Appendix 13-B

Hydrodynamic Modelling of Brucejack Lake: Effect of Proposed Tailings Discharge

ERM

Hydrodynamic Modelling of Brucejack Lake: Effect of Proposed Tailings Discharge

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1. Background and Objectives

As part of mining operations proposed for the Brucejack Project, Pretium Resources is proposing to discharge tailings subaqueously to Brucejack Lake. A key environmental objective associated with this disposal strategy is to ensure the protection of downstream aquatic resources in Brucejack Creek. In this regard, it is essential that the tailings discharge does not result in unacceptable degradation of water quality at the lake outlet with respect to total suspended sediments (*e.g.*, tailings particles) and other mine-related parameters (*e.g.*, sulfate and total/dissolved metals). Further, the proposed placement of waste rock within the near-shore lake environment adjacent to the lake outflow has the potential to affect the quality of lake discharges.

In order to support feasibility planning, and ultimately EA level permitting, one-dimensional hydrodynamic modelling of Brucejack Lake was conducted to assess the potential environmental risks associated with the tailings discharge. Modelling was used to assess the physical stability and mixing properties of the water column for three scenarios:

1. *Existing conditions*: Modelling of the existing lake was conducted to improve our understanding of present lake dynamics (*i.e*., pre-tailings discharge) as well as to validate the model for operational scenarios;
2. *The initial period of tailings discharge*: This initial operating scenario assumes the absence of a tailings mound and uses existing lake bathymetry; and
3. *The final period of tailings discharge*: This operational scenario assumes the maximum mound footprint and predicted lake bathymetry for the end of operations.

The above modelling scenarios were used to address the following objectives:

- Develop a conceptual model for present lake dynamics based on a review of model output and analysis of *in situ* temperature and conductivity data;
- Validate the model using data for the existing lake. This entailed running model simulations over time intervals for which existing measurements of physical properties (temperature, conductivity, *etc*.) could be compared with model output;
- Assess the effect of tailings discharge on lake vertical stability and mixing at both the start and end of the tailings discharge period;
- Quantify the magnitude of tailings supernatant dilution at the lake outflow on a seasonal basis; and

- Provide a conservative estimate of potential tailings particle concentration in the surface layer of Brucejack Lake (with and without flocculation prior to tailings discharge).

The potential effects of waste rock deposition on water quality were not considered. Further, the report does not address mitigation or contingency measures related to TSS management for Brucejack Lake.

In the following sections, a description of the model is provided, including a description of all model inputs for the Brucejack Lake assessment (Chapter 2). The results for all three modelling scenarios are presented in Chapter 3, while conclusions and recommendations are summarized in Chapter 4.

2. Modelling Methods

2. Modelling Methods

2.1 Model Overview

2.1.1 Introduction

The evolution of water quality conditions in Brucejack Lake will be strongly dictated by the mixing characteristics of the water column. This can be viewed as the tendency for a given lake system to stratify, which may be expressed as vertical changes in density, chemistry or dissolved oxygen. The potential for stratification, which may be seasonal or permanent, is a fundamental variable for assessing the merits of remediation strategies (*e.g.*, water management, passive treatment). Accordingly, the hydrodynamic model must be capable of achieving accurate predictions with regards to lake vertical structure (*e.g.*, evolution in vertical distribution of temperature, salinity, density and redox conditions).

In natural fresh water lakes, density differences are largely dictated by temperature. In such systems, vertical mixing is driven primarily by surface wind and thermally-driven convective turn-over. Convective turn-over is common to temperate and high-latitude lakes in the fall and spring and is a function of the temperature-dependent density properties of water. In mine-influenced systems, the input of dissolved salts associated with tailings and/or waste rock loadings can have a marked influence of lake density and mixing characteristics. Accordingly, the model must also be able to predict accurately the vertical distribution of salinity in the water column.

Hydrodynamic modelling of Brucejack Lake was conducted using PitMod. PitMod is a one-dimensional hydrodynamic and geochemical model used for predicting the vertical distribution of temperature, salinity, density, and other water quality variables in lakes. Implementation of a one-dimensional numerical model was recommended as the appropriate initial step in assessing the impact of the proposed tailings discharge on the dynamics, stability, and water quality of Brucejack Lake. The one-dimensional vertical structure of PitMod relies on the assumption that water temperature and the concentrations of dissolved solids are approximately laterally homogeneous.

PitMod is a proprietary model developed by Lorax that has been used in numerous projects requiring predictions of water properties over periods of up to a 100 years or more (Crusius *et al*., 2002; Dunbar *et al*., 2004). PitMod includes all relevant thermodynamic and hydrodynamic processes governing the water properties of lakes.

PitMod requires bathymetric data to construct the volume and planar area *versus* depth curves used in the mass and energy balance equations. PitMod also requires a water balance providing values for all significant inflows and outflows to and from the lake.

Implementation of PitMod requires the following steps:

- Processing bathymetry data to extract the volume and planar area of the lake as a function of elevation above the lake bottom.
- Prescribing the water balance for the lake.
- Prescribing required meteorological time-series data (monthly or more frequent), including:
    - Air temperature
    - Relative humidity
    - Evaporation (optional)
    - Precipitation
    - Incident solar short- and long-wave radiation
    - Surface wind speed
- Preparing input data files containing the vertical distribution of properties in the lake (temperature, TDS, *etc*.) at the start of the model simulation.

In the absence of evaporation data, PitMod uses values of other meteorological variables to calculate evaporation. PitMod also calculates the formation and melting of surface ice using an algorithm that accounts for the thermodynamic properties of snow and ice-snow layers in addition to the ice itself.

2.1.2 Limitations

PitMod is a time-varying one-dimensional numerical model that explicitly assumes that lateral variations in water properties are negligible compared to vertical variations. PitMod also assumes that water currents are negligible, or may be parameterized through energy fluxes (*e.g.*, wind-driven currents) or vertical diffusive mixing coefficients.

Numerical models have two distinct sources of error: one resulting from approximations and fundamental assumptions such as a reduced number of spatial dimensions, and the other resulting from errors or uncertainty in the physical data and coefficient values provided as model inputs. A one-dimensional model generally requires far less input data than higher dimensional models. This is a significant advantage in most realistic scenarios where data collection may be limited to a small number of sites or relatively short time periods.

2.1.3 Inflows and Outflows

PitMod accommodates an arbitrary number of time-varying mass inflows and outflows that may be specified at any depth. Groundwater flows may be distributed uniformly over the lake depth or by using an explicit formula. Inflows have assigned physical and geochemical properties. For example, temperature, salinity, dissolved oxygen and an arbitrary set of geochemical species concentrations may all be specified on a daily or monthly basis.

2.1.4 Heat Balance

PitMod incorporates a complete heat balance that includes lake surface albedo and surface fluxes of thermal energy through long- and short-wave radiation; sensible (conductive) and latent (evaporative) heat fluxes; thermal insulation from cloud cover; and turbulent dispersive heat transfer due to surface winds.

2.1.5 Ice Formation/Melting

PitMod includes ice formation and melting calculations that model the ice/snow cover as a three-layer system, comprised of an upper snow layer, a middle snow-ice layer, and a bottom ice layer. The initial snow depth decreases over time as the snow compacts and is incorporated into the snow-ice layer. During a period of ice cover the lake surface evaporation and wind-driven mixing are suppressed, although a rate of sublimation may be specified if desired.

2.1.6 Suspended Solids

In order to examine the effects of tailings solids discharged at the lake bottom on water density and total suspended solids concentration (TSS) in the lake, modifications to PitMod were required. These modifications include the ability to simulate the discharge of a slurry containing solids with an arbitrary particle size distribution. Estimates provided by Rescan of solids concentration in the tailings slurry, the specific gravity of the tailings solids, and a particle size distribution (PSD) for the tailings particles, were used in the Scenario 2 (initial period of tailings discharge) and Scenario 3 (final period of tailings discharge) simulations.

The PitMod source code was modified to include solids discharge into an arbitrary model layer and with an arbitrary PSD. The model can input a set of particle diameters, each with an associated fraction of the total solids mass. Together with the specific gravity of the solids and the fluid density in each model layer, the Stoke's settling velocity, V_s (*m/s*), is calculated for each particle size using the formula:

$$V_s = \frac{g\left(\rho_s - \rho_w\right)d^2}{18\mu_w \rho_w}, \quad (1)$$

where g is gravitational acceleration (9.81 $m\ s^{-2}$); ρ_s is the specific gravity of the tailings solids (2680 $kg\ m^{-3}$); ρ_w is the density of ambient water (approximately 1000 $kg\ m^{-3}$); μ is the kinematic viscosity of the ambient water ($10^{-6}\ m^2\ s^{-1}$); and d is the particle diameter (m).

Ambient water density ρ_w was calculated by adding together the masses of fluid and solids in each layer, and then dividing by the layer volume. The fluid density was calculated from the temperature and salinity of the water in each model layer using an equation of state.

The time step used in the model is one day; however, the settling velocities of some particles are large enough that a smaller time step is required to accurately simulate particle settling. The algorithm for implementing the addition of particle settling is summarized in the following sequence of steps carried out for each diurnal time step:

- A mass of tailings slurry (water plus solids) corresponding to one day of discharge is added to the bottom 0.5 m thick layer in the model, thereby displacing upward a portion of all model layers.
- A suitable time step for the vertical advection of particles is calculated from the largest settling velocities in each layer. The value is selected to ensure that the largest particles fall less than 80% of the layer thickness during one time step.
- Starting at the surface layer of the model and working downward to the bottom layer, the flux of each particle into the layer from the top (zero for the surface layer) and out of the layer at the bottom is calculated using the settling velocity V_s for the layer occupied by the particle.
- The concentration of each particle in each model layer is updated using the calculated vertical fluxes at the top and bottom of each layer.
- Particles that fall out of the bottom layer are permanently removed from the model (no potential for resuspension).

2.2 The Brucejack Lake Model

As stated previously, the purpose of the Brucejack Lake model is to quantify estimates of vertical mixing, dilution and surface layer discharge of suspended solids in the lake, thereby providing a tool to assess water quality at the outflow for three scenarios:

1. Existing conditions prior to commencement of tailings discharge;

2. Conditions at the start of tailings discharge (existing lake bathymetry); and
3. Conditions at the end of tailings discharge (final lake bathymetry taking into account tailings deposition).

The Brucejack Lake model simulations required numerous input data, including lake volume and planar surface areas; time-dependent meteorological data; inflow and outflow volumes; tailings solids particle size distribution, and water quality for all inflows. These various model inputs are described in detail below.

2.2.1 Lake Morphometry

Scenarios 1 and 2 incorporate the existing Brucejack Lake morphometry, while Scenario 3 utilizes the estimated morphometry at the end of tailings discharge approximately 22 years from the start of tailings deposition. The morphometry at the end of operations includes the effect of adding a total of 2,256,683 m^3 of waste rock and 5,092,291 m^3 of tailings solids to the lake. Elevation-dependent areas and volumes associated with the existing lake and end of operations scenarios are shown in Table 2-1.

Table 2-1:
Brucejack Lake volumes and planar areas at present and after 22 years of tailings discharge (Source: Rescan)

	Layer Volume ($m^3 \times 10^6$)				Cumulative Volume ($m^3 \times 10^6$)		Planar Area (ha)	
Elevation[1]	**Waste Rock**	**Tailings**	**Present**	**22 Yr**	**Present**	**22 Yr**	**Present**	**22 Yr**
1361.4	0.290		3.273	2.983	24.711	17.277	69.592	59.653
1356.4	0.290		2.931	2.641	21.442	14.295	61.524	52.820
1351.4	0.276		2.652	2.375	18.517	11.654	55.729	47.509
1346.4	0.245		2.405	2.160	15.862	9.278	50.497	43.204
1341.4	0.290		2.160	1.970	13.458	7.118	45.761	39.402
1336.4	0.179		1.978	1.790	11.281	5.148	41.367	35.969
1331.4	0.171	0.004	1.793	1.618	9.303	3.349	37.838	32.369
1326.4	0.165	0.258	1.615	1.192	7.501	1.731	34.040	23.847
1321.4	0.162	0.818	1.446	0.466	5.889	0.539	30.578	9.328
1316.4	0.149	1.055	1.272	0.068	4.439	0.072	27.396	1.360
1311.4	0.111	0.932	1.047	0.004	3.165	0.004	23.359	0.084
1306.4	0.028	0.744	0.771		2.116		18.497	
1301.4		0.587	0.587		1.326		13.639	
1296.4		0.412	0.412		0.730		10.126	
1291.4		0.213	0.213		0.313		6.469	
1286.4		0.070	0.070		0.088		2.771	

[1] Elevation at top of 5 m thick layer measured from mean sea level

The cumulative lake volumes and planar areas listed in Table 2-1 provide the basis for the lake morphometry inputs required for the Brucejack Lake model. Cumulative layer volumes and planar areas were linearly interpolated to the model layer thickness of 0.5 m from the values listed in Table 2-1 (Figure 2-1). The lake bottom in Scenario 3 is 30 m above the level in Scenarios 1 and 2 to reflect the change in bathymetry resulting from 22 years of tailings deposition and dumping of waste rock. These activities also affect the planar areas of the lake.

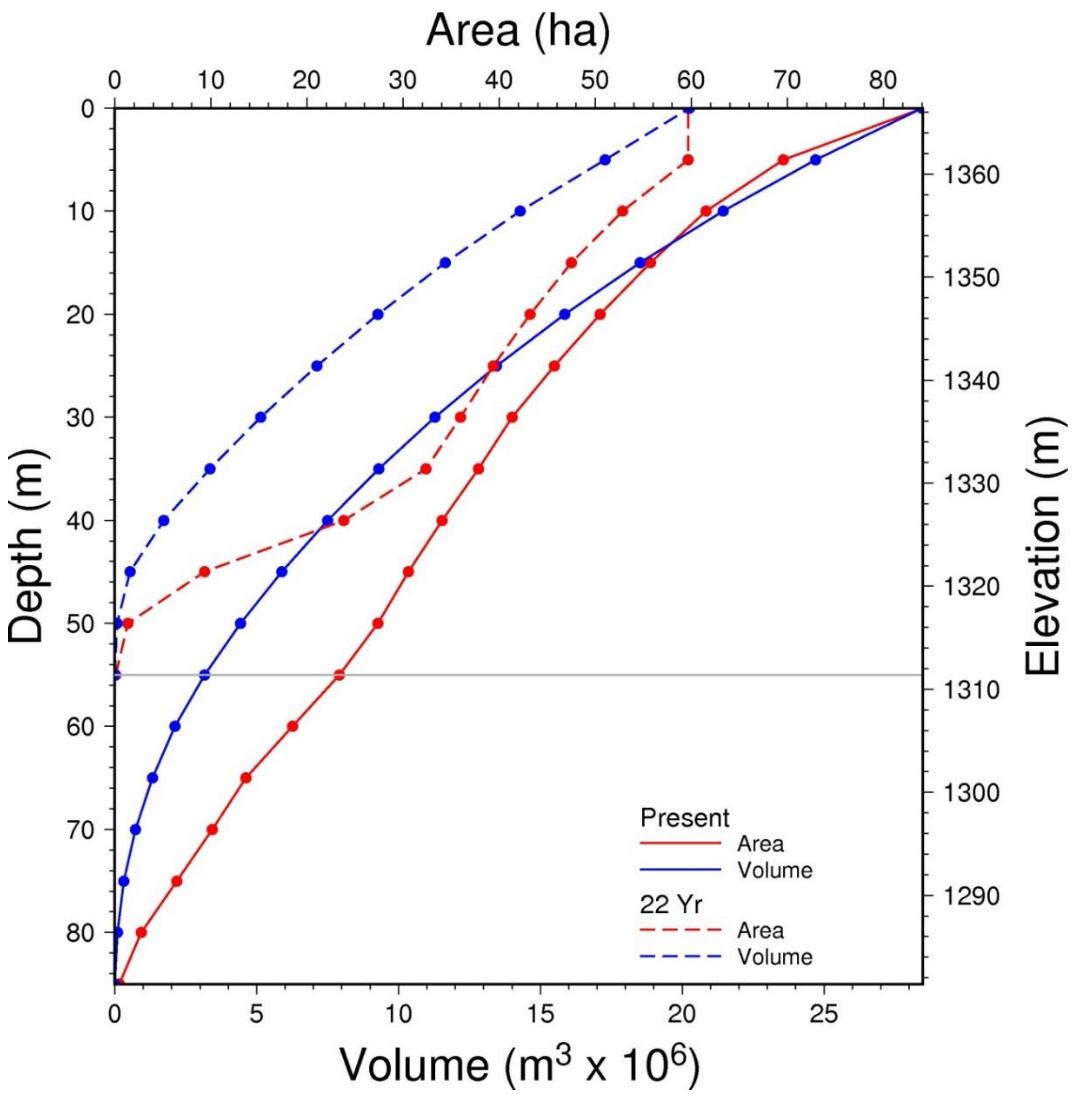


Figure 2-1: Cumulative volume and planar areas used in the Brucejack Lake hydrodynamic models. Scenarios 1 and 2 use values for the existing lake while Scenario 3 uses values for Year 22

2.2.2 Initial Conditions

The initial conditions for the Brucejack Lake model include temperature and salinity values at each level in the model. Vertical profiles of conductivity, temperature, and depth (CTD) measurements made in August 2010 provided the initial conditions for all model runs (Figure 2-2). Fundamental properties of Brucejack Lake for each model scenario are listed in Table 2-2 including the lake discharge elevation, bottom elevation, maximum depth, maximum surface area and maximum volume.

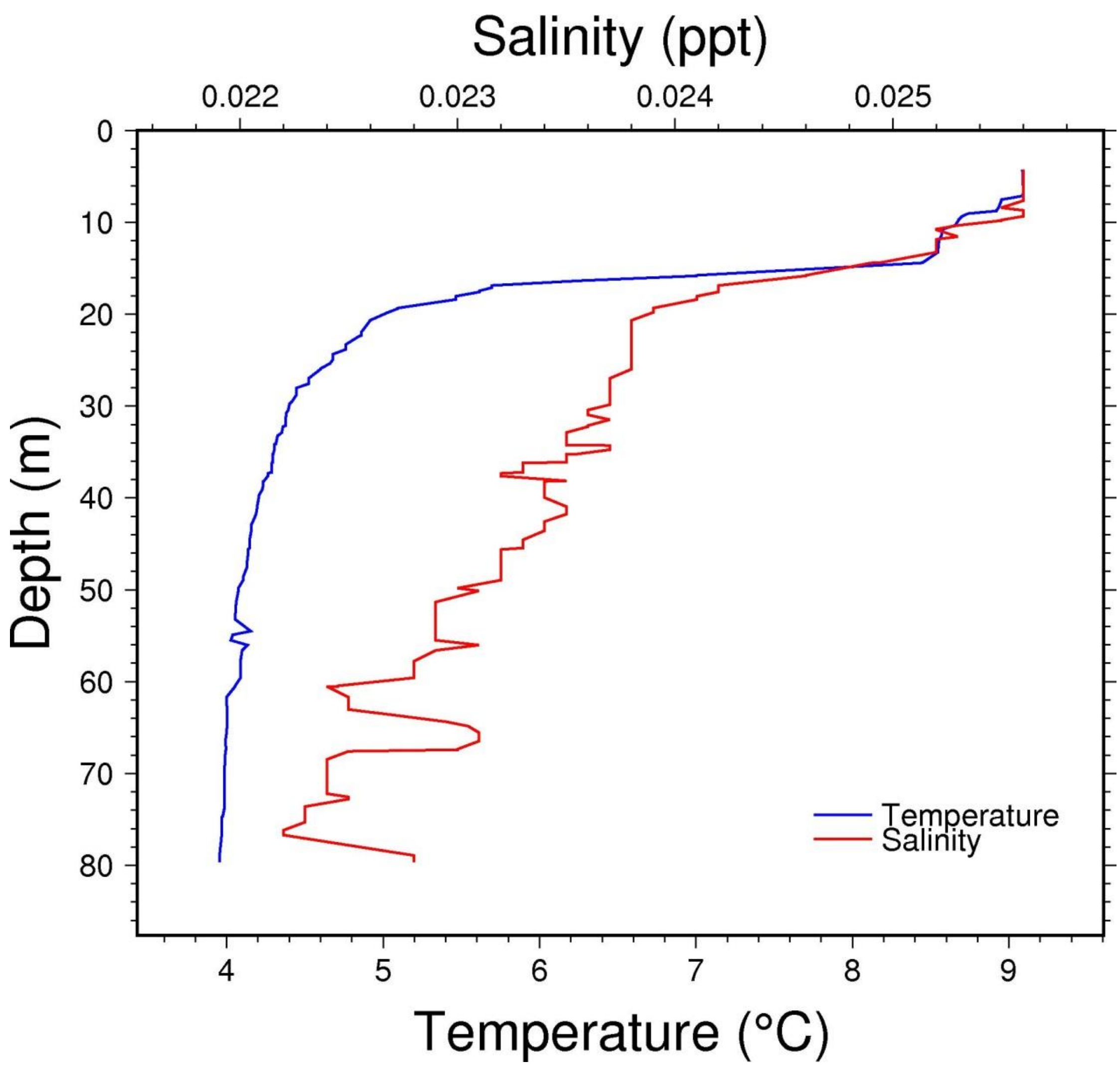


Figure 2-2: Vertical profiles of salinity and temperature in Brucejack Lake measured using a Conductivity-Temperature-Depth (CTD) profiler in August 2010 and used for the initial conditions in all model simulations.

Table 2-2:
Brucejack Lake properties used for PitMod simulations

Parameter	Scenario 1	Scenario 2	Scenario 3
Lake discharge elevation[1]	1366.4 m	1366.4 m	1366.4 m
Lake bottom elevation[1]	1281.4 m	1281.4 m	1311.4 m
Maximum Lake depth	85 m	85 m	55 m
Maximum Lake surface area	69.59 ha	69.59 ha	59.65 ha
Maximum Lake volume	28.46 Mm^3	28.46 Mm^3	20.26 Mm^3

[1]measured from mean sea level

2.2.3 Lake Water Balance

The water balance model for Brucejack Lake specifies the timing and depth of all flows to and from the lake during the 22-year period during which tailings deposition and surface dumping of waste rock occur. The water includes the following time-varying water sources and sinks for the lake:

- Surface runoff to the lake;
- Groundwater base flow to the lake;
- Recirculation of fluidization water to and from the lake. During periods when the mill is not operating or when tailings slurry is discharged to the underground, fluidizing water will be passed through the pipeline to prevent freeze up and clogging;
- Subsurface discharge of tailings slurry;
- Water withdrawal (*e.g.*, mill make up water); and
- Discharge from Brucejack Lake.

All inflow/outflow components of the water balance are specified as monthly means in Table 2-3. Direct precipitation to the lake surface and surface evaporation are included in the Brucejack Lake model as daily values. Undisturbed runoff is prescribed as a non-zero surface inflow for the months of April through December. A groundwater component flows into the lake throughout the year. This baseflow is distributed within ten elevation ranges over the depth of the lake as discussed in the next section. Each groundwater inflow is distributed evenly over the corresponding model layers, with the flux in each layer weighted by the appropriate cross-sectional surface area. Volume associated with the solids component is ignored in all simulations.

Table 2-3:
Monthly inflow/outflow model components of the water balance for Brucejack Lake

	Inflows (m^3/month)						Outflows (m^3/month)
	Undisturbed Runoff		Fluidizing Water				
Month	**Groundwater[1]**	**Surface Runoff**	**Tailings Slurry**	**Underground Mine Excess**	**Lake Water[2]**	**Total[3]**	**Fluidizing Water[1]**
Depth	**spread over 10 levels**	**Surface**	**Bottom**	**Bottom**	**Bottom**	**Bottom**	**Surface**
Jan	110,695 | 98,119	0	52,605	Variable	Variable	106,858	Variable
Feb	106,506 | 93,525	0	47,515	Variable	Variable	96,517	Variable
Mar	103,345 | 89,777	0	52,605	Variable	Variable	106,858	Variable
Apr	93,536 | 80,341	249,977	50,909	Variable	Variable	103,411	Variable
May	89,421 | 76,464	2,340,261	52,605	Variable	Variable	106,858	Variable
Jun	82,054 | 70,073	5,346,735	50,909	Variable	Variable	103,411	Variable
Jul	80,363 | 68,596	2,852,502	52,605	Variable	Variable	106,858	Variable
Aug	77,305 | 65,980	1,148,242	52,605	Variable	Variable	106,858	Variable
Sep	85,017 | 73,221	985,275	50,909	Variable	Variable	103,411	Variable
Oct	99,772 | 86,777	868,128	52,605	Variable	Variable	106,858	Variable
Nov	111,165 | 97,830	273,831	50,909	Variable	Variable	103,411	Variable
Dec	126,951 | 112,911	37,424	52,605	Variable	Variable	106,858	Variable

[1] start of tailings discharge | end of tailings discharge
[2] Fluidizing water returns at depth with the same properties as Tailings Slurry
[3] Constant at 3447 m^3/day

2.2.4 Groundwater Inflow

The properties of the groundwater inflows specified in the Brucejack Lake PitMod model were adopted from MODFLO simulations. MODFLO output is partitioned into 10 elevation ranges, and is bi-monthly in frequency. Monthly values for use in PitMod were generated using linear interpolation. Two sets of outputs were specified: one for the period prior to the start of tailings discharge (Scenarios 1 and 2), and one for the period at the end of tailings deposition (Scenario 3). The paired values shown in Table 2-3 represent the mean total inflow over all ten levels in each month.

Time-series plots of groundwater inflow at ten elevation intervals are shown in Figure 2-3. The upper figure corresponds to the periods prior to the start of tailings discharge and the lower figure to the period after tailings discharge has ceased. Each figure displays the time-series of groundwater inflow within ten elevation ranges. Time-series are colour-coded to match the elevation intervals shown on the right side of each figure.

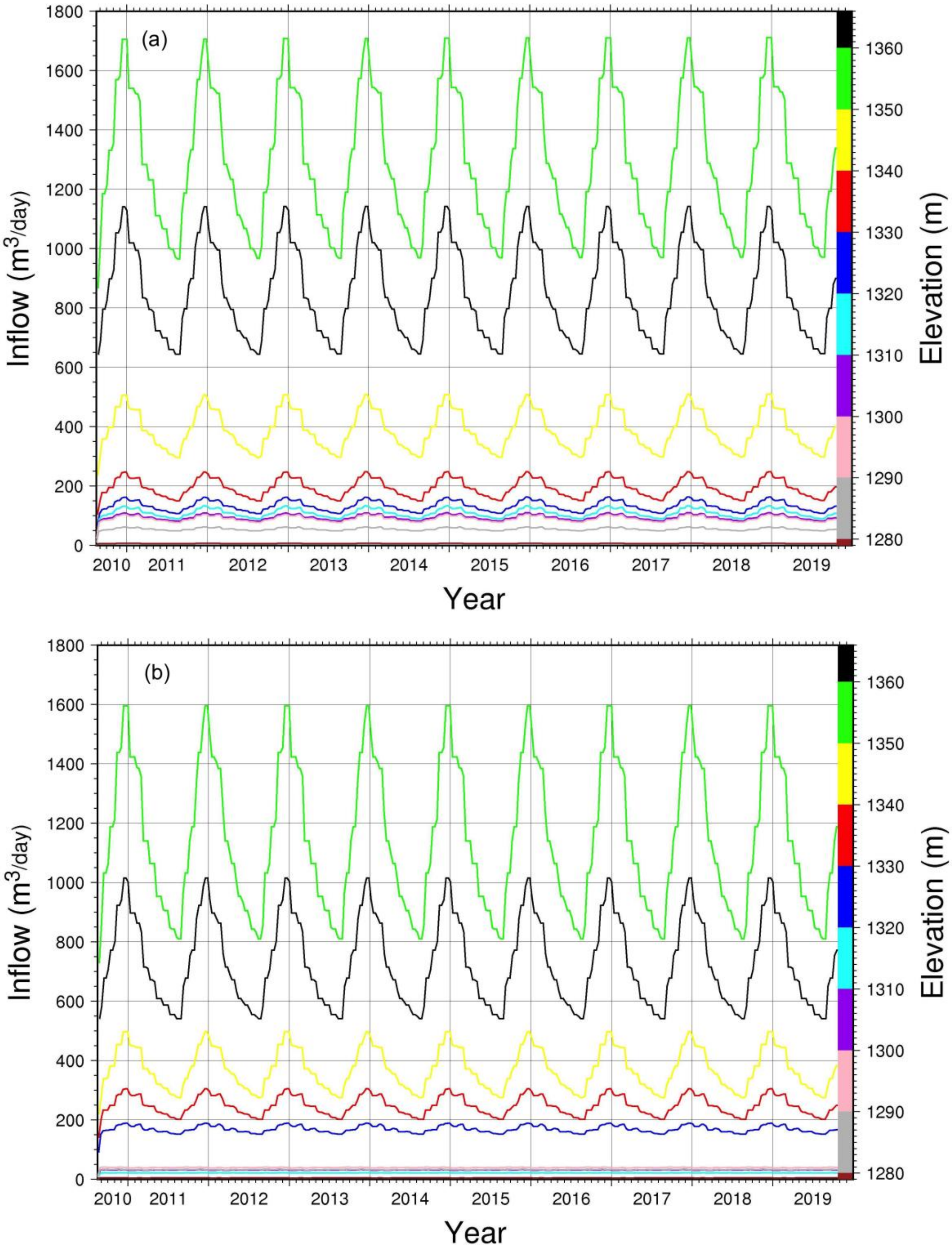


Figure 2-3: Groundwater inflows within ten elevation ranges used for PitMod (a) Scenario 1 and 2 simulations; (b) Scenario 3 simulations. Data are from a MODFLO model developed by BGC.

2.2.5 Inflow Water Properties

Each inflow to the model has associated values for monthly temperature and total dissolved solids (salinity). These two properties are used in the model to calculate water density. The values for temperature and salinity used in the model are listed in Table 2-4. The salinity value of 0.071 for the Tailings Slurry Supernatant was calculated based on a conductivity value of 130 μS/cm (provided by BGC).

2.2.6 Suspended Solids

Scenario 2 and 3 model simulations include suspended solids in the tailings slurry discharge that were prescribed using particle size distributions and TSS concentrations provided by Rescan. The specific gravity of the solids is 2680 $kg\ m^{-3}$ and the bulk slurry density is expected to be 1282 $kg\ m^{-3}$. This yields a solids concentration in the tailings discharge of 450 $kg\ m^{-3}$ (~17% by volume).

In the first of two runs completed for both Scenarios 2 and 3 (runs 2a and 3a), the PSD for the tailings solids was extrapolated to 0.5 μm to simulate the case where no flocculant is added to the discharge (Figure 2-4). In the second of the two runs (runs 2b and 3b), the PSD for the tailings solids was terminated at 5 μm to simulate the minimum predicted particle size resulting from flocculation prior to discharge (Rescan, pers. comm.).

