noted that model predictions are compared to Water Quality Benchmarks calculated for a low hardness of 4 mg/L (or at 25 mg/L hardness for chloride due to restrictions with application of benchmark at low hardness values), which is a typical hardness for natural water at in the Ekati area. This value was chosen to provide consistent benchmarks throughout the report to allow comparison of results from different pit lakes and as these benchmarks might be considered representative of natural receiving waters in the Ekati area. Within pit lakes hardness may be higher than this and as a result, within the pits higher Water Quality Benchmarks would be warranted.

Model simulations assume that groundwater flow rates to pit lakes tend to zero as they fill. If there were a net flux of groundwater to the pit lakes once they were filled, meromixis modelling in Chapter 6 indicated the potential for a lower layer of saline water in the pit lake to rise over time, with the top of this layer mixing with the upper fresh water layer. If evidence was obtained that there is the potential for a net flux of groundwater to the pit lakes once filled, further assessment of this groundwater would be required to evaluate its potential influence on pit lake stratification and water quality.

8. Summary of Conclusions of Modelling Study

8. Summary of Conclusions of Modelling Study

The conclusions from the modelling study are summarised in Table 8-1.

Table 8-1. Summary of Modelling Results

Pit	Meromixis	Water Quality in Surface Layer of Full Pit Lake[a]	Comment
Sable	Low likelihood for meromixis	All key water quality variables likely < WQBs	-
Pigeon	Low likelihood for meromixis	Potential for exceedances of selected metals due to loadings from pit wall runoff.	Key loading is from pit wall runoff from meta-sediment. Uncertainties over pit wall runoff chemistry and rock type exposed in pit wall of full pit lake. However, annual outflow volume from pit lake is very low, tending to zero in summer months, due to small (0.03 to 0.1 km^2) watershed draining to pit lake. As a result likely negligible loads to downstream water body even if surface water quality exceeds WQBs.
Beartooth	Low likelihood for meromixis	Potential for exceedances for nitrate, chloride and sulphate in first 10 years post-infilling, with concentrations < WQBs by Year 10.	Bearetooth pit lake will be filled with FPK up to 30 m from the full level of the pit lake. It will then be capped by a layer of water. Water quality in the surface layer will depend on how much mine water remain above FPK at the time of capping with fresh water.
Misery	Low likelihood for meromixis	Potential for exceedances of selected metals due to loadings from pit wall runoff.	Key loading is from pit wall runoff. Uncertainties over pit wall runoff chemistry and rock type exposed in pit wall of full pit lake. However, annual outflow volume from pit lake is very low, tending to zero in summer months, due to small (0.02 km^2) watershed draining to pit lake. As a result likely negligible loads to downstream water bodies even if surface water quality exceeds WQBs.
Fox	Moderate likelihood for meromixis	All key water quality variables likely < WQBs.	Key uncertainties are groundwater inflow rates and how these vary over time and WRSA runoff rates and chemistry. WRSAs surrounding Fox pit will drain to pit lake at closure.
Panda	High likelihood for meromixis	Potential for exceedances of chloride, nitrate and sulphate concentrations up to 100 years post-infilling of pit lake.	Key uncertainties are groundwater inflow rates and how they vary over time and WRSA runoff rates and chemistry. Base Case assumes conservative (high) groundwater flow rates for the end of operations at Panda underground. If lower rates, based on current observed data, are used, modelling predicts all water quality variables will be < WQBs. Model assumes around 1.4 km^2 of WRSAs to the west of Panda pit draining to the pit lake.
Koala/ Koala North	High likelihood for meromixis	Potential for exceedances of chloride, nitrate and sulphate concentrations up to 100 years post-infilling of pit lake.	Key uncertainty is groundwater inflow rates and how these vary over time. Base Case assumes conservative (high) groundwater flow rates for the end of operations at Koala/Koala North underground. If lower rates, based on current observed data, are used, modelling predicts all water quality variables will be < WQBs.

[a] Excluding cadmium, which is exceeded in all pit lakes. However, cadmium benchmark is known to be low (Rescan 2012).
Notes: WQB = Water Quality Benchmark; WRSA = Waste Rock Storage Area; FPK = Fine Processed Kimberlite

The key general conclusions of this study are:

- Pumping of fresh water to fill pit lakes improves the quality of water in the pit lakes. Higher infilling rates, and/or commencement of pumping as soon as possible following end of mine operations, will produce cleaner pit lake water. At pumping rates of 0.2 to 0.4 m^3/s the pumped inflows are the dominant source of inflow water for all pit lakes.
- Pit lakes with larger upstream watersheds are likely to have better quality water in the surface layer of the pit lakes than pits with smaller upstream watersheds.
- Only those pit lakes with groundwater inputs have the potential for the formation of meromixis, with the likelihood of meromixis related to the rate of groundwater inflow, the rate of change of groundwater inflows as pit lake levels rise, and the speed at which the pit lakes are filled.
- Pit wall runoff is the main source of long-term loadings to full pit lakes, as there will be areas of exposed pit walls above the pit lake surface of all pit lakes. Most rock types exposed in pit walls (i.e., granite, diabase, kimberlite) are relatively unreactive. However, meta-sediments exposed in Misery and Pigeon pit walls may produce loadings to pit lakes that have the potential of causing exceedances of Water Quality Benchmarks in the surface layers of these pit lakes.
- The quality of water in the surface layer of the pit lakes is likely to be below Water Quality Benchmarks, unless certain conditions arise for selected pit lakes. Water quality in Sable and Fox pit lakes is expected to be below Water Quality Benchmarks for all conditions. Water quality in Beartooth pit is expected to be below Water Quality Benchmarks as long as mine water is pumped out of the pit lake prior to final infilling with a fresh water cover. Water quality in Panda and Koala/Koala North is expected to be below Water Quality Benchmarks unless groundwater inflows are much higher than current observed underground water flows in the underground workings. Even in such a case the placement of a fresh water cover at the surface of these pit lakes is expected to reduce concentrations in the surface layer below Water Quality Benchmarks. The largest concerns related to exceedances of Water Quality Benchmarks are for Misery and Pigeon pit lakes, where loadings from exposed meta-sediments in the pit walls have the potential to increase concentrations in the surface water layer above Water Quality Benchmarks. However, there is evidence that current pit wall runoff predictions for meta-sediment may be overly conservative, and with additional research there is some opportunity to constrain loading estimates from meta-sediments at Misery.

8.1 UNCERTAINTIES, DATA GAPS, AND CONSIDERATIONS FOR FUTURE RESEARCH

The model predictions are limited by the assumptions inherent within each modelling technique used, and these assumptions are discussed in detail in the relevant sections of the report. In addition, the inputs to the model are based on data made available during the development of the modelling tools. With additional data collection over the remaining lifetime of the Ekati mine the inputs to the models could be refined and the models re-run to update estimates of pit lake water quality.

Key uncertainties within the model predictions and which have an important impact on model results are:

- Pumped inflow rates from donor lakes to pit lakes during the pit lake infilling process. Values used in this report are best estimates based on work undertaken for the ICRP. However, if pumping rates are changed from those used in the modelling study this would result in significant changes in predictions of initial pit lake water chemistry when the pit lakes are filled. For example, if rates could be increased from those considered within this report, it would result in improved water quality within the pit lakes at the point that the pit lakes become full.

- Groundwater flow rates to Panda, Koala/Koala North and Fox pit lakes. There are differences between groundwater flow rates predicted from modelling studies and those observed at the mine site. Groundwater flow rates have a key influence on water chemistry in Panda, Koala/Koala North and Fox pit lakes and on the likelihood of meromixis and its stability.
- Runoff from WRSAs. At closure, runoff from WRSAs surrounding Fox pit will flow into Fox pit lake. Similarly runoff from WRSAs will flow into Panda pit lake. The current model assumes runoff from WRSAs surrounding the pit lake will have similar chemistry to natural runoff, as the reactive WRSA cores are predicted to be frozen at closure. If there are loadings from the WRSAs this would result in an increase of loadings to the pit lake at closure.
- Runoff from pit walls during infilling and closure. This is of particular importance for Misery and Pigeon pit lakes where reactive meta-sediments are exposed in the pit walls. Changes in pit wall runoff chemistry result in large changes in pit lake water chemistry at these locations. Also important is the distribution of different rock types in the exposed pit walls once the pit lakes are full. In the model it is assumed that the distribution of rock types in the exposed pit walls is similar to the distribution for the pit as a whole. However, if the proportions of different rock types in the section exposed above the pit lake water level are different this would have an impact on long-term pit lake chemistry.
- The modelling work presented in this report does not consider the future effects of climate change. It is clear that there are large uncertainties as to the impact of climate change on Northern Canada; however, as knowledge develops, model inputs (e.g., precipitation rates) could be reviewed in the light of this work to refine model predictions.

The model is data driven in that many parameters and inputs are based on analysis of observed data at the Ekati mine. Many of the assumptions of the model are conservative; however, the long term nature of the predictions (hundreds of years) creates inherent uncertainty in the predictions. As with all modelling there remain uncertainties in simulating the behaviour of managed and natural systems, particularly over a span of hundreds of years. Nonetheless, this study has used available monitoring data to make reasonable predictions of water quality in the future pit lakes at the Ekati site based on the closure concepts developed in the ICRP.

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Appendix 1

Calculation of Runoff Coefficient for Pit Wall Runoff

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Appendix 1
Calculation of Runoff Coefficient for Pit Wall Runoff

Monthly totals of pumped flows from pit sumps are collected at EKATI. There is multi-year data for Misery pit, Fox pit, Beartooth pit, Panda pit and Koala pit. Data for Misery, Fox, Beartooth and Koala pits are used to calibrate simple pit water balance models, as catchment and pit areas for these pits were calculated as part of the pit lakes modelling work for the EKATI area (BHP Billiton 2009). For Panda pit the calculated catchment area is for post-closure and does not reflect the current inflowing catchment area.

The simple pit water balance model considers inflows to the pit from the catchment surrounding the pit and from runoff over the pit walls. Runoff totals are estimated based on the following equation;

Total annual runoff (mm) = Total annual precipitation (mm) x runoff coefficient

For the historical period observed annual precipitation totals are considered along with observed runoff coefficients for natural catchments. The average runoff coefficient for natural catchments is 0.5, i.e., half of the precipitation total is converted into runoff.

The runoff coefficient for pit wall runoff is calibrated by varying the value until a reasonable fit was obtained with observed data. The best fit was obtained for a runoff coefficient of 0.85. This would appear reasonable as runoff from pit walls is expected to be significantly higher than from a natural catchment, but there would still be losses due to evaporation, sublimation and water held in broken rock sitting on benches within the open pit.

Groundwater inflows are considered zero for all pits. Only surface pits are considered, underground operations are not considered.

Groundwater held within mined kimberlite or waste rock and water removed from the pit within kimberlite ore or waste rock is considered negligible compared to other inflows.

Within each pit the surface area of the pit sump is considered negligible and there is assumed to be a balance between precipitation landing directly on the sump (runoff coefficient = 1) and evaporation from the sump.

Pit areas and catchments were calculated as part of the pit lakes modelling work for the EKATI area.

For each pit, predicted and observed average annual inflows are compared for the period of record, in order to calibrate results to a constant pit runoff coefficient. Given the uncertainties associated with all input parameters (i.e., precipitation at each pit, natural runoff coefficient, pit wall runoff), trying to calibrate for each year of record would only calibrate the pit wall runoff coefficient to the uncertainties in the data and is unlikely to improve our understanding of runoff and would not aid prediction of future conditions.

A1-1 MISERY PIT SUMP

Records of monthly pumped water totals have been recorded for Misery pit since 2000, Table A1-1.

Table A1-1. Summary of Recorded Annual Pumped Volumes from Misery Pit

Year	Pumped Volume (m^3)	Operational Status	Averages (m^3/year)	
2000	656,277	Lake dewatering		
2001	472,992	Lake dewatering pre-stripping	Pre-stripping	565,000
2002	120,245	Operations		
2003	72,609	Operations		
2004	89,662	Operations	Operations	94,200
2005	55,340 [a]	Temporary closure		
2006	0	Temporary closure		
2007	129,650	Temporary closure		
2008	0	Temporary closure		
2009	0	Temporary closure		
2010	169,000 [b]	Temporary closure		
2011	300,000 [c]	Temporary closure	Closure	93,427
			Operations and closure	93,700

[a] *Water allowed to accumulate in pond and pumped out in October and November 2005*
[b] *Pumping volume for summer 2010 provided by A Conley, BHP Billiton*
[c] *Estimate of future pumping in 2011 (prior to push-back of pit) provided by A Conley, BHP Billiton*

In 2000 and 2001 activities focussed on dewatering of Misery Lake and pit pre-stripping. Pumped volumes at this time reflect pumping of the existing lake and are significantly higher than volumes in later years (i.e., average of 565,000 m^3/year, Table A1-1).

Between 2002 and 2004, the pit was under active mining and during this period pumped totals reflect runoff reaching the sump at the pit bottom. It is assumed that water was not stored at this time and all pumped inflows were quickly pumped to the surface. During this period there was an average pumping rate of 94,200 m^3/year.

From 2005 to the present day, Misery pit has been in temporary closure and water has been allowed to accumulate at the bottom of the pit, being pumped to KPSF periodically. Hence, in some years (e.g., 2006, 2008 and 2009) no water was pumped from the bottom of the pit. In September 2005 water depths at the bottom of the pit reached around 11.4 m, before water was pumped out. Pumping also occurred in 2007 and 2010 and there is already a permitted pumped volume for 2011. Taking all available data the annual average pumping rate during the temporary closure period is 93,400 m^3/year, very similar to the rate during operations.

Taking all data from period of operations and temporary closure (including 2011) the annual average pumped flow rate is 93,700 m^3.

The simple water balance model was run for the period 2002 – 2011 (operations and temporary closure), using observed precipitation and natural watershed runoff coefficients, Table A1-2. The model predicted an average annual inflow to the pit that was very similar to the observed average annual pumping rate from Misery pit.

A1-2 FOX PIT SUMP

Records of monthly pumped water totals have been recorded for Fox pit since 2003, Table A1-3.