Table 2-4:
Brucejack Lake Model Inflow Water Properties

Source	Discharge Depth	[1]Model Scenarios	Temperature (°C) Summer (Jul-Oct)	Temperature (°C) Winter (Nov-Jun)	Salinity (‰) All Seasons (Jan-Dec)
		INFLOW			
Baseflow (groundwater)	Spread[2]	1,2,3	1.63	1.63	0.249
Undisturbed Runoff	Surface	1,2,3	4.0	1.0	0.025
Tailings Slurry Supernatant	Bottom	2,3	10.0	7.5	0.071
Mine Excess Water	Bottom	2,3	10.0	7.5	0.358
Fluidization Water	Bottom	2,3	10.0	7.5	0.071
		OUTFLOW			
Fluidization Water	Surface Withdrawal	2,3	Modelled Surface	Modelled Surface	Modelled Surface

[1] Scenario 1 = existing condition; Scenario 2 = start of tailings discharge; Scenario 3 = end of tailings discharge
[2]Specified as separate inflows within ten elevation ranges

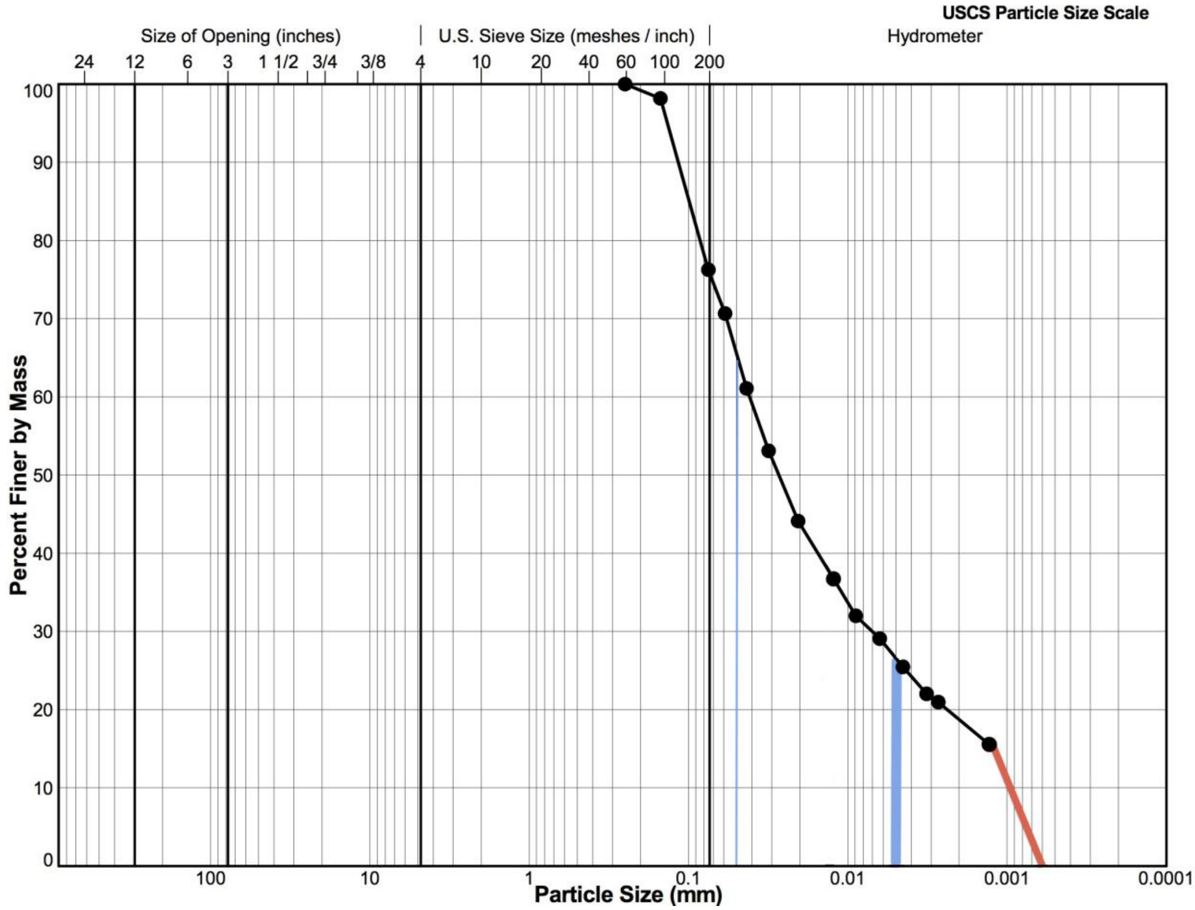


Figure 2-4: Particle size distribution (PSD) of tailings solids used in the model of TSS concentration in Brucejack Lake. For simulations that omit flocculation (2a and 3a) the PSD was extrapolated to 0.5 µm (red line). For simulations that include flocculation (2b and 3b) the PSD was terminated at 5 µm (blue line).

In each of cases (a) and (b), the suspended solids were partitioned into 20 equally sized divisions, each containing 5% of the total suspended solids mass and with an associated particle diameter and settling velocity (Equation 1, Table 2-5).

Table 2-5:
Properties of particles used in Scenario 2 and 3 model simulations for Brucejack Lake.

	Diameter (μm)		Settling Velocity ($mm\ s^{-1}$) ($r_w = 1000\ kg\ m^{-3}$)	
Particle No.	**(a) No Floc**	**(b) With Floc**	**(a) No Floc**	**(b) With Floc**
1	0.58	5.10	0.00031	0.024
2	0.80	5.31	0.00059	0.026
3	1.09	5.52	0.0011	0.028
4	1.74	5.75	0.0028	0.031
5	3.18	5.98	0.0093	0.033
6	5.45	6.54	0.027	0.039
7	8.74	8.74	0.070	0.070
8	12.94	12.94	0.15	0.15
9	18.07	18.07	0.30	0.30
10	23.94	23.94	0.52	0.52
11	30.35	30.25	0.84	0.84
12	37.56	37.56	1.3	1.3
13	45.32	45.32	1.9	1.9
14	53.49	53.49	2.6	2.6
15	64.18	64.18	3.8	3.8
16	77.42	77.42	5.5	5.5
17	91.37	91.37	7.6	7.6
18	107.13	107.13	11	11
19	125.60	125.60	14	14
20	184.28	184.28	31	31

Mass fraction for each particle = 0.05 (5%)
Specific gravity for each particle = 2680 $kg\ m^{-3}$

2.2.7 Meteorological Data

Meteorological data (Table 2-6) are required in the Brucejack Lake model for calculations of the heat budget, and for surface fluxes of mass (precipitation and evaporation) and kinetic energy (wind). Precipitation and hourly wind data are available from an on-site met station for the period October 2009 through December 2012. The subset of precipitation, wind and temperature data from January 2011 through December 2012 are used in the model. The remainder of the meteorological values were obtained from The National Centers for Environmental Prediction (NCEP) reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. NCEP data are available as gridded sets of meteorological variables derived from the reanalysis of computer weather model output and provide continuous 6-hourly (4x daily) time-series on a 0.5° grid for the period Jan 1, 1983 – Dec 31, 2009 (27 years). Values were extracted from the nearest 0.5° grid point to the location of Brucejack Lake at 130.173° W, 56.470° N.

Table 2-6:
Meteorological data sources for PitMod simulations of Brucejack Lake

Parameter	Units	Source
Incident short-wave energy flux	W m^{-2}	NCEP (1983-2009)
Incident long-wave energy flux	W m^{-2}	NCEP (1983-2009)
Cloud cover	%	NCEP (1983-2009)
Mean daily air temperature	°C	Site (2010-2012)
Minimum daily air temperature	°C	Site (2010-2012)
Maximum daily air temperature	°C	Site (2010-2012)
Vapour pressure	hPa	NCEP (1983-2009)
Hourly wind speed	m s^{-1}	Site (2010-2012)
Precipitation	mm day^{-1}	Site (2010-2012)
Evaporation	mm day^{-1}	Calculated
Mean daily relative humidity	%	NCEP (1983-2009)
Minimum daily relative humidity	%	NCEP (1983-2009)
Maximum daily relative humidity	%	NCEP (1983-2009)

Model data for all meteorological input variables are presented graphically in Appendix A for the following parameters:

- Maximum daily relative humidity
- Minimum daily relative humidity
- Daily mean relative humidity
- Evaporation
- Precipitation
- Mean daily wind speed at 10 m elevation (from hourly data)
- Mean daily vapour pressure
- Maximum daily air temperature
- Minimum daily air temperature
- Mean daily air temperature
- Cloud cover
- Incident longwave radiation
- Incident shortwave radiation

Each figure in Appendix A consists of three panels. The top panel shows annual mean values for each year of the simulation. The middle panel shows the complete time-series of daily values through twelve months with all years plotted together. The red line represents the average daily value over all years, while the bottom panel shows the distribution of values for each variable over all years.

3. Model Results

3. Model Results

This section presents results from the numerical model simulations of three scenarios:

Scenario 1 - Existing conditions in Brucejack Lake.

Scenario 2 - Conditions in Brucejack Lake at the start of tailings discharge: This simulation considers the effect of tailings supernatant and solids on water quality. The potential effects of waste rock deposition on water quality were not considered. Scenario 2a assumes no flocculation and therefore no particle size cut-off for tailings particles. Scenario 2b assumes flocculation and a minimum particle diameter of 5 μm.

Scenario 3 - Conditions in Brucejack Lake at the end of tailings discharge: This simulation includes the effect of discharged tailings supernatant and solids on water quality, as well as the changes in volume and planar areas from an estimated 30 m decrease in lake depth resulting from 22 years of tailings deposition. The effect of waste rock deposition in reducing lake volume was also included. Scenario 3a assumes no flocculation and therefore no particle size cut-off. Scenario 3b assumes flocculation and a minimum particle diameter of 5 μm.

The Brucejack Lake model produces output for a set of variables including density, temperature, salinity, TSS, and suspended solids concentration for a set of particle sizes. To provide a means to calculate the mixing and dilution of tailings supernatant, the in-pipe concentration of effluent was set to a reference value of 100. Plots of variations in effluent concentration reveal the degree of mixing and dilution with depth and time.

In the discussion of each scenario some, or all, of the following variables are graphically represented:

- Cumulative inflow/outflow volumes: These show the cumulative volume over time of each inflow and outflow source/sink in a simulation.
- Ice/snow thickness: The ice module in PitMod calculates the thicknesses of three layers: snow, snow/ice, and ice. Plots show time-series of each layer thickness during the simulation.
- For each of density, temperature, salinity, suspended solids, and effluent concentration, the following plots are provided:

- Monthly vertical profiles during the final year of the simulation, and where appropriate, dates when the vertical density profile is homogeneous. Periods of homogeneous density are indicative of lake mixing events.
- Temporal and vertical variations in concentration. Top panel: time-series at the lake surface (1 m depth) and lake bottom (1 m elevation); Middle panel: colour coded variation with time and depth in the upper 25 m; Bottom Panel: colour coded variations with time and elevation above the bottom for the entire water column.
- Exceedance plots showing the value of a model output variable (*e.g.*, temperature, salinity or TSS) exceeded by a specified percentage value.

In order to model the exchange of deep water with the lake surface for each scenario, a passive tracer was included in the model. Specifically, the tracer concentration was maintained at a concentration of 100 units in the layer within 4 m of the simulated lake bottom. The initial concentrations at other depths were set to zero. In this manner, the modelled tracer concentration in the lake surface can be used to quantify vertical mixing in Brucejack Lake.

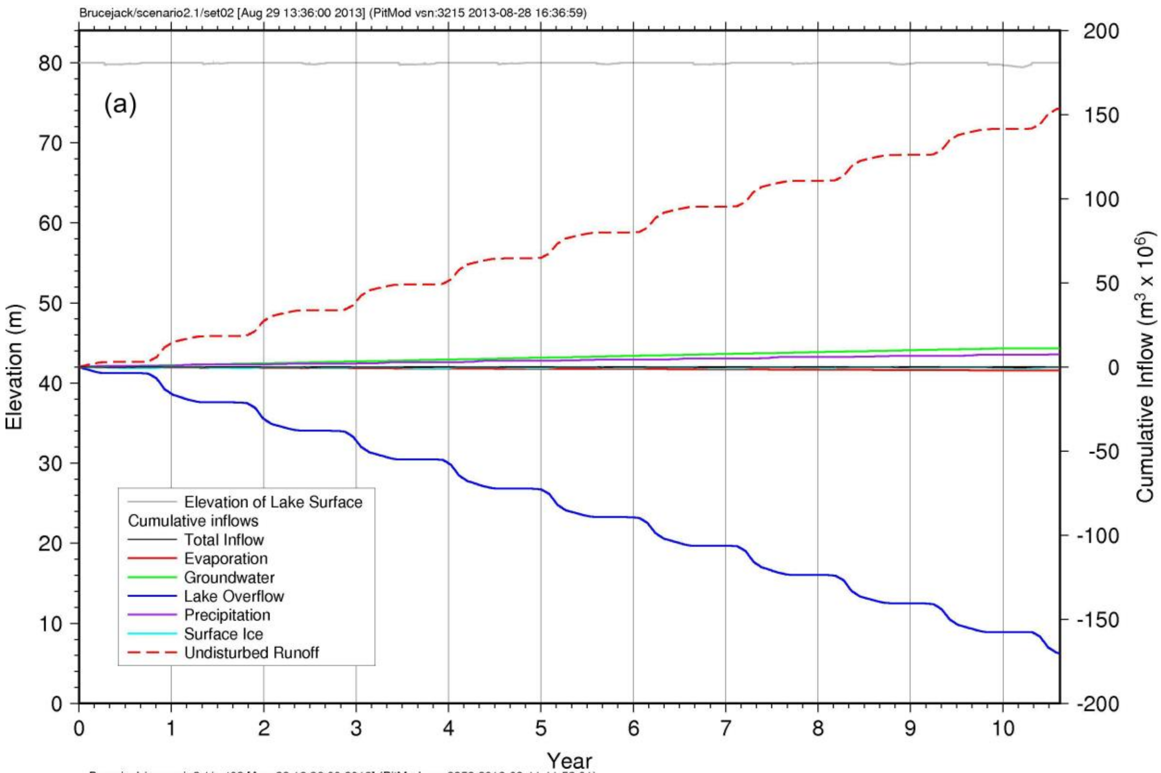
Scenarios 2 and 3 include the discharge of tailings supernatant (effluent) and suspended solids at 1 m elevation above the bottom of the lake. As outlined above, the in-pipe effluent concentration was set to 100 units, while the initial concentration of effluent in Brucejack Lake was set to zero. Therefore, the modelled values represent the proportion (as a percentage) of effluent in the water column.

3.1 Scenario 1 (Existing Conditions)

3.1.1 General Features

The water balance of the existing lake shows runoff as the dominant input with smaller contributions from groundwater and precipitation (Figure 3-1). Water is removed from the lake through evaporation and overflow. Ice formation/melting removes/adds water with no net addition of mass to the lake. The model output generates an ice depth range of 0.7 to 1.1 m, with ice formation typically commencing in November and open water occurring in late June or early July (Figure 3-2).

Seasonal changes in the vertical distribution of density are shown in Figure 3-3, with monthly profiles plotted from model year 10. Figure 3-4 shows the continuous density distribution over the 10-year model period. Note that units of density are expressed as



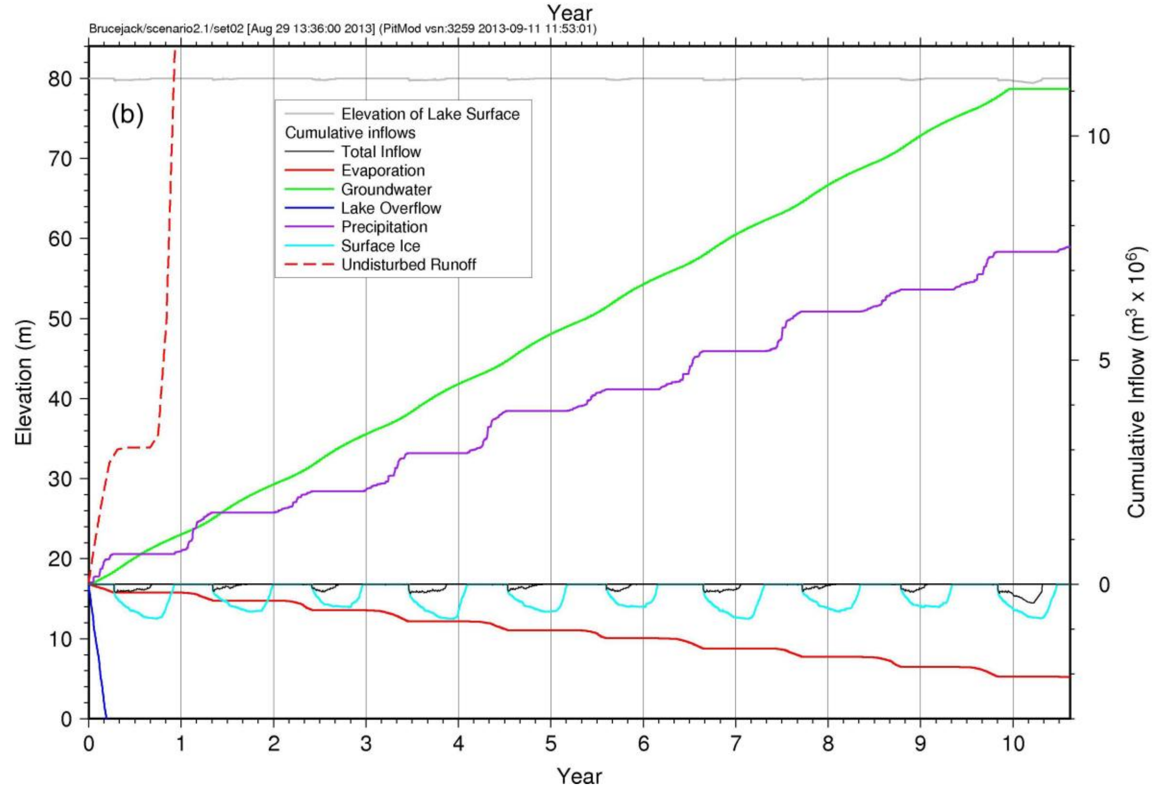


Figure 3-1: PitMod output for Scenario 1 - Cumulative inflow and outflow volumes (bottom image (b) is shown with an expanded scale to reveal detail).

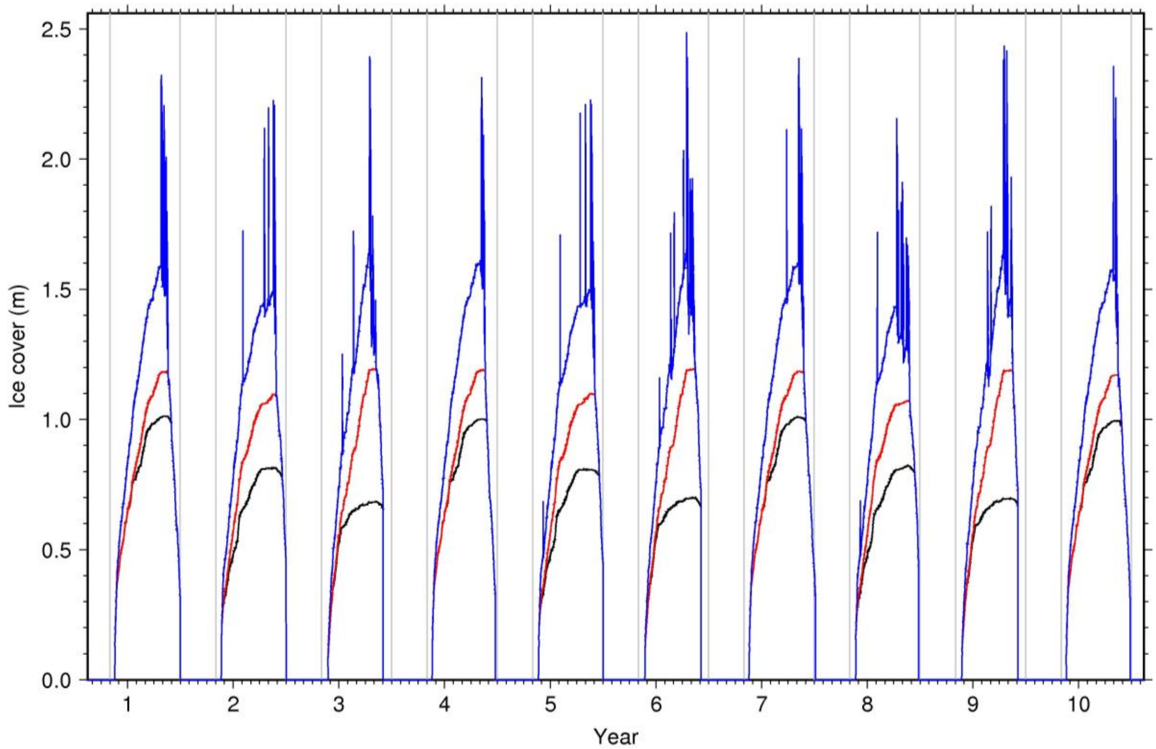


Figure 3-2: PitMod output for Scenario 1 with respect to snow (blue), snow-ice (red), and ice (black). Thicknesses are shown for a 10-year model simulation.

sigma-t (σ_t), (density minus 1000 kg/m^3). Each monthly profile exhibits nearly uniform density below 25 m depth (Figure 3-3). Over the course of the year, σ_t values below 25 m vary from approximately -0.12 to 0.0. In the upper 10 m, the density profiles exhibit greater variability due to strong thermal gradients nearer the surface.

The time-series of surface and bottom water density show that conditions are vertically uniform from late spring/early summer (late June in the model) until mid- to late-fall (early November in the model) (Figure 3-4). These periods are presumed to correspond to episodes of lake turnover. The model predictions are consistent with field data from Brucejack Lake that suggest the lake is dimictic (*i.e.*, lake turnover occurs twice per year). Indeed, thermal turnover is common to temperate and high-latitude lakes in the fall and spring and is a function of the temperature-dependent density properties of water. When surface waters cool in the fall/winter towards 4°C (temperature of maximum density) the temperature, and hence density differences between the upper and lower layers diminish, allowing water layers to mix more easily in response to wind energy and convective overturn.

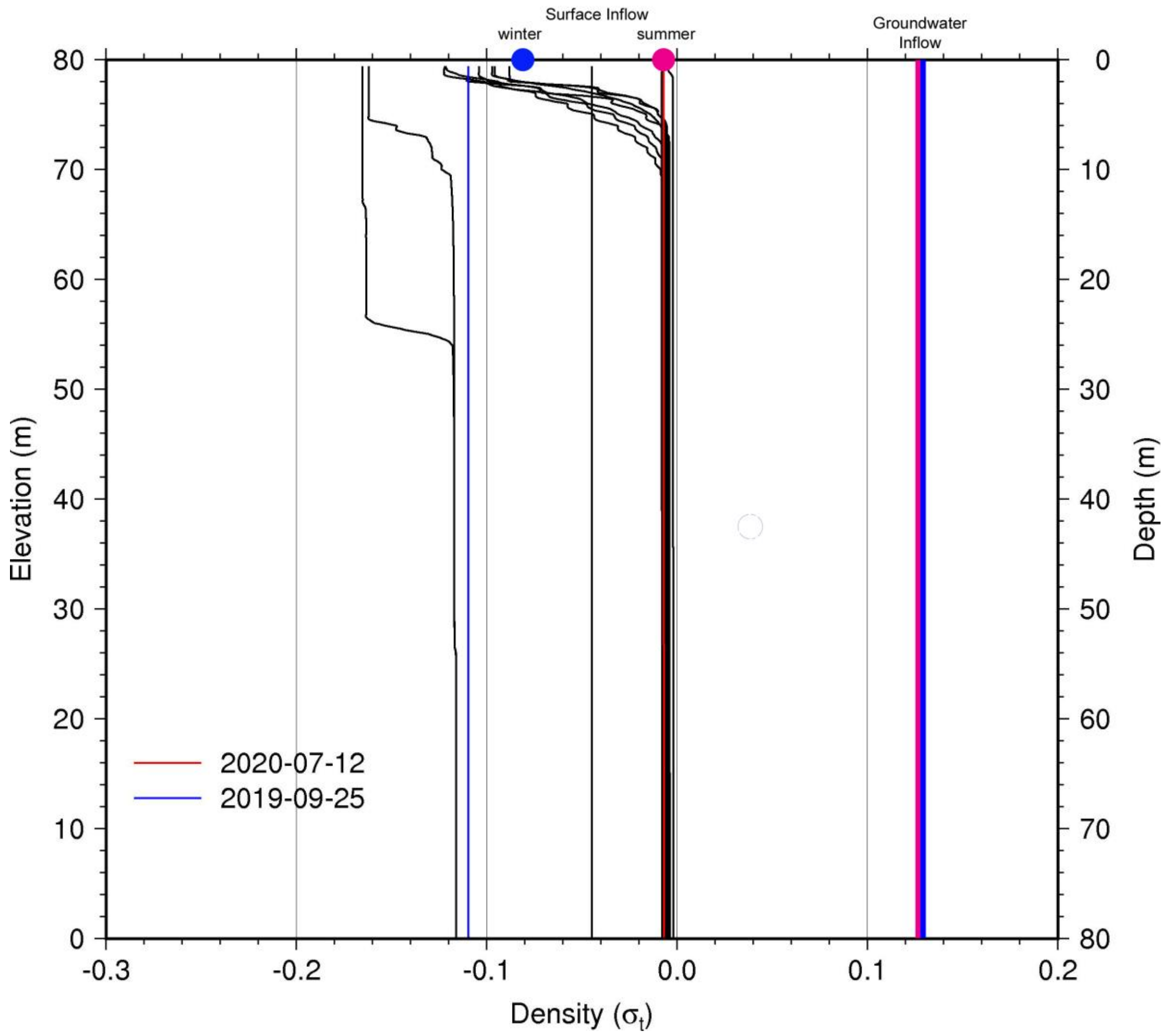


Figure 3-3: PitMod output for Scenario 1 - Monthly profiles of density in Brucejack Lake during the final year of a ten-year model simulation. The July 12 and September 25 dates correspond to times of uniform density and inferred periods of lake turnover. Seasonal density values for surface inflows (summer and winter) and groundwater inflow (spread over entire lake depth) are indicated. Units of density equal σ_t or density-1000 (kg/m^3).

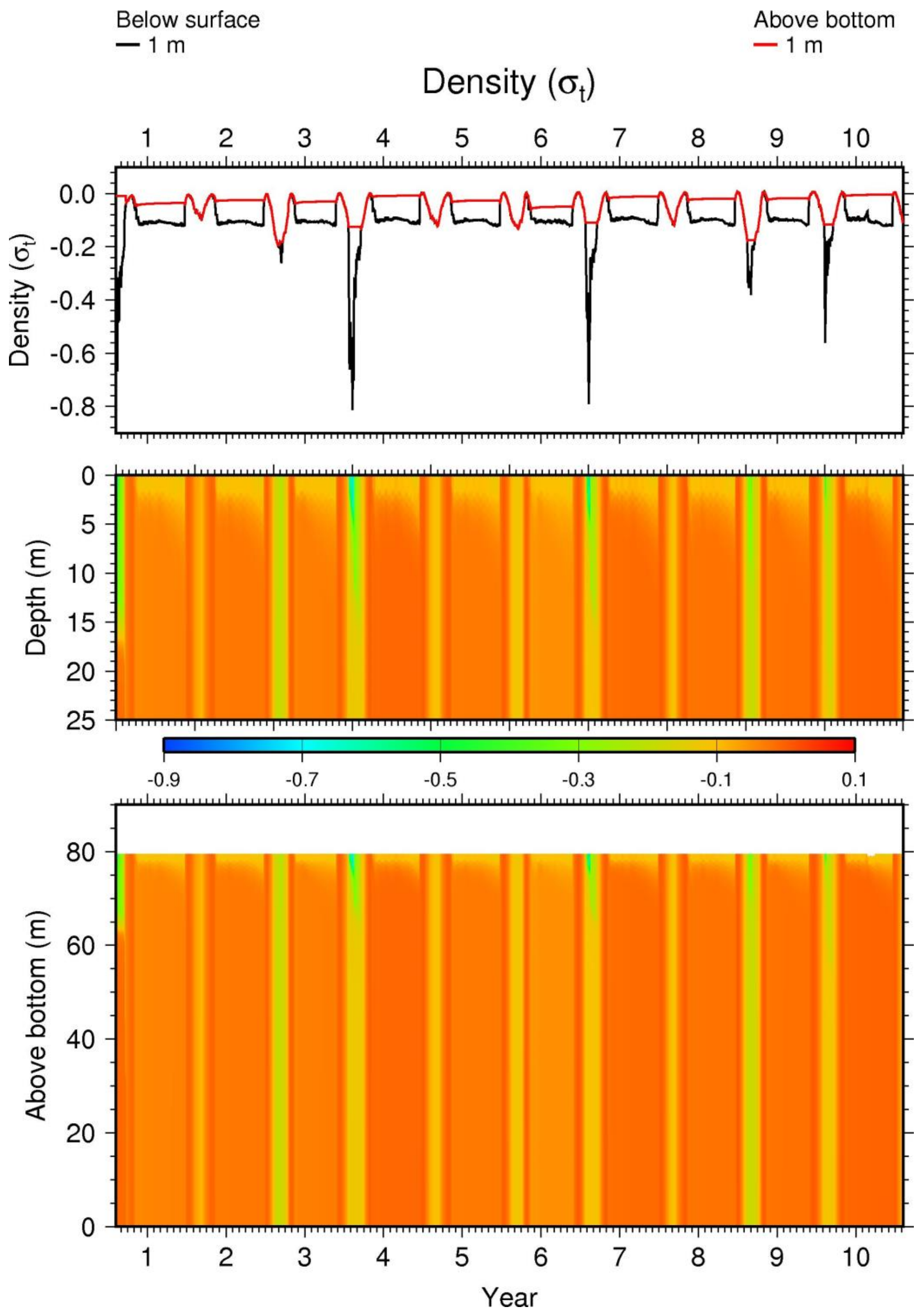


Figure 3-4: PitMod output for Scenario 1 - Density in Brucejack Lake over a ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom). Units of density equal σ_t or density-1000 (kg/m^3).

Monthly vertical profiles of temperature from year 10 of the Scenario 1 simulation show annual variability from 3ºC to 8ºC in the bottom layer and from 0ºC to 9ºC in the surface layer (Figure 3-5). Within the profile for each month there is little variability below 25 m. Maximum annual temperatures through the 10-year simulation range from 7.5ºC to 15ºC (Figure 3-5 and Figure 3-6). The seasonal temperature variations drive convective turnover as water temperatures pass through the temperature of maximum density at 4ºC. Given the dilute nature of all model inflows to the lake for existing conditions, low salinity is maintained at all depths throughout the model simulation (Figure 3-7 and Figure 3-8). Salinity is nearly constant below a depth of 15 m at 0.041‰. Above 15 m, salinity varies from 0.028‰ to 0.059‰ in response to seasonal changes in runoff to the lake surface.

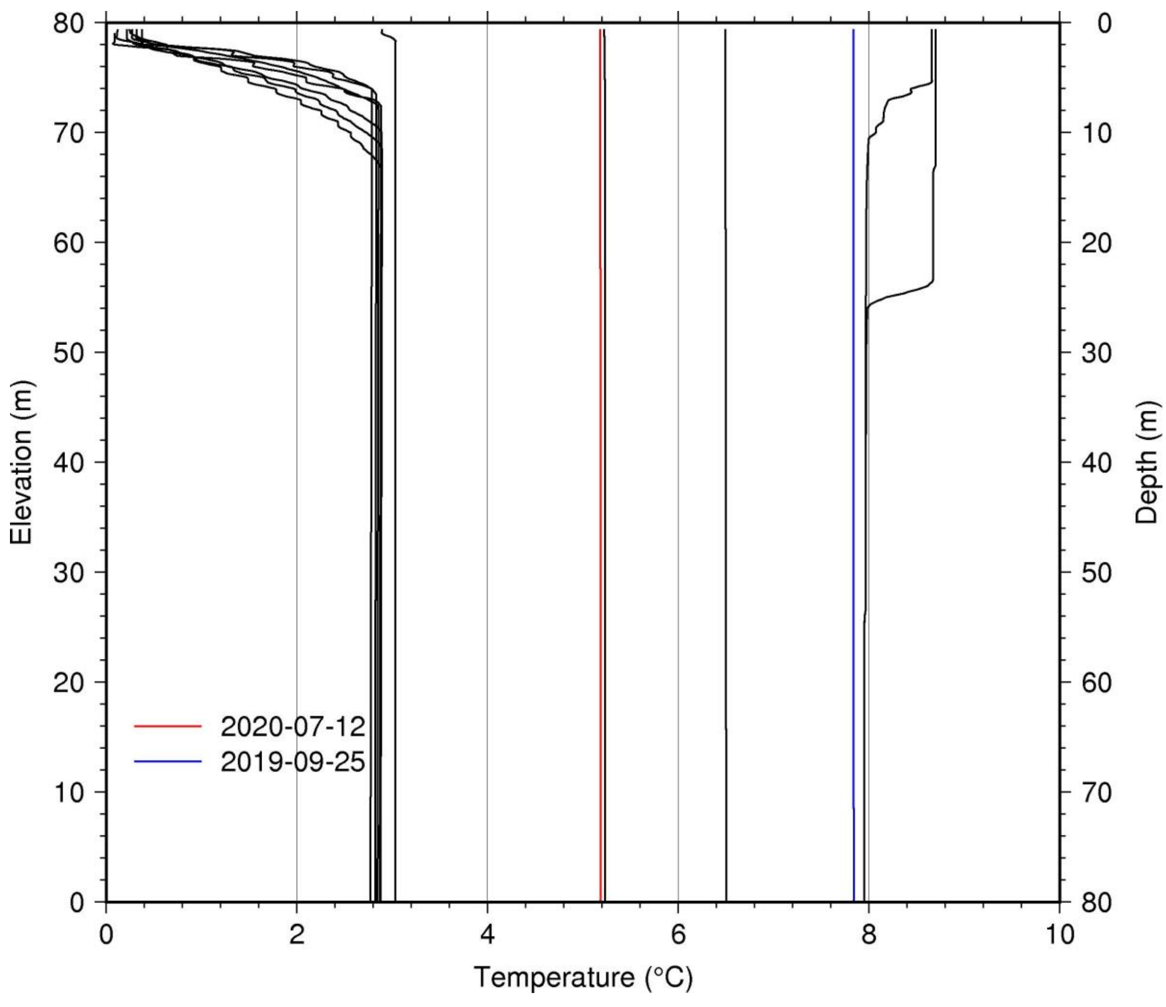


Figure 3-5: PitMod output for Scenario 1 - Monthly profiles of temperature in Brucejack Lake during the final year of a ten-year model simulation. Dates indicated (July 12 and September 25) correspond to times of uniform density and inferred periods of lake turnover.

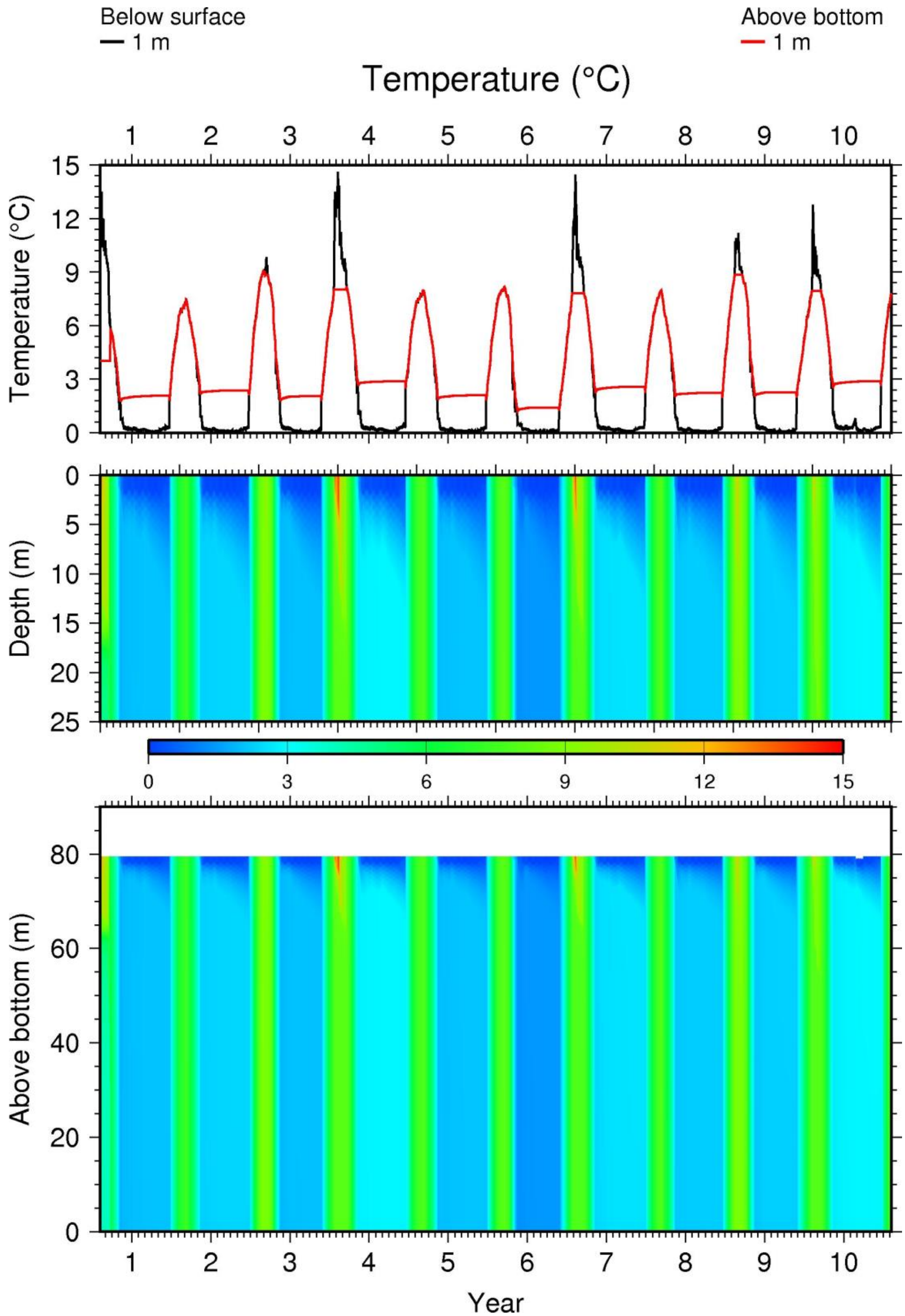


Figure 3-6: PitMod output for Scenario 1 - Temperature in Brucejack Lake over ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

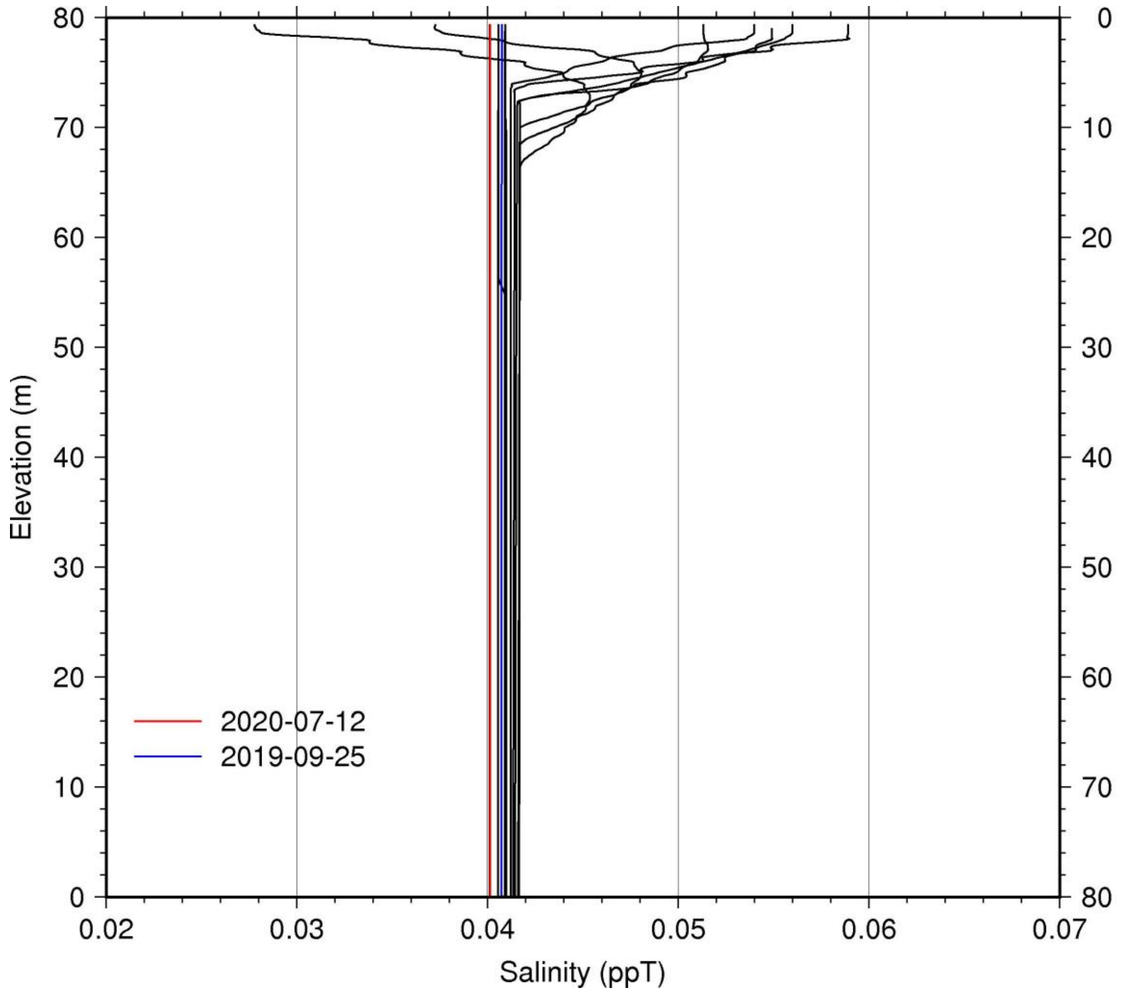


Figure 3-7: PitMod output for Scenario 1 - Monthly profiles of salinity in Brucejack Lake during the final year of a ten-year model simulation. Dates indicated (July 12 and September 25) correspond to times of uniform density and inferred periods of lake turnover.

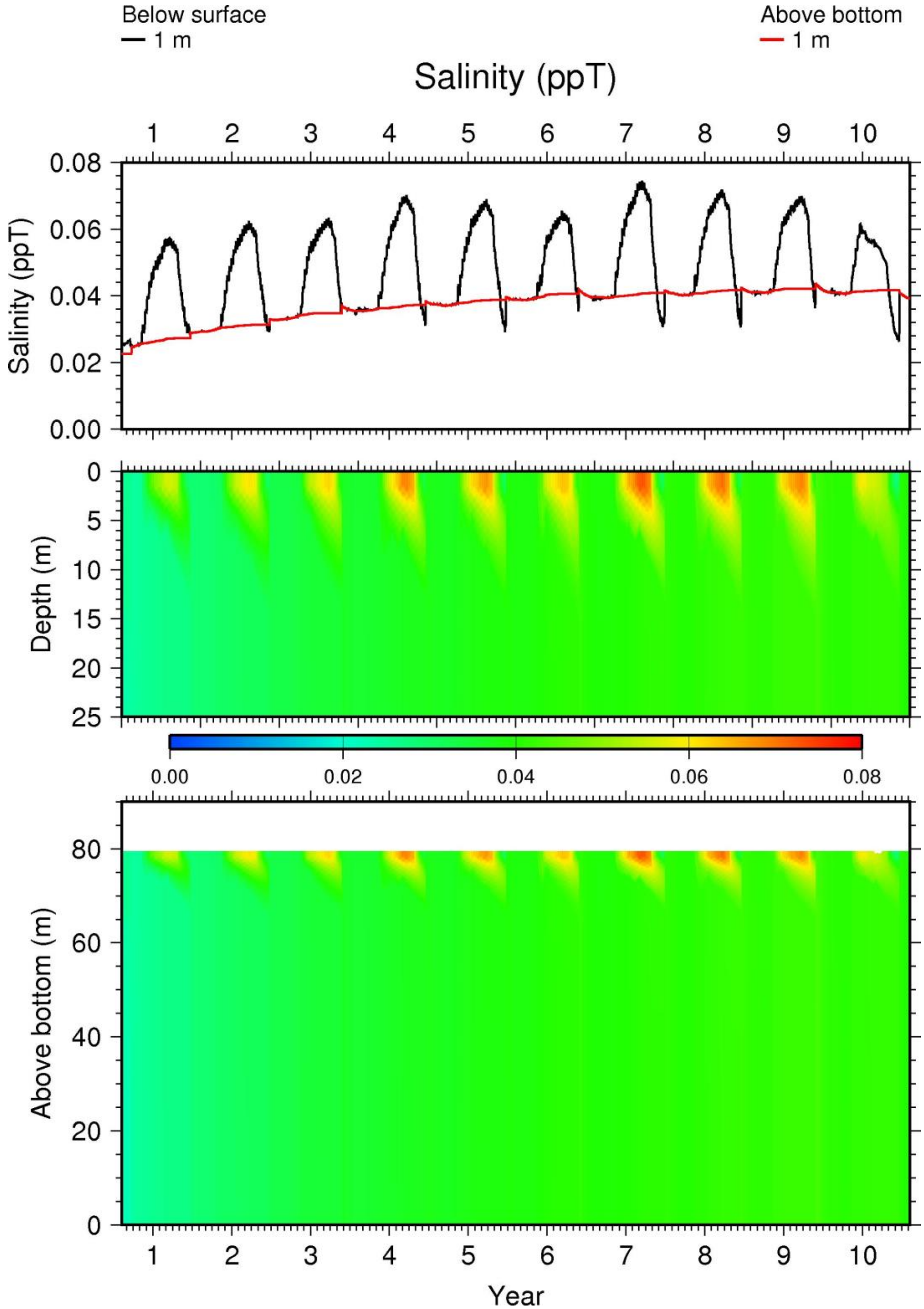


Figure 3-8: PitMod output for Scenario 1 - Salinity in Brucejack Lake over ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

The modelled temperature distribution differs considerably from CTD data collected in Brucejack Lake. In particular, vertically homogeneous temperatures as high as 8ºC have not been observed in the lake. The reason for their occurrence in the model is a direct result of the prescribed groundwater inflow, which is derived from a separate groundwater model, and which is specified as distinct inflows within ten layers. The largest inflow occurs within the layer from 7 – 17 m depth, while the second largest occurs within the layer from 0 – 7 m depth (Figure 2-3). The groundwater inflow temperature and salinity are 1.63ºC and 0.249‰, respectively, yielding a relatively high density of 0.129 σ_t. Although the volume of inflowing surface runoff is much greater than the groundwater inflow, most of the runoff component, after mixing into the surface layer to a depth of less than 10 m, leaves the lake through Brucejack Creek and does not significantly dilute the groundwater inflow below this level. Therefore, the near-surface groundwater inflow has a large influence on the vertical and temporal stratification, and other water properties in the lake.

The large seasonal flux of relatively dense groundwater inflow near the surface generates strong downward mixing and vertically homogeneous conditions from approximately the time of ice-off (June/July) through October each year. The annual groundwater inflow cycle reaches a minimum in June or July and a maximum in December. Thus, the period of vertically homogeneous conditions coincides with the increased addition of more saline and denser groundwater near the surface.

Overall, it can be concluded that the model overestimates the degree of mixing in the lake. While the model conditions may not accurately represent the observed water properties in Brucejack Lake, they do represent a very conservative scenario from which to assess lake mixing and the potential for the introduction of tailings solids and supernatant into the lake surface.

3.1.2 Lake Mixing and Flushing

The model output for temperature and density suggest that the water column of Brucejack Lake currently undergoes convective overturn twice per year (dimictic). This is consistent with field data that show surface water temperatures passing through the point of maximum density (4ºC) in the summer and fall.

To estimate the amount of mixing and the flushing rate for bottom waters in Brucejack Lake, the model includes a layer of a neutral tracer in the bottom 4 m of the lake. With each model iteration, the concentration of tracer in this layer is reset to 100. Over time, the tracer is mixed upward, primarily by convective mixing (overturning). The monthly profiles from year 10 demonstrate that convective mixing transports the tracer upward through the water column (Figure 3-9). At the surface, tracer values range from 20-90%. Complete and partial mixing events are evident over the 10-year model simulation in

Figure 3-10. The median level in the surface layer is approximately 81% (Figure 3-11). Overall, the results of the tracer simulation support the assumption that bottom waters in Brucejack Lake mix into the surface layer on a seasonal basis.

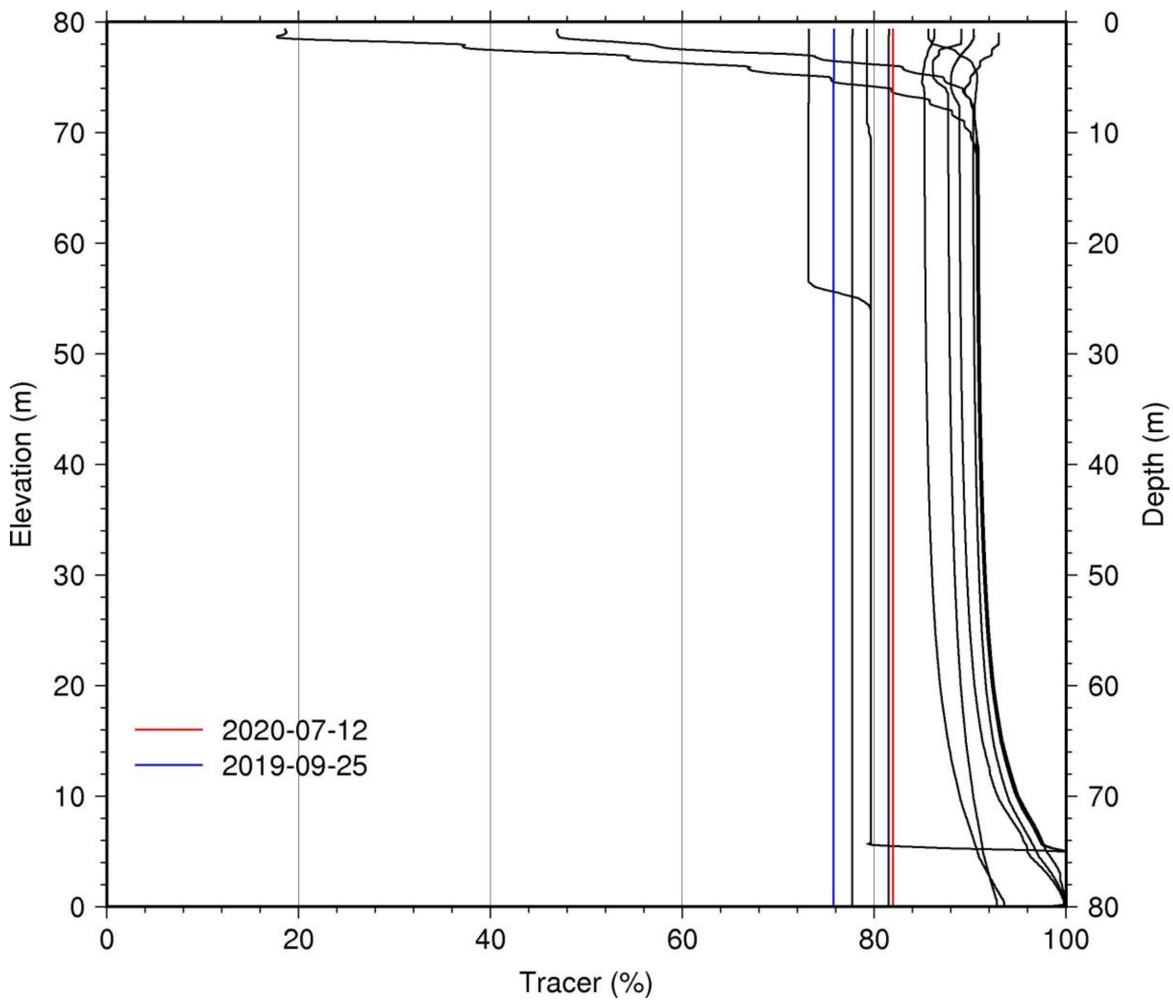


Figure 3-9: PitMod output for Scenario 1 - Monthly profiles of tracer concentration in Brucejack Lake during the final year of a ten-year model simulation. Dates correspond to times of uniform density and inferred periods of lake overturn.

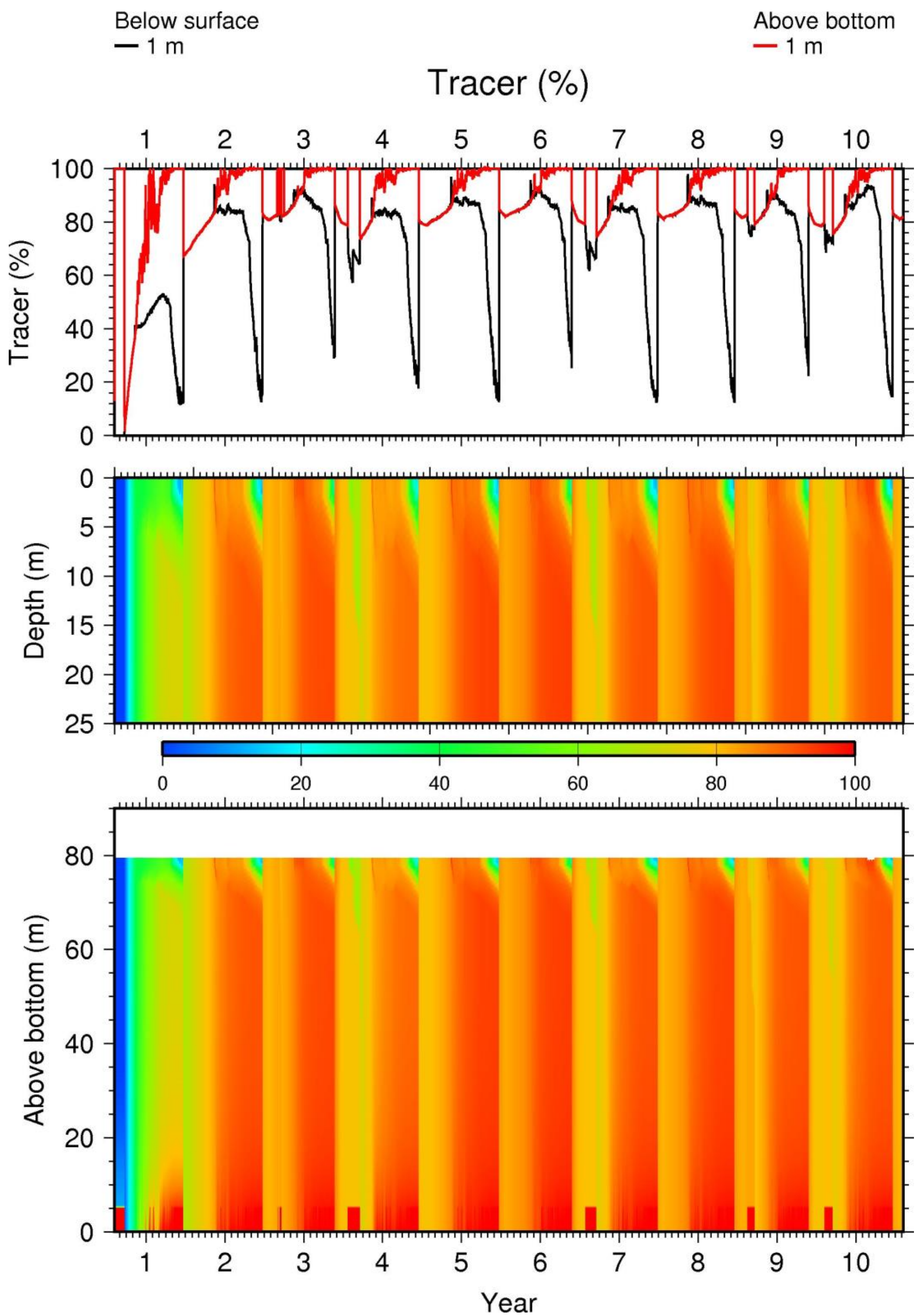


Figure 3-10: PitMod output for Scenario 1 - Tracer concentration in Brucejack Lake over ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

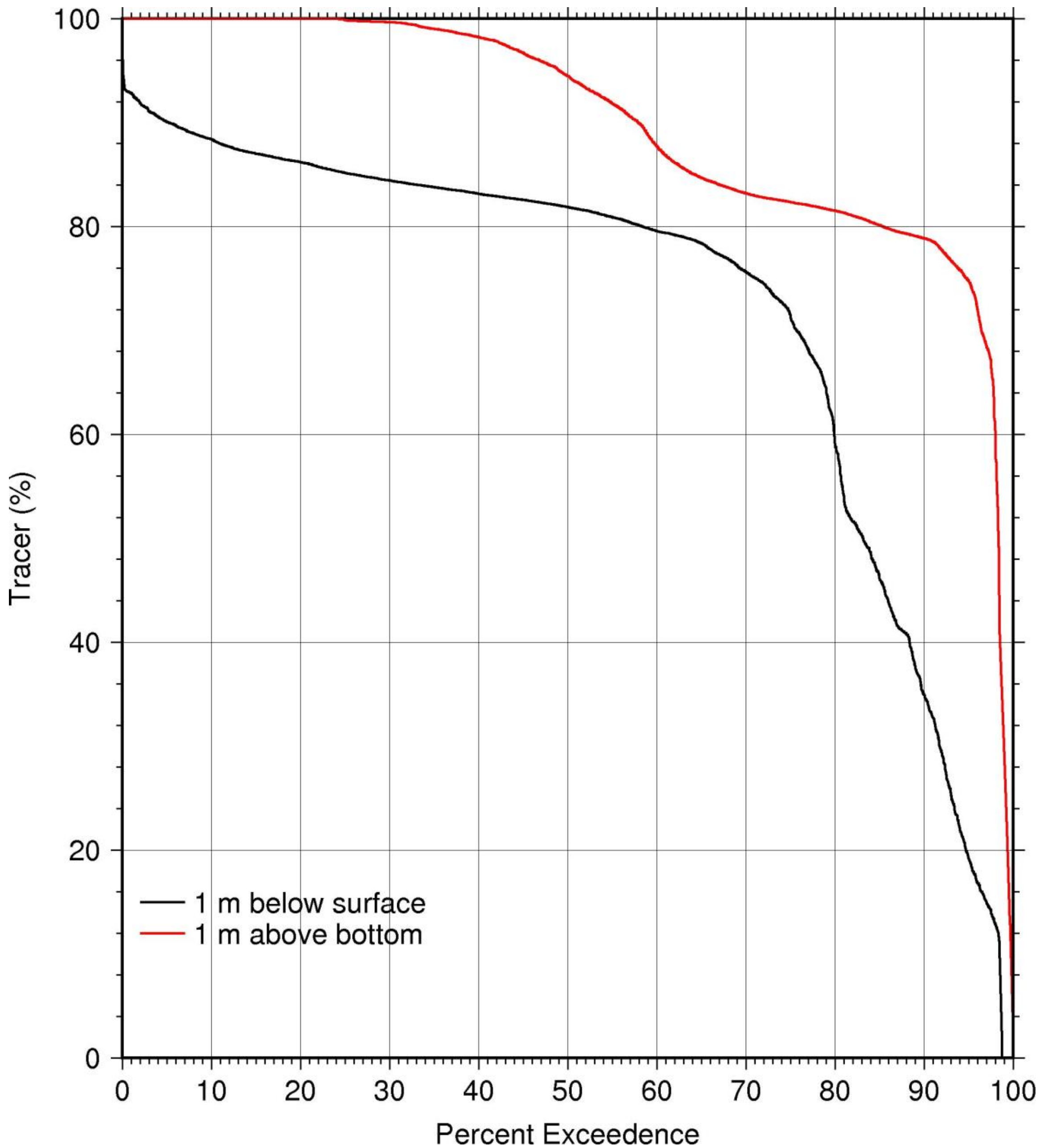


Figure 3-11: PitMod Output for Scenario 1 - Tracer concentration: percent exceedance in the surface and bottom layers of Brucejack Lake over a 10-year model simulation.

3.1.3 Comparison of Model Output to Field Data

Vertical profiles of modelled temperature, salinity, and density were extracted from the Scenario 1 model output for comparison with Conductivity-Temperature-Depth (CTD) profiles from July, September, and December 2012 (Figure 3-12 through Figure 3-14). The September profile was taken during open water, while the July and December profiles were taken under ice.

Overall, the model reproduces the dimictic behaviour believed to be characteristic of Brucejack Lake, although there are significant differences between the modelled and observed values. For example, measured temperature below 50 m depth increases from 3° to 4° C over the period from July to September then decreases back to 3° C by December, whereas the model temperature increases from 4° C to 9° C over the same period. These differences reflect the fact that the model overestimates mixing in Brucejack Lake. Specifically, the prescribed groundwater inflow results in more vigorous and prolonged mixing events than are observed currently in the lake (as described above).

The measured salinity profiles exhibit little vertical or seasonal variability. The modelled salinity exhibits approximately the same amount of seasonal variability below approximately 10 m depth; however, the modelled salinity in the upper 10 m exhibits much larger variability at certain times of the year (Figure 3-13). The increase in model salinity in the upper 10 m is due to the exclusion of salt from ice as it forms throughout the late fall and winter.

Monthly vertical profiles of density from year 10 of Scenarios 2a and 2b show strikingly different behaviour (Figure 3-17). In Scenario 2a, the density increases rapidly beginning at a depth of 40 m to a maximum of 170 σ_t units at the bottom. Above a depth of 40 m the values of σ_t are too small to be noticeable due to the density scale used. The much higher densities below a depth of 40 m for Scenario 2a (no flocculation) in comparison to 2b (flocculation) demonstrate that virtually all of the suspended solids mass in Scenario 2a contributing to density resides in the <5 µm particle fraction.

3.2 Scenario 2 (Initial Period of Tailings Discharge)

3.2.1 General Features

For the initial period of tailings discharge, surface inflows include precipitation and undisturbed runoff, while bottom inflows include tailings slurry water, fluidizing water, and underground mine excess water (Figure 3-15). Water is removed from the lake via evaporation and pumping of fluidizing water. The latter is discharged to the lake bottom with the same properties as the tailings slurry water. Ice formation/melting removes/adds water with no net addition of mass to the lake. Ice depth ranges from 0.7 to 1.0 m, with ice formation typically occurring in late October or early November and open water occurring in July (Figure 3-16).