Table A1-2. Results of Annual Mass Balance Modelling

Year	Observed Precipitation (mm)	Observed Runoff Coefficient	Pit Runoff Coefficient	Catchment Area	300,000 m^2
				Pit	200,000 m^2
				Estimated Annual Runoff (m^3)	Observed Annual Pumped Out (m^3)
2002	321	0.43	0.85	95,979	120,245
2003	292	0.30	0.85	75,920	72,609
2004	222	0.46	0.85	68,273	89,662
2005	248	0.54	0.85	81,985	55,340
2006	426	0.52	0.85	139,143	0
2007	257	0.45	0.85	78,730	129,650
2008	422	0.27	0.85	105,940	0
2009	251	0.47	0.85	78,370	0
2010	338	0.50	0.85	108,160	169,000
2011	338	0.50	0.85	108,160	300,000
Average				**94,066**	**93,651**

Table A1-3. Summary of Recorded Annual Pumped Volumes from Misery Pit

Year	Pumped Volume (m^3)	Operational Status	Averages (m^3/year)	
2003	2,825,767	Lake dewatering	Lake dewatering	2,825,767
2004	139,349	Operations		
2005	68,483	Operations		
2006	389,720	Operations		
2007	169,530	Operations		
2008	273,570	Operations		
2009	137,109	Operations	Operations	196,293
			Operations	196,293

In 2003 activities focussed on dewatering of Fox Lake and pumped volumes at this time reflect pumping of the existing lake and are significantly higher than volumes in later years.

Between 2004 and 2009, the pit was under active mining and during this period pumped totals reflect runoff reaching the sump at the pit bottom. It is assumed that water was not stored at this time and all pumped inflows were quickly pumped to the surface. During this period there was an average pumping rate of 196,293 m^3/year.

The simple water balance model was run for the period 2004 – 2009 (operations), using observed precipitation and natural watershed runoff coefficients, Table A1-4. The model predicted an average annual inflow to the pit that was very similar to the observed average annual pumping rate from Fox pit.

A1-3 BEARTOOTH PIT SUMP

Records of monthly pumped water totals have been recorded for Beartooth pit since 2003, Table A1-5.

Table A1-4. Results of Annual Mass Balance Modelling

Year	Observed Precipitation (mm)	Observed Runoff Coefficient	Pit Runoff Coefficient	Catchment Area	280,000 m^2
				Pit	575,000 m^2
				Estimated Annual Runoff (m^3)	Observed Annual Pumped Out (m^3)
2004	222	0.46	0.85	137,000	139,349
2005	248	0.54	0.85	158,380	68,483
2006	426	0.52	0.85	270,483	389,720
2007	257	0.45	0.85	158,313	169,530
2008	422	0.27	0.85	238,173	273,570
2009	251	0.47	0.85	155,996	137,109
Average				**186,391**	**196,293**

Table A1-5. Summary of Recorded Annual Pumped Volumes from Beartooth Pit

Year	Pumped Volume (m^3)	Operational Status	Averages (m^3/year)	
2003	52.036	Operations		
2004	39,048	Operations		
2005	37,419	Operations		
2006	82,440	Operations		
2007	33,705	Operations		
2008	54,758 [a]	Operations		
2009	No data	Operations	Operations	49,901
			Operations	49,901

[a] *No data for May and June, so long-term averages for these months used in the assessment*

Between 2004 and 2009, the pit has been under active mining and during this period pumped totals reflect runoff reaching the sump at the pit bottom. It is assumed that water was not stored at this time and all pumped inflows were quickly pumped to the surface. During this period there was an average pumping rate of 49,901 m^3/year.

The simple water balance model was run for the period 2004 – 2009 (operations), using observed precipitation and natural watershed runoff coefficients, Table A1-6. The model predicted an average annual inflow to the pit that was higher than the observed average annual pumping rate from Beartooth pit. It is noted that this is the only pit where a pit wall runoff coefficient of 0.85 did not produce a reasonable fit to the observed data. A value of 0.5 would be required to provide a reasonable fit. It is unclear why Beartooth pit results are anomalous and may indicate that there have been errors in estimating the pit or catchment areas.

A1-4 KOALA PIT SUMP

Records of monthly pumped water totals have been recorded for Koala pit since 1999, Table A1-7.

In 1999 and 2000 activities focussed on dewatering of lakes above Koala pit. Pumped volumes at this time reflect pumping of the existing lake and are significantly higher than volumes in later years (i.e., average of 1,535,926 m^3/year, Table A1-7).

Table A1-6. Results of Annual Mass Balance Modelling

Year	Observed Precipitation (mm)	Observed Runoff Coefficient	Pit Runoff Coefficient	Catchment Area	210,000 m^2
				Pit	157,000 m^2
				Estimated Annual Runoff (m^3)	Observed Annual Pumped Out (m^3)
2003	292	0.30	0.85	57,363	52.036
2004	222	0.46	0.85	50,999	39,048
2005	248	0.54	0.85	60,973	37,419
2006	426	0.52	0.85	103,556	82,440
2007	257	0.45	0.85	58,825	33,705
2008	422	0.27	0.85	80,256	54,758
2009	251	0.47	0.85	-	-
Average				**68,662**	**49,901**

Table A1-7. Summary of Recorded Annual Pumped Volumes from Koala Pit

Year	Pumped Volume (m^3)	Operational Status	Averages (m^3/year)	
1999	1,819,398	Lake dewatering		
2000	1,252,454	Lake dewatering	Lake dewatering	1,535,926
2001	403,776	Operations		
2002	140,522	Operations		
2003	105,080	Operations		
2004	82,295	Operations		
2005	82,819	Operations		
2006	251,091	Operations		
2007	120,591	Operations		
2008	- [a]	Operations		
2009	94,971	Operations	Operations	160,143
			Operations	160,143

[a] *Full year not recorded, gauge malfunction*

Between 2001 and 2009, the pit was under active mining and during this period pumped totals reflect runoff reaching the sump at the pit bottom. It is assumed that water was not stored at this time and all pumped inflows were quickly pumped to the surface. During this period there was an average pumping rate of 160,143 m^3/year.

The simple water balance model was run for the period 2001 – 2009 (operations), using observed precipitation and natural watershed runoff coefficients, Table A1-8. The model predicted an average annual inflow to the pit that was very similar to the observed average annual pumping rate.

Table A1-8. Results of Annual Mass Balance Modelling

				Catchment Area	320,000 m^2
				Pit	520,000 m^2
Year	Observed Precipitation (mm)	Observed Runoff Coefficient	Pit Runoff Coefficient	Estimated Annual Runoff (m^3)	Observed Annual Pumped Out (m^3)
2001	336	0.63	0.85	216,250	403,776
2002	321	0.43	0.85	186,052	140,522
2003	292	0.30	0.85	157,096	105,080
2004	222	0.46	0.85	130,693	82,295
2005	248	0.54	0.85	152,096	82,819
2006	426	0.52	0.85	259,464	251,091
2007	257	0.45	0.85	150,970	120,591
2008	422	0.27	0.85	-	-
2009	251	0.47	0.85	149,022	94,971
Average				**175,205**	**160,143**

A1-5 SUMMARY

Results from a simple water balance model for four operation pits in the EKATI area were compared to observed pit sump pumping data. Based on the use of a pit wall runoff coefficient of 0.85, the difference between predicted and observed average annual pumped volumes for each pit were:

- Misery: 0%;
- Fox: -5%;
- Beartooth: +50%; and
- Koala: +9%.

For three of the pits the simple model produced results within 10% of the observed. Acknowledging the uncertainties associated with the input parameters, results indicate that the modelling approach probably does represent the main processes affecting inflows to the pits. The Beartooth results are anomalously high and this may reflect uncertainties in the estimation of catchment areas.

However, based on data available, the results indicate that the water balance model can be used to estimate pit inflows for other pits with no available data, i.e., Pigeon pit.

Appendix 2

Analysis of Water Quality of Misery “Mini-pit Lake”

Engineers and Scientists

Appendix 2
Analysis of Water Quality of Misery 'Mini-Pit Lake'

In the summer of the 2005, the Misery Pit was temporarily closed and water was allowed to build up naturally at the bottom of the pit. On September 16, 2005, the Misery Pit water level was at an elevation of 286.37 m with the bottom of the pit at approximately 275.00 m elevation, giving an approximate water depth of 11.37 m. The volume of the Misery pit on this date was estimated to be 58,800 m^3. This 'mini-pit lake' represented about 0.2% of the expected pit lake volume at closure of 26,000,000 m^3 for Misery.

In effect the formation of this 'mini-pit lake' is representative of what may happen in the early weeks or months of the closure period. The quality of water in the pit lake can be used to assess to what extent the initial infilling water will have the same chemistry as operational sump water. Estimating initial loadings to pit lakes is an important input to the pit lakes infilling model and while there is data on sump water quality for each operation pit, there is no data (other than for Misery) on water quality in a partially filled pit lake.

This appendix compares the water quality characteristics of the Misery Pit water sampled in September 2005 (from mini pit lake) to the water quality of the sump water collected and pumped from the base of the Misery pit over a four year period (September 2000 to September 2004). Sampling of the Misery sump water was undertaken on 28 occasions over the four years, at an irregular sampling frequency (intervals varied between approximately monthly to up to 8 months apart).

The Misery mini-pit lake was sampled on September 6, 2005 using a GO-FLO bottle and samples were collected at 1 m, 5 m, and 10 m. Replicate samples were collected at each sample depth. The depth of the lake at the sample location was measured as 10.6 m. Table A2-1 shows the results of the mini-pit lake sampling, using the average of the replicate samples at each depth. In almost all cases there was negligible difference between the replicate samples, hence the average was used. The mean and standard deviation for the same parameters of the sump water at Misery are also shown in Table A2-1.

The results of the chemical analysis for the mini-pit lake indicate that the water column is generally well mixed as for most parameters there is not a considerable difference between concentrations at the bottom (i.e., the 10 m depth) and the surface (i.e., the 1 m depth), Table A2-1. However, there is generally a slight decrease in concentrations moving up the water column (i.e., concentrations at the 10m depth are generally slightly higher than the upper samples).

With the exception of one metal, concentrations of dissolved metals in the sump water samples were higher than that sampled in the mini-pit lake, indicating that dilution is occurring even at low lake volumes for most metals. For example, average concentrations of dissolved aluminum in the sump samples was 0.0265 mg/L compared to concentrations in the mini-pit lake of between 0.0017 and 0.0018 mg/L, Table A2-1. The exception is dissolved molybdenum, which had slightly higher concentrations in the mini-pit lake (0.302 to 0.340 mg/L) than the average of the sump samples (0.128 mg/L).

Table A2-1. Water Quality Data for Misery Mini-Pit Lake and Misery Sump

Parameter		Misery mini-pit lake (6-Sep-05) Depth of sample			Misery Sump Data (Average of Samples collected between Sep 2000 and Sep 2004)			Dilution Factor Between Average Sump Concentration and mini-pit lake concentrations		
		10m	5m	1m	Mean	SD	N	10m	5m	1m
Hardness	$CaCO_3$	245	246	247	316	245	24	1.3	1.3	1.3
pH		7.09	7.57	7.72	7.55	0.55	24	n/a	n/a	n/a
Total Suspended Solids		12.7	5.4	5.7	241.0	756	25	19.0	45.0	42.7
Chloride	Cl	7.33	6.43	6.38	14.32	14.43	24	2.0	2.2	2.2
Sulphate	SO_4	378	343	346	178	157	24	0.5	0.5	0.5
Nutrients										
Ammonia Nitrogen	N	1.90	1.91	1.82	11.70	16.43	27	6.2	6.1	6.4
Nitrate Nitrogen	N	19.4	18.4	18.1	35.3	39.0	25	1.8	1.9	2.0
Nitrite Nitrogen	N	1.38	0.98	1.03	1.50	1.58	24	1.1	1.5	1.5
Total Phosphate	P	0.0081	0.0054	0.0077	0.0836	0.094	27	10.4	15.5	10.9
Dissolved Metals										
Aluminum	D-Al	0.0019	0.0018	0.0017	0.0265	0.0336	19	14.0	15.2	15.6
Cadmium	D-Cd	0.000076	0.000058	0.000051	0.00024	0.00016	19	3.2	4.2	4.7
Chromium	D-Cr	<0.00050	<0.00050	<0.00050	0.0006	0.0007	19	n/a	n/a	n/a
Copper	D-Cu	0.00033	0.00030	0.00028	0.02041	0.03477	19	62.8	68.0	72.9
Lead	D-Pb	0.000053	0.000125	0.000053	0.000162	0.000382	19	3.1	1.3	3.1
Molybdenum	D-Mo	0.340	0.302	0.306	0.128	0.0876	19	0.4	0.4	0.4
Nickel	D-Ni	0.0187	0.0221	0.0215	0.0533	0.0397	19	2.8	2.4	2.5
Selenium	D-Se	0.0030	0.0037	0.0037	0.0046	0.0029	19	1.5	1.2	1.3
Zinc	D-Zn	0.0021	0.0020	0.0013	0.0042	0.0043	19	2.0	2.2	3.3

Results are expressed as milligrams per litre except where noted.
Anion/Cation sums are expressed as milli-equivalents per litre.
< = Less than the detection limit indicated.