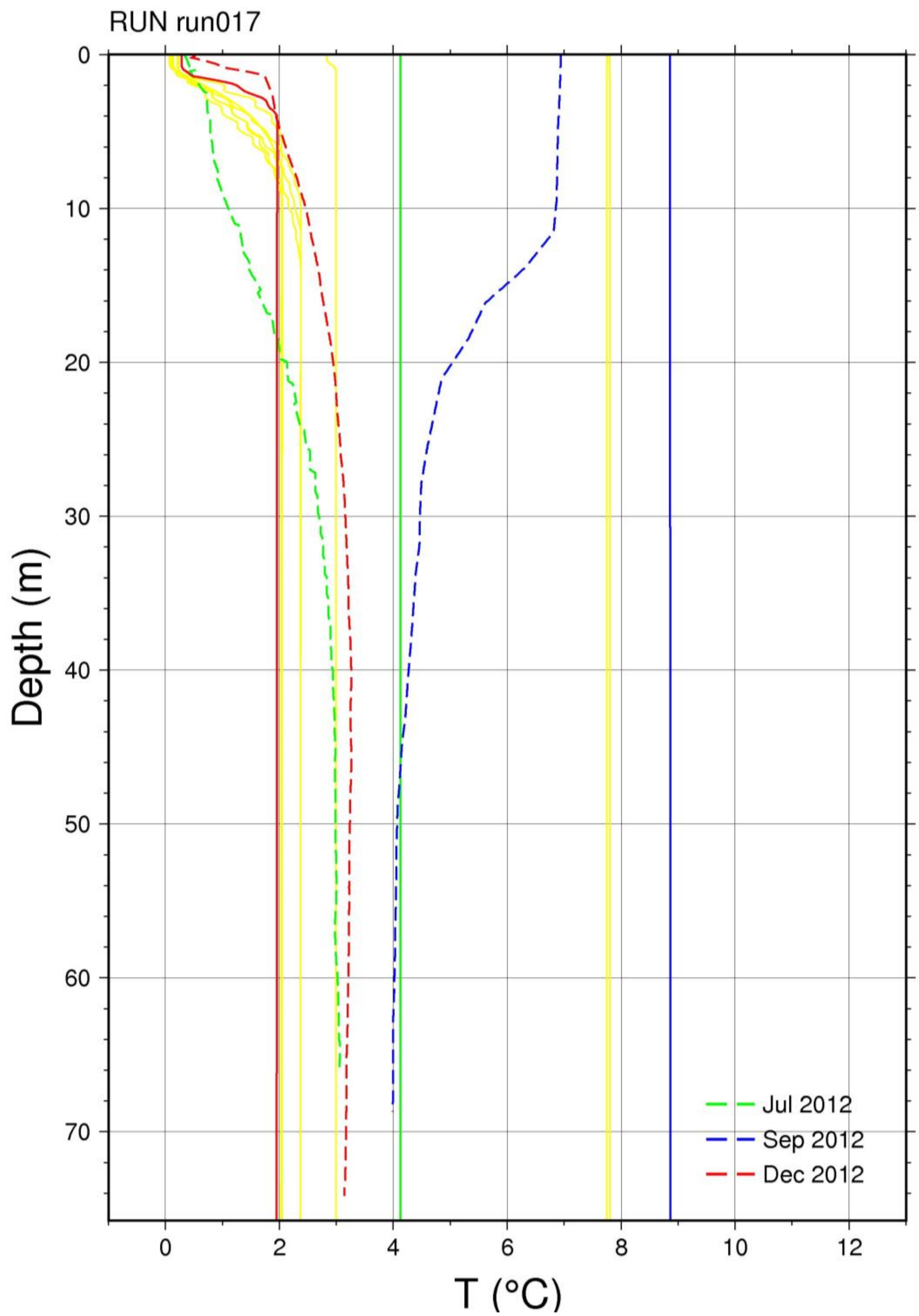


Figure 3-12: Temperature profiles from Brucejack Lake CTD casts made during July, September and December, 2012 (dashed lines), and monthly profiles from the PitMod Scenario 1 simulation (solid lines). PitMod profiles for July, September and December are the same colours as the CTD profiles, while other months are yellow.

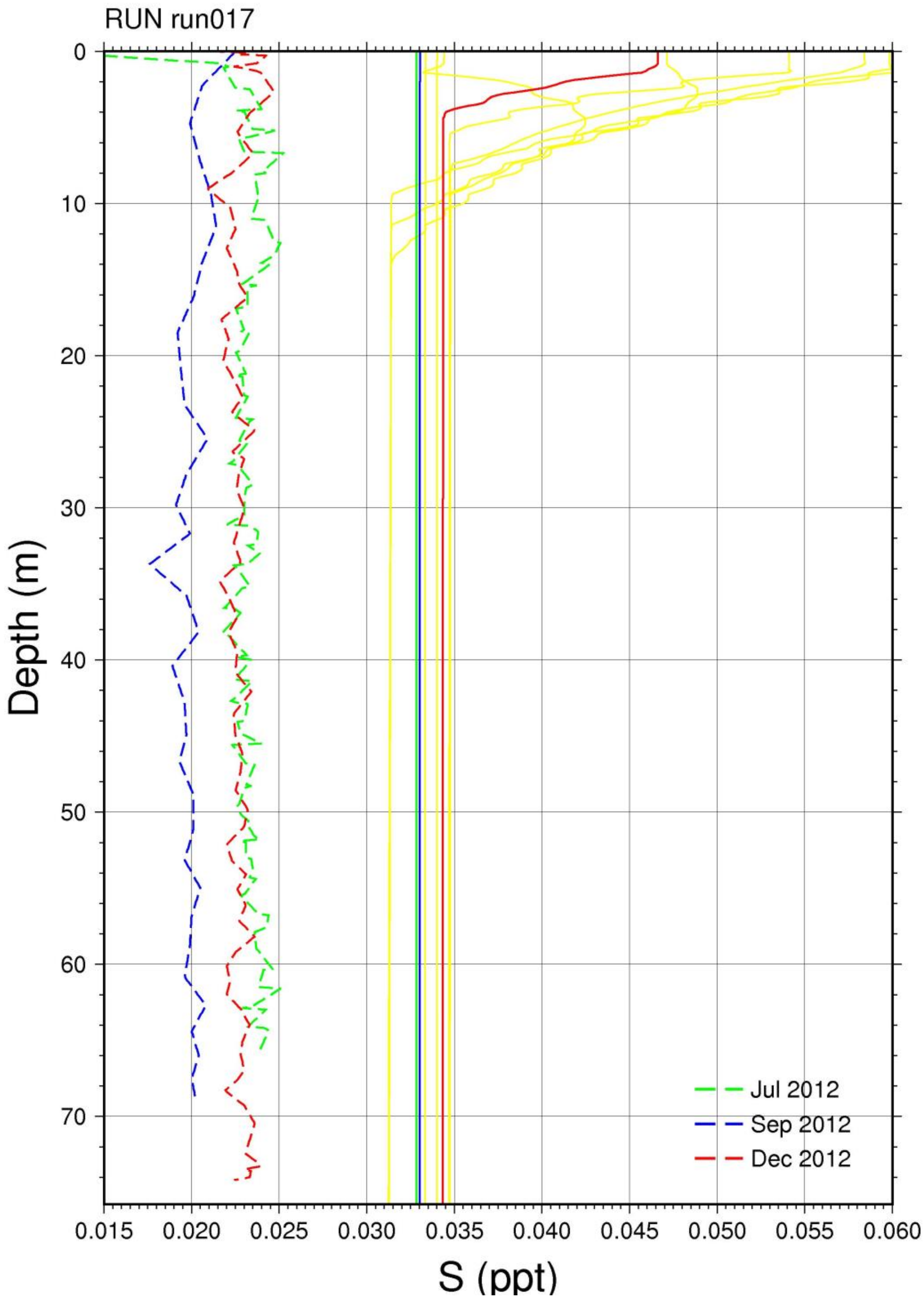


Figure 3-13: Salinity profiles (in parts per thousand) from Brucejack Lake CTD casts made during July, September and December, 2012 (dashed lines), and monthly profiles from the PitMod Scenario 1 simulation (solid lines). PitMod profiles for July, September and December are the same colours as the CTD profiles, while other months are yellow.

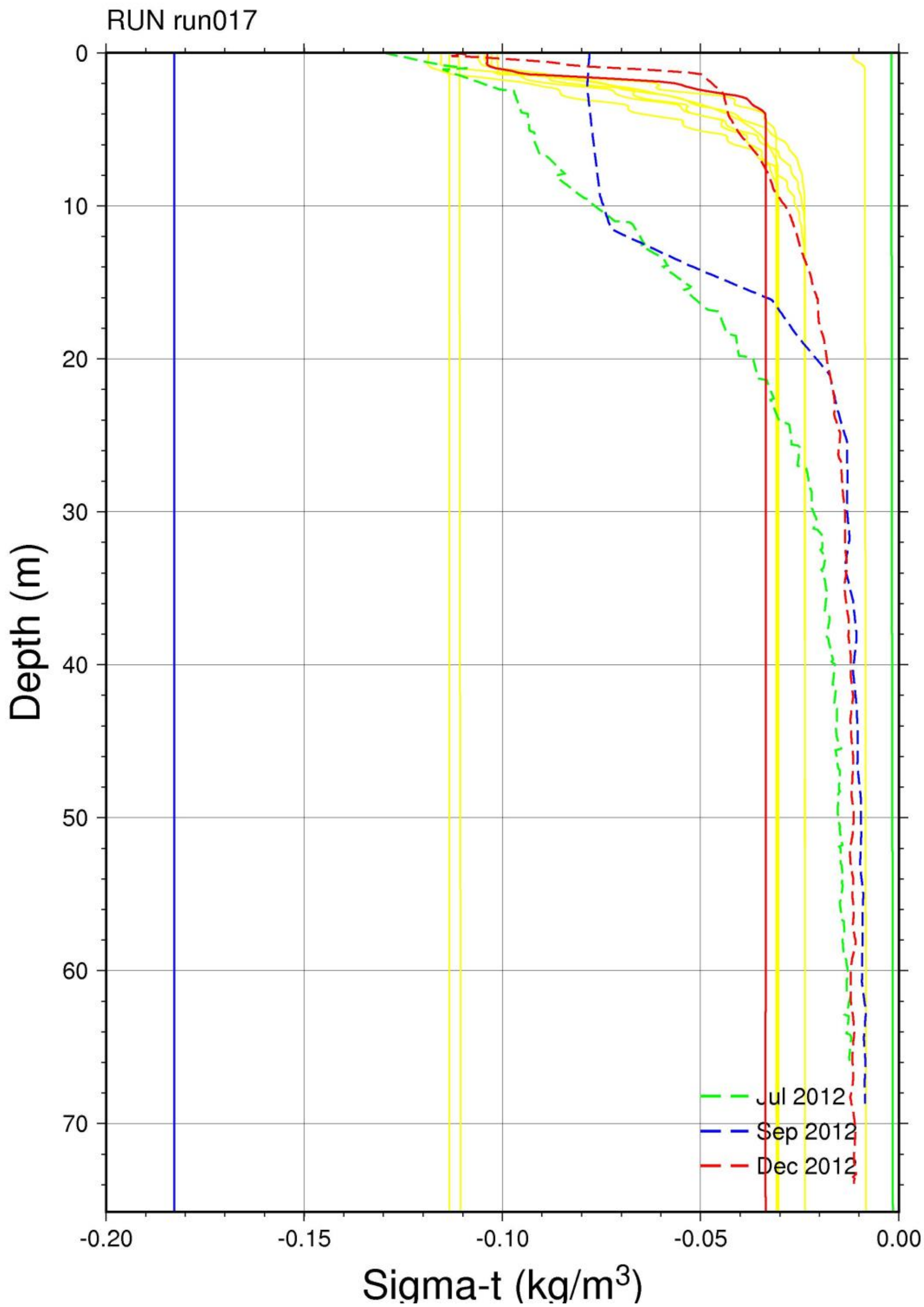


Figure 3-14: Density profiles from Brucejack Lake CTD casts made during July, September and December, 2012 (dashed lines), and monthly profiles from the PitMod Scenario 1 simulation (solid lines). PitMod profiles for July, September and December are the same colours as the CTD profiles, while other months are yellow.

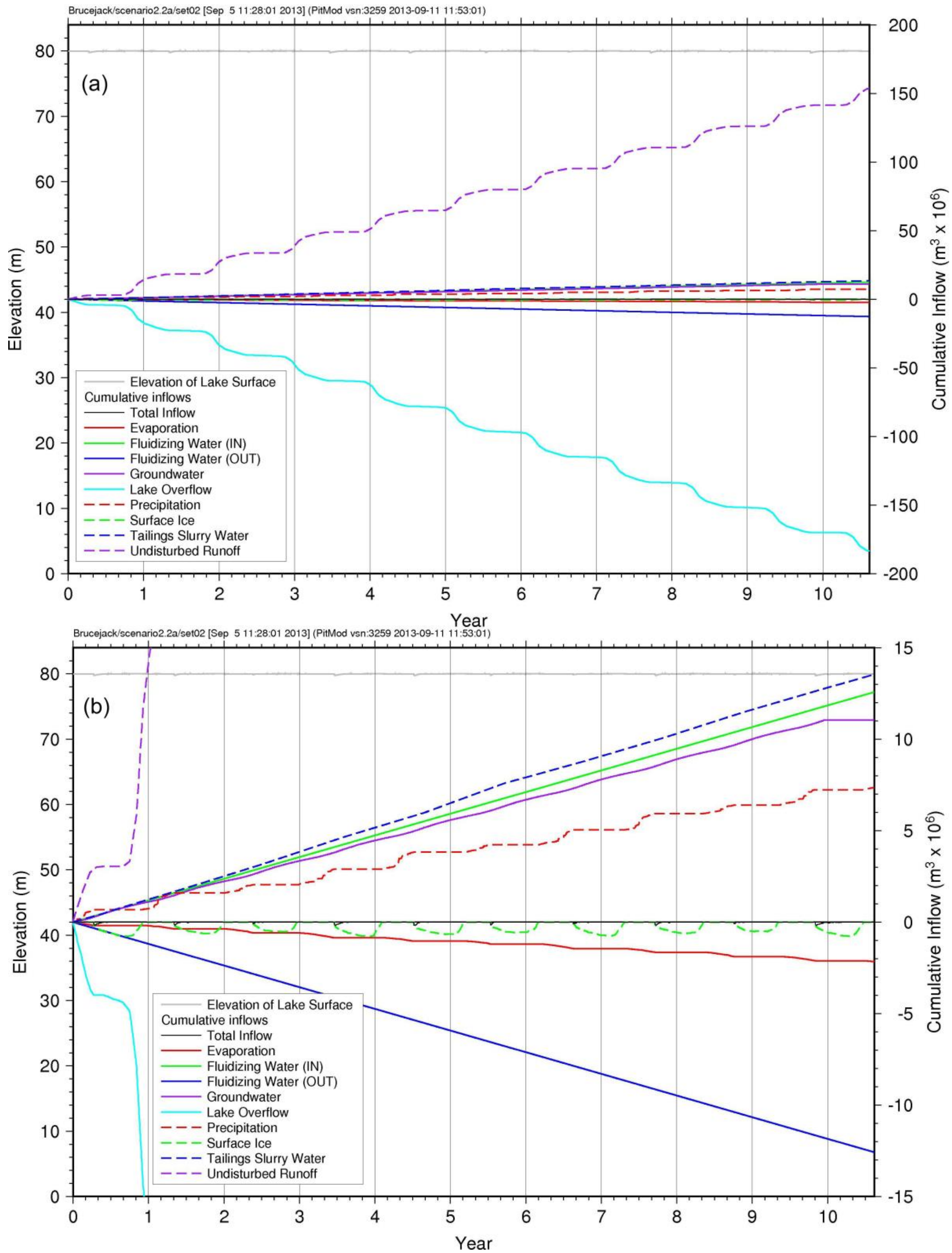


Figure 3-15: PitMod output for Scenario 2 - Cumulative inflow and outflow volumes (bottom image (b) shows an expanded scale to reveal detail).

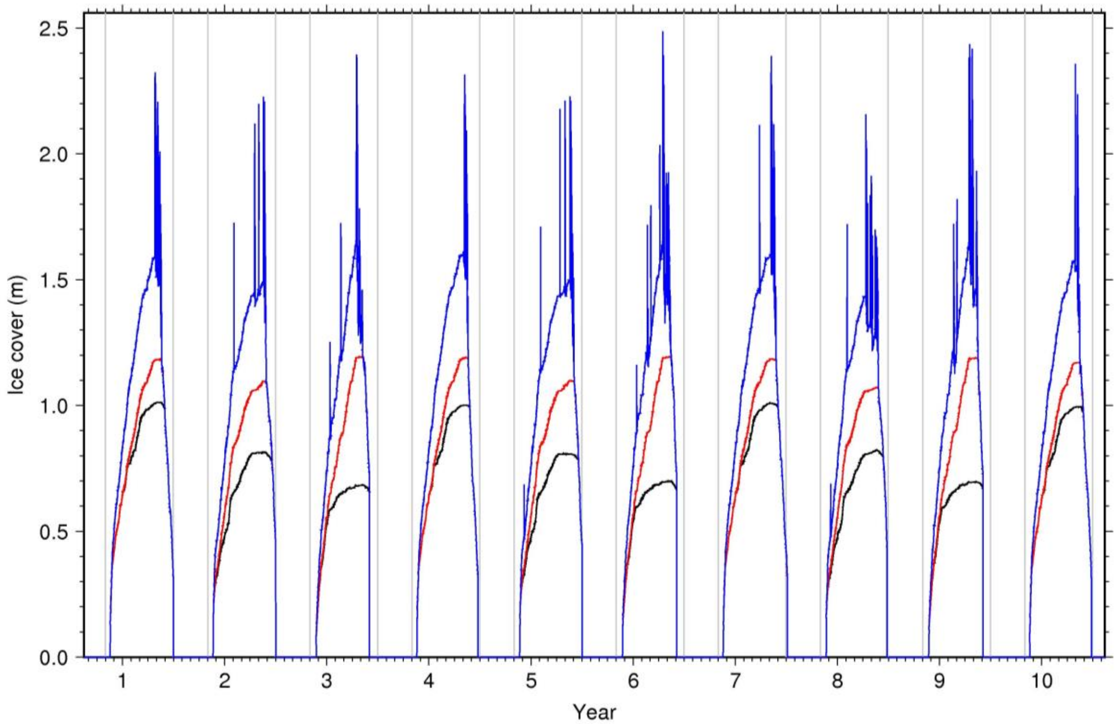


Figure 3-16: PitMod output for Scenario 2 - snow (blue), snow-ice (red), and ice (black). Thicknesses are shown for a 10-year model simulation.

The largest difference between the Scenario 1 and Scenario 2 simulations is the addition of suspended solids in the tailings slurry discharge at the lake bottom. The suspended solids contribute to the water density based on the specific gravity of the solids and their concentration in the water column. In Scenario 2a, the particle size distribution of the suspended solids includes all particle diameters, while the PSD for Scenario 2b has a minimum particle diameter of 5 µm.

In Scenario 2b, the density variation at the surface (from -0.60 to 0.01 σ_t units) reveals the effect on density relating to seasonal temperature variations (as observed for existing conditions in Scenario 1) (Figure 3-17). The time-series of surface and bottom layer density show that for Scenario 2a the much larger density of the bottom layer prevents turnover events from extending to the bottom of the lake. In contrast, the density data for Scenario 2b are closer to existing conditions, with the water column exhibiting vertically homogeneous conditions two times per year (dimictic). The more complete vertical mixing in Scenario 2b results from the much lower bottom layer density compared to Scenario 2a. For Scenario 2b, turnover events occur in late spring/early summer and then again in mid to late fall (Figure 3-18).

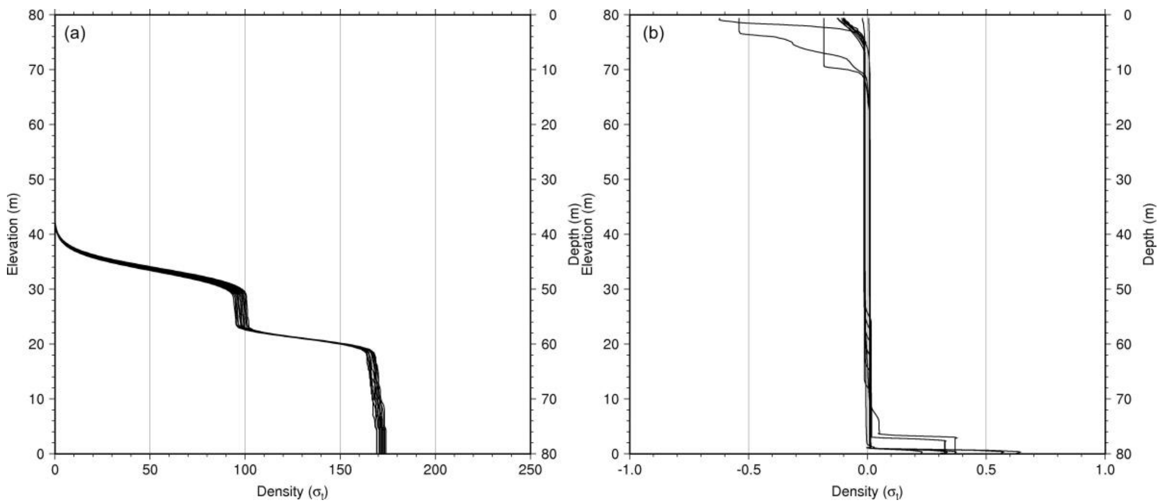


Figure 3-17: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Monthly profiles of density in Brucejack Lake during the final year of a ten-year model simulation (note different density scales on x-axis).

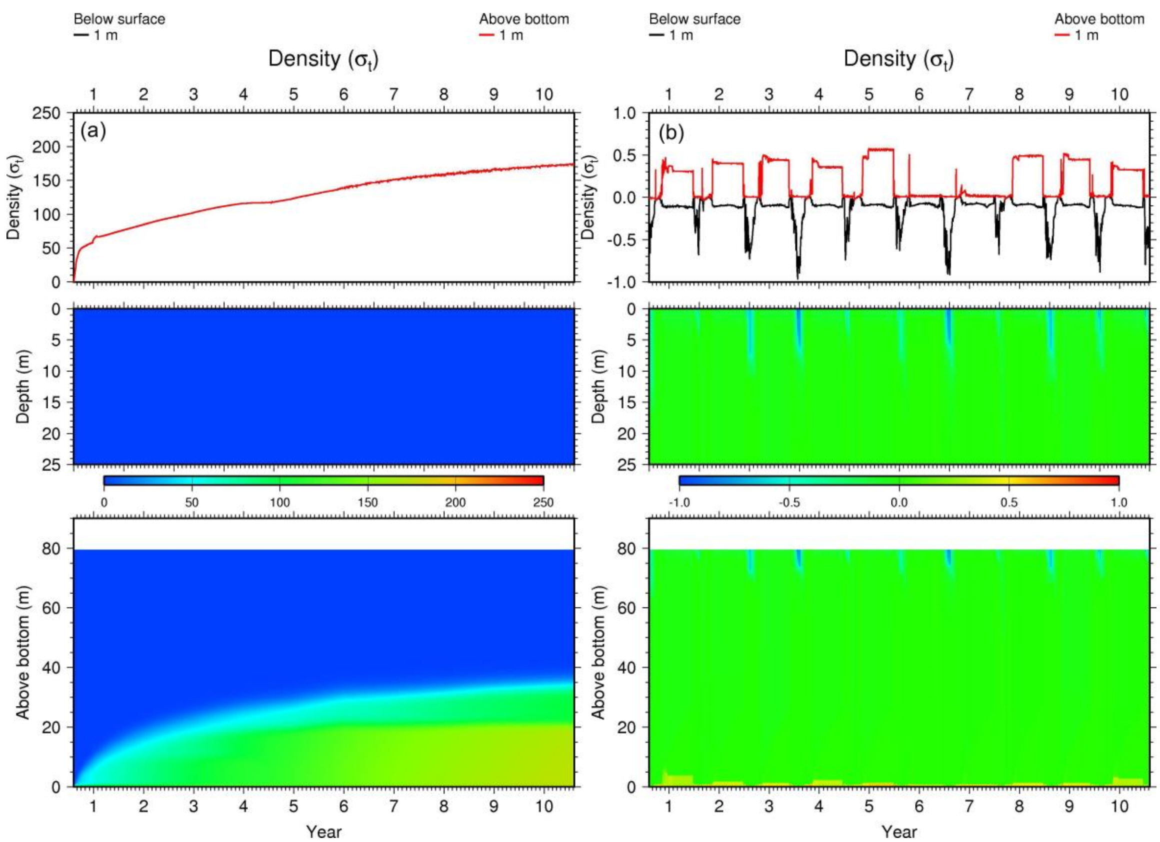


Figure 3-18: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Density in Brucejack Lake over a ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom). Note different density scales between scenarios.

The persistence of fine particle suspensions in the deep water column in Scenario 2a, and the corresponding effect on lake mixing, also has an effect on temperature and salinity (Figure 3-19 through Figure 3-22). In Scenario 2a, vertical mixing events penetrate only to the top of the suspended solids layer at 40 m depth. Below 40 m, the temperature remains between 8º and 9º C. The high bottom water temperatures can be attributed to the relatively-high temperatures prescribed to the tailings supernatant, mine excess water and fluidization water (7.5 to 10°C) (Table 2-4).

In Scenario 2b, the dense layer of suspended solids is absent, and this allows the water column to mix to the bottom during some months. Temperatures near the bottom range from 2º to 6º C. Above a depth of roughly 50 m, both Scenarios 2a and 2b exhibit approximately the same thermal structure throughout the year, suggesting that the upper layer responds independently of the bottom layer. Maximum annual temperatures in the surface layer range from 13º to 15º C (Figure 3-20), which contribute to seasonal density fluctuations in the lake surface (shown in Figure 3-18).

The input of more saline water associated with the tailings discharge and subsequent vertical mixing, results in higher water column salinity in comparison to existing conditions (Scenario 1) (Figure 3-21). In Scenario 2a, salinity remains nearly constant between 10 m and 35 m depth, and from 40 m to the bottom. Between 35 m and 40 m there is a very strong halocline due to the presence of the relatively-high salinity tailings water contained below 40 m. Variations in salinity near the surface from 0.025 to 0.12‰ are caused by seasonal variations in the flux of low salinity runoff to the surface layer, as well as ice formation and melting. Salt is excluded from the ice during formation, causing surface salinity to increase, while the addition of fresh water during melting causes surface salinity to decrease.

In Scenario 2b (with flocculation), a deep halocline associated with tailings supernatant is also evident (Figure 3-22). However, due to the mixing that occurs periodically to the lake bottom in Scenario 2b, the salinity gradient is weaker and less persistent in comparison to Scenario 2a (no flocculation).

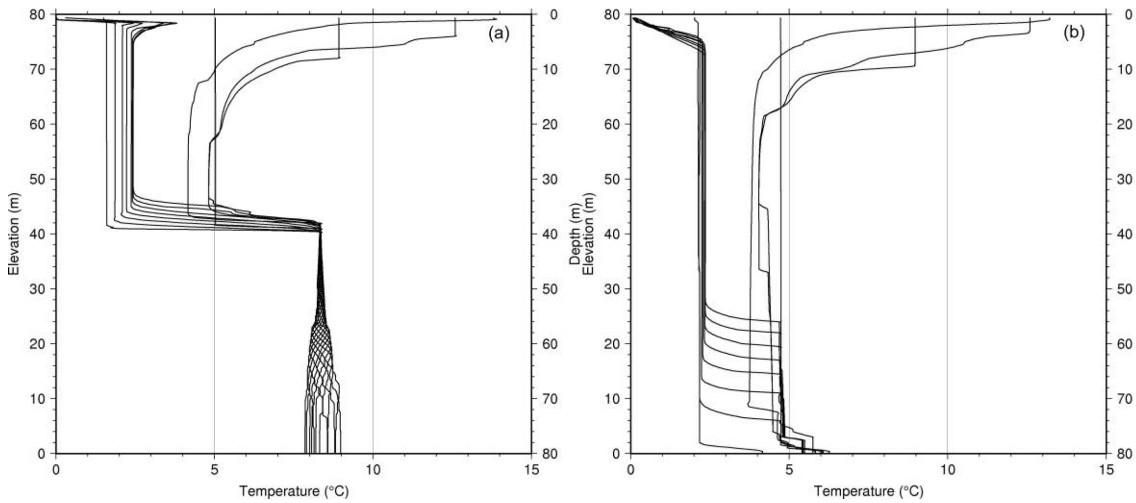


Figure 3-19: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Monthly profiles of temperature in Brucejack Lake during the final year of a ten-year model simulation.

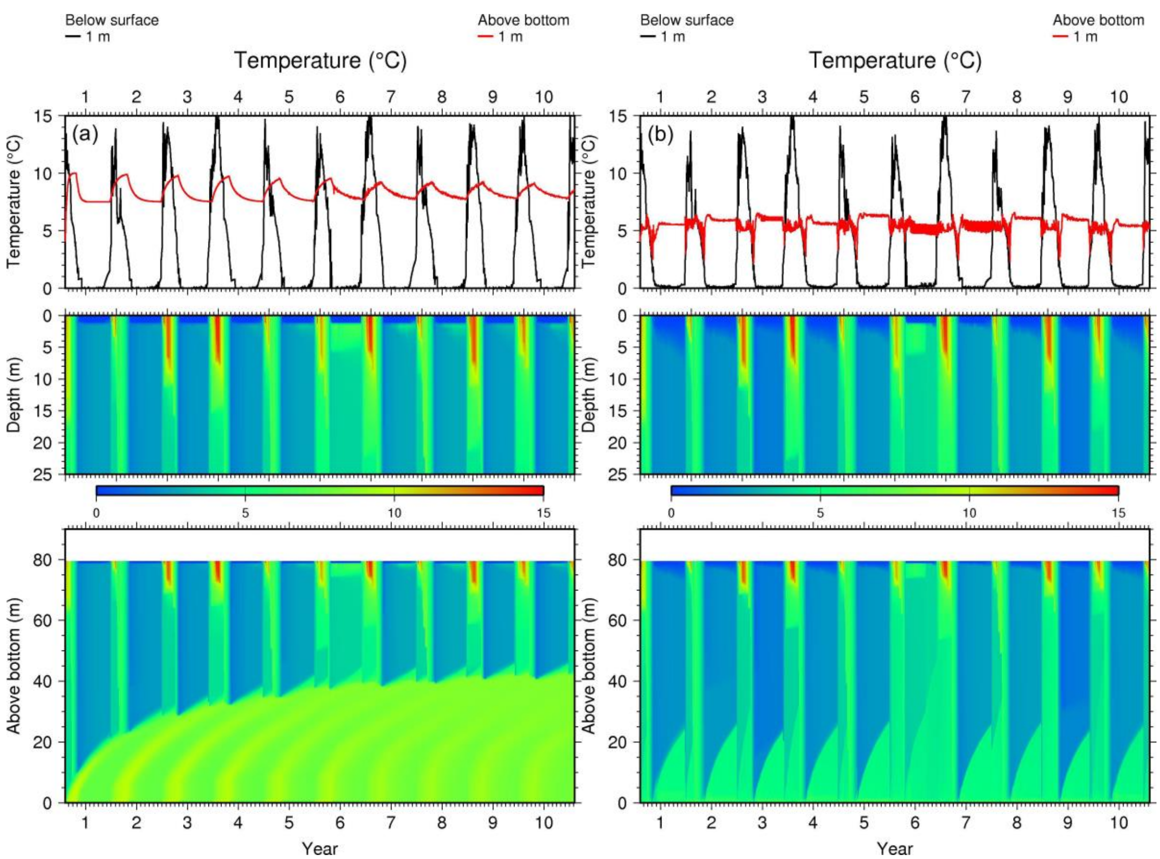


Figure 3-20: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Temperature in Brucejack Lake over a ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

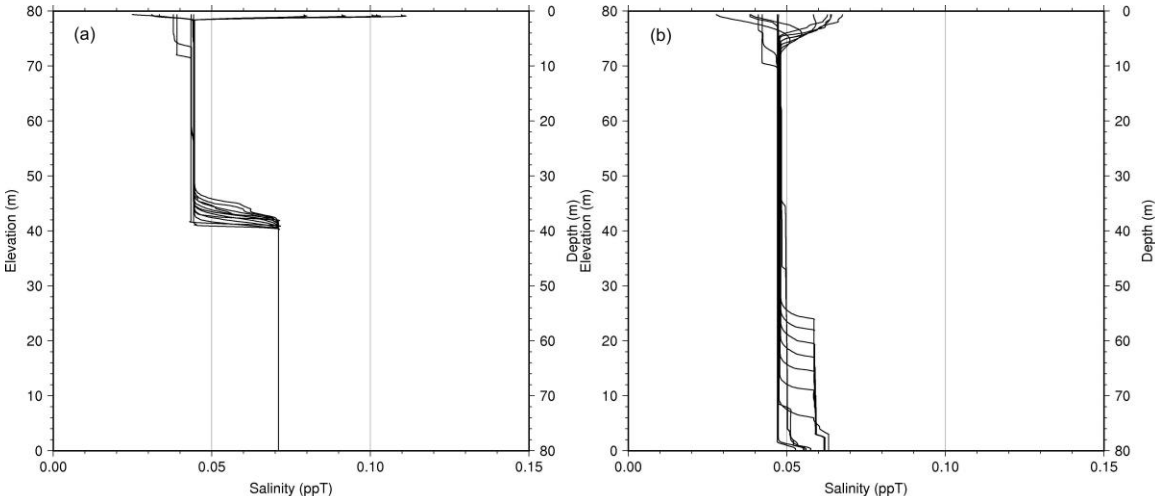


Figure 3-21: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Monthly profiles of salinity in Brucejack Lake during the final year of a ten-year model simulation.