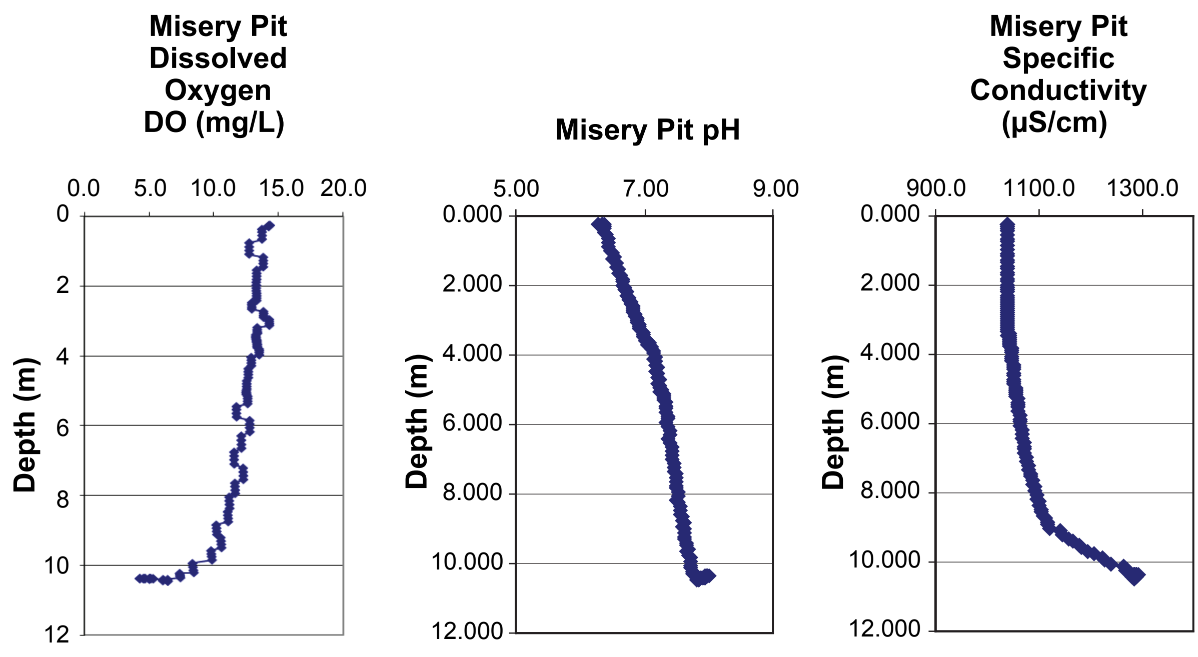
The final three columns in Table A2-1 present the calculated dilution factors between the sump water concentrations and the mini-pit lake concentrations for selected parameters at a range of depths. This gives an indication of how the sump water compares to actual pit water at various depths. It is apparent from the table that concentrations of some parameters (i.e., dissolved copper and aluminum) are considerably higher in the sump water than in the actual mini-pit water, with dilution factors of up to 68 for dissolved copper and 15.6 for dissolved aluminum. For most other parameters the dilution is not as large, and is generally around 2 or 3.

Figure A2-1 shows profiles of pH, specific conductivity, temperature and dissolved oxygen collected in the Misery mini-pit lake on September 6, 2005. The profiles indicate the structure of the lake. There is a trend of increasing pH with depth; the pH at the surface of the lake is around 6.27 increasing to 8.00 at depth. The specific conductivity of the water is also higher at depth, but remains relatively constant until around 8m deep. The temperature of the lake water decreases with depth, with a relatively big drop around the 8m depth mark, Figure A2-1. Dissolved oxygen concentrations also decrease with depth, ranging from 14.33 mg/L close to the surface to 4.64 mg/L at depth. The DO profile also shows a steady decline in concentrations with depth, until a marked change at around 8 m where DO concentrations drop off considerably.

CONCLUSIONS

The conclusions of the assessment is that even with a small amount of infilling of a pit (0.2% of total volume) the quality of water accumulating at the bottom of the pit lake is better (for most parameters) than operational sump water quality. Sump water accumulates in small volumes at the bottom of the operational pit and may have reached the sump b passing over pit walls and seeping through loose material at the pit bottom, flow pathways likely to result in relatively high concentrations of many parameters. In contrast once a pit lake forms at the bottom of the pit direct precipitation can enter the lake without coming in contact with pit walls and runoff over the pit walls can enter the lake without seeping through material at the pit bottom.

For the purposes of water quality modelling we need to identify an initial loading to the pit lake and based on available data it would be ideal if this could be defined in terms of sump water quality (as there is available sump water quality for all operational pits). We propose to assume that until the pit lake is 1% full, natural runoff entering the pit will take on average sump water quality. Based on the assessment outlined above this may provide slightly conservative initial loadings (even at 0.2% full the pit lake quality in Misery Pit appeared to be better than sump water quality), but a slightly conservative value appears reasonable based on the high degree of uncertainty associated with the assessment and the limited amount of available data.



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Temperature, pH and Specific Conductivity Profiles from Misery Pit Collected on September 6, 2005

FIGURE A2-1

Rescan™

Appendix 3
Ekati Pit Wall Source Terms

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Memo

To:	Marc Wen	**Client:**	Rescan
From:	Stephen Day Kirsty Ketchum	**Project No:**	1CR003.022
Cc:		**Date:**	November 6, 2013
Subject:	Ekati Pit Wall Source Terms		

1 Background

SRK was retained by Rescan Environmental Services to provide source term geochemical predictions for rock types exposed in the walls of each pit at the Ekati Diamond Mine. The work plan for this project was given in Statements of Work dated August 30, 2011 and May 3, 2013. The August 2011 work scope covered the original development of source terms for all rock types in pit walls. The May 2013 work scope covered refinement of the Misery Pit wall source terms and included a scoping level comparison of observed Misery Pit water chemistry with mixed water chemistry predicted by the source terms.

SRK understands these source terms will be used by Rescan to predict pit lake water chemistry.

2 Pit Wall Geochemical Conceptual Model

2.1 Mineral Weathering and Leaching Processes

For the purpose of this assessment, the pit walls are considered as small-scale waste-rock piles formed by blasting and physical weathering processes. Blasting results in fracturing of the wall rock due to the over-blasting needed to create rock that can be removed by shovels during mining. The walls therefore contain rock that is not as fractured as the rock that was mined. Physical weathering processes such as water erosion, freeze-thaw and exfoliation result in breakdown of the rock and creates locally fine-grained materials often reflected as talus cones and local wall failures.

Due to the coarse nature of wall rock, the entire rock mass is not exposed to atmospheric conditions and weathering is limited to fracture surfaces and fine particles. Physical breakdown through time will increase surface areas available for weathering but the bulk of rock is expected to be protected from weathering and will only become available for reaction with the atmosphere over centuries.

Geochemical weathering processes in pit walls will be dominated by meteoric weathering of silicate minerals to produce alumino-silicate clays and carbonate minerals. The latter form as a result of reaction of carbon dioxide dissolved in rainwater (carbonic acid) with silicates containing calcium and magnesium. Where sulphide minerals are present, these will be oxidized by atmospheric oxygen, producing iron oxides and sulphates. Trace elements contained in the sulphide minerals will be incorporated into the oxidation products. Acidity produced by oxidation of sulphides will react with silicate minerals and their weathering products resulting in neutralization unless the rate of acid generation exceeds the rate at which acid consuming minerals can neutralize the acid.

Reaction rates under cool site conditions at Ekati are expected to be low relative to warmer sites and laboratory conditions. This will affect the above geochemical processes.

Conversion of primary minerals to weathering products will result in depletion of the primary minerals and possibly passivation of reactive surfaces. These processes together may result in slowing reaction rates over time.

Weathering products enter the water column due to leaching by runoff derived from melting snow, rainfall and to a lesser degree groundwater. The finite solubility of primary minerals and their weathering products indicates that concentrations in wall runoff will be constrained. Solubility constraints for individual ions depend on the solubility of the minerals they form, the solubility of mineralogical hosts, and the behaviour of reactive mineral surfaces under the prevailing pH conditions.

2.2 Geological Setting

Four rock types are present at Ekati and each have distinctive geochemical characteristics. These are described in detail elsewhere (BHP Billiton, 2011) and summarized below.

Diamonds are contained in kimberlite which is composed predominantly of magnesium silicates. Calcium and magnesium carbonates are also present and offset the potential for acid generation from oxidation of low levels of iron sulphide (pyrite). As a result, water in contact with kimberlite can be expected to be alkaline.

The dominant rock type hosting kimberlite is referred to generally as granite. It is composed predominantly of alumino-silicates with very low levels of carbonate and sulphide minerals. Water in contact with granite is expected to be weakly alkaline due to meteoric weathering of silicates with a lack of acid generation potential.

At Misery Pipe, schist is an important rock type. It is also composed of alumino-silicates but at Misery contains sufficient iron sulphide and negligible carbonate that weathering can result in acidic runoff. Schist is also present in the Pigeon and Beartooth Pipes host rocks but the sulphide content is low enough that acid generation appears unlikely. At Beartooth Pipe, schist is a small proportion of the rock type.

Diabase is a minor rock type composed of fine-grained silicate minerals. It occurs as sheet-like intrusions. Sulphide and carbonate mineral concentrations are, like granite, typically low.

In summary, water in contact with most rock types at Ekati is alkaline to varying degrees but one rock type (schist) has potential for generation of acidic runoff. This is primarily a consideration for the Misery Pit.

3 Source Term Method

3.1 Overview

The source term method consisted of the following steps:

- Use of laboratory measured weathering rates (determined from humidity cells) to represent the primary weathering of each major rock type.
- Adjustment of laboratory weathering rates to reflect site conditions.
- Conversion of major element release rates to mineral weathering rates.
- Dissolution of weathering products by infiltrating water.
- Use of geochemical equilibrium modelling software to predict bulk water chemistry.
- Adjustment of trace element water chemistry to reflect leaching observed under site conditions.

A similar approach was used for all rock types but was modified to address the specific acid generating characteristics of Misery Schist.

Details of the calculation steps are provided below. Inputs and results are provided in Section 4.

3.2 Modelling Steps

3.2.1 Weathering Rates

Weathering rates were calculated from humidity cell experiments. Humidity cells were operated on a weekly cycle consisting of aeration of a fixed mass of sample then a rinse at the end of the weekly cycle to leach soluble weathering products. Data were reduced as follows:

- Weekly cycle data were reduced to weathering rates expressed as mg/kg/week calculated from the concentration of each parameter, the leachate volume (about 500 mL) recovered in the cycle and the mass of sample (about 1 kg).
- Average weathering rates for all rock types except Misery Schist were typically obtained by averaging the last few weeks. In some cases, a longer period was used to calculate the average rate to make use of a longer stable trend in rates.

For the purpose of the calculation, one sample representing each of the major lithological types in the walls of each pit was selected to provide the input rates for the source term calculation.

For Misery Schist, two weathering rate models were used. The first model assumed that the sulphide oxidation reaction would be “zero order” which means that the rate of reaction is held constant regardless of the reacting mass remaining. The effect of the zero order model is that the reaction proceeds at the same rate until the reacting mass is fully depleted. The zero order model was also applied to the other rock types at Misery and the other pits.

The second model assumed the sulphide oxidation reaction is “first order” which means the rate of the reaction (dM/dt) is proportional to the remaining reacting mass (M) and results in the reaction rate decreasing over time:

$$\frac{dM}{dt} = -kM$$

k in this equation is the reaction rate constant and determines how fast the reaction proceeds. A higher k reflects a faster reaction than a lower k.

3.2.2 Adjustment for Site Conditions

Three factors are usually considered important for adjusting laboratory measured weathering rates (in mg/kg/week) to field conditions: temperature, particle size, and water contact. Three factors (k_T, k_p, k_c, respectively) were used to adjust the laboratory rate (R_{lab}) to obtain the rate under site conditions (R_{site}):

$$R_{site} = R_{lab}k_Tk_pk_c$$

3.2.3 Mineral Weathering Rates

The rates for selected parameters were converted to mineral weathering rates for calculation of major ion chemistry in the next step. The elements and minerals selected are shown in Table 1. Mineral weathering rates ($R_{site,mineral}$) were calculated in mmol/kg/year from R_{site}, the mole weight of the element (M_w, mg/mmol) and conversion for weeks to years (52.2 weeks/year):

$$R_{site,mineral}=R_{site}.M_w.52.2$$

The reacting mass was based on the thickness of the rock mass in the pit wall which was expressed as a wall thickness (d) and a wall area of 1 m^2. Total weathering rate ($R'_{site,mineral}$) was expressed as mmol/m^2 of wall/year:

$$R'_{site,mineral}=R_{site,mineral}.1.d.\rho$$

ρ is the density of the rock which was conservatively assumed to be the bulk density of silicate minerals.

3.2.4 Dissolution of Weathering Products

The quantity of water dissolving the weathering products in 1 m^2 of wall area was assumed to be total annual net precipitation.

Initial calculation of the resulting chemistry was performed by reacting the minerals shown in Table 1 with this amount of water under atmospheric conditions using the geochemical modelling software Geochemists Workbench. Partial pressures of oxygen and carbon dioxide were assumed to be 0.2 and $10^{-3.4}$, respectively. The secondary minerals expected to form during weathering were also considered. For schist, the acidic sulphate mineral K-jarosite may form due to the weathering of potassium (K)-containing biotite mica (modelled using the Fe and Mg end members, annite and phlogopite, respectively). Modelling compared the effect of whether or not K-jarosite formed, due to its influence on long term water chemistry and duration of acidic conditions.

For those parameters not specified as originating from a particular mineral, the mass indicated by the site weathering rate was simply dissolved in the water volume.

Table 1. Conversion of Element Release Rates to Mineral Weathering

Parameter	Granite	Diabase	Schist	Kimberlite	Secondary
Sulphate	Pyrite	Pyrite	Pyrite	Pyrite	Gypsum, K-Jarosite (schist only)
Al					Gibbsite
Ba					Barite
Ca	Anorthite	Anorthite	Anorthite	Calcite	Calcite
Cu	Chalcopyrite	Chalcopyrite	Chalcopyrite	Chalcopyrite	Tenorite, malachite
Fe					Ferrihydrite
Mg	Phlogopite	Diopside	Phlogopite	Forsterite	Magnesite (kimberlite only)
K	Annite	K-feldspar	Annite	Annite	K-Jarosite
Na	Albite	Albite	Albite		
Si					Silica

Source:P:\01_SITES\Ekati\1CR003.022_PitWallSourceTerms\201109_SourceTerms\2.Calculations\[PitWallSourceTerms_1CR003.002_SJD_20110902_VER00.xlsx]

3.2.5 Available Reacting Mass

For all rock types except schist, replenishment of reactive mass by physical weathering will likely outpace depletion processes. As a result, depletion was not considered for these rock types.

For schist, the available reacting mass was considered for pyrite in schist because acid generation is an important factor controlling the solubility of weathering products, oxidation reactions are expected to be fast enough to deplete the sulphide mass in a relatively short time frame, and the first order model depends on the reacting mass to determine the rate of oxidation.

The available reacting mass was set as a fixed proportion of the initial reacting mass. In fact, the reacting mass may increase with time due to physical breakdown of rock and this was evaluated by considering a range of reacting masses.

3.2.6 Consideration of Site Leaching Conditions

The resulting concentrations from the previous calculation step were then compared to statistics from seepage monitoring data collected since 1999. If the concentrations exceeded site values, the final value from the calculation was the site value otherwise the concentration from the previous step was used. This comparison was only performed for granite and kimberlite wall source terms because the seepage database does not uniquely reflect diabase and schist. For these rock types, no correction for site leaching conditions was performed.

4 Inputs

4.1 Weathering Rates

Humidity cells operated at various times were used to develop weathering rates as follows:

- Panda and Koala Pits – A granite sample (KDC03 480) was tested prior to mining at Ekati (Norecol Dames & Moore 1997). Previously calculated rates were used.
- Beartooth Pit – Humidity cells HCT 15, 28, 16 and 17 reported by SRK (2003) were used to calculate source terms for granite, mafic schist, diabase and kimberlite, respectively.
- Sable Pit - Humidity cells HCT 4, 5 and 6 reported by SRK (2002b) were used to calculate source terms for granite, diabase and kimberlite, respectively.
- Pigeon Pit - Humidity cells HCT 9, 31, 11 and 12 reported by SRK (2002a) were used to calculate source terms for granite, schist, diabase and kimberlite, respectively.
- Fox Pit – Pre-mining HCT results for samples FX41188, FUC3370 and F11216 were used to calculate source terms for granite, diabase and kimberlite, respectively (Norecol Dames & Moore 1997).
- Misery Pit – HCTs 26 and 27 (SRK 2004) were used to represent weathering of the range of sulphur content in the Misery Schist (typical and elevated respectively). Data for granite, diabase and kimberlite could not be located for Misery Pit. Leaching behaviour of these rock types should be based on relevant geological analogs which for granite is Sable Pit granite. For diabase and kimberlite, source terms from all other pipes can be considered as indicators of leaching of these rock types at Misery.

Table 2 shows weathering rates used in the calculations.

For the first order model for oxidation of pyrite in Misery Schist, values of k were needed to represent sulphide oxidation rate. These were estimated using the short term initial oxidation rate (R_0, as sulphate release) in humidity cells and the starting mass of sulphide (M_o):

$$k = -R_0 / M_0$$

The resulting values of k from humidity cells were 0.07 and 0.12 year^{-1} for typical and high sulphide samples respectively.

For other parameters, the rate of release was assumed to be correlated with sulphide oxidation and therefore acid generation. The initial rate was determined from the humidity cells and then decreased in proportion to the change in sulphate release. For example, if the sulphate release rate decreased by 10%, the rates for all other parameters was assumed to decrease by 10%.

Table 2. Laboratory Weathering Rates Used to Develop Source Terms (mg/kg/week)

Pit	Rock Type	SO_4	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb
Koala	Granite	0.86	0.000041	0.073	0.0012	-	0.0042	0.000063	2.8	0.000073	0.000034	0.00032	0.002	0.013	2	0.27	0.00069	0.00022	0.7	0.0003	0.025	0.0024
Beartooth	Granite	0.79	0.0000016	0.089	0.00097	0.00055	0.004	0.000054	2.2	0.0000054	0.000011	0.000054	0.0016	0.0033	1.2	0.19	0.00015	0.000082	0.22	0.000011	0.033	0.000011
Beartooth	Mafic Schist	5.8	0.0000038	0.047	0.00023	0.0025	0.001	0.000063	3.7	0.0000063	0.000013	0.000063	0.0001	0.0038	1.6	0.43	0.00025	0.00026	0.25	0.00011	0.038	0.0000063
Beartooth	Diabase	0.59	0.0000015	0.011	0.00015	0.00044	0.0015	0.000073	0.23	0.0000073	0.000015	0.000073	0.0014	0.0044	0.47	0.12	0.00027	0.000029	0.29	0.000022	0.044	0.0000073
Beartooth	Kimberlite	6.1	0.0000014	0.0026	0.002	0.0056	0.015	0.000069	2.8	0.0000069	0.000014	0.000069	0.0029	0.0042	2.5	4.7	0.000056	0.0023	0.28	0.00082	0.042	0.0000069
Sable	Granite	0.73	0.0000013	0.00077	0.00018	0.0014	0.0019	0.000064	0.21	0.0000064	0.000026	0.000064	0.0084	0.0039	0.3	0.15	0.0058	0.00004	0.26	0.00067	0.039	0.000077
Sable	Diabase	0.41	0.0000014	0.0026	0.00033	0.0016	0.00069	0.000068	0.31	0.0000068	0.000014	0.000068	0.0013	0.0041	0.22	0.13	0.0021	0.000018	0.27	0.000014	0.041	0.0000068
Sable	Kimberlite	5.3	0.0000013	0.0018	0.00076	0.006	0.016	0.000064	2.5	0.0000064	0.000013	0.00012	0.0022	0.0038	6.2	3.5	0.000071	0.012	2.8	0.00098	0.038	0.000023
Pigeon	Granite	2.6	0.0000014	0.0051	0.00046	0.0033	0.0018	0.000068	0.64	0.0000068	0.00098	0.000068	0.0027	0.0041	0.97	0.36	0.0075	0.00022	0.27	0.0011	0.041	0.00013
Pigeon	Schist	7.2	0.0000014	0.014	0.00036	0.0028	0.0067	0.000069	0.58	0.000033	0.0069	0.000069	0.00048	0.067	0.83	1.2	0.036	0.0000069	0.28	0.051	0.042	0.000089
Pigeon	Diabase	1	0.0000014	0.0063	0.00089	0.0015	0.00066	0.000069	0.46	0.0000069	0.00051	0.000069	0.0018	0.0042	0.34	0.2	0.0036	0.00023	0.28	0.0006	0.042	0.00002
Pigeon	Kimberlite	10	0.00014	0.0033	0.0091	0.012	0.032	0.000054	4.6	0.0000054	0.000043	0.00031	0.0051	0.0032	7.3	3.2	0.00082	0.009	0.54	0.0034	0.032	0.000033
Misery	Schist (median S)	7.6	0.000011	0.039	0.00028	0.0017	0.0058	0.00011	1	0.000077	0.028	0.000085	0.0092	0.58	0.87	0.53	0.061	0.0000085	0.34	0.091	0.051	0.00008
Misery	Schist (elevated S)	23	0.0000069	0.76	0.0013	0.0051	0.0047	0.00089	1.4	0.00022	0.076	0.00012	0.059	0.86	2.8	1.6	0.097	0.0000057	0.23	0.32	0.034	0.00022
Fox	Granite	0.45	0.000034	0.066	0.00069	-	0.015	0.000068	2.2	0.000094	0.000032	0.00035	0.0023	0.017	1.4	0.12	0.0012	0.0002	0.22	0.00036	0.024	0.0023
Fox	Kimberlite	3.5	0.000027	0.061	0.0019	-	0.008	0.000071	0.47	0.000087	0.00018	0.0016	0.0041	0.086	5	0.27	0.0014	0.00038	29	0.0038	0.027	0.0021
Fox	Diabase	15	0.00066	0.0055	0.00036	-	0.006	0.000077	4.3	0.000097	0.0034	0.00015	0.0046	0.013	0.48	1.2	0.067	0.00024	0.13	0.011	0.024	0.0027

Pit	Rock Type	Sb	Se	Tl	U	V	Zn	Hg
Koala	Granite	0.00099	0.00026	-	-	0.00058	0.0026	0.000052
Beartooth	Granite	0.00078	0.00011	0.0000054	0.00051	0.00044	0.00087	-
Beartooth	Mafic Schist	0.001	0.00013	0.000013	0.00025	0.00076	0.00089	-
Beartooth	Diabase	0.00086	0.00015	0.0000073	0.000015	0.00022	0.00088	-
Beartooth	Kimberlite	0.0012	0.00014	0.0000069	0.00006	0.0028	0.00035	-
Sable	Granite	0.00072	0.00013	0.0000064	0.000028	0.00013	0.014	-
Sable	Diabase	0.00078	0.00014	0.0000068	0.0000082	0.00055	0.0054	-
Sable	Kimberlite	0.0025	0.00013	0.0000064	0.00014	0.00051	0.00038	-
Pigeon	Granite	0.00083	0.00014	0.0000068	0.000014	0.00014	0.01	-
Pigeon	Schist	0.0007	0.00014	0.000014	0.00011	0.00014	0.017	-
Pigeon	Diabase	0.00098	0.00014	0.0000069	0.0000056	0.0043	0.0097	-
Pigeon	Kimberlite	0.0024	0.0013	0.000017	0.00051	0.036	0.00065	-
Misery	Schist (median S)	0.00028	0.00017	0.000017	0.00027	0.00017	0.038	-
Misery	Schist (elevated S)	0.00013	0.00035	0.000011	0.0011	0.00011	0.17	-
Fox	Granite	0.00043	0.00033	-	-	0.0005	0.0027	0.000057
Fox	Kimberlite	0.0006	0.00046	-	-	0.0037	0.0037	0.000055
Fox	Diabase	0.00045	0.00032	-	-	0.00041	0.0074	0.0001

Source: P:\01_SITES\Ekati\1CR003.022_Pit Wall Source Terms\2011-09_SourceTerms\2.Calculations\[Copy of PitWallSourceTerms_1CR003.002_SJD_20110902_VER01.xlsx]

Note

"-" indicates not determined in humidity cell leachates

4.2 Adjustment for Site Conditions

The factor k_T was set at 0.2 to reflect the low temperatures at the site and the slower oxidation rate of sulphide minerals compared to laboratory rates. Sulphide oxidation is expected to be the main source of leachable heavy elements. For oxidation of pyrite, this corresponds at an annual average site temperature of about 8^oC based on the Arrhenius equation. For pyrrhotite, the temperature would be lower at 2^oC. These temperatures are warmer than site conditions and are therefore conservative when predicting leaching behaviour.

The value of k_p was set to 0.2. There are limited data to set this value which reflects the difference in reactive surface area for a 1 kg crushed laboratory sample and in situ wall rock which can be expected to have a much lower surface area than the laboratory samples.

The value of k_c was set to 1. This is the maximum possible value and assumes complete contact of infiltrating water with weathering rock.

The resulting composite scaling factor is 0.2 x 0.2 x 1 = 0.04 which indicates that weathering rates under field conditions are 4% of laboratory rates. SRK (2011) have reported composite factors for waste rock in a warmer climate of 0.01 based on comparison of tests at several different scales. The factor of 0.04 appears to be conservative.

4.3 Potential and Actual Reacting Mass

The potential reacting mass was based on two values of d. A value of 2 m was selected because this is the typical thickness that blast holes extend below the target depth. A second value of 4 m was also used as an input to evaluate greater wall thicknesses and talus resulting from wall weathering.

For Misery Schist, actual reacting mass was evaluated as 10% and 20% of potential mass primarily to evaluate the predicted duration of acidic conditions.

A density of 2.65 t/m^3 was used in the calculations.

4.4 Infiltration

An infiltration value of 333 mm/year was used.

4.5 Seepage Statistics

Median and 95^{th} percentile concentrations were calculated from long term monitoring data from the northeast seepage of the Panda, Koala and Beartooth Waste Rock Storage area were waters are mainly in contact with granitic waste rock and the southwest area where seepage originates from coarse kimberlite reject (CKR) disposal. Statistics are provided in Table 3.

Table 3. Statistics for Seepage Concentrations

Parameter	Unit	WRSA		CKRSA	
		Median	**P_{95}**	**Median**	**P_{95}**
Field pH	s.u.	5.8	7.2	6.5	7.8
Lab pH	s.u.	6.1	7.6	7.0	8.0
TSS	mg/L	4.6	67	6.4	34
Alkalinity	mg $CaCO_3$/L	6	39	37	190
SO_4	mg/L	52	660	570	4200
Al	mg/L	0.18	3.6	0.07	3.7
As	mg/L	0.00027	0.0022	0.00097	0.0052
Cd	mg/L	0.00004	0.0015	0.0002	0.0022
Ca	mg/L	17	140	120	350
Cr	mg/L	<0.0004	0.0043	<0.0004	0.0041
Co	mg/L	0.0022	0.08	0.0048	0.04
Cu	mg/L	0.0028	0.024	0.0031	0.012
Fe	mg/L	0.15	3.5	0.047	6
Pb	mg/L	<0.00005	0.00053	<0.00005	0.0009
Mg	mg/L	9.8	74	100	830
Mn	mg/L	0.053	1.2	0.3	1.2
Mo	mg/L	0.0007	0.032	0.07	1.1
Ni	mg/L	0.008	0.75	0.036	0.26
K	mg/L	5.3	31	25	110
Si	mg/L	2.5	4.5	4.2	7.7
Na	mg/L	4.6	31	21	150
Zn	mg/L	0.007	0.25	0.009	0.07

Source: P:\01_SITES\Ekati\1CR003.022_Pit Wall Source Terms\2011-09_SourceTerms\2.Calculations\[Copy of PitWallSourceTerms_1CR003.002_SJD_20110902_VER01.xlsx]

5 Results

Tables 4 and 5 show predicted runoff chemistry for all walls expected to be non-acidic. For each rock type, a range of conditions is provided by:

- Two reacting thicknesses (2 and 4 m).
- Best judgement case based on using 50^{th} percentile seepage concentrations in the final step and reasonable worst case using 95^{th} percentile seepage concentrations.

Not all parameters were calculated for each term. Boron, bismuth, lithium, tin, thallium and uranium were not determined in leachates of pre-mine humidity cells. Likewise, mercury was determined for the pre-mine tests but not the subsequent humidity cells.

Table 6 shows the range of outcomes predicted for Misery Schist.

An initial finding was the important role played by jarosite as a long term control on water chemistry if it forms from weathering of biotite. Oxidation of sulphide minerals and the resulting reaction of acidity with biotite leads to an accumulation of acidic salts that was predicted to slowly dissolve and sustain acidic chemistry of the type shown in the first two rows of Table 6 beyond 100 years (perpetual time step). The two cases are for average and worst case sulphide concentrations represented by the two humidity cells.