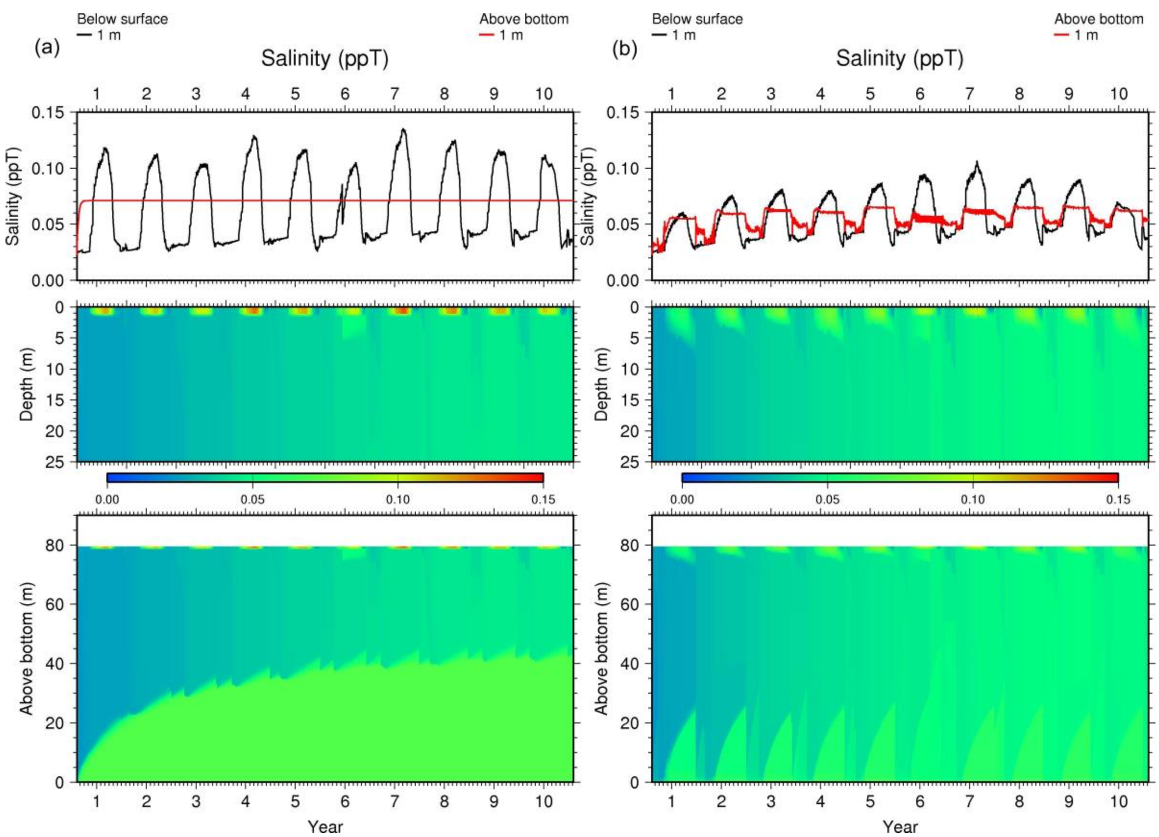


Figure 3-22: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Salinity in Brucejack Lake over a ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

3.2.2 Lake Mixing and Flushing

The addition of tailings supernatant in Scenarios 2 and 3 results in upward movement of water in the lake as the added volume of supernatant mixes with and displaces resident bottom waters. The monthly profiles from year 10 of the Scenario 2 model simulations show that for both scenarios (2a and 2b) vertical mixing transports tailings supernatant upward through the water column (Figure 3-23 and Figure 3-24). In the case of Scenario 2a, this flux originates at the upper surface of the dense layer of suspended solids. In both scenarios, the upper layer effluent concentration reaches roughly the same value of ~25% (3:1 dilution). The proportion of effluent remains relatively constant throughout the year below 10 m. Shallower than 10 m, the effluent concentration shows more variability in response to seasonal changes in surface runoff.

Plots of effluent concentration over the 10-year model duration illustrate the progressive evolution of the water column (Figure 3-24). The effluent concentration in the surface layer during Simulation 2a increases throughout the simulation, whereas in Simulation 2b the effluent concentration reaches a steady-state after approximately 4-5 years. At the end of the 10-year period, however, the surface layer effluent concentrations in both Scenarios 2a and 2b are quite similar over an annual cycle.

In the surface layer, maximum monthly mean effluent concentrations of 11-15% (Scenario 2a) and 15-19% (Scenario 2b) are predicted to occur between October and April, while minimum monthly means of 3-11% (Scenario 2a) and 7-15% (Scenario 2b) are predicted from May through September (Table 3-1). The annual mean surface layer concentration of tailings effluent for Scenario 2a is 11% and for Scenario 2b is 15%. The median effluent concentration at 1 m depth is approximately 11% (9:1 dilution) for Scenario 2a and approximately 16% (6:1 dilution) for Scenario 2b. The maximum concentration is 34% (2.9:1 dilution) for Scenario 2a and 28% (3.6:1 dilution) for Scenario 2b (Figure 3-25).

Overall, the lake mixing and flushing behaviour predicted in the model indicates that in the case where no flocculation occurs (Scenario 2a), very small particles suspend and form a dense bottom layer of suspended solids below 40 m. Within this dense bottom layer, the temperature and salinity signatures of the tailings supernatant are retained. This lake structure restricts the mixing of surface waters to depth. In the case where flocculation limits the smallest particle size to 5 µm (Scenario 2b), no such layer forms as the particle settling velocities are sufficiently large to overcome any upward advection caused by convective mixing. In this case, the downward mixing of surface waters occurs to the lake bottom. For both scenarios, vertical mixing transports tailings supernatant upward into the surface layer.

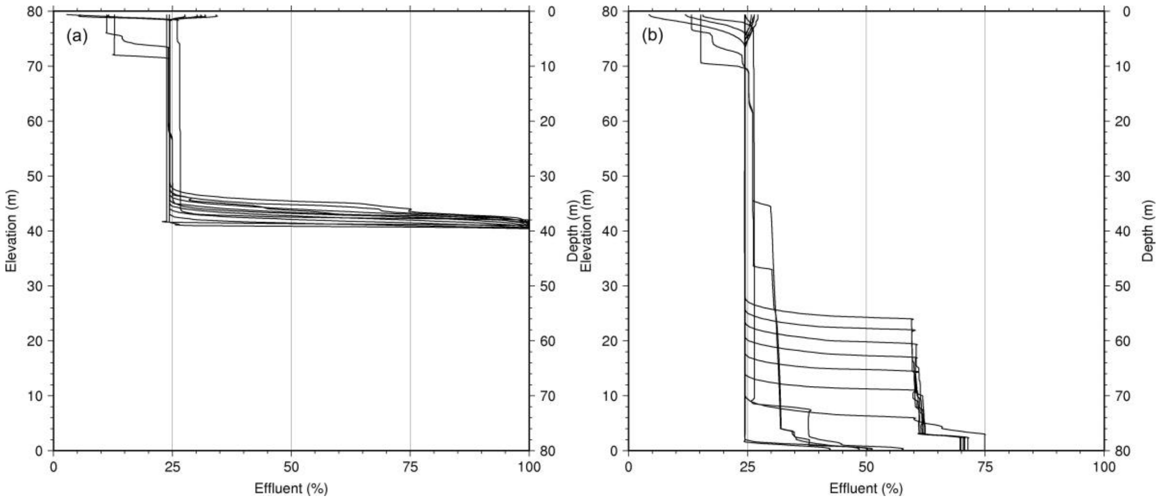


Figure 3-23: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Monthly profiles of effluent concentration in Brucejack Lake during the final year of a ten-year model simulation.

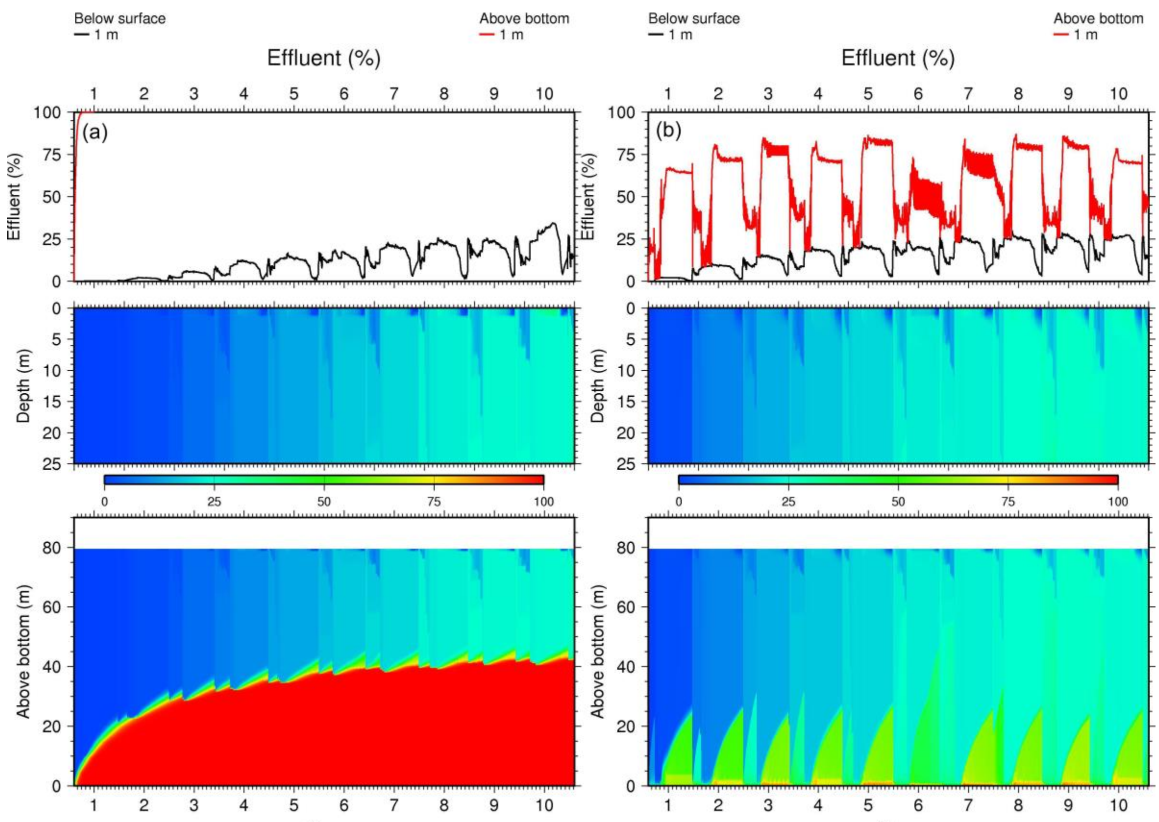


Figure 3-24: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Effluent concentration in Brucejack Lake over a ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

Table 3-1:
Scenarios 2a and 2b – Modelled monthly mean effluent concentrations in the surface layer of Brucejack Lake over the 10-year model period.

Month	Mean Effluent Concentration (%)		Month	Mean Effluent Concentration (%)	
	(2a)	(2b)		(2a)	(2b)
Jan	15	19	Jul	11	15
Feb	14	18	Aug	9	13
Mar	14	18	Sep	10	14
Apr	11	15	Oct	13	18
May	3	7	Nov	14	19
Jun	8	10	Dec	15	19
			Annual	**11**	**15**

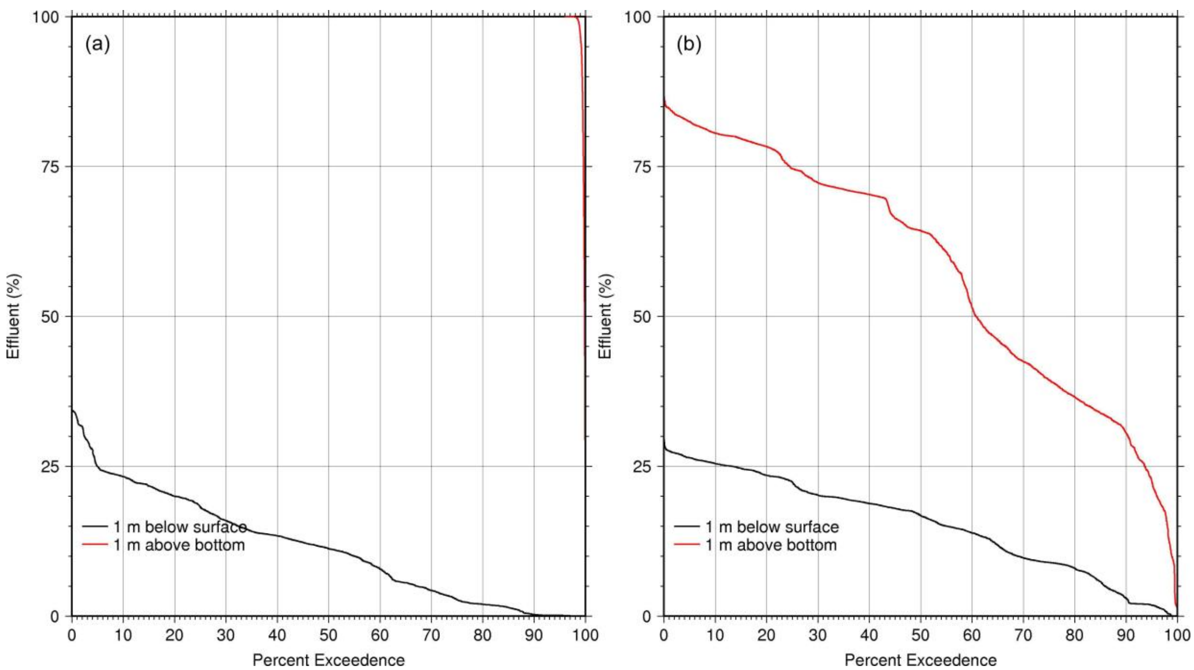


Figure 3-25: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) - Effluent concentration: percent exceedance in the surface and bottom layers of Brucejack Lake during a 10-year model simulation. The median effluent concentration at 1 m depth is approximately (a) 12% (8.3:1 dilution) (b) 17% (5.9:1 dilution).

3.2.3 Suspended Solids

The vertical and temporal variations of TSS for Scenarios 2a and 2b are presented in Figure 3-26, with the corresponding exceedance plots presented in Figure 3-27. Scenario 2a (no flocculation) predicts the formation of a dense layer of suspended solids occupying the bottom 40 m of the lake after 10 years, with the particle inventory comprised of tailings fractions <5 µm. In contrast, in Scenario 2b, which includes flocculation, virtually all of the tailings particles settle out (Figure 3-26). Only in Scenario 2a does any significant upward transport of tailings solids to the lake surface occur as shown in the TSS exceedance plots (Figure 3-27). For Scenario 2a, the median surface layer TSS concentration is 8 *mg L*$^{-1}$ and the maximum TSS concentration is 40 *mg L*$^{-1}$. In Scenario 2a, only particles smaller <1 *µm* are transported upward into the surface layer, as illustrate in Figure 3-28. In Scenario 2b, which has a minimum particle size of 5 µm, no tailings-derived suspended solids are found in the surface layer.

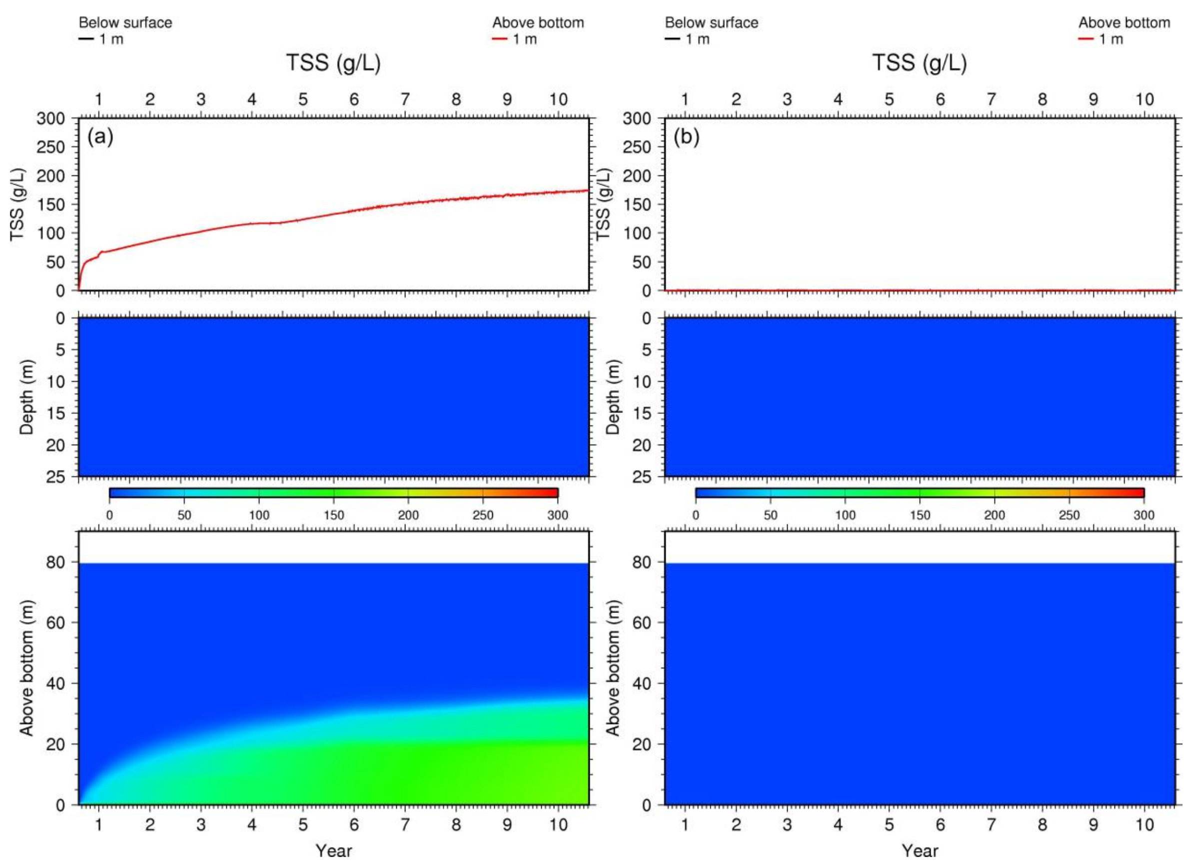


Figure 3-26: PitMod output for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation) – Tailings-derived TSS concentration in Brucejack Lake over a ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

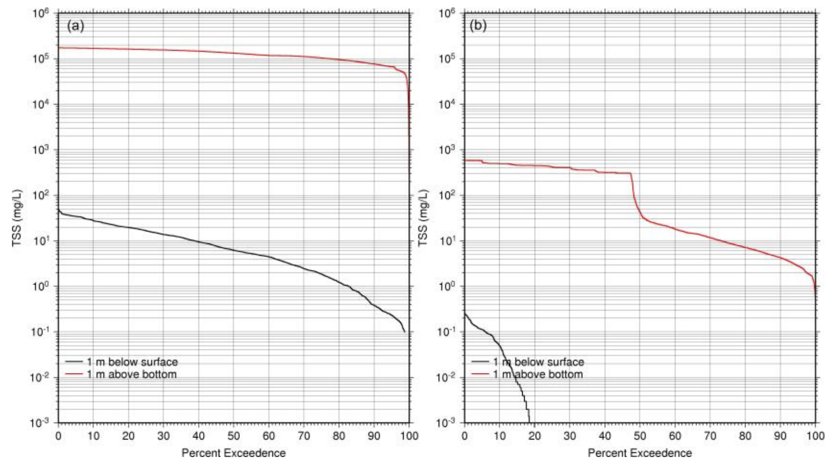


Figure 3-27: Tailings-derived TSS exceedance plots for (a) Scenario 2a (no flocculation) and (b) Scenario 2b (flocculation).

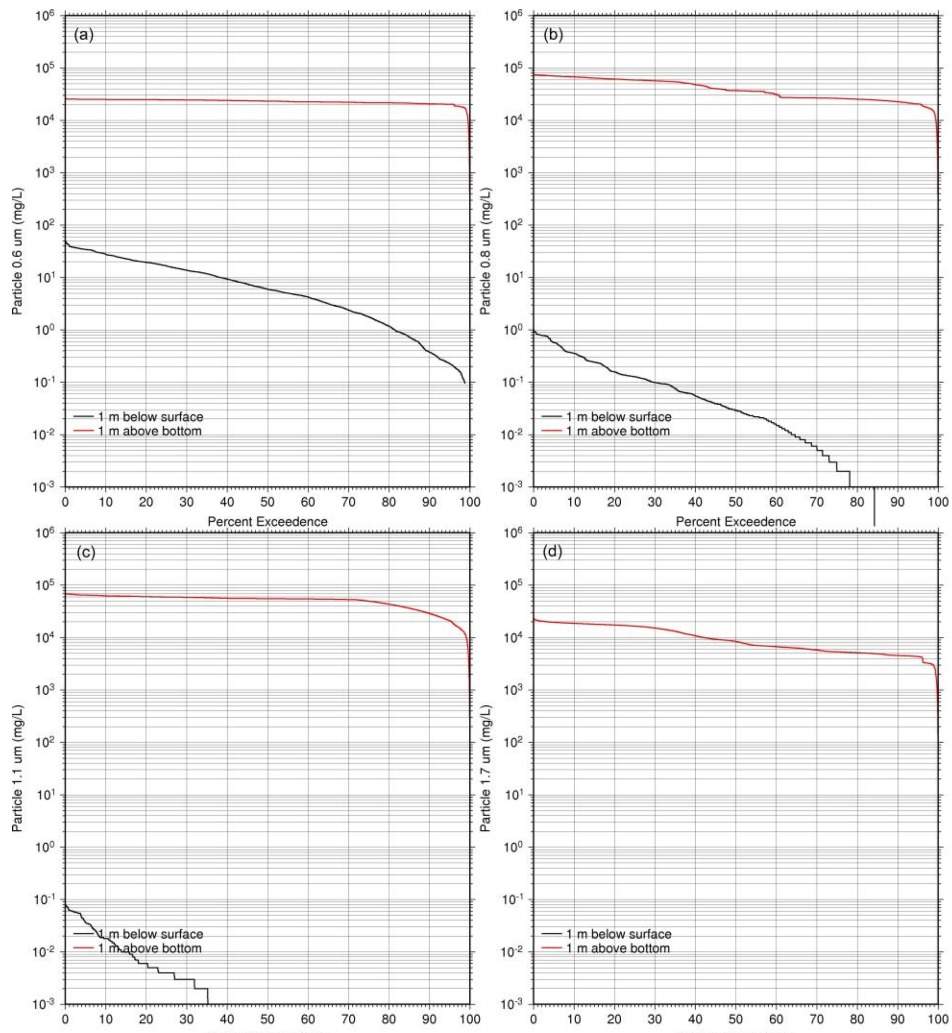


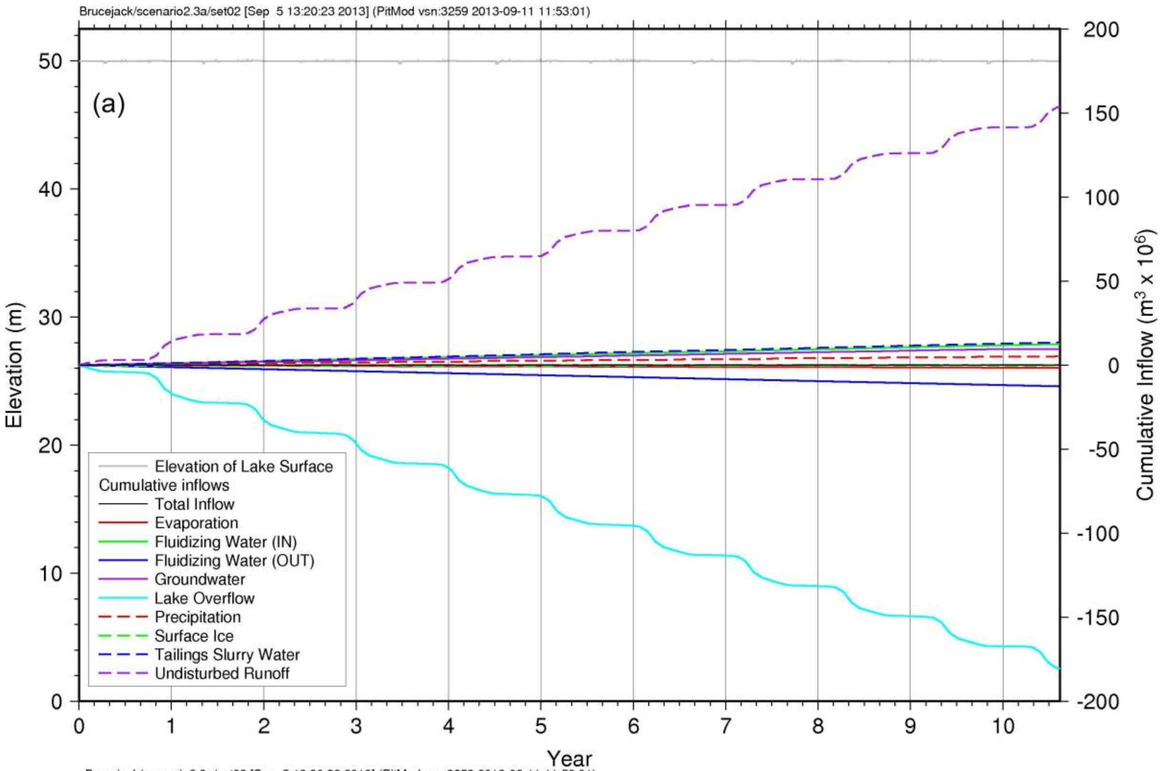
Figure 3-28: Exceedance plots for the four smallest particle sizes in Scenario 2a (no flocculation): 0.6, 0.8, 1.1, and 1.7 µm.

3.3 Scenario 3 (Final Period of Tailings Deposition)

3.3.1 General Features

For the end of operations simulations, the depth and volume of Brucejack Lake are reduced to reflect the final footprint of tailings on the lake floor. The lake volume and surface area are further reduced by the placement of waste rock in the lake. Surface inflows include precipitation and undisturbed runoff, while bottom inflows include tailings slurry water, suspended solids, fluidizing water, and underground mine excess water (Figure 3-29). Water is removed from the lake via evaporation and pumping of fluidizing water. The latter is discharged at the lake bottom with the same properties as the tailings slurry water. Ice formation/melting removes/adds water with no net addition of mass to the lake. Ice depth ranges from 0.7 to 1.0 m, with ice formation typically occurring in late October or early November and open water occurring in July Figure 3-30). Ice formation and melting is not appreciably affected by the tailings discharge.

As is the case with Scenario 2, monthly vertical profiles of density from year 10 of Scenarios 3a (no flocculation) and 3b (flocculation) are very different (Figure 3-31). In Scenario 3a, density increases rapidly beginning at a depth of 26 m to a maximum of nearly 270 σ_t units at the bottom. Above a depth of 26 m, the values of σ_t are too small to be noticeable due to the density scale used. Comparison of the density profiles for Scenarios 3a and 3b shows that virtually all of the suspended solids associated with Scenario 3a (no flocculation) resides in the <5 µm fraction. As observed for Scenario 2a, the density profiles for Scenario 3a show that the increased bulk density imparted by the solids content prevents complete turnover. For Scenario 3b, however, the density time-series indicate that the water column is vertically homogeneous twice each year (dimictic), with turnover occurring in late spring/early summer and again in mid to late fall (Figure 3-32).



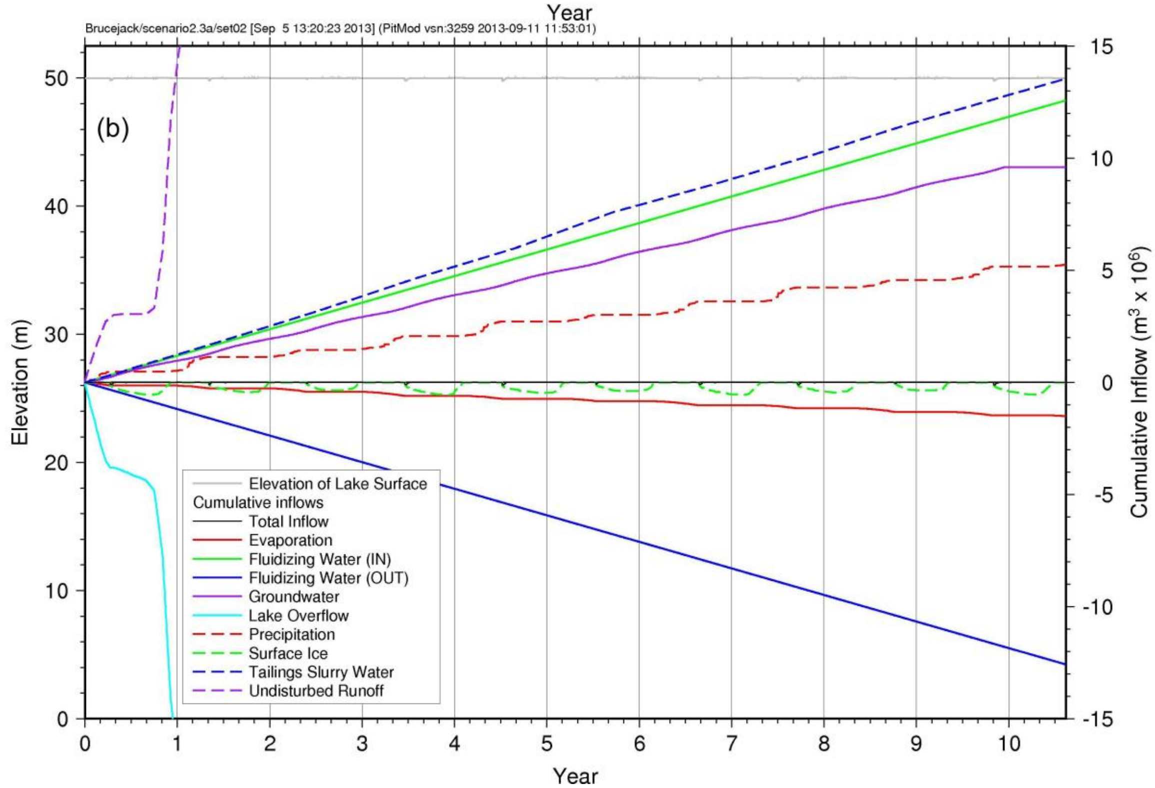


Figure 3-29: PitMod output for Scenario 3 - Cumulative inflow and outflow volumes (bottom image (b) shows expanded scale to reveal detail).