All other cases in Table 6 assume that jarosite is not formed. For the four zero-order cases (average and extreme sulphide content, and 10% and 20% availability of the potential mass reacting) indicate that drainage chemistry of the type shown would be sustained for 12 to 36 years. In all cases drainage would be acidic and the range in pH reflects whether the input oxidation rate is based on typical or more sulphidic rock.

Use of a first order rate equation shows that most sulphide content is depleted early on with all sulphide depleted by 60 years (compared to less than 24 years for the zero order case). If jarosite were to form, it will extend these time frames though eventually the kinetics of dissolution of jarosite will also result in decreases in concentrations in runoff. It is not possible to predict this decrease with the available data.

Table 4. Wall Rock Source Term Concentrations (Koala, Beartooth, Sable)

Pit Area	Rock Type	Rubble Thickness m	Case	Parameters																												
				pH	Alkalinity	SO4	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	Hg	K	Mg	Mn	Mo	Na	Ni	P	Pb	Sb	Se	U	V	Zn
				s.u.	mg/L CaCO3	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Koala	Granite	2	Best	8.6	150	29	0.0001	0.0039	0.00027	-	0.044	0.0005	4.9	0.00004	0.0011	0.0004	0.0013	0.002	0.00005	5.3	8.9	0.023	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	-	0.0003	0.007
			Worst	8.6	150	29	0.00001	0.0039	0.0022	-	0.14	0.00061	4.9	0.0015	0.0011	0.0043	0.0013	0.002	0.00002	31	8.9	0.023	0.0072	23	0.01	0.04	0.00053	0.0021	0.0058	-	0.0018	0.088
		4	Best	8.9	270	52	0.0001	0.0071	0.00027	-	0.044	0.0005	17	0.00004	0.0022	0.0004	0.00074	0.002	0.00005	5.3	9.8	0.046	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	-	0.0003	0.007
			Worst	8.9	270	57	0.00001	0.0071	0.0022	-	0.16	0.00061	66	0.0015	0.0023	0.0043	0.00074	0.002	0.00002	31	18	0.046	0.014	31	0.02	0.04	0.00053	0.0021	0.0058	-	0.0018	0.18
Beartooth	Granite	2	Best	8.4	94	26	0.000054	0.0025	0.00027	0.007	0.044	0.0005	11	0.00004	0.00036	0.0004	0.0022	0.0019	-	5.3	6.4	0.0048	0.0007	4.6	0.00036	0.3	0.00005	0.00005	0.0001	0.00022	0.0003	0.007
			Worst	8.4	94	26	0.00001	0.0025	0.0022	0.018	0.13	0.00061	11	0.00018	0.00036	0.0018	0.0022	0.0019	-	31	6.4	0.0048	0.0027	7.2	0.00036	0.04	0.00037	0.0021	0.0036	0.017	0.0018	0.029
		4	Best	8.6	140	52	0.0001	0.0038	0.00027	0.007	0.044	0.0005	5.5	0.00004	0.00072	0.0004	0.0014	0.002	-	5.3	9.8	0.0097	0.0007	4.6	0.00072	0.3	0.00005	0.00005	0.0001	0.00022	0.0003	0.007
			Worst	8.6	140	52	0.00001	0.0038	0.0022	0.036	0.16	0.00061	5.5	0.00036	0.00072	0.0036	0.0014	0.002	-	31	13	0.0097	0.0055	14	0.00072	0.04	0.00053	0.0021	0.0058	0.034	0.0018	0.058
	Schist	2	Best	8.2	55	190	0.00013	0.0015	0.0075	0.084	0.033	0.0021	44	0.00021	0.00042	0.0021	0.0034	0.002	-	55	14	0.0082	0.0087	8.4	0.0036	1.3	0.00021	0.034	0.0042	0.0084	0.025	0.029
			Worst	8.2	55	190	0.00013	0.0015	0.0075	0.084	0.033	0.0021	44	0.00021	0.00042	0.0021	0.0034	0.002	-	55	14	0.0082	0.0087	8.4	0.0036	1.3	0.00021	0.034	0.0042	0.0084	0.025	0.029
		4	Best	8.2	51	380	0.00025	0.0014	0.015	0.17	0.066	0.0042	64	0.00042	0.00084	0.0042	0.0054	0.002	-	110	29	0.016	0.017	17	0.0072	2.5	0.00042	0.068	0.0084	0.017	0.05	0.059
			Worst	8.2	51	380	0.00025	0.0014	0.015	0.17	0.066	0.0042	64	0.00042	0.00084	0.0042	0.0054	0.002	-	110	29	0.016	0.017	17	0.0072	2.5	0.00042	0.068	0.0084	0.017	0.05	0.059
	Diabase	2	Best	8.2	57	19	0.000049	0.0015	0.0049	0.014	0.049	0.0024	7.7	0.00024	0.00049	0.0024	0.0038	0.002	-	16	4.1	0.009	0.00097	9.7	0.00072	1.5	0.00024	0.029	0.0049	0.00048	0.0072	0.029
			Worst	8.2	57	19	0.000049	0.0015	0.0049	0.014	0.049	0.0024	7.7	0.00024	0.00049	0.0024	0.0038	0.002	-	16	4.1	0.009	0.00097	9.7	0.00072	1.5	0.00024	0.029	0.0049	0.00048	0.0072	0.029
		4	Best	8.5	100	39	0.000097	0.0027	0.0097	0.029	0.099	0.0049	10	0.00049	0.00097	0.0049	0.0021	0.0019	-	31	8.2	0.018	0.0019	19	0.0014	2.9	0.00049	0.057	0.0097	0.00097	0.014	0.058
			Worst	8.5	100	39	0.000097	0.0027	0.0097	0.029	0.099	0.0049	10	0.00049	0.00097	0.0049	0.0021	0.0019	-	31	8.2	0.018	0.0019	19	0.0014	2.9	0.00049	0.057	0.0097	0.00097	0.014	0.058
	Kimberlite	2	Best	8.6	130	200	0.000046	0.0034	0.00097	0.012	0.046	0.0005	8.7	0.0002	0.00046	0.0004	0.0017	0.002	-	25	47	0.0018	0.07	9.2	0.027	0.3	0.00005	0.00063	0.00083	0.002	0.00005	0.009
			Worst	8.6	130	200	0.000032	0.0034	0.0052	0.054	0.14	0.0006	8.7	0.00023	0.00046	0.0023	0.0017	0.002	-	84	47	0.0018	0.077	9.2	0.027	0.028	0.00023	0.0049	0.0046	0.002	0.0021	0.012
		4	Best	8.5	120	400	0.000092	0.0032	0.00097	0.012	0.046	0.0005	12	0.0002	0.00092	0.0004	0.002	0.002	-	25	64	0.0037	0.07	18	0.036	0.3	0.00005	0.00063	0.00083	0.0035	0.00005	0.009
			Worst	8.5	120	400	0.000032	0.0032	0.0052	0.054	0.14	0.0006	12	0.00046	0.00092	0.0041	0.002	0.002	-	110	64	0.0037	0.15	18	0.054	0.028	0.00046	0.0049	0.0092	0.004	0.0021	0.023
Sable	Granite	2	Best	8.1	43	24	0.000043	0.0012	0.00027	0.007	0.044	0.0005	7.1	0.00004	0.00086	0.0004	0.0028	0.002	-	5.3	4.9	0.053	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	0.00022	0.0003	0.007
			Worst	8.1	43	24	0.00001	0.0012	0.0022	0.041	0.064	0.00061	7.1	0.00021	0.00086	0.0021	0.0054	0.002	-	10	4.9	0.19	0.0013	8.6	0.022	0.04	0.00053	0.0021	0.0043	0.00094	0.0018	0.25
		4	Best	8.4	85	49	0.000086	0.0023	0.00027	0.007	0.044	0.0005	14	0.00004	0.0017	0.0004	0.0025	0.0019	-	5.3	9.8	0.053	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	0.00022	0.0003	0.007
			Worst	8.4	85	49	0.00001	0.0023	0.0022	0.041	0.13	0.00061	14	0.00043	0.0017	0.0043	0.0025	0.0019	-	20	9.9	0.39	0.0027	17	0.045	0.04	0.00053	0.0021	0.0058	0.0019	0.0018	0.25
	Diabase	2	Best	8.2	58	14	0.000045	0.0016	0.011	0.054	0.023	0.0023	10	0.00023	0.00045	0.0023	0.0037	0.0019	-	7.4	4.4	0.07	0.00059	9.1	0.00045	1.4	0.00023	0.026	0.0045	0.00027	0.018	0.18
			Worst	8.2	58	14	0.000045	0.0016	0.011	0.054	0.023	0.0023	10	0.00023	0.00045	0.0023	0.0037	0.0019	-	7.4	4.4	0.07	0.00059	9.1	0.00045	1.4	0.00023	0.026	0.0045	0.00027	0.018	0.18
		4	Best	8.4	93	27	0.000091	0.0025	0.022	0.11	0.046	0.0045	12	0.00045	0.00091	0.0045	0.0022	0.0019	-	15	8.8	0.14	0.0012	18	0.00091	2.7	0.00045	0.052	0.0091	0.00054	0.036	0.36
			Worst	8.4	93	27	0.000091	0.0025	0.022	0.11	0.046	0.0045	12	0.00045	0.00091	0.0045	0.0022	0.0019	-	15	8.8	0.14	0.0012	18	0.00091	2.7	0.00045	0.052	0.0091	0.00054	0.036	0.36
	Kimberlite	2	Best	8.9	320	180	0.000042	0.008	0.00097	0.012	0.046	0.0005	1.8	0.0002	0.00042	0.0004	0.0007	0.002	-	25	9.2	0.0024	0.07	21	0.032	0.3	0.00005	0.00063	0.00083	0.0035	0.00005	0.009
			Worst	8.9	320	180	0.000032	0.008	0.0052	0.054	0.14	0.0006	1.8	0.00021	0.00042	0.0039	0.0007	0.002	-	110	9.2	0.0024	0.4	93	0.032	0.028	0.00077	0.0049	0.0042	0.0046	0.0021	0.013
		4	Best	9.1	570	350	0.000085	0.014	0.00097	0.012	0.046	0.0005	0.86	0.0002	0.00085	0.0004	0.0004	0.0022	-	25	4.2	0.0047	0.07	21	0.036	0.3	0.00005	0.00063	0.00083	0.0035	0.00005	0.009
			Worst	9.1	570	350	0.000032	0.014	0.0052	0.054	0.14	0.0006	0.86	0.00042	0.00085	0.0041	0.0004	0.0022	-	110	4.2	0.0047	0.8	150	0.065	0.028	0.0009	0.0049	0.0085	0.0092	0.0021	0.025

Source: P:\01_SITES\Ekati\1CR003.022_Pit Wall Source Terms\2011-09_SourceTerms\2.Calculations\[PitWallSourceTerms_1CR003.002_SJD_20110902_VER06.xlsx]

Table 5. Wall Rock Source Term Concentrations (Pigeon, Fox)

Pit Area	Rock Type	Rubble Thickness m	Case	Parameters																												
				pH	Alkalinity	SO_4	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	Hg	K	Mg	Mn	Mo	Na	Ni	P	Pb	Sb	Se	U	V	Zn
				s.u.	mg $CaCO_3$/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Pigeon	Granite	2	Best	8.3	71	52	0.000045	0.0019	0.00027	0.007	0.044	0.0005	17	0.00004	0.0022	0.0004	0.0028	0.0019	-	5.3	9.8	0.053	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	0.00022	0.0003	0.007
			Worst	8.3	71	87	0.00001	0.0019	0.0022	0.041	0.06	0.00061	21	0.00022	0.033	0.0022	0.0032	0.0019	-	22	12	0.25	0.0074	9	0.035	0.04	0.00053	0.0021	0.0045	0.00045	0.0018	0.25
		4	Best	9.3	72	52	0.00009	0.0019	0.00027	0.007	0.044	0.0005	17	0.00004	0.0022	0.0004	0.0028	0.0019	-	5.3	9.8	0.053	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	0.00022	0.0003	0.007
			Worst	9.3	72	170	0.00001	0.0019	0.0022	0.041	0.12	0.00061	25	0.00045	0.065	0.0043	0.0032	0.0019	-	31	24	0.5	0.015	18	0.07	0.04	0.00053	0.0021	0.0058	0.0009	0.0018	0.25
	Schist	2	Best	7.7	17	27	0.000046	0.0004	0.012	0.092	0.22	0.0023	19	0.0011	0.23	0.0023	0.016	0.0021	-	28	39	1.2	0.00023	9.2	1.7	1.4	0.0029	0.023	0.0046	0.0038	0.0046	0.57
			Worst	7.7	17	27	0.000046	0.0004	0.012	0.092	0.22	0.0023	19	0.0011	0.23	0.0023	0.016	0.0021	-	28	39	1.2	0.00023	9.2	1.7	1.4	0.0029	0.023	0.0046	0.0038	0.0046	0.57
		4	Best	7.9	32	480	0.000092	0.00086	0.024	0.18	0.45	0.0046	38	0.0022	0.46	0.0046	0.011	0.002	-	55	78	2.4	0.00046	18	3.4	2.8	0.0059	0.046	0.0092	0.0076	0.0092	1.1
			Worst	7.9	32	480	0.000092	0.00086	0.024	0.18	0.45	0.0046	38	0.0022	0.46	0.0046	0.011	0.002	-	55	78	2.4	0.00046	18	3.4	2.8	0.0059	0.046	0.0092	0.0076	0.0092	1.1
	Diabase	2	Best	8.3	64	34	0.000046	0.0017	0.029	0.05	0.022	0.0023	15	0.00023	0.017	0.0023	0.0034	0.0019	-	11	6.5	0.12	0.0078	9.2	0.02	1.4	0.00068	0.032	0.0046	0.00018	0.14	0.32
			Worst	8.3	64	34	0.000046	0.0017	0.029	0.05	0.022	0.0023	15	0.00023	0.017	0.0023	0.0034	0.0019	-	11	6.5	0.12	0.0078	9.2	0.02	1.4	0.00068	0.032	0.0046	0.00018	0.14	0.32
		4	Best	8.4	87	67	0.000092	0.0023	0.059	0.1	0.044	0.0046	14	0.00046	0.034	0.0046	0.0025	0.0019	-	23	13	0.24	0.016	18	0.04	2.8	0.0014	0.065	0.0092	0.00037	0.29	0.65
			Worst	8.4	87	67	0.000092	0.0023	0.059	0.1	0.044	0.0046	14	0.00046	0.034	0.0046	0.0025	0.0019	-	23	13	0.24	0.016	18	0.04	2.8	0.0014	0.065	0.0092	0.00037	0.29	0.65
	Kimberlite	2	Best	8.6	160	340	0.0001	0.0042	0.00097	0.012	0.046	0.0005	6.7	0.00018	0.0014	0.0004	0.0014	0.002	-	25	36	0.027	0.07	18	0.036	0.3	0.00005	0.00063	0.00083	0.0035	0.00005	0.009
			Worst	8.6	160	340	0.000032	0.0042	0.0052	0.054	0.14	0.0006	6.7	0.00018	0.0014	0.0041	0.0014	0.002	-	110	36	0.027	0.3	18	0.11	0.028	0.0009	0.0049	0.0095	0.017	0.0021	0.021
		4	Best	8.7	170	570	0.0001	0.0045	0.00097	0.012	0.046	0.0005	7.5	0.0002	0.0029	0.0004	0.0014	0.002	-	25	39	0.055	0.07	21	0.036	0.3	0.00005	0.00063	0.00083	0.0035	0.00005	0.009
			Worst	8.7	170	670	0.000032	0.0045	0.0052	0.054	0.14	0.0006	7.5	0.00036	0.0029	0.0041	0.0014	0.002	-	110	39	0.055	0.6	36	0.23	0.028	0.0009	0.0049	0.0095	0.034	0.0021	0.043
Fox	Granite	2	Best	8.5	97	15	0.0001	0.0026	0.00027	-	0.044	0.0005	10	0.00004	0.0011	0.0004	0.0021	0.0019	0.00005	5.3	4	0.039	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	-	0.0003	0.007
			Worst	8.5	97	15	0.00001	0.0026	0.0022	-	0.16	0.00061	10	0.0015	0.0011	0.0043	0.0021	0.0019	0.00002	31	4	0.039	0.0068	7.2	0.012	0.04	0.00053	0.0021	0.0058	-	0.0018	0.089
		4	Best	8.7	150	30	0.0001	0.0041	0.00027	-	0.044	0.0005	4.6	0.00004	0.0021	0.0004	0.0013	0.002	0.00005	5.3	8	0.053	0.0007	4.6	0.008	0.3	0.00005	0.00005	0.0001	-	0.0003	0.007
			Worst	8.7	150	30	0.00001	0.0041	0.0022	-	0.16	0.00061	4.6	0.0015	0.0021	0.0043	0.0013	0.002	0.00002	31	8	0.078	0.014	14	0.024	0.04	0.00053	0.0021	0.0058	-	0.0018	0.18
	Kimberlite	2	Best	9.6	2100	120	0.0001	0.039	0.00097	-	0.046	0.0005	0.25	0.0002	0.0048	0.0004	0.0002	0.003	0.00005	25	0.96	0.047	0.013	21	0.036	0.3	0.00005	0.00063	0.00083	-	0.00005	0.009
			Worst	9.6	2100	120	0.000032	0.039	0.0052	-	0.14	0.0006	0.25	0.0022	0.0059	0.0041	0.0002	0.003	0.0018	110	0.96	0.047	0.013	150	0.13	0.028	0.0009	0.0049	0.0095	-	0.0021	0.07
		4	Best	9.8	4300	240	0.0001	0.062	0.00097	-	0.046	0.0005	0.2	0.0002	0.0048	0.0004	0.0001	0.003	0.00005	25	0.71	0.094	0.025	21	0.036	0.3	0.00005	0.00063	0.00083	-	0.00005	0.009
			Worst	9.8	4300	240	0.000032	0.062	0.0052	-	0.14	0.0006	0.2	0.0022	0.012	0.0041	0.0001	0.003	0.0037	110	0.71	0.094	0.025	150	0.25	0.028	0.0009	0.0049	0.0095	-	0.0021	0.07
	Diabase	2	Best	8	36	510	0.022	0.00094	0.012	-	0.2	0.0025	140	0.0032	0.11	0.0048	0.0093	0.002	0.0035	16	40	2.2	0.008	4.2	0.36	0.8	0.091	0.015	0.011	-	0.014	0.25
			Worst	8	36	510	0.022	0.00094	0.012	-	0.2	0.0025	140	0.0032	0.11	0.0048	0.0093	0.002	0.0035	16	40	2.2	0.008	4.2	0.36	0.8	0.091	0.015	0.011	-	0.014	0.25
		4	Best	7.9	31	1000	0.044	0.0008	0.024	-	0.4	0.0051	290	0.0065	0.23	0.0096	0.014	0.002	0.0069	32	79	4.4	0.016	8.3	0.72	1.6	0.18	0.03	0.021	-	0.027	0.49
			Worst	7.9	31	1000	0.044	0.0008	0.024	-	0.4	0.0051	290	0.0065	0.23	0.0096	0.014	0.002	0.0069	32	79	4.4	0.016	8.3	0.72	1.6	0.18	0.03	0.021	-	0.027	0.49

Source: P:\01_SITES\Ekati\1CR003.022_Pit Wall Source Terms\2011-09_SourceTerms\2.Calculations\[PitWallSourceTerms_1CR003.002_SJD_20110902_VER06.xlsx]

Table 6. Predicted Runoff Chemistry for Misery Schist Pit Walls

Case Description	Time Step	S Depleted	pH	SO_4	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Mn	Mo	Na	Ni	P	Pb	Sb	Se	Si	V	Zn
			s.u.	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
All cases with jarosite control, average	Perpetual		4.3	250	0.00038	1.3	0.0092	0.056	0.19	0.0038	34	0.0026	0.92	0.0028	0.31	0.98	0.11	2	0.00028	11	3	1.7	0.0026	0.0095	0.0056	33	0.0056	1.3
All cases with jarosite control, extreme	Perpetual		4.2	710	0.00023	25	0.042	0.17	0.16	0.03	47	0.0073	2.5	0.004	2	1.9	0.013	3.2	0.00019	0.25	11	1.1	0.0073	0.0043	0.012	46	0.0038	5.8
Zero Order, no jarosite, average, 10% available	0 to 18 years, then no source		4.2	410	0.00038	1.3	0.0092	0.056	0.19	0.0038	34	0.0026	0.92	0.0028	0.31	1.4	29	2	0.00028	11	3	1.7	0.0026	0.0095	0.0056	33	0.0056	1.3
Zero Order, no jarosite, average, 20% available	0 to 36 years, then no source		4.2	410	0.00038	1.3	0.0092	0.056	0.19	0.0038	34	0.0026	0.92	0.0028	0.31	1.4	29	2	0.00028	11	3	1.7	0.0026	0.0095	0.0056	33	0.0056	1.3
Zero Order, no jarosite, extreme, 10% available	0 to 12 years, then no source		3.7	1200	0.00023	25	0.042	0.17	0.16	0.03	46	0.0073	2.5	0.004	2	18	91	3.2	0.00019	7.5	11	1.1	0.0073	0.0043	0.012	46	0.0038	5.8
Zero Order, no jarosite, extreme, 20% available	0 to 24 years, then no source		3.7	1200	0.00023	25	0.042	0.17	0.16	0.03	46	0.0073	2.5	0.004	2	18	91	3.2	0.00019	7.5	11	1.1	0.0073	0.0043	0.012	46	0.0038	5.8
First Order, no jarosite, extreme, 10% available	0 years	79%	3.7	1200	0.00023	25	0.042	0.17	0.16	0.03	46	0.0073	2.5	0.004	2	18	91	3.2	0.00019	7.5	11	1.1	0.0073	0.0043	0.012	46	0.0038	5.8
	20 years	96%		280	0.000052	5.8	0.0097	0.039	0.035	0.0068	11	0.0017	0.57	0.00091	0.45	4.1	21	0.73	0.000043	1.7	2.4	0.26	0.0017	0.00098	0.0027	10	0.00086	1.3
	40 years	99%		59	0.000011	1.2	0.002	0.0082	0.0075	0.0014	2.2	0.00035	0.12	0.00019	0.095	0.87	4.4	0.16	0.0000091	0.36	0.51	0.055	0.00035	0.00021	0.00057	2.2	0.00018	0.28
	60 years	100%		12	0.0000023	0.26	0.00043	0.0017	0.0016	0.0003	0.47	0.000074	0.026	0.000041	0.02	0.19	0.93	0.033	0.0000019	0.077	0.11	0.012	0.000074	0.000044	0.00012	0.47	0.000039	0.059
	80 years	0%		2.6	0.00000049	0.055	0.000092	0.00037	0.00034	0.000064	0.1	0.000016	0.0055	0.0000087	0.0043	0.039	0.2	0.007	0.00000041	0.016	0.023	0.0024	0.000016	0.0000094	0.000025	0.099	0.0000082	0.012
	100 years	0%		0.56	0.0000001	0.012	0.000019	0.000078	0.000071	0.000014	0.021	0.0000033	0.0012	0.0000018	0.0009	0.0083	0.042	0.0015	0.000000087	0.0035	0.0049	0.00052	0.0000033	0.000002	0.0000054	0.021	0.0000017	0.0026
First Order, no jarosite, extreme, 20% available	0 years	54%	3.7	1200	0.00023	25	0.042	0.17	0.16	0.03	46	0.0073	2.5	0.004	2	18	91	3.2	0.00019	7.5	11	1.1	0.0073	0.0043	0.012	46	0.0038	5.8
	20 years	78%		590	0.00011	12	0.02	0.082	0.075	0.014	22	0.0035	1.2	0.0019	0.95	8.7	44	1.6	0.000091	3.6	5.1	0.55	0.0035	0.0021	0.0057	22	0.0018	2.8
	40 years	90%		270	0.000051	5.7	0.0096	0.038	0.035	0.0067	10	0.0016	0.57	0.0009	0.44	4.1	21	0.73	0.000042	1.7	2.4	0.25	0.0016	0.00097	0.0027	10	0.00085	1.3
	60 years	95%		130	0.000024	2.7	0.0045	0.018	0.016	0.0031	4.9	0.00076	0.27	0.00042	0.21	1.9	9.6	0.34	0.00002	0.79	1.1	0.12	0.00077	0.00046	0.0012	4.8	0.0004	0.61
	80 years	0%		60	0.000011	1.2	0.0021	0.0084	0.0076	0.0015	2.3	0.00036	0.12	0.0002	0.097	0.89	4.5	0.16	0.0000093	0.37	0.52	0.056	0.00036	0.00021	0.00058	2.2	0.00019	0.28
	100 years	0%		28	0.0000052	0.58	0.00098	0.0039	0.0036	0.00068	1.1	0.00017	0.058	0.000092	0.045	0.42	2.1	0.074	0.0000043	0.17	0.24	0.026	0.00017	0.000099	0.00027	1	0.000087	0.13

Source: P:\01_SITES\Ekati\1CR003.022_Pit Wall Source Terms\2013-05_Misery_Wall\Sensitivity Models\[PitWallSourceTerms_1CR003.002_SJD_REV07.xlsx]

6 Comparison of Misery Pit Water with Predicted Water Chemistry Indicated by Source Terms

Monitoring of water chemistry in the Misery Pit both during operation and as the pit flooded, provided an opportunity to evaluate the degree to which the source terms can predict pit water chemistry.

Rescan provided monitoring data for the open pit sump for 2000 to 2005 and the pit lake from 2005 to 2010.

Mixed water chemistry was calculated by assuming that total production of the three main rock types (kimberlite, granite and schist) approximates the areas of the rock types in the pit walls. Source terms for kimberlite and granite were obtained from the other pits due to a lack of data from Misery Pit. For schist, three source terms (a) jarosite control for typical, (b) extreme sulphide content; and (c) zero order with no jarosite control and extreme sulphide content) were used to represent the range of short term source water chemistry. Results are represented as the ratios of mixed water chemistry to observed chemistry for the sump and pit lake in Figures 1 and 2, respectively. Overall patterns were similar for both monitoring locations.

In terms of predicted net alkalinity (i.e. alkalinity less acidity), the case with schist runoff represented by jarosite control and average sulphide concentrations correctly predicted that pit water is non-acidic. Acidity was 11 mg $CaCO_3$/L compared to alkalinity of 52 mg $CaCO_3$/L. The other two schist runoff cases both predicted that the overall pit water should be acidic and are therefore considered probably unrepresentative of the schist runoff chemistry.