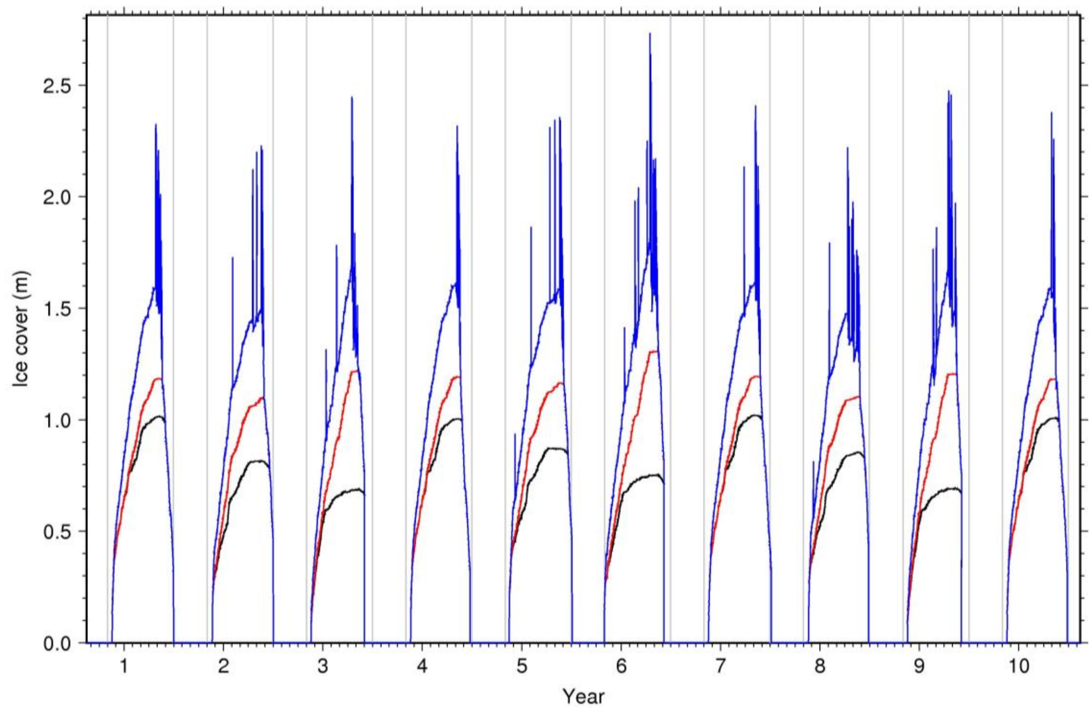


Figure 3-30: PitMod output for Scenario 3 - snow (blue), snow-ice (red), and ice (black). Thicknesses are shown for a 10-year model simulation.

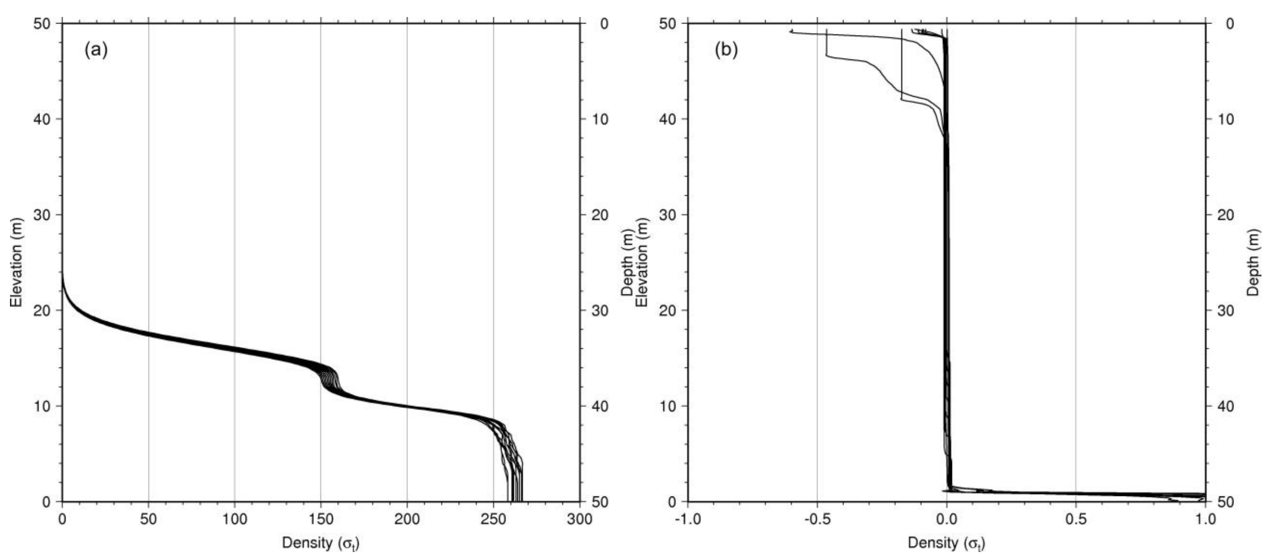


Figure 3-31: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Monthly profiles of density in Brucejack Lake during the final year of a ten-year model simulation (note change of density scale).

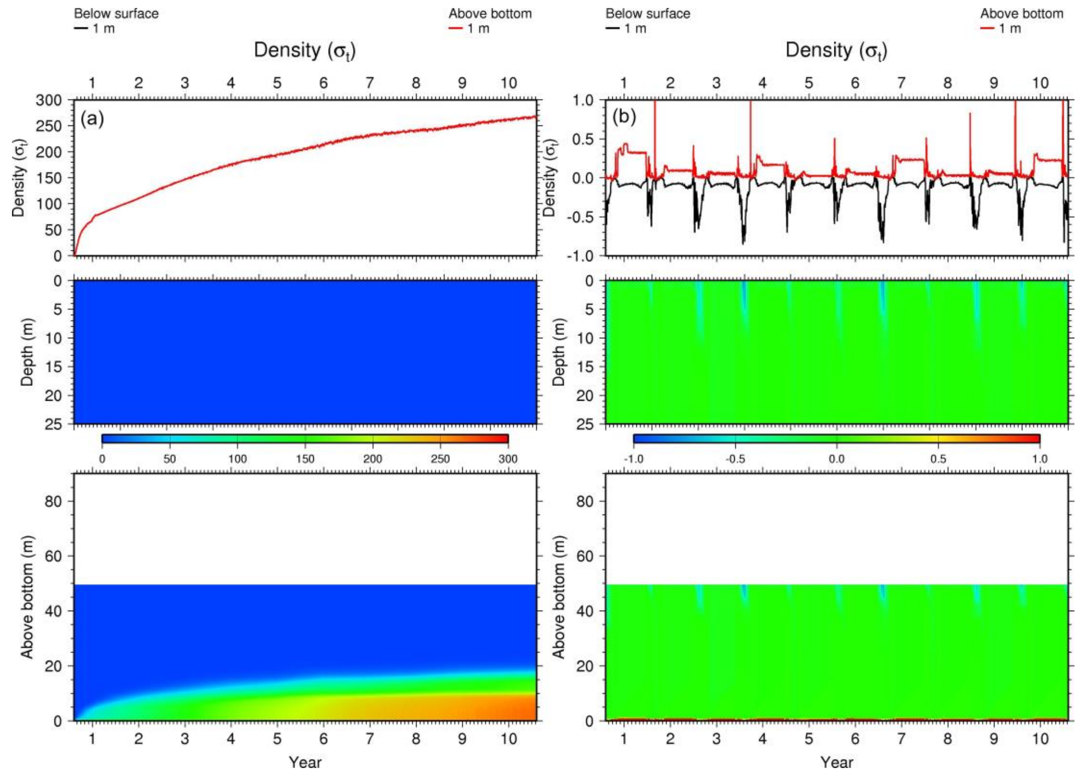


Figure 3-32: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Density in Brucejack Lake over ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom). Note change of density scale between scenarios.

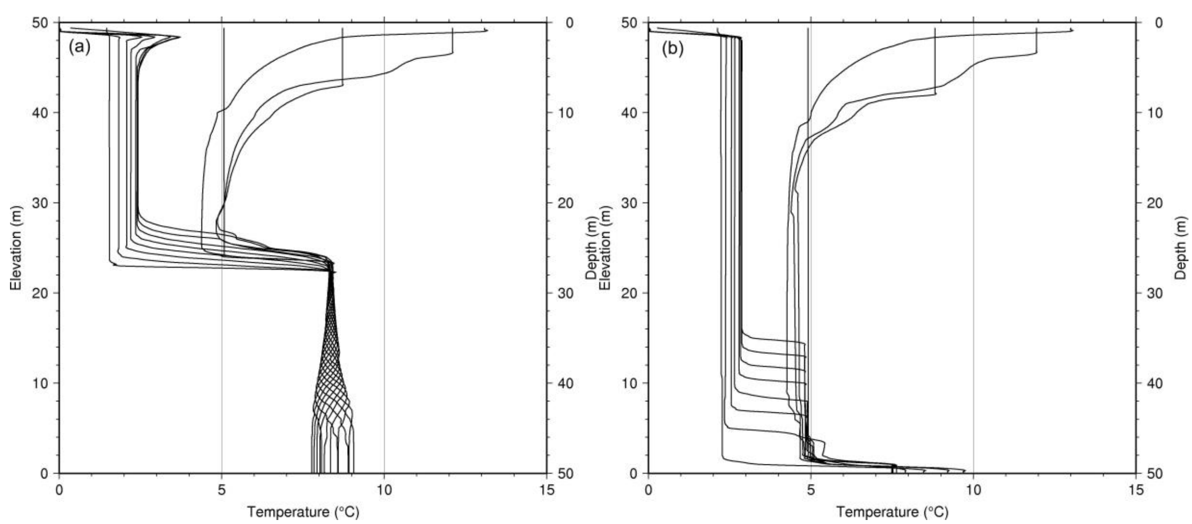


Figure 3-33: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Temperature in Brucejack Lake over 10 year model simulation: surface and bottom layers (top); and variation with depth and time (middle and bottom).

Monthly vertical profiles of temperature from year 10 of the Scenario 3a and 3b simulations show significant seasonal variability at all depths. In Scenario 3a, vertical mixing events penetrate to the top of the suspended solids layer at 26 m depth. Below 26 m, temperature remains between 8º and 9º C reflecting the presence of tailings supernatant. In Scenario 3b, the absence of tailings suspensions allows the water column to mix to the bottom during some months; temperatures near the bottom range from 2º to 10º C. Shallower than 24 m, both Scenarios 3a and 3b exhibit very similar thermal structures throughout the year, suggesting that the upper layer responds independently of the bottom layer. Maximum annual temperatures in surface waters range from 13º to 15º C (Figure 3-33). Such temperature fluctuations contribute to seasonal density fluctuations in the surface layer (shown in Figure 3-34).

The input of saline water associated with the tailings discharge and subsequent vertical mixing results in higher water column salinity in comparison to existing conditions (Scenario 1) (Figure 3-35 and Figure 3-36). In Scenario 3a, salinity remains nearly constant between 10 m and 20 m depth, and from 28 m to the bottom. Between 20 m and 28 m there is a very strong halocline due to the presence of saline tailings supernatant below 28 m. As noted above, the high bulk density of the tailings suspension presents an effective barrier to downward mixing; hence, the higher salinity supernatant in the bottom layer is not diluted by fresher water from above. As discussed previously, the variation in salinity near the surface (0.025 to 0.10‰) is caused by the seasonal variation in freshwater surface inflow and by ice formation and melting.

Consistent with Scenario 2, the halocline in the deep waters for Scenario 3b is less pronounced in comparison to Scenario 3a (Figure 3-35 and Figure 3-36). For Scenario 3b, a deep halocline is evident at a range of depths within the bottom 18 m of the lake. The weaker and less persistent salinity gradients in Scenario 3b relate to more complete vertical mixing in the absence of a thick layer of suspended tailings particles.

3.3.2 Lake Mixing and Flushing

The monthly profiles from year 10 of the Scenario 3 model simulations show that for both Scenarios 3a and 3b, vertical mixing transports tailings supernatant upward into the lake surface layer (Figure 3-37). In both scenarios, the upper layer effluent concentration reaches the same value of approximately 25% (3:1 dilution). In the uppermost 10 m, effluent concentrations vary markedly owing to seasonal changes in the runoff input. Plots of effluent concentration over the 10-year model duration show that at the end of the 10-year model period, the surface layer effluent concentrations in both Scenarios 3a and 3b are quite similar over an annual cycle (Figure 3-38).

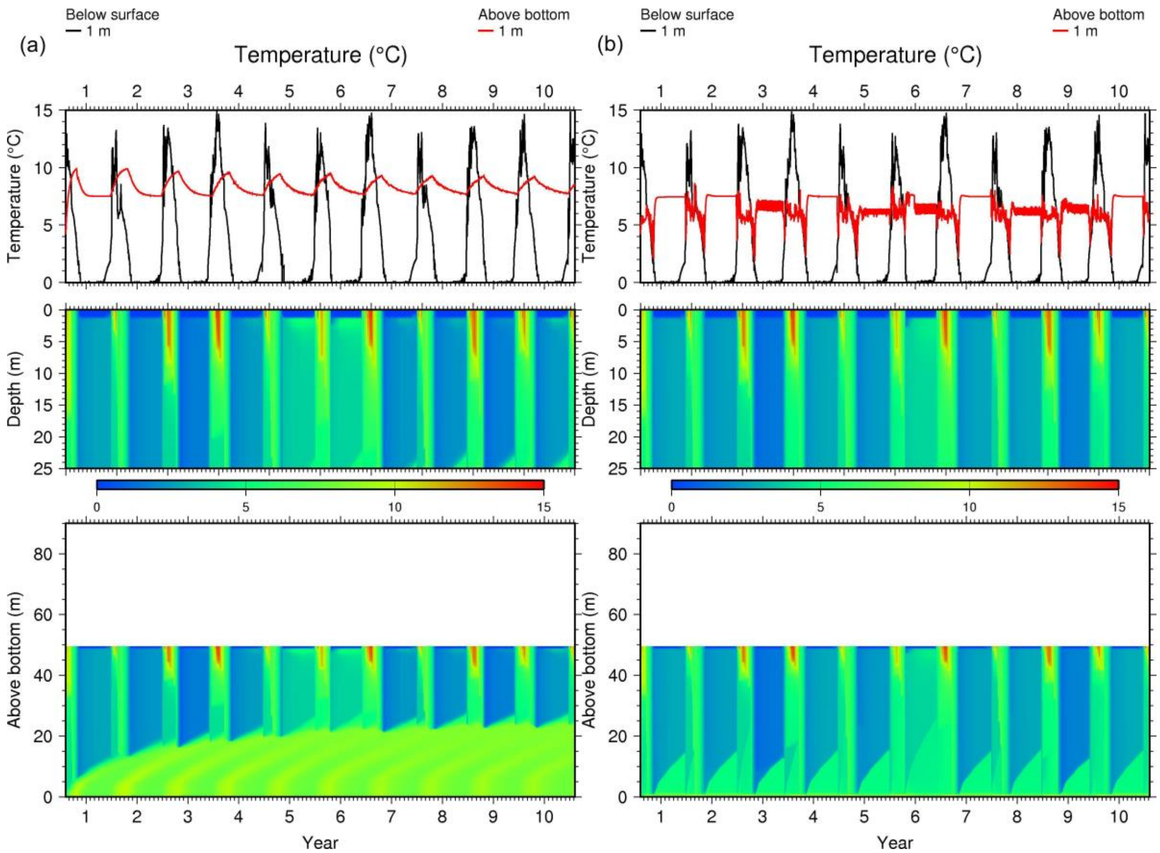


Figure 3-34: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Temperature in Brucejack Lake 10 year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

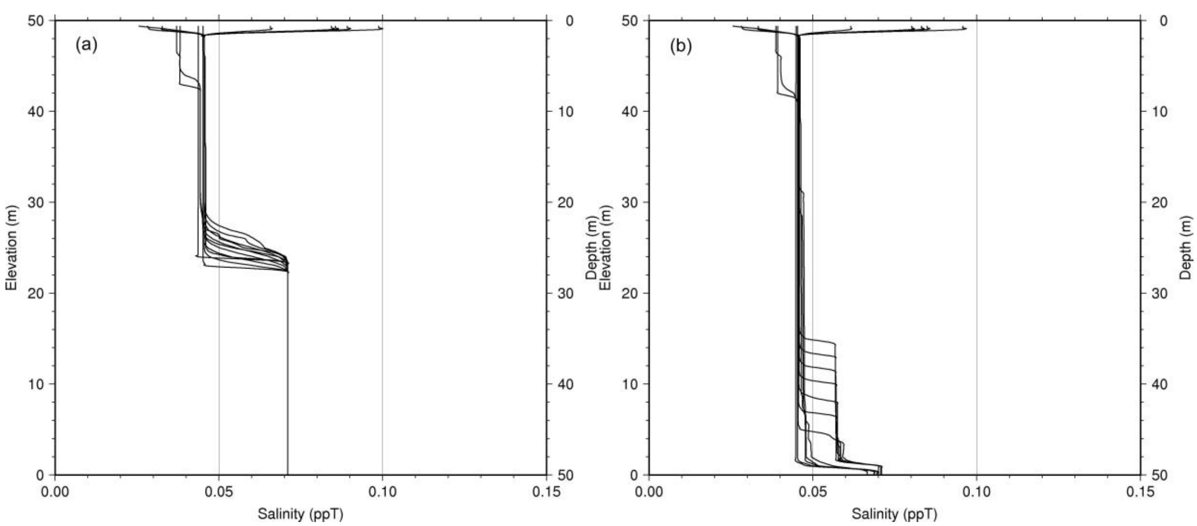


Figure 3-35: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Monthly profiles of salinity in Brucejack Lake during the final year of a ten-year model simulation.

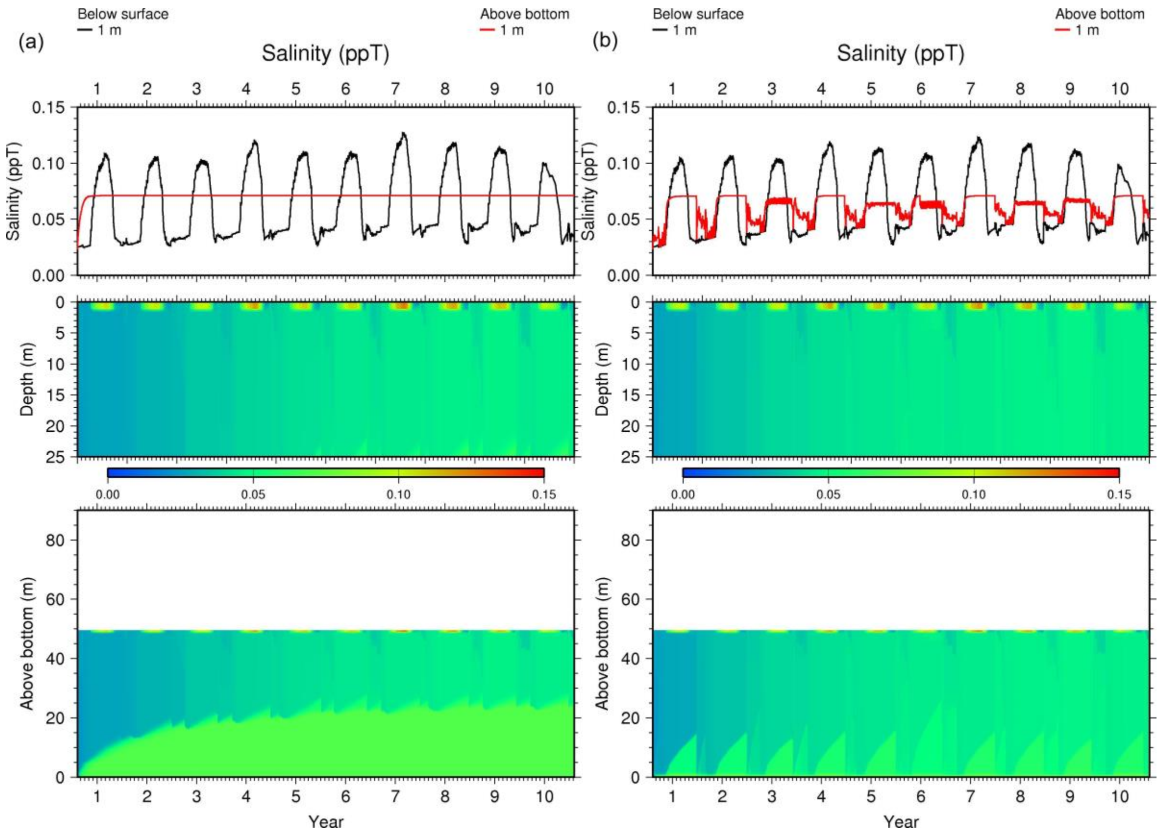


Figure 3-36: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Salinity in Brucejack Lake over ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

In the surface layer, maximum monthly mean effluent concentrations of 13-18% (Scenario 3a) and 15-23% (Scenario 3b) are predicted to occur between October and April, while minimum monthly means of 4-13% (Scenario 3a) and 5-18% (Scenario 3b) are predicted from May through September (Table 3-2). The annual mean surface layer concentration of tailings effluent for Scenario 3a is 14% and for Scenario 3b is 18% (over 10-year simulation). The median effluent concentration at 1 m depth is approximately 15% (7:1 dilution) for Scenario 3a and approximately 19% (5:1 dilution) for Scenario 3b. The maximum concentration is 35% (2.9:1 dilution) for Scenario 3a and 34% (2.9:1 dilution) for Scenario 3b (Figure 3-39). The effluent percentages in the surface waters for Scenario 3 (shallower lake depth) are greater than those for Scenario 2 (deeper lake depth), illustrating a greater influence of the tailings discharge under end-of-mine conditions.

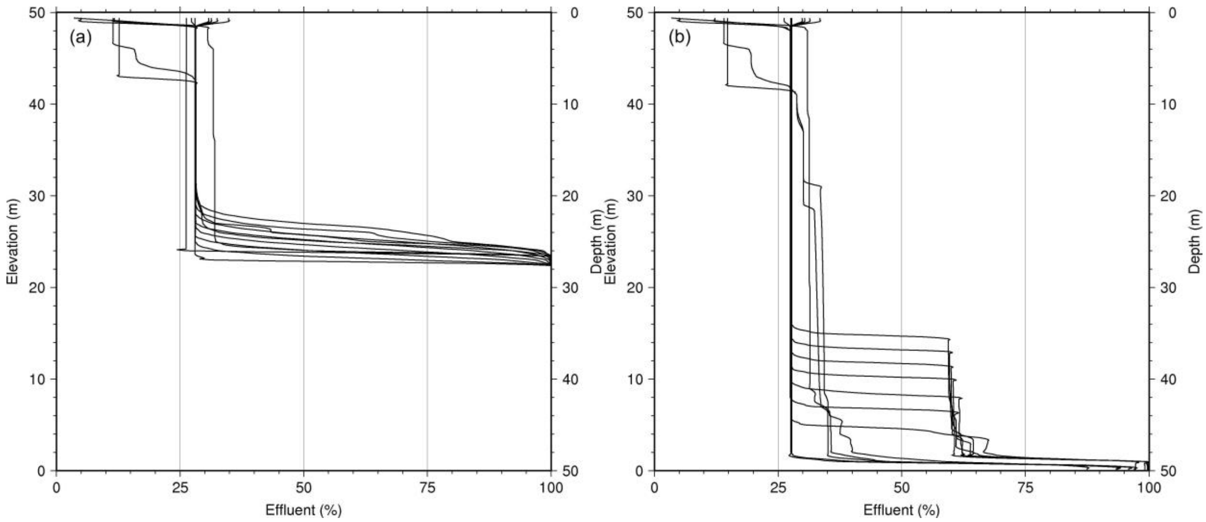


Figure 3-37: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Monthly profiles of effluent concentration in Brucejack Lake during the final year of a ten-year model simulation.

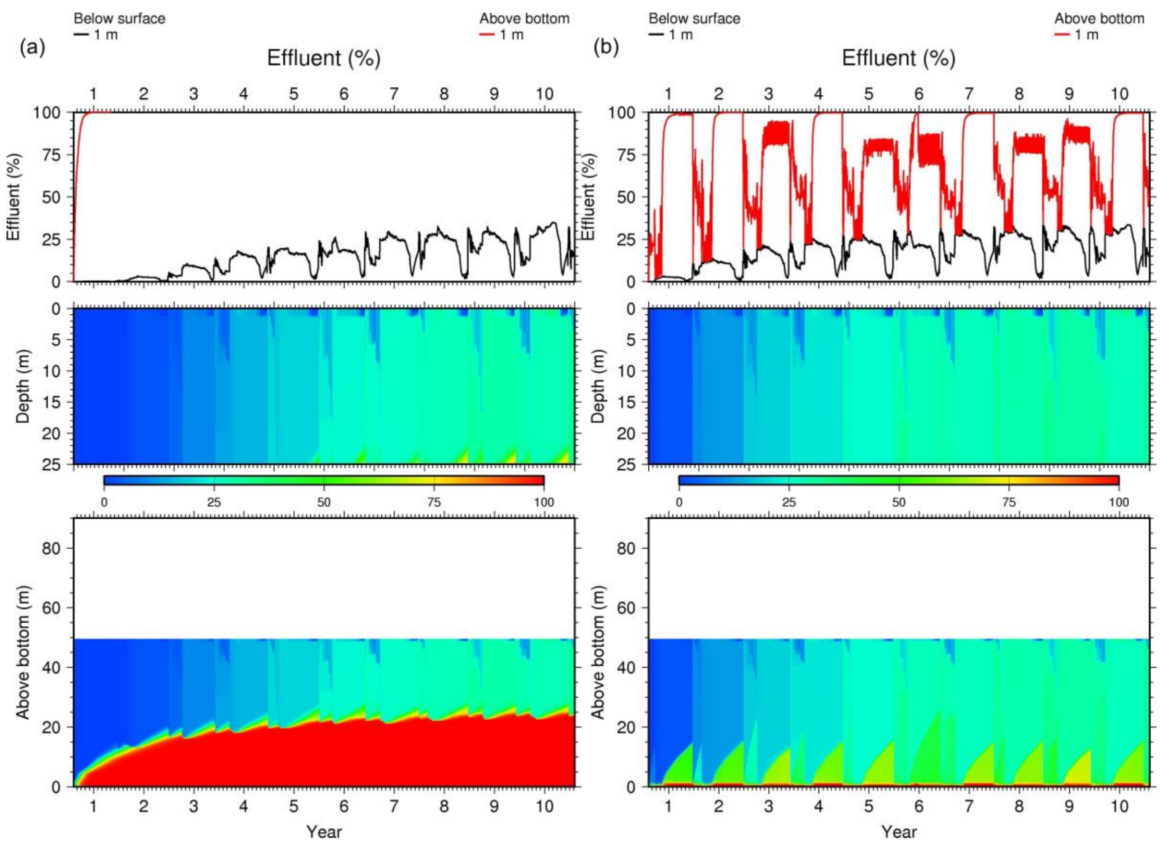


Figure 3-38: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Effluent concentration in Brucejack Lake over ten year model simulation: surface and bottom layers (top); and variation with depth and time for upper 25 m (middle) and entire water column (bottom).

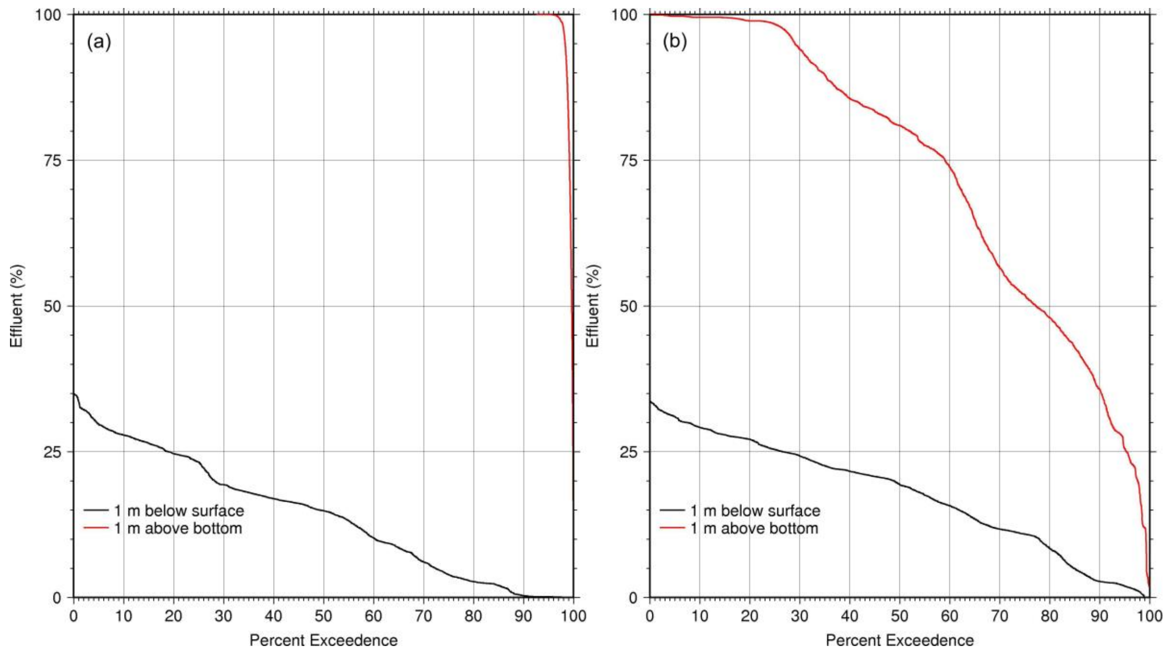


Figure 3-39: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - Effluent concentration: percent exceedance in the surface and bottom layers of Brucejack Lake during a 10-year model simulation. The median effluent concentration at 1 m depth is approximately (a) 15% (6.7:1 dilution) (b) 19% (5.3:1 dilution).

Table 3-2:
Scenarios 3a and 3b - Modelled monthly mean effluent concentrations in the surface layer of Brucejack Lake over the 10-year model period.

Month	**Mean Effluent Concentration (%)**		**Month**	**Mean Effluent Concentration (%)**	
	(3a)	**(3b)**		**(3a)**	**(3b)**
Jan	17	22	Jul	13	18
Feb	17	21	Aug	11	15
Mar	17	20	Sep	12	17
Apr	13	16	Oct	17	22
May	4	5	Nov	18	23
Jun	11	14	Dec	18	22
Annual				**14**	**18**

3.3.3 Suspended Solids

The vertical and temporal variations of TSS in the Scenario 3a and 3b simulations are presented in Figure 3-40, with the corresponding exceedance plots presented in Figure 3-41. Scenario 3a (no flocculation) predicts the formation of a dense layer of suspended solids occupying the bottom 20 m of the lake after 10 years, while in Scenario 3b (with flocculation), virtually all of the tailings particles settle out (Figure 3-40). As observed for Scenario 2a, only Scenario 3a shows evidence of significant transport of tailings particles into the surface layer (Figure 3-41). For Scenario 3a, the median surface layer TSS concentration is 9 $mg\ L^{-1}$ while the maximum TSS concentration is 60 $mg\ L^{-1}$. In this regard, only particles smaller than approximately 1 μm are transported upward into the surface layer (Figure 3-42). In Scenario 3b, which has a minimum particle size of 5 µm, suspended solids are not predicted to migrate into the surface layer.