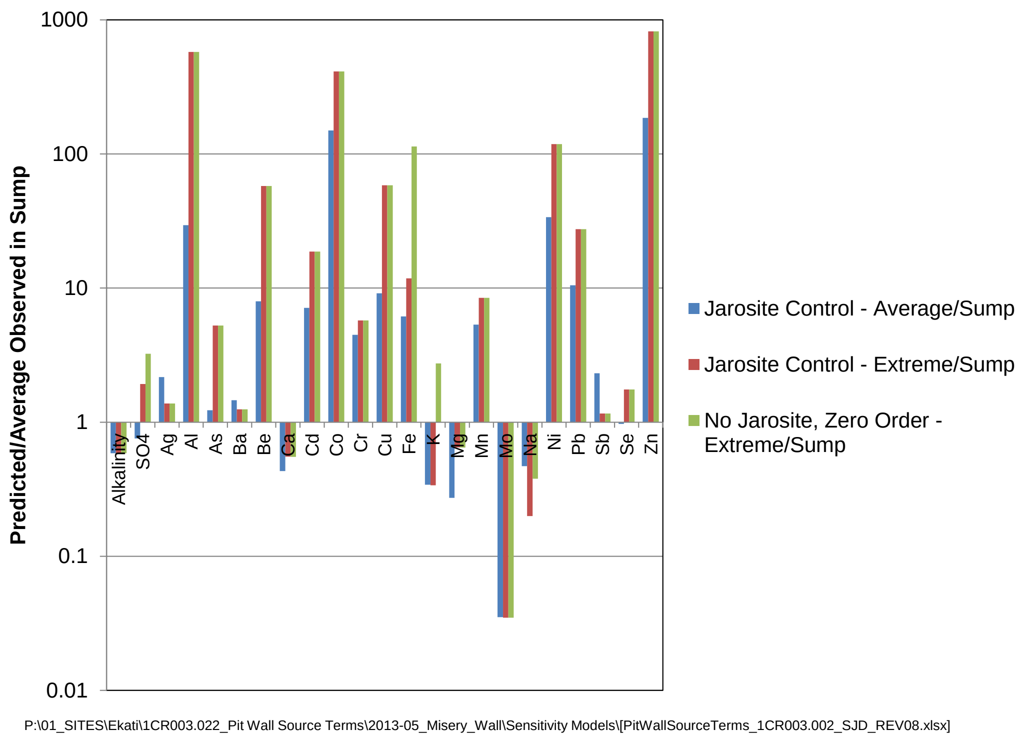

Figure 1. Ratio of Predicted Pit Water Chemistry to Average Sump Water Chemistry

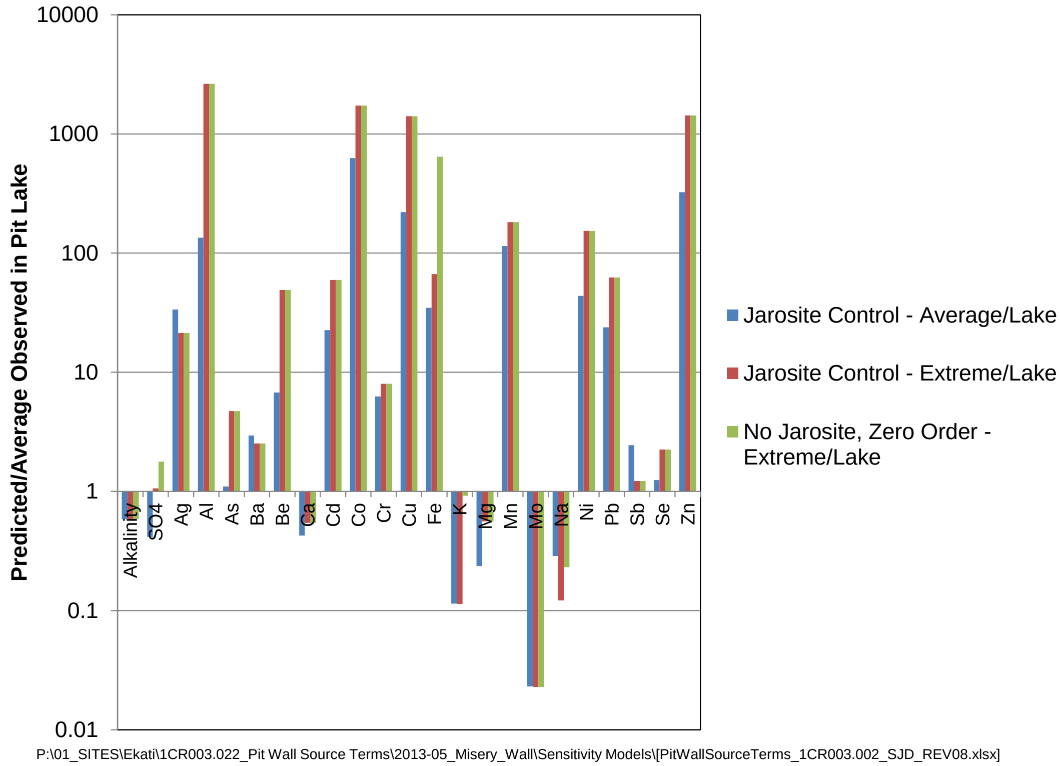

Figure 2. Ratio of Predicted Pit Water Chemistry to Average Pit Lake Water Chemistry

The method significantly over-predicted concentrations of numerous heavy elements occurring in solution as cations including, for example, copper, iron, nickel and zinc, all of which are predicted to occur at elevated concentrations in runoff from acidic Misery Pit walls. While this may indicate that the influence of the schist walls is much less than predicted, it also reflects the basic pH of pit waters (about 7.7 on average) which would result in removal of these ions from solution either by precipitation as oxides or by adsorption to iron hydroxides.

The method tended to under-predict major cations (Ca, Mg, Na and K). For Ca and Mg, the under-predictions were relatively small and reflect the relatively narrow range of concentrations in the source terms. Differences between predicted and observed concentrations were more significant for K and Na. For K, concentrations were over-predicted if jarosite was assumed to not be controlling concentrations. Assuming that jarosite is likely to be controlling runoff from pit walls, the under-prediction implies that the influence of kimberlite is under-predicted. The source term for kimberlite is 63 mg K/L compared to observed average concentrations from 22 and 65 mg K/L in the sump and pit lake, respectively. Likewise the Na source term for kimberlite is 37 mg/L compared to 23 to 38 mg Na/L in the sump and pit lake, respectively. The under-prediction of kimberlite influence likely reflects a greater surface area for kimberlite than other rock types due to its initially high rate of physical weathering.

Sulphate was slightly under-predicted by the jarosite-controlled case though the small difference between sulphate concentrations in kimberlite and schist runoff limits conclusions about sulphate sources. Alkalinity was slightly under-predicted again implying that the contribution of kimberlite was under-represented.

The most severely under-predicted parameter was molybdenum. Predicted concentrations were 0.005 mg/L compared to observed concentrations of 0.1 to 0.2 mg/L. Since only kimberlite leaches molybdenum at these concentrations (Table 3), the influence of kimberlite is probably under-represented by the calculation method.

In summary, under-prediction of indicator parameters (K, Na and Mo) indicates that kimberlite rather than schist exerted a much stronger influence on pit water chemistry than schist from 2000 to 2010. This is consistent with the observed fine grained nature of kimberlite pit walls compared to the more competent schist and granite.

7 Conclusions

This report provides source term concentrations for pit wall runoff for the major rock types at Ekati. The main conclusions are:

- For rock types other schist at Misery, runoff is expected to be non-acidic due to dissolution of primary carbonate minerals (kimberlite) or meteoric weathering of silicates minerals (granite, diabase and schist at other pipes).
- For Misery Schist runoff is expected to be acidic (pH less than 5) with actual predicted chemistry and trends in chemistry depending on the model used to represent sulphide oxidation:
  - The likely case is that K-jarosite formation exerts a long-term control on water chemistry and due to its slow dissolution rate sustains acidic conditions beyond 100 years.
  - If jarosite is not formed, the zero order weathering rate model predicted acidic drainage is sustained for 12 to 36 years.
  - If jarosite is not formed, the first order weathering rate model predicted acidic drainage is sustained for approximately 60 years.
- Comparison of monitoring data from the Misery Pit with mixed water chemistry predicted by the source terms showed that pit water is more strongly influenced by kimberlite than implied by its relative exposure in pit walls. Kimberlite at Ekati weathers rapidly, significantly increasing the surface area available for leaching. This implies that kimberlite walls may have a long term role in moderating the influence of acidic Misery Pit walls though it is not known if schist walls were acidic at the time of monitoring.

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Appendix 4

Comparison of Pit Wall Runoff Predictions with Sump Water Quality in Operational Pits

Engineers and Scientists

Appendix 4
Comparison of Pit Wall Runoff Quality Predictions with Sump Water Quality in Operational Pits

SRK Consultants provided predictions of pit wall runoff quality for each of the pits at the EKATI site (see BHP Billiton 2009). In BHP Billiton (2009) these pit wall runoff predictions were used to predict runoff to the infilling pits post-closure. However, additional modelling of Misery pit (BHP Billiton 2011) indicated that the pit wall runoff predictions might over-predict observed pit sump water quality. Hence, for this assessment for Pigeon pit, we undertake a comparison of predicted pit wall chemistry with observed pit sump quality for four operational pits:

- Misery;
- Fox;
- Panda; and
- Koala.

There was insufficient observed pit sump data (Dissolved Metals) for Beartooth pit to allow a comparison of modelled and observed sump chemistry in this pit.

For Misery pit a simple mixing model approach was considered, assuming pit sump water is a mix of natural runoff from the watershed surrounding the pit and precipitation falling on the pit walls. The approach is described in detail in BHP Billiton (2011).

For the other pits there is assumed to be a significant groundwater inflow to the pit sumps, as indicated by high anion concentrations. Due to the high groundwater flows, the water quality in the sump is strongly influenced by the groundwater quality. As a result, for Fox, Panda and Koala pits the observed data is compared to the raw SRK pit wall runoff quality and groundwater quality.

It should be noted that this assessment provides an overview of the available data only and an initial comparison between observed and predicted data. Detailed work on the chemistry of each pit sump is beyond the scope of this assessment.

Rock types for each pit wall are shown in Table A4-1.

Table A4-1. Rock Types Exposed in Each Pit Wall (BHP Billiton 2009)

Pit Sump	Rock Types
Panda	Predominantly granite
Koala	Predominantly granite
Misery	Granite 48%, metasediment /high-metasediment 52%,
Fox	Granite 90%, kimberlite 5%, diabase 5%
Beartooth	Granite 85%, ,metasediment 5%, kimberlite 5%, diabase 5%

A4-1 RESULTS

Results for each pit are provided in Figures A4-1 to A4-4 and summarised in Table A4-2.

Overall the results show no clear pattern between the various pits, with key observations outlined below:

- Molybdenum is under-predicted for all pits and all scenarios;
- For Misery pit the pit wall runoff estimates significantly over predict all metals except molybdenum and arsenic. In some cases the observed data is over-predicted by orders of magnitude. Overall, Misery predictions provide the poorest fit to observed data of all the operation pits;
- For Fox pit the predictions compare reasonably well with observed data, with only molybdenum significantly under-predicted and lead and zinc over-predicted. The results are improved with addition of groundwater loadings;
- For Panda pit the sump water quality is explained by groundwater inputs; and
- For Koala pit most of sump chemistry can be predicted based on pit wall runoff estimates and groundwater loadings, except molybdenum.

Comparing modelled and observed pit sump data for four operational pits at EKATI did not produce consistent results. Based on these results it is not possible to derive any scaling or correction factors that can be applied to predicted pit runoff to allow predictions to provide better estimates of observed water quality. Hence, for the purpose of Pigeon pit modelling raw pit wall runoff predictions will be used, with sensitivity analyses undertaken to assess the impact of uncertainties in the runoff predictions on sump water quality.

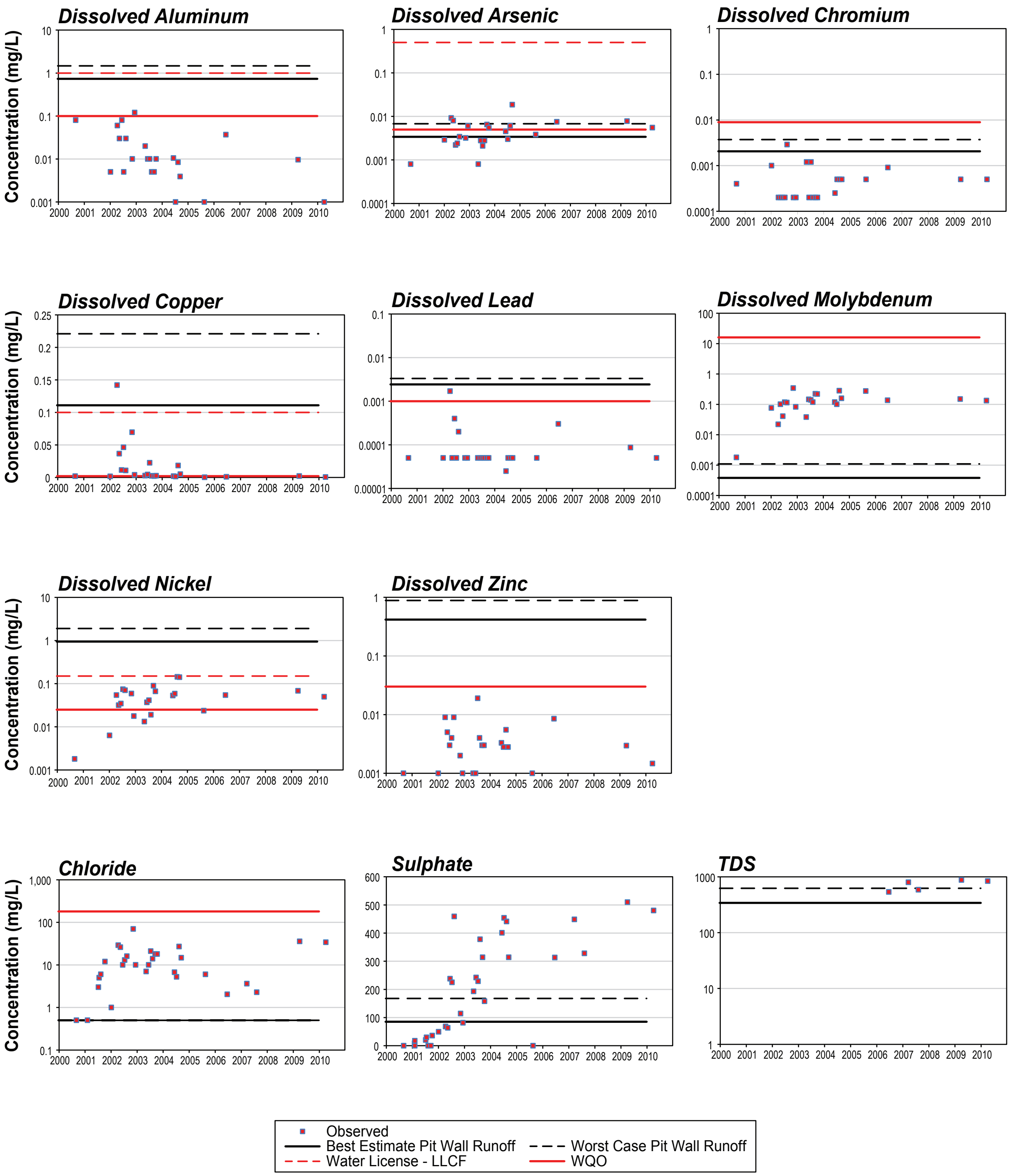

Figure A4-1

Misery Pit, Comparison of Modelled and Observed Pit Sump Data

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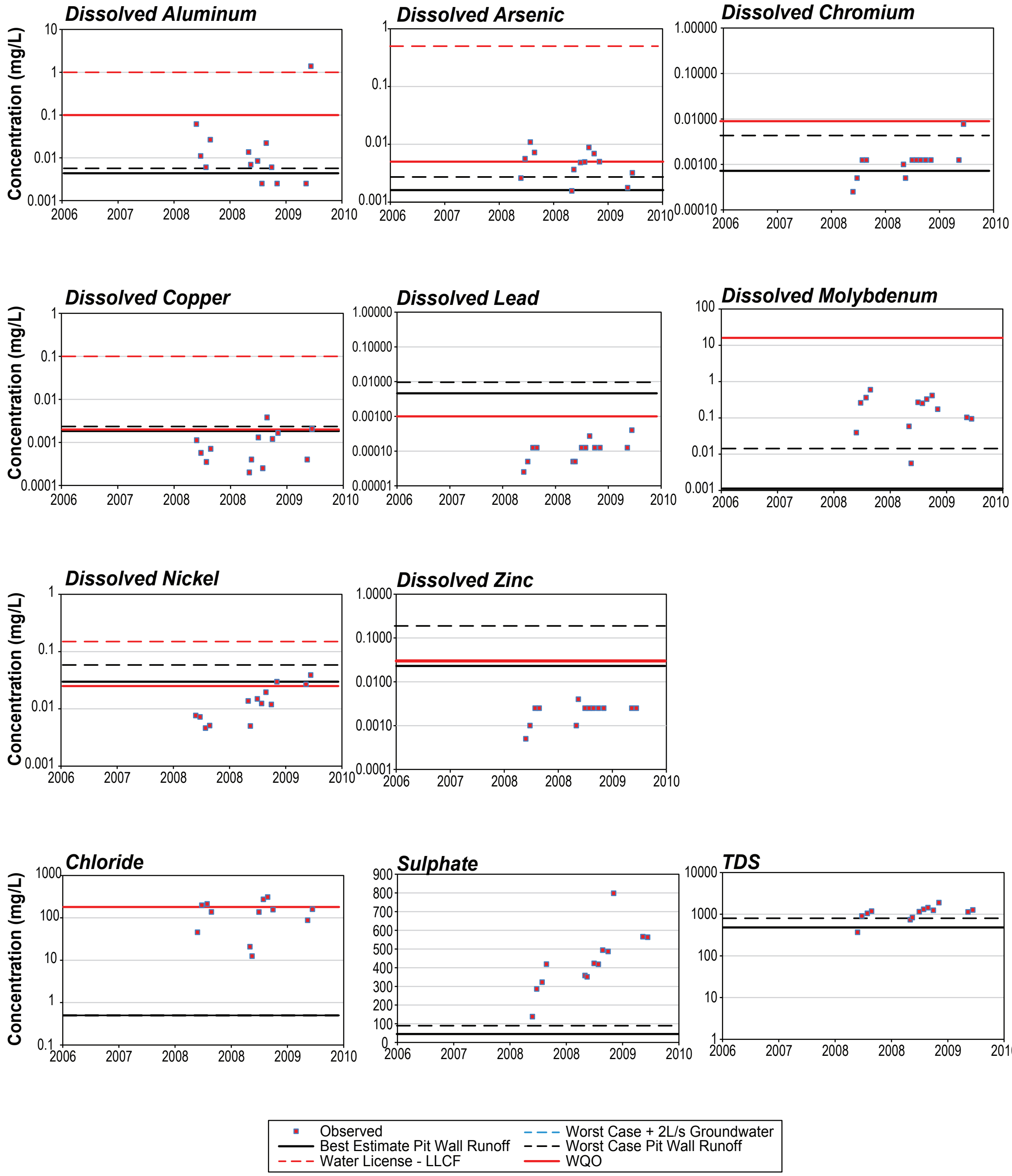

Figure A4-2

Fox Pit, Comparison of Modelled Pit Wall Runoff Quality and Observed Pit Sump Data

DOMINION DIAMOND

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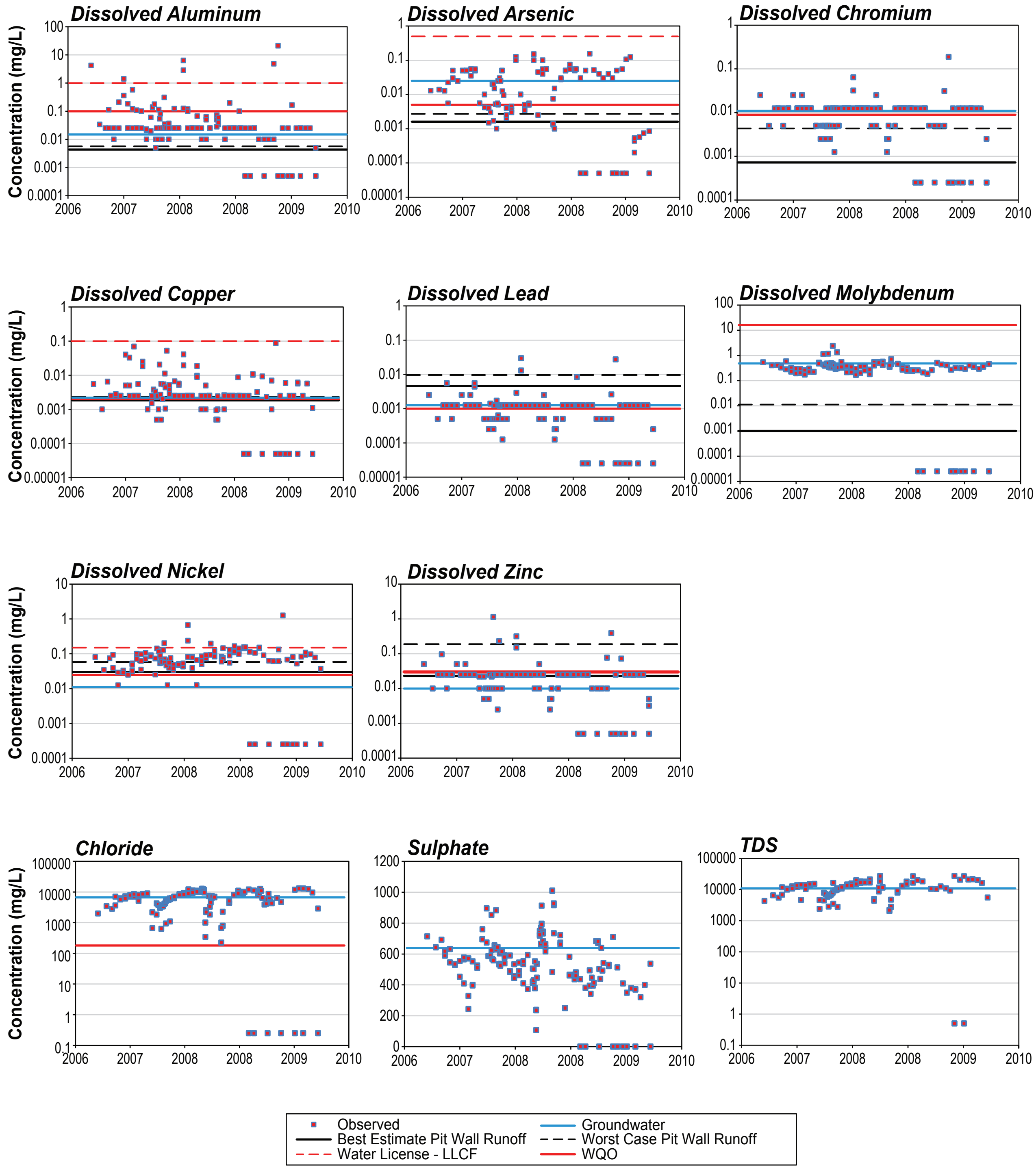

Figure A4-3

Panda Pit, Comparison of Modelled Pit Wall Runoff Quality and Observed Pit Sump Data

DOMINION DIAMOND

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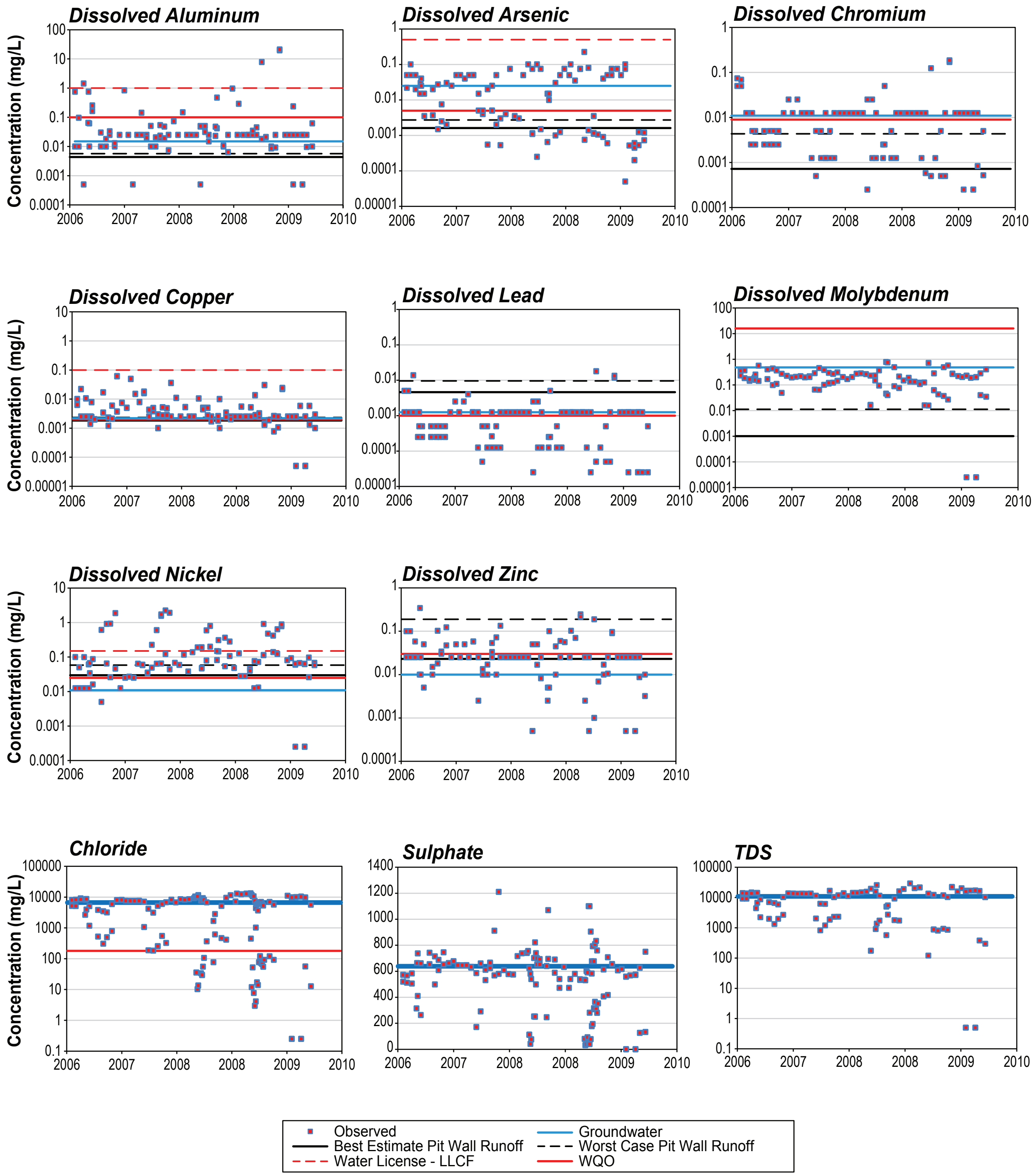

Figure A4-4

Koala Pit, Comparison of Modelled Pit Wall Runoff Quality and Observed Pit Sump Data

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Table A4-2. Comparison of Predicted Pit Wall Runoff and Groundwater with Observed Pit Sump Quality

	Factor - Ratio of Predicted (Best Case) Pit Wall Runoff versus Median Observed Pit Sump Quality												
	Aluminum	Arsenic	Chromium	Copper	Molybdenum	Nickel	Lead	Zinc	TDS	Chloride	Ammonia-N	Nitrate-N	Sulphate
Misery	74	0.89	5.2	40	0.0032	18	49	139	0.43	-	-	-	-
Fox	0.52	0.33	0.58	2.6	0.0045	2.4	37	9.2	0.42	-	-	-	-
Panda	0.17	0.29	0.14	0.73	0.0044	0.50	9.3	2.3	0.049	-	-	-	-
Koala	0.17	0.08	0.06	0.73	0.0047	0.41	3.7	0.92	0.72	-	-	-	-

	Factor - Ratio of Predicted (Best Case) Pit Wall Runoff versus Median Observed Pit Sump Quality												
	Aluminum	Arsenic	Chromium	Copper	Molybdenum	Nickel	Lead	Zinc	TDS	Chloride	Ammonia-N	Nitrate-N	Sulphate
Misery	147	1.8	9.3	79	0.0092	36	67	293	0.78	-	-	-	-
Fox	0.68	0.55	3.5	3.3	0.057	4.7	77	76	0.70	-	-	-	-
Panda	0.23	0.50	0.87	0.94	0.056	0.98	19	19	0.081	-	-	-	-
Koala	0.23	0.14	0.35	0.94	0.053	0.81	7.7	7.6	0.73	-	-	-	-

	Factor - Ratio of Predicted (Best Case) Pit Wall Runoff versus Median Observed Pit Sump Quality												
	Aluminum	Arsenic	Chromium	Copper	Molybdenum	Nickel	Lead	Zinc	TDS	Chloride	Ammonia-N	Nitrate-N	Sulphate
Fox	1.8	5.1	8.8	3.1	0.044	39	10	4.0	9.5	45	7.3	1.2	1.5
Panda	0.6	4.5	2.2	0.88	0.043	8.1	2.5	1.0	1.1	1.1	2.8	0.48	1.2
Koala	0.6	0.75	1.2	6	0.070	0.21	12	0.6	1.1	1.2	1.2	0.52	1.1

Values within half an order of magnitude above or below observed highlighted in pink (i.e., 0.5 - 5)