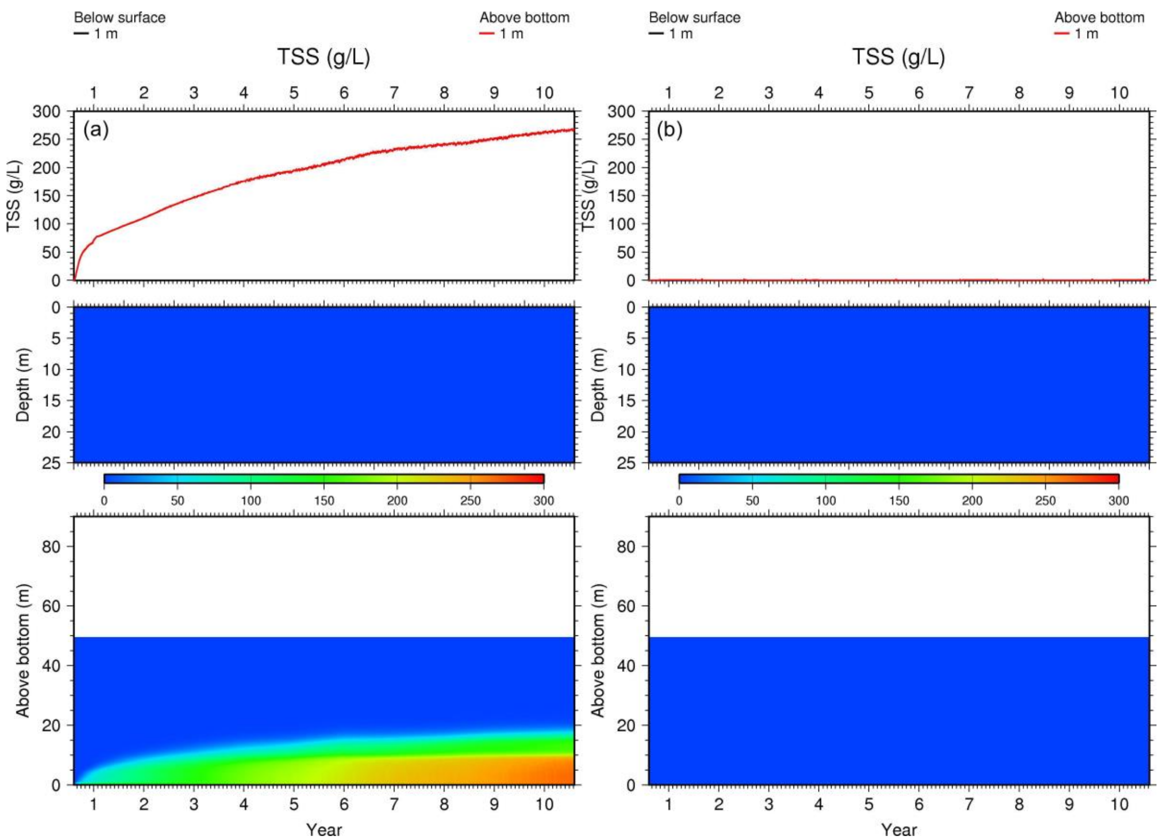


Figure 3-40: PitMod output for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation) - TSS concentration in Brucejack Lake over 10 year model simulation: surface and bottom layers (top); variation with depth and time for upper 25 m (middle & entire water column (bottom).

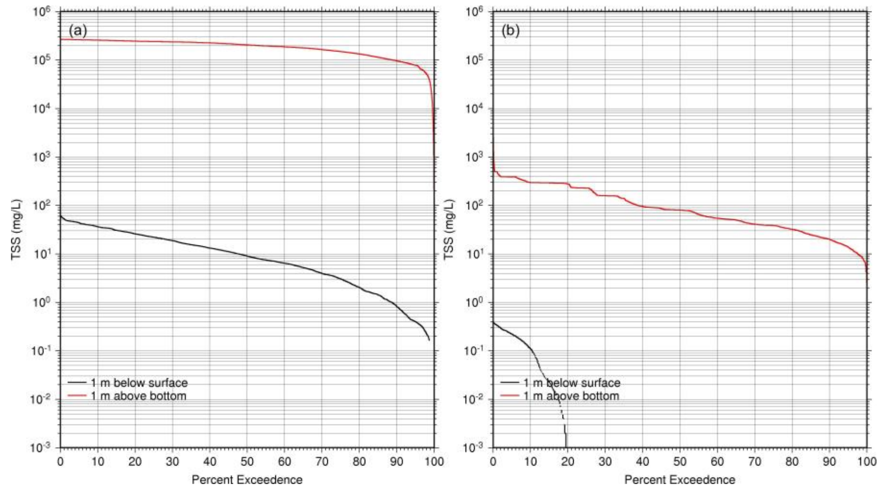


Figure 3-41: TSS Exceedance plots for (a) Scenario 3a (no flocculation) and (b) Scenario 3b (flocculation).

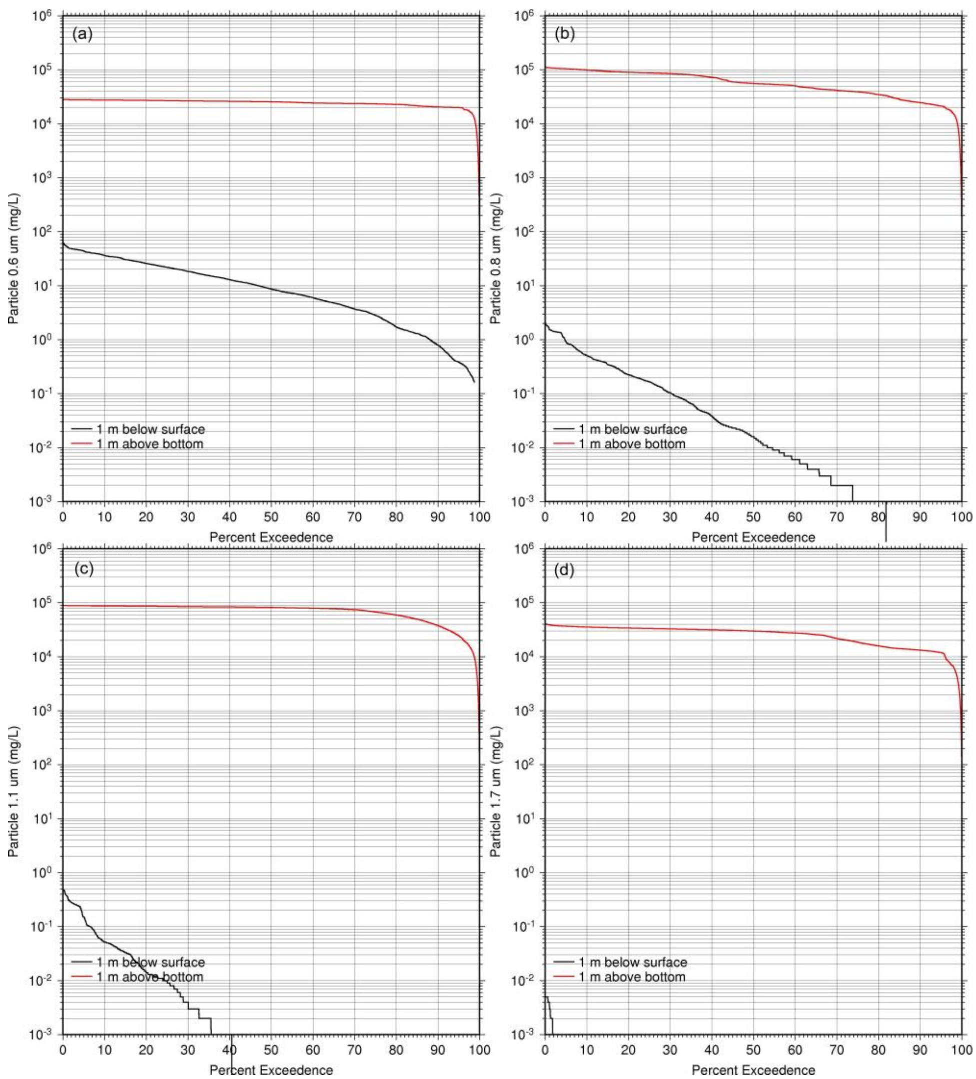


Figure 3-42: Exceedance plots for the four smallest particle sizes in Scenario 3a (no flocculation): 0.6, 0.8, 1.1, and 1.7 µm.

4. Conclusions and Recommendations

4. Conclusions and Recommendations

The most salient conclusions from this report are summarized below. Relevant properties of the three model scenarios and general results from the model simulations are summarized in Table 4-1. Recommendations for future consideration are also presented.

Conclusions:

- Temperature, salinity and density profiles produced by the Scenario 1 model simulation were compared with measured profiles from July, September, and December 2012. Although the field measurements and the model results show some differences between individual profiles, the model reproduces the dimictic behaviour believed to be characteristic of Brucejack Lake (*i.e.*, two turnover events per year). Overall, both the model output and observed field data suggest convective overturn is the primary mechanism for mixing bottom waters upward into the surface layer.
- Differences between the Scenario 1 (existing conditions) model predictions and field measurements of temperature, salinity, and density are predicted to result primarily from the groundwater inflows specified in the model. These inputs are specified as seasonally varying inflows within ten layers extending throughout the full depth of the lake. The groundwater inflows are heavily weighted toward the near-surface of the lake, and therefore introduce dense, saline water to the surface layer. This water then sinks and mixes with deeper waters, transporting heat and salt downward in the process. Overall, the results demonstrate that the model overestimates the degree of mixing in the lake. This imparts a considerable degree of conservatism from which to assess lake mixing and the potential for the introduction of tailings solids and supernatant into the lake surface.
- The input of more saline water associated with the tailings discharge and subsequent vertical mixing results in higher water column salinity in comparison to existing conditions. The addition of tailings supernatant also results in the upward movement of water in the lake as the added volume of effluent mixes with and displaces resident bottom waters.

Table 4-1:
Summary of Scenario Information and Model Results

Item	**Sub-Item**	**Scenario 1**	**Scenario 2b**	**Scenario 3b**
Description		Existing	Start of discharge	End of discharge
Lake discharge elevation		1366.4 m	1366.4 m	1366.4 m
Lake bottom elevation		1281.4 m	1281.4 m	1311.4 m
Max Lake depth		85 m	85 m	55 m
Max Lake surface area		69.59 ha	69.59 ha	59.65 ha
Max Lake volume		28.46 Mm^3	28.46 Mm^3	20.26 Mm^3
Inflows	Surface Runoff	Yes	Yes	Yes
	Groundwater	Yes	Yes	Yes
	Tailings Slurry	No	Yes	Yes
	Mine Excess	No	Yes	Yes
	Fluidizing water	No	Yes	Yes
Outflows	Fluidizing water	No	Yes	Yes
Results				
Ice/snow thickness		[0.7,1.1 m]	[0.7,1.0 m]	[0.7,1.0 m]
Density (sigma t)	pycnocline depth	15 m	15 m	10 m
	surface range	[-.74,-.02]	[-.70,.01]	[-.55,.05]
	dimictic	Yes	Variable	Variable
Temperature (°C)	surface range	[0°,14°]	[0°,14°]	[0°,13°]
	maximum	[13°,17°]	[13°,17°]	[13°,15°]
Salinity (ppt)	surface range	[.025,.035]	[.039,.135]	[.040,.170]
	sub-surface	.025	.090	.090
Effluent (%)	surface range	—	[3-15%]	[5-22%]

- The model predictions for Scenarios 2 and 3 reveal the critical role that the tailings particles have in regulating lake stratification and mixing characteristics. In the absence of flocculation, tailings suspensions (<1 µm particle size) occupy a dense layer in the lower portion the lake that inhibits vertical mixing below the pycnocline, but does not inhibit the upward movement of supernatant. The thickness of the dense bottom layer is governed by a dynamic equilibrium between the upward advection velocity generated by the tailings discharge and the downward particle settling velocities. In the case where flocculation limits the minimum particle size to 5 µm (Scenarios 2b and 3b), this dense layer of suspended particles is absent, and the stratification in the lake is predicted to be similar to existing conditions.

- For Scenario 2a (initial period of tailings discharge with flocculation), the interaction of tailings effluent in surface waters reaches an approximate steady-state after ~7 years. The maximum proportion of effluent in the surface layer is observed between October and April (15-19%), while minimum monthly proportions (7-15%) are observed in May through September. The annual mean proportion of tailings effluent in surface water for Scenario 2a is 15%.
- For Scenario 3b (final period of tailings discharge with flocculation), the range in the proportion of tailings effluent in surface waters (5 to 23%) is higher in comparison to Scenario 2b (7-15%). The results indicate that on a seasonal basis, the proportion of effluent in lake discharges has the potential to be higher under conditions of a shallower water column (end-of-mine conditions).
- The addition of flocculant, and the imposition of a 5 µm minimum particle size cutoff, has a critical effect on suspended solids concentrations in the lake. In the absence of flocculant, the model predicts significant suspended particle concentrations in the lake surface, with a median surface layer TSS concentration for Scenario 2a of 8 mg L^{-1} (maximum = 40 mg L^{-1}). The bulk of the particle inventory in the surface layer resides in the <1 µm size fraction. In contrast, the results for Scenarios 2b and 3b (flocculant addition) predict that tailings particles will not migrate into the surface layer of the lake if the minimum particle diameter is greater than or equal to 5 µm.
- For Scenario 3a (end-of-mine conditions in absence of flocculation), the median and maximum surface layer TSS concentrations are higher (9 mg L^{-1} and 60 mg L^{-1}, respectively), illustrating the greater effect of the tailings discharge under conditions of a shallower water column.

Recommendations:

- The model results demonstrate that the potential for tailings particle migration into lake surface waters is strongly dependent on particle size. Monitoring during the early period of operation will be essential to verify tailings particle size assumptions and to ensure that tailings solids remain in the lower lake depths. In this regard, this report does not address mitigation or contingency measures that relate to TSS management in Brucejack Lake. Further, the potential effects of waste rock deposition on water quality and TSS levels were not considered.
- The model results demonstrate that the lake mixing properties are sensitive to the prescribed groundwater inputs with respect to depths of the groundwater inflows

and their associated salinity. If future refinements to the groundwater inflow model are conducted, consideration should be given to re-running the model scenarios.

- The physical stability of the water column will be strongly sensitive to the salinity of mine-related inputs. Accordingly, if the salinity of the inputs changes as part of on-going assessment, it would be advisable to re-run to model to assess the effect on lake circulation and stratification.

References

References

Crusius J., Dunbar D., McNee J.J. (2002) Predictions of pit lake water column properties using a coupled mixing and geochemical speciation model., Transactions for the Society for Mining, Metallurgy and Exploration, Feb. 26-28, 2001, Denver, Colorado, USA. Vol. 312: 49-56, Denver.

Dunbar D., Pieters, R., McNee, J.J. (2004) Modeling a negatively buoyant plume and related surface dissolved metal removal in the Equity MainZone Pit Lake. U.S. EPA Pit Lakes Conference. November 16-18, 2004, Reno, Nevada, USA.

Appendix A
Meteorological Inputs to Model

PRETIVM

Appendix A: Meteorological Inputs to Model

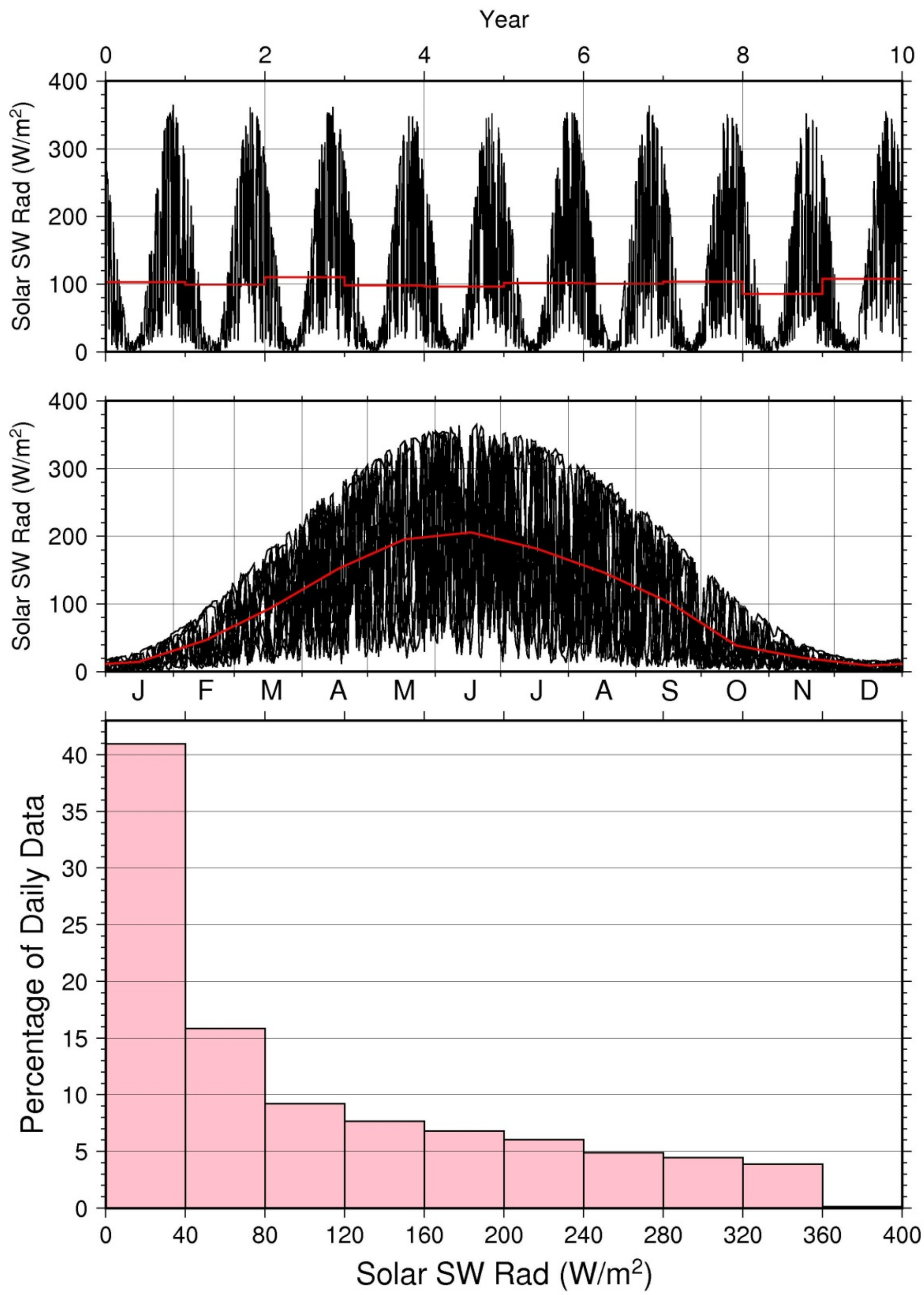


Figure A-1: Incident shortwave radiation flux used in the Brucejack Lake model (source: NCEP 1983-2009)

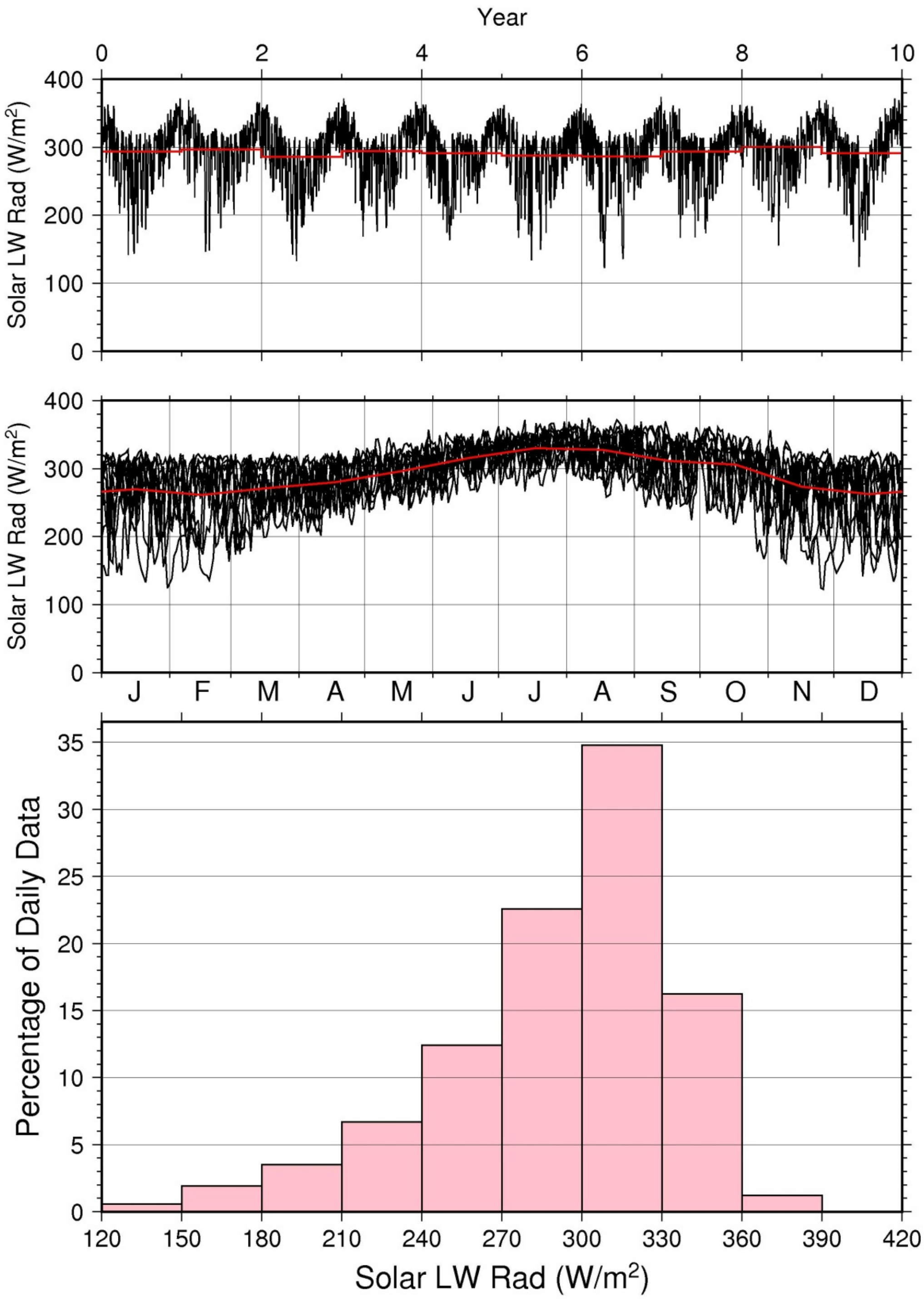


Figure A-2: Incident longwave radiation flux used in the Brucejack Lake model (source: NCEP 1983-2009)

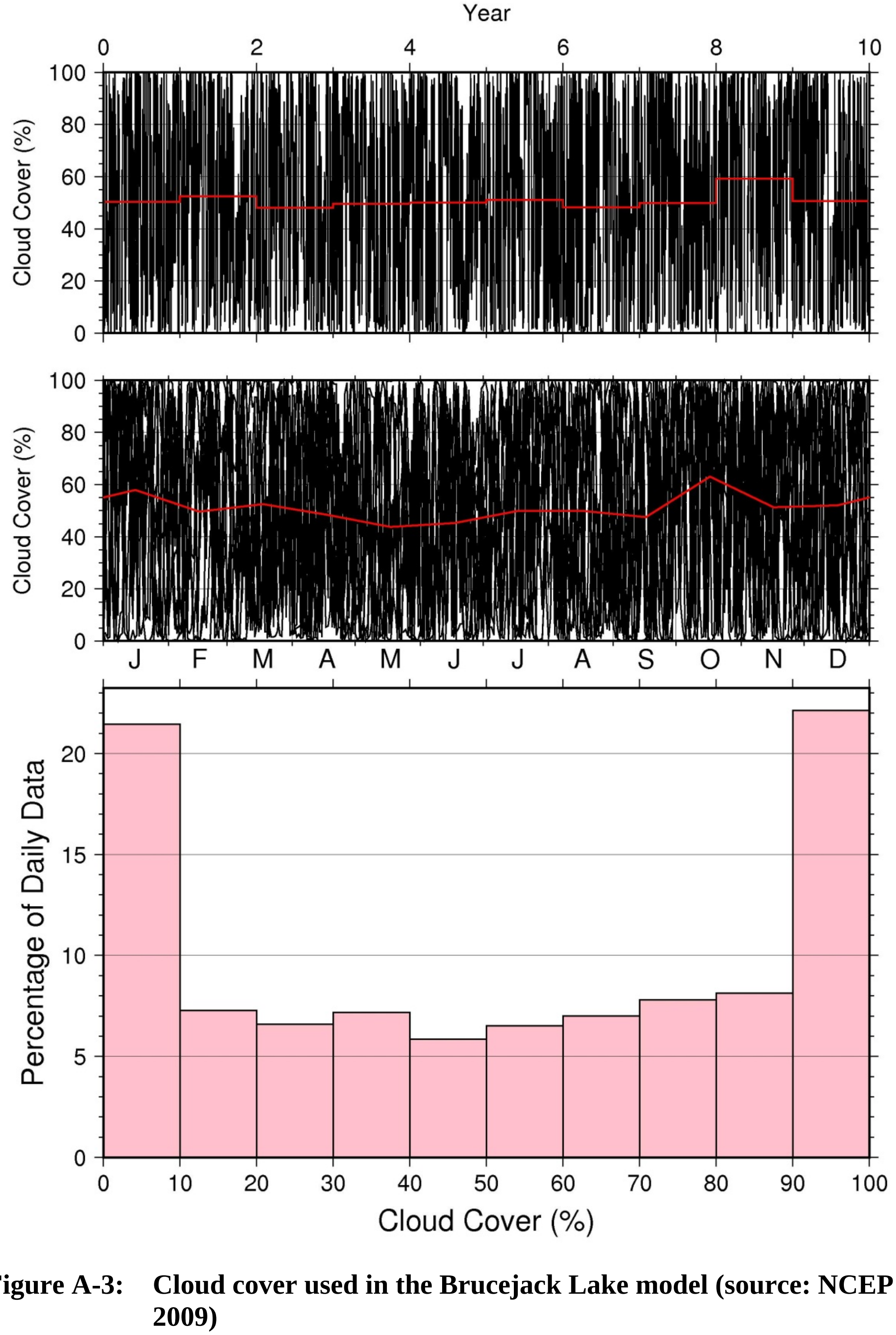


Figure A-3: Cloud cover used in the Brucejack Lake model (source: NCEP 1983-2009)

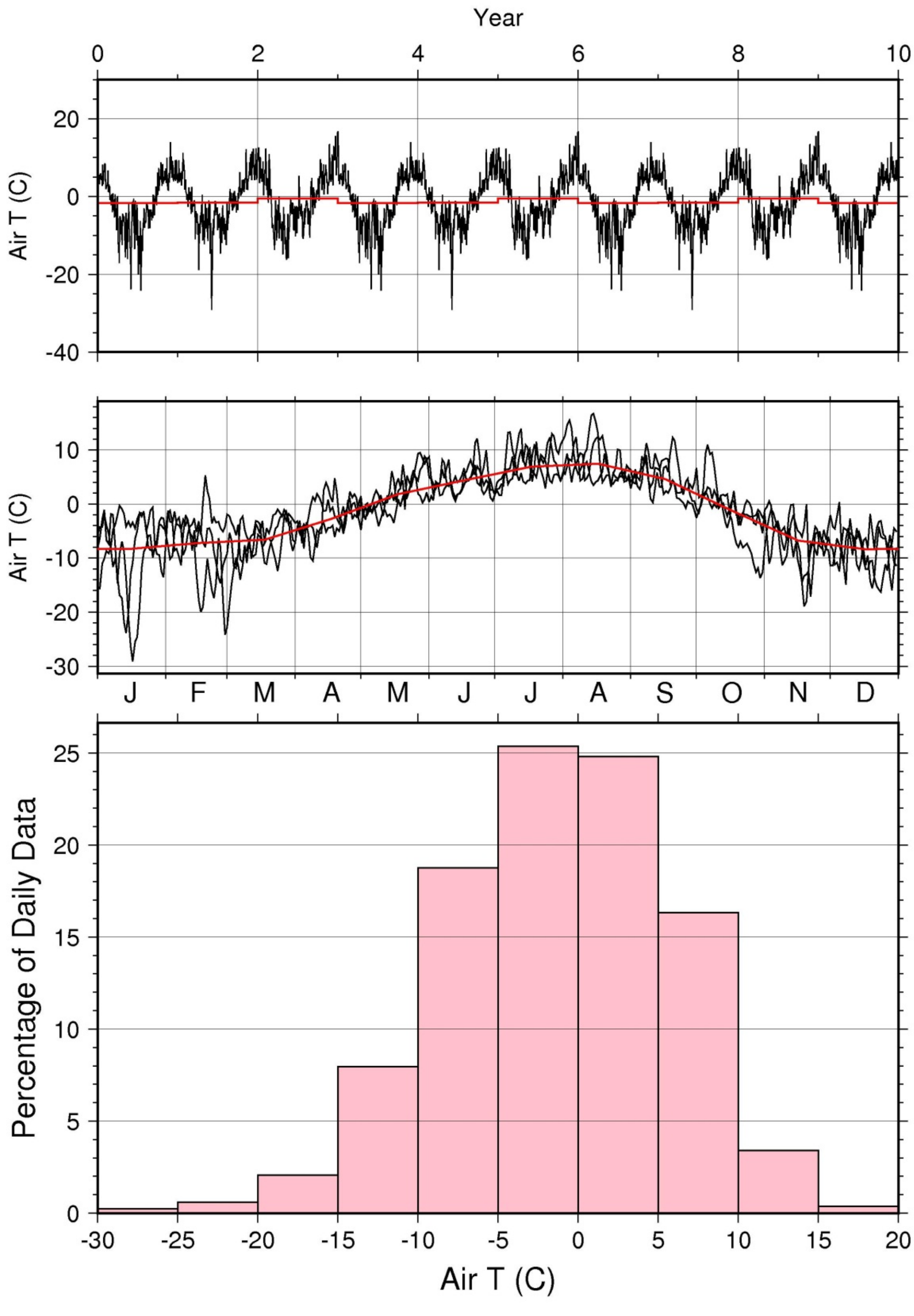


Figure A-4: Mean daily air temperature used in the Brucejack Lake model (site measurements)

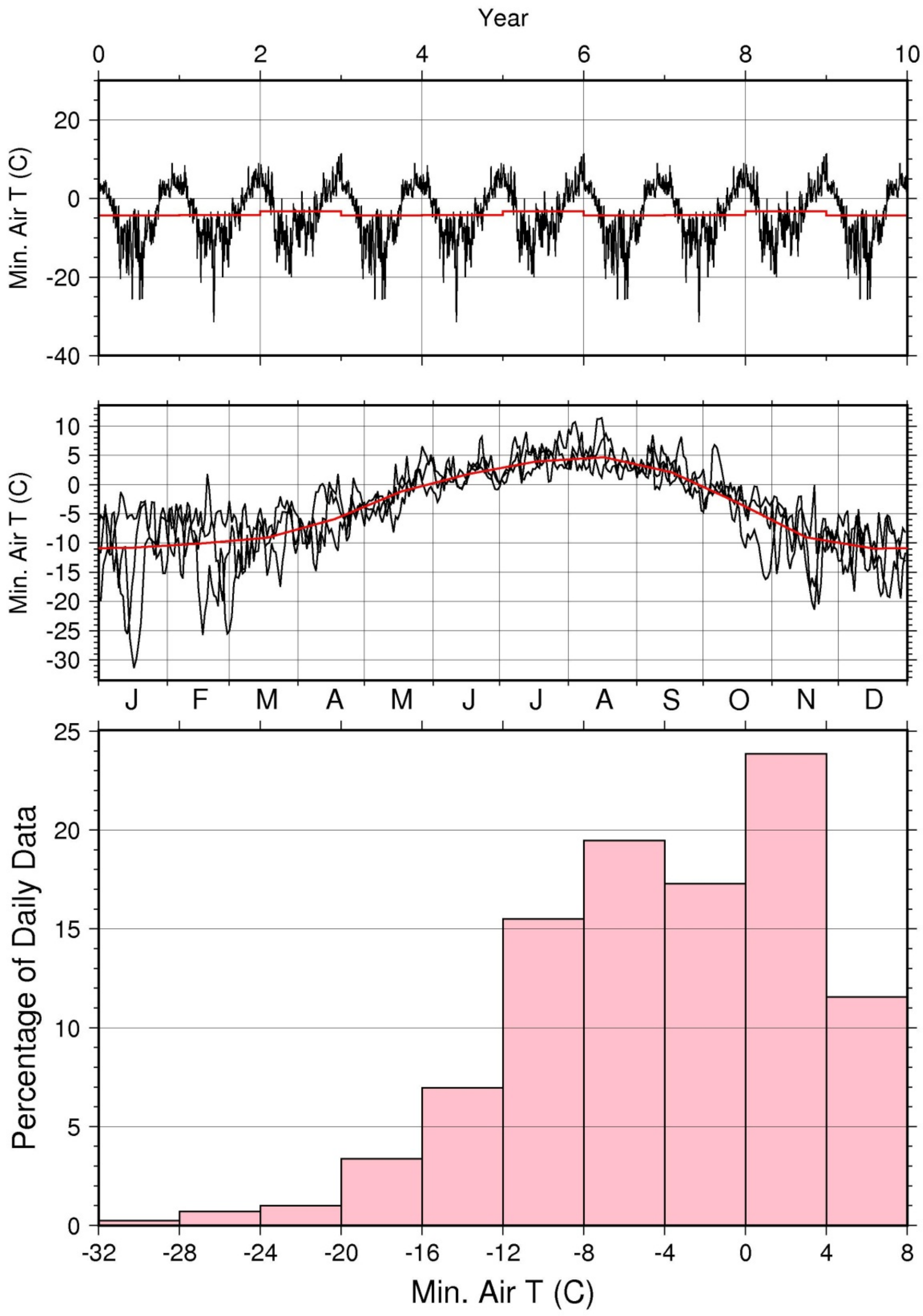


Figure A-5: Minimum daily air temperature used in the Brucejack Lake model (site measurements)

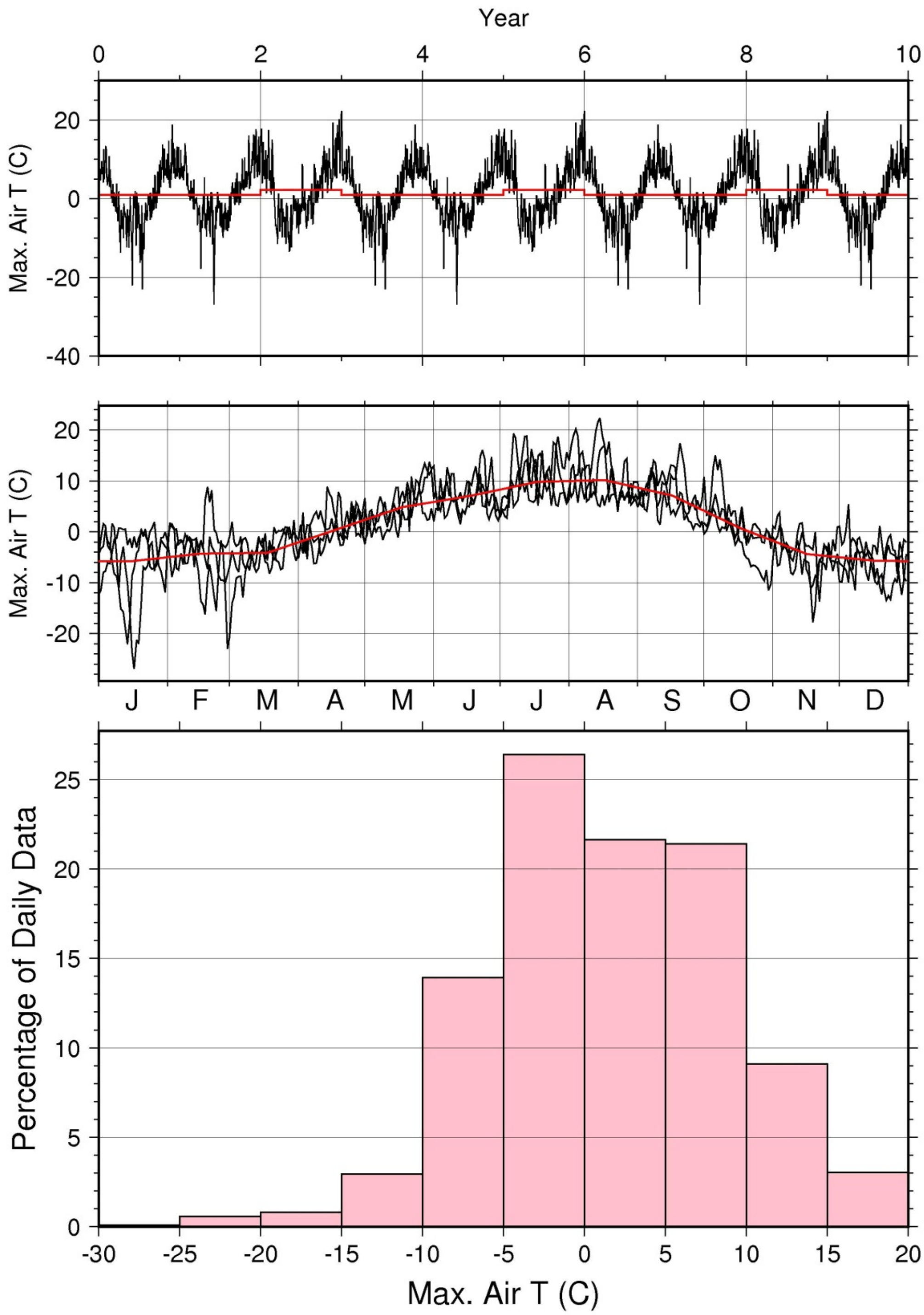


Figure A-6: Maximum daily air temperature used in the Brucejack Lake model (site measurements)

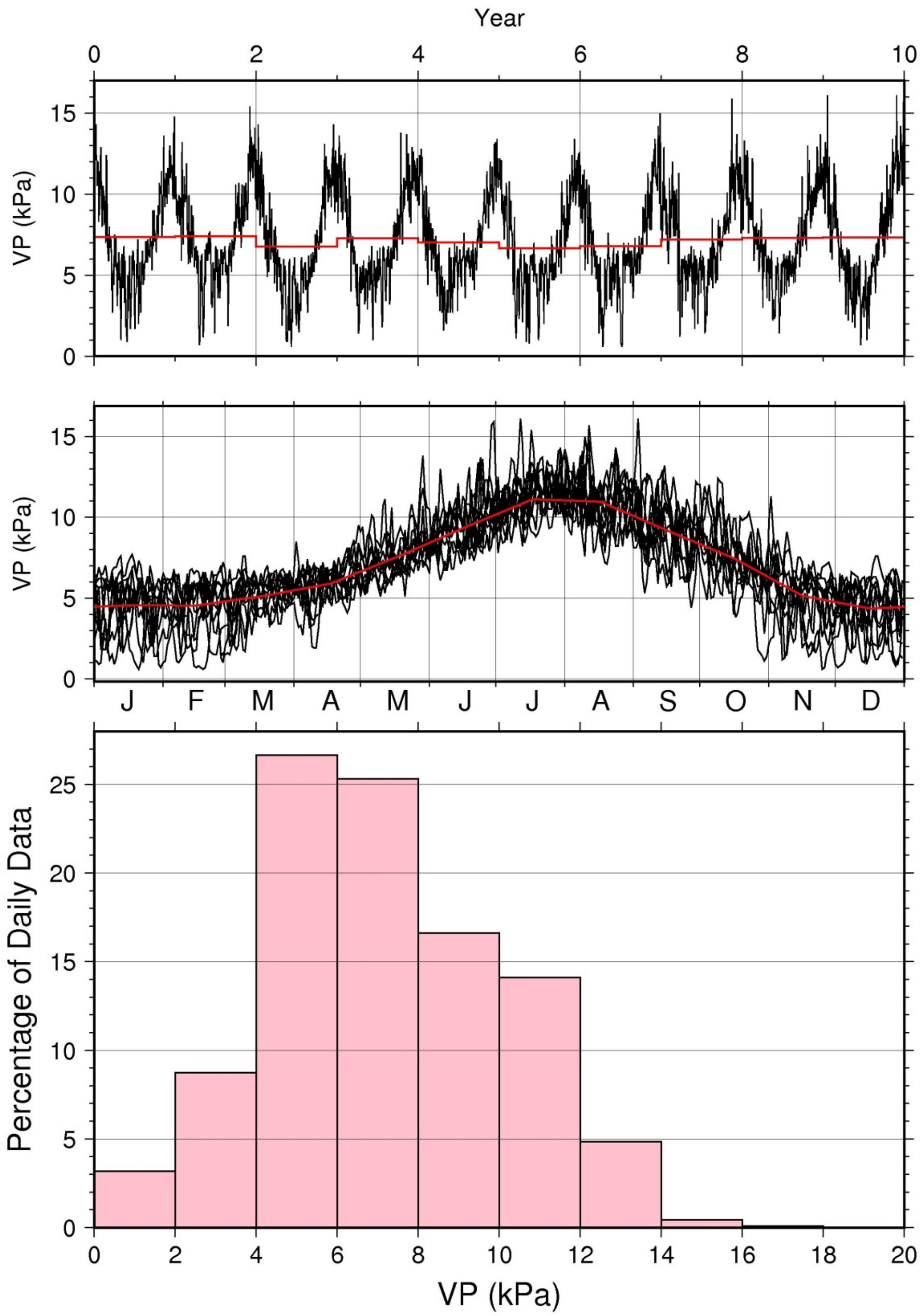


Figure A-7: Mean daily Vapour Pressure used in the Brucejack Lake model (source: NCEP 1983-2009)

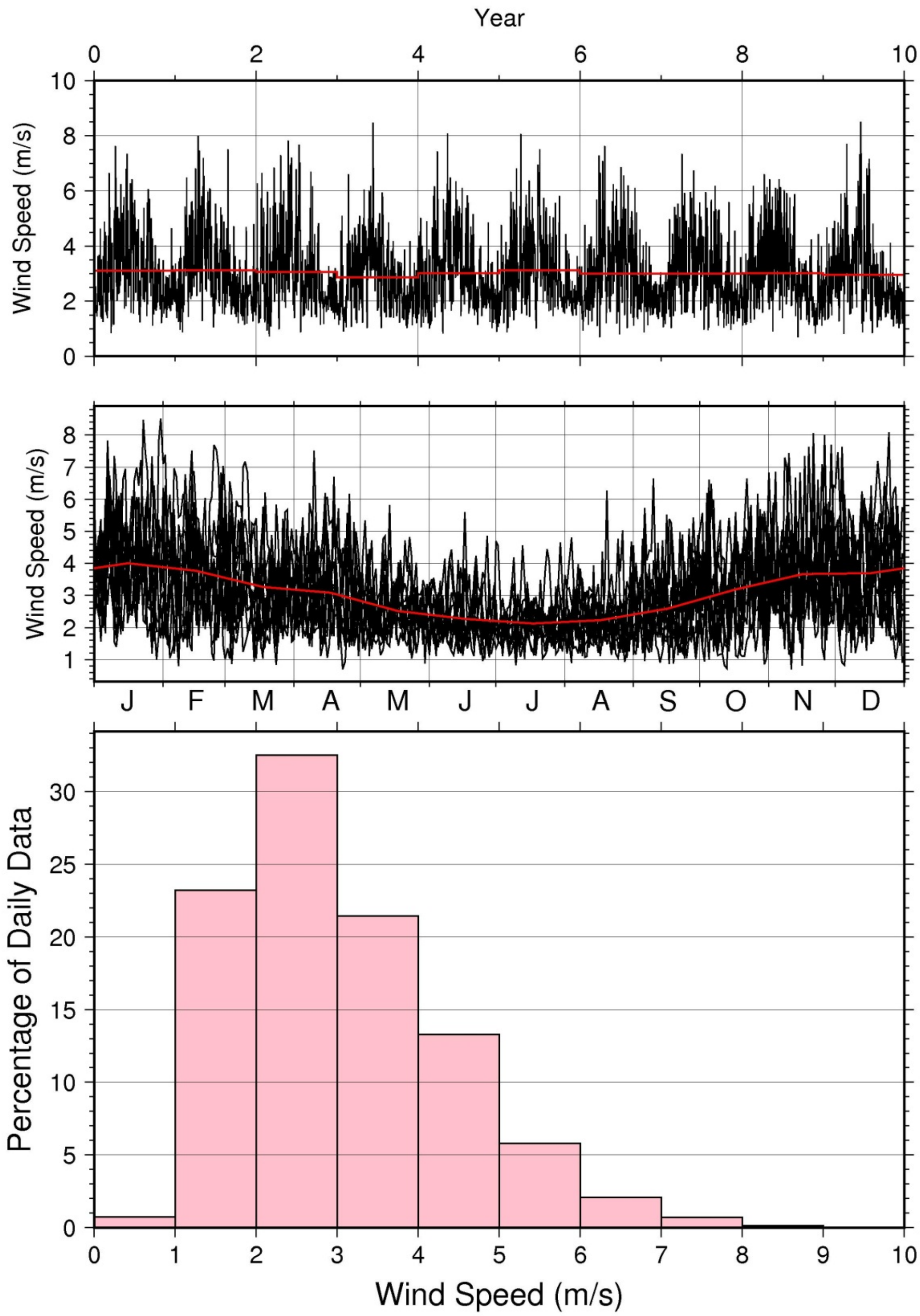


Figure A-8: Mean daily wind speed at 10 m elevation used in the Brucejack Lake model (source: NCEP 1983-2009)

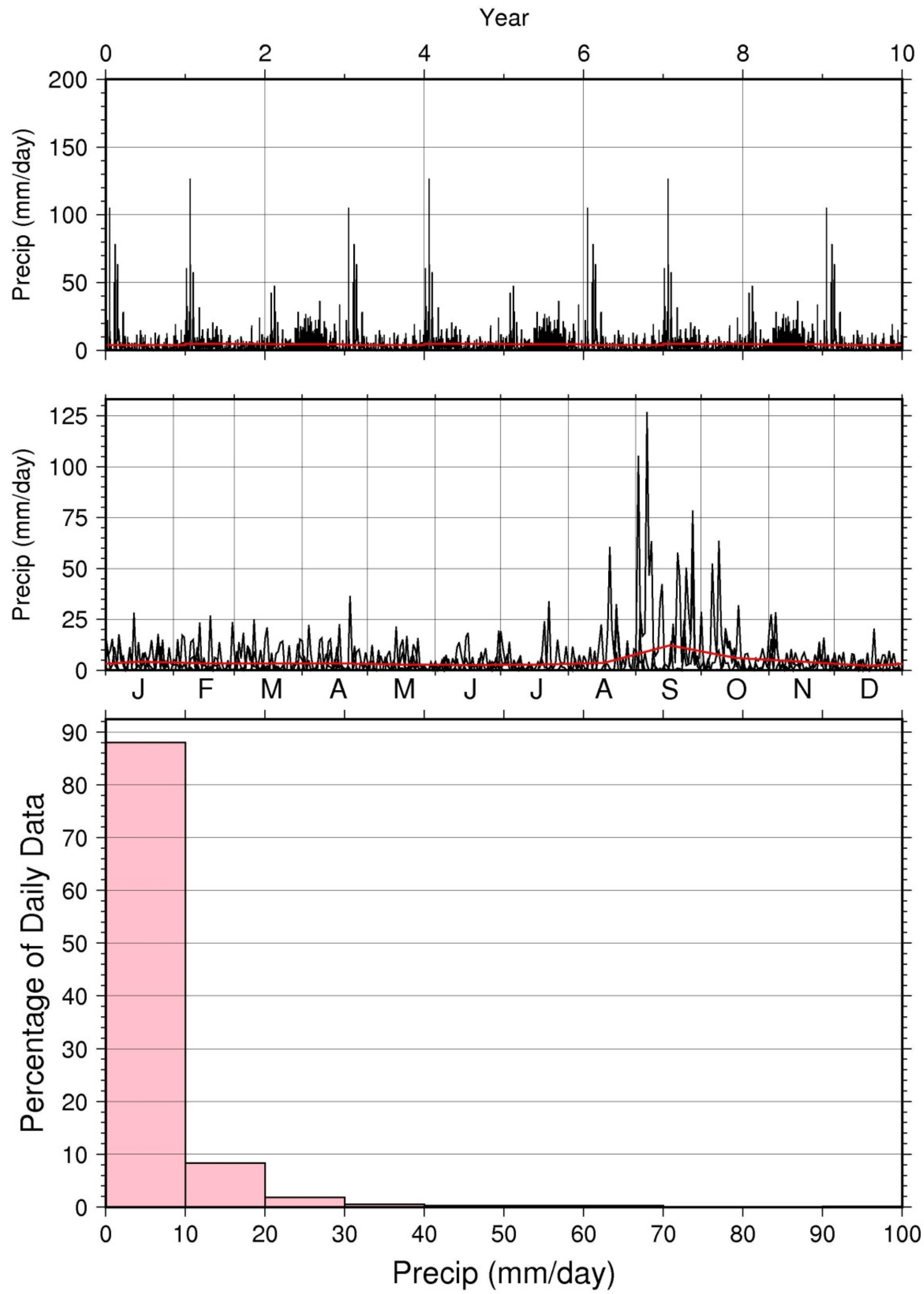


Figure A-9: Precipitation used in the Brucejack Lake model (source: site measurements)

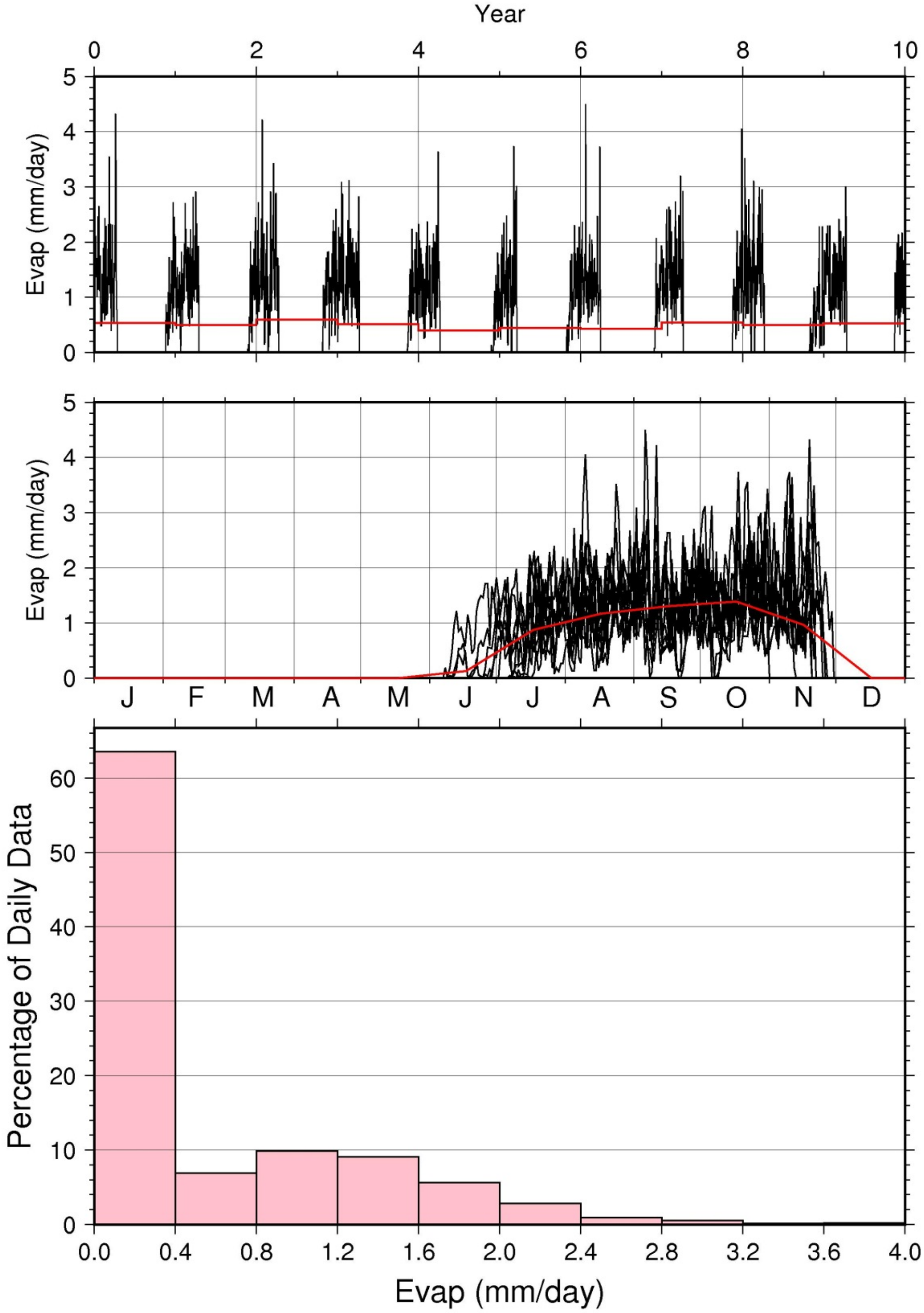


Figure A-10: Evaporation used in the Brucejack Lake model (source: calculated in the model)

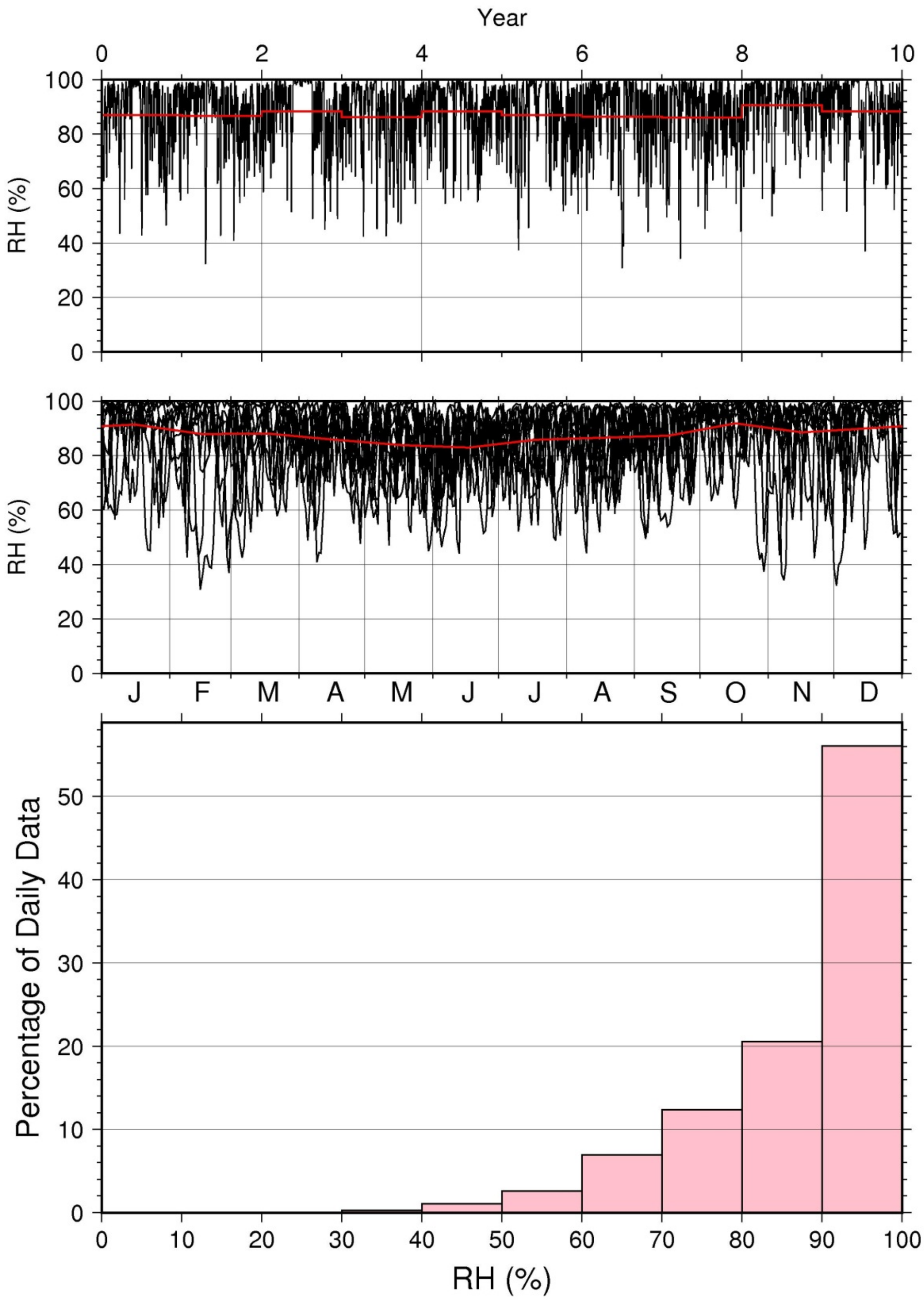


Figure A-11: 1Daily mean Relative Humidity used in the Brucejack Lake model (source: NCEP 1983-2009)

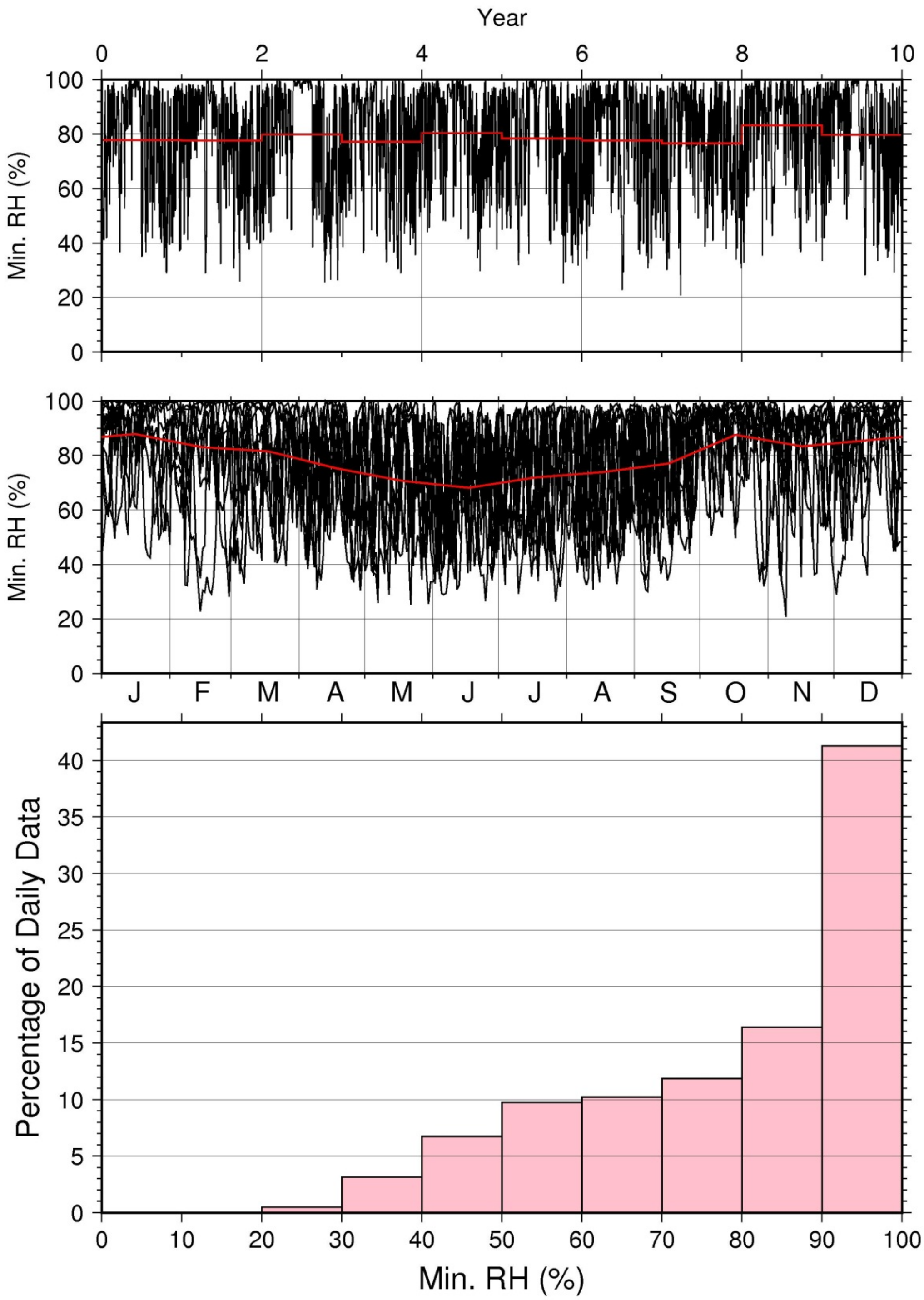


Figure A-13: Minimum daily Relative Humidity used in the Brucejack Lake model (source: NCEP 1983-2009)

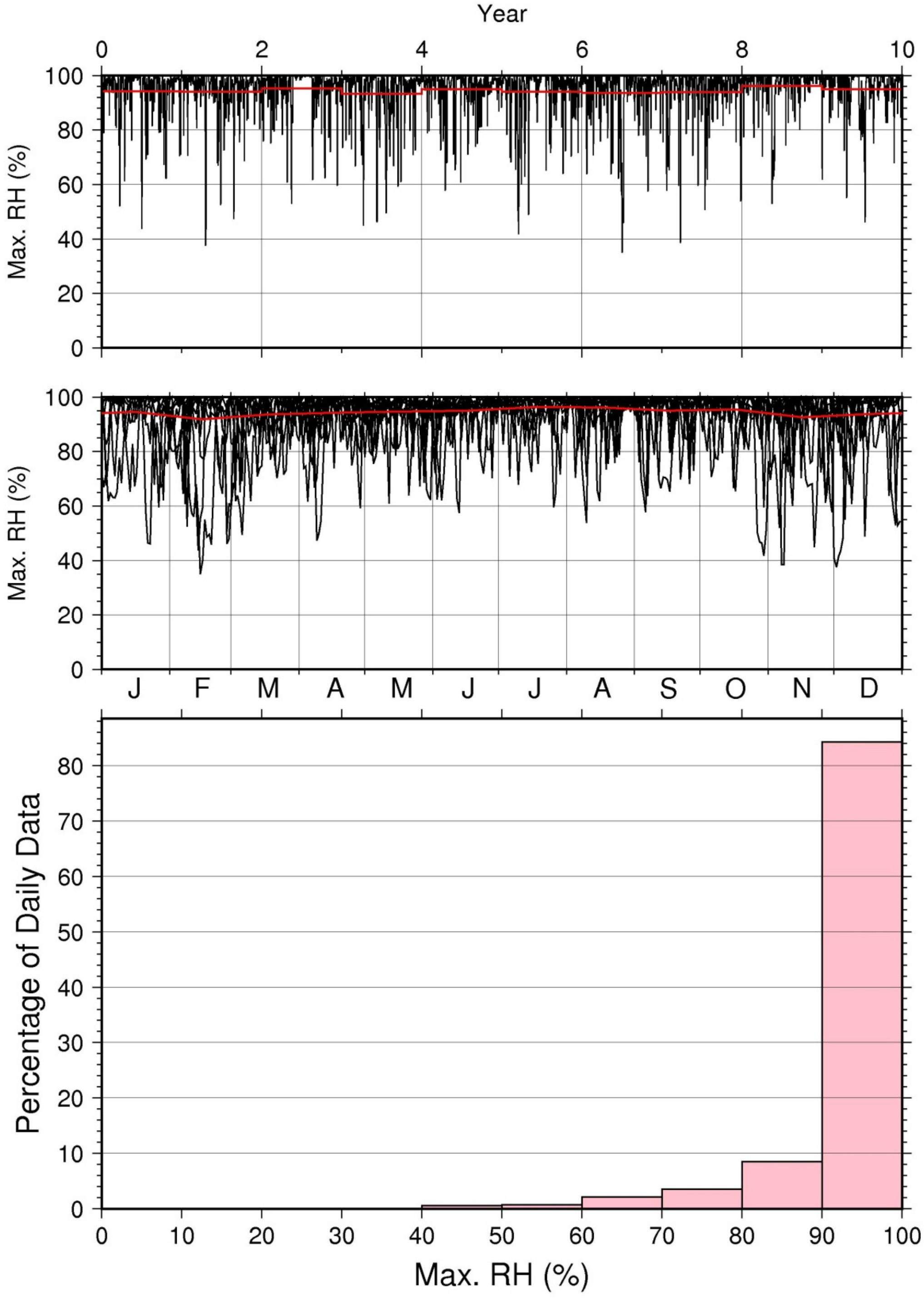


Figure A-14: Maximum daily Relative Humidity used in the Brucejack Lake model (source: NCEP 1983-2009